

Probabilistic Consequence Model of Accidental or Intentional Chemical Releases

Decision and Information Sciences Division



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by

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for

U.S. Department of Homeland Security

Science and Technology Directorate

November 2007



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NOTATION

ACRONYMS AND ABBREVIATIONS

ACH	air change(s) per hour
AEGL	acute exposure guideline level
AFTOX	Air Force Toxic Chemical Dispersion Model
AIHA	American Industrial Hygiene Association
ALOHA	Areal Locations of Hazardous Atmospheres
API	American Petroleum Institute
AR	area affected
AS	source area
ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning Engineers
ATSDR	Agency for Toxic Substance Disease Registry
C ₂ H ₂ O	ethylene oxide
CAP-88	Clean Air Act Assessment Package-1988
CEPPO	Chemical Emergency Preparedness and Prevention Office
CIP/DSS	Critical Infrastructure Protection Decision Support System
DEGADIS	Dense Gas Dispersion (model)
DHHS	U.S. Department of Health and Human Services
DOA	dead on arrival
DOE	U.S. Department of Energy
DTRA	Defense Threat Reduction Agency
EPA	U.S. Environmental Protection Agency
ER	emergency room
ERPG	Emergency Response Planning Guidelines
GUI	graphical user interface
HB	hospital beds affected
HC 1, 2, 3	health criterion level 1, 2, 3
HCl	hydrochloric acid
HCIO	hypochlorous acid
HF	hydrogen fluoride
Hg	mercury
HPAC	Hazard Prediction and Assessment Capability (model)
HS	height of release
HUSWO	Hourly U.S. Weather Observations
IARC	International Agency for Research on Cancer
ICU	intensive care unit

IDLH	immediately dangerous to life or health
IDSPL	spill source type
ISCLT3	Industrial Source Complex – Long Term (model)
LC ₁₀	lethal concentration, low
LC ₅₀	lethal concentration, 50%
LC ₁₀₀	lethal concentration, 100%
LFL	lower flammability limit
LOAEL	lowest observed adverse effect level
LOC	level of concern
MIC	methyl isocyanate
NAC	National Advisory Committee
NBC	nuclear, biological, and chemical
NIOSH	National Institute for Occupational Safety and Health
NOAA	National Oceanic and Atmospheric Administration
NOAEL	no observed adverse effect level
NRC	National Research Council
OSHA	Occupational Safety and Health Administration
PC	personal computer
PCRAMMET	PC version of the original RAMMET program
PEL	permissible exposure limit
PVC	polyvinyl chloride
RMP	risk management plan
SCAPA	Subcommittee on Consequence Assessment and Protective Actions
SIP	shelter-in-place
STAR	Stability Array (model)
STEL	short-term exposure limit
TAV	averaging time
TC	typical case
TEEL	temporary emergency exposure limit
TS	source temperature
TWA	time-weighted average
USAF	U.S. Air Force
WC	worst case
WMD	weapons of mass destruction

UNITS OF MEASURE

°C	degree(s) Celsius
d	day(s)
°F	degree(s) Fahrenheit
h	hour(s)
in.	inch(es)
J	joule(s)
kg	kilogram(s)
km	kilometer(s)
l	liter(s)
lb	pound(s)
m	meter(s)
m ²	square meter(s)
m ³	cubic meter(s)
mi	mile(s)
min	minute(s)
mm	millimeter(s)
mph	mile(s) per hour
ppm	part(s) per million
s	second(s)
wk	week(s)

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ABSTRACT

In this work, general methodologies for evaluating the impacts of large-scale toxic chemical releases are proposed. The potential numbers of injuries and fatalities, the numbers of hospital beds, and the geographical areas rendered unusable during and some time after the occurrence and passage of a toxic plume are estimated on a probabilistic basis. To arrive at these estimates, historical accidental release data, maximum stored volumes, and meteorological data were used as inputs into the SLAB accidental chemical release model. Toxic gas footprints from the model were overlaid onto detailed population and hospital distribution data for a given region to estimate potential impacts. Output results are in the form of a generic statistical distribution of injuries and fatalities associated with specific toxic chemicals and regions of the United States. In addition, indoor hazards were estimated, so the model can provide contingency plans for either shelter-in-place or evacuation when an accident occurs. The stochastic distributions of injuries and fatalities are being used in a U.S. Department of Homeland Security-sponsored decision support system as source terms for a Monte Carlo simulation that evaluates potential measures for mitigating terrorist threats. This information can also be used to support the formulation of evacuation plans and to estimate damage and cleanup costs.

1 INTRODUCTION

Across the United States, thousands of industrial facilities use and store hazardous chemicals in large quantities. These chemicals are subject to major releases that could be triggered either accidentally (e.g., operational mishaps, such as human error or mechanical failure) or intentionally (e.g., through sabotage or terrorism). Such releases could endanger thousands or even millions of people who live in communities in close proximity to these facilities. According to the U.S. Environmental Protection Agency (EPA), 106 facilities would each endanger at least 1 million people in the event of a worst-case chemical release (Purvis and Herman 2005). Another 3,000 facilities would endanger at least 10,000 people. Nearly 5,000 facilities store more than 100,000 lb of at least one EPA-classified “extremely hazardous substance.”

Each year, an enormous number of chemical release accidents occur in the United States. According to Lewis (2002), each year, between 25,000 and 50,000 accidental releases of hazardous materials to the environment occurred at industrial facilities where extremely

hazardous substances were used, stored, and/or produced (Lewis 2002). These releases resulted in 100 or more deaths and thousands of injuries at refineries, chemical plants, water utilities, and in other industries. “Routine” accidents at industrial facilities were a pervasive problem long before the more recent concerns about terrorism. The magazine *Risk & Insurance* identified “industrial accident” as one of the 10 greatest risks we currently face in the United States (RMS 2004). Recently, the Bush Administration listed 15 potential disaster scenarios on which to focus homeland security procedures; one of these scenarios involved the deliberate explosion of a chlorine tank at an industrial facility (HSC 2005).

The greatest industrial disaster in history occurred in December 1984 in Bhopal, India (located in central India). A highly toxic and heavier-than-air cloud of methyl isocyanate (MIC) burst from the Union Carbide pesticide plant and rolled over the ground throughout the city under a light wind and stable atmosphere. Of the 800,000 people living in Bhopal at the time, 2,000 died immediately, another 13,000 died in subsequent years as a result of the accident, and as many as 300,000 were injured. The Bhopal disaster resulted from a combination of legal, technological, organizational, and human errors. The immediate cause of the chemical reaction was the seepage of water (500 l) into the MIC storage tank. The results of this reaction were exacerbated by the failure of containment and safety measures and by a complete absence of community information and emergency procedures. The incident marked a turning point for many concerned parties, including the chemical industry, neighboring communities, government regulating agencies, policy makers, and others. As a result, industrial safety standards came of age.

The Bhopal tragedy, followed by a subsequent release of the same substance (MIC) from Bhopal’s sister facility in Institute, West Virginia, resulted in great public concern in the United States about the potential danger posed by major chemical accidents. This public concern was translated into law in section 112(r) of the 1990 Clean Air Act Amendments and became the basis of the EPA’s rule on “Risk Management Programs for Chemical Accidental Release Prevention.”

National security experts recognize that a terrorist attack on chemical facilities and refineries is more likely than an attack that uses a conventional chemical weapon. Developing chemical weapons — one of the weapons of mass destruction (WMD) that terrorist groups are believed to be aggressively pursuing — is still a complex and expensive process, although it is not as complex and expensive as developing nuclear weapons. Further, developing these weapons poses great dangers to terrorists themselves because of toxicity and/or chemical instability. On the other hand, the proximity of ubiquitous industrial facilities to population centers provides relatively easy access to large amounts of chemicals from which a significant chemical release could harm considerable numbers of people and infrastructures. In short, facilities that routinely store and produce chemicals can be converted into sites of mass destruction by terrorists. Such attacks could inflict massive human loss and economic damage. Above all, an attack could disrupt the very core of democratic society and create widespread and long-term psychological trauma, as did the 9-11 terrorist assaults.

Since September 11, 2001, it has become increasingly apparent that chemical facilities, refineries, and modes of hazardous chemical transportation may become targets of terrorist

attacks. For example, federal investigators have warned that terrorist networks may be targeting hazardous materials in trucks or in stockpiles. A southwest Tennessee pilot reported that Mohamed Atta, the suspected ringleader of the 9-11 hijackings, asked about a chemical plant and water reservoir that he flew over in a light airplane. Also, copies of U.S. chemical trade publications were found in one of Osama bin Laden's hideouts (Grimaldi and Gugliotta 2001). These revelations indicate that terrorist organizations are interested in chemical plant attacks as a viable option to inflict large impacts.

As part of a risk management planning program, companies have been required to generate and submit to the EPA worst-case and alternative (more likely) release scenarios. In the past, many companies asserted that the worst-case scenarios were highly unlikely. However, as the 9-11 incident revealed, terrorists who are intent on causing mass casualties and property damage could potentially override all the safety measures in place at industrial facilities to prevent releases and could cause catastrophic chemical releases through assaults on storage tanks by aircraft, rocket launchers, or other currently unanticipated and inconceivable methods. In the face of potential terrorist assaults, it can no longer be taken for granted that worst-case release scenarios could not occur.

Even before September 11, 2001, the Agency for Toxic Substances and Disease Registry (ATSDR) addressed the issue of hazardous chemicals at industrial facilities in the United States (ATSDR 1999). The study focused on chemical site security in two key chemical communities: the Kanawha Valley in West Virginia and Las Vegas, Nevada. The study found that the chemical industry was unable to fend off terrorist attacks, noting that industrial chemicals provide terrorists with "effective and readily accessible materials to develop improvised explosives, incendiaries and poisons."

An Army Surgeon General's analysis showed that attacks on toxic chemical plants or chemical stockpiles could produce more than twice as many casualties as the number previously assumed in other worst-case scenarios envisioned by the U.S. Government (Pianin 2002). The study ranked the risks from attacks against chemical plants second only to the risks from the widespread use of biological weapons, such as the introduction of a smallpox virus or the contamination of the country's water or food supply (which could generate more than 4 million casualties).

Since September 11, 2001, our nation has tightened security in a variety of venues. Airports and airlines have numerous new regulations they must follow; critical infrastructures and national borders have routinely been patrolled by persons using many modes of transportation (e.g., airplanes, boats, cars, or on foot). The U.S. Government also established an entire new governmental department, the U.S. Department of Homeland Security, to coordinate security measures. Across the country, many industrial facilities have made major progress by switching to inherently safer chemicals and processes that pose a lesser threat to surrounding communities in the event of a major chemical release. For example, soon after 9-11, the Blue Plains Sewage Treatment Plant in Washington, D.C., switched from using and storing chlorine and sulfur dioxide on-site to using sodium hypochlorite bleach in its processes, which is far more benign if accidentally released (Leonnig and Hsu 2001). Also, many industrial facilities bolstered their physical security through such measures as hiring more guards, conducting employee

background checks more rigorously, and fortifying perimeter security. These steps may all be part of a strong security plan, but they do not actually reduce the threat to the community if a release were to occur. If facilities were to switch chemicals and processes to less volatile alternatives, both the chemical hazard to the community and the need for costly add-on security measures could be reduced, and the attractiveness of the facility as a target for attack could be lessened. Nevertheless, many industrial facilities around the country remain vulnerable to an accident or terrorist attack for various reasons: Facilities may store and use high volumes of toxic chemicals near population centers, or there may be a lack of awareness of potential hazards, lax security measures, poor emergency response capabilities, etc.

Fortunately, the United States has not yet experienced a Bhopal-scale catastrophic chemical disaster. However, as long as the industrial facilities near population centers produce, store, and/or use large amounts of hazardous materials, the potential exists for a tragedy of large magnitude to occur, whether triggered by the accidental or intentional release of chemicals.

In this study, an urban chemical model was developed to estimate total risk to populations and to aid in the formulation of emergency plans to address chemical releases triggered by accidents or terrorist attacks. It runs probabilistic simulations of large-scale chemical releases in metropolitan areas, while accounting for uncertainties in weather conditions and release amounts. For initial modeling runs, chlorine was selected because it is a commonly used chemical that is stored in large quantities in the United States. Chlorine and ammonia together account for about half of all the facilities in the United States that store high volumes of extremely hazardous substances reported under risk management planning. They also account for the most releases reported in risk management plans. On the basis of historical chemical accidents that occurred from 1994 through 1999 in the United States, anhydrous ammonia was recorded as the chemical released in the highest number of accidents, followed by chlorine (Lewis 2002).

The outputs of the simulations were frequency distributions for the numbers of persons affected (e.g., fatalities, injuries), percentages of hospital beds that became unavailable, and geographic areas affected. Appropriate health criteria were used to convert the numbers of persons affected to the damage level variables (e.g., numbers treated in an emergency room [ER], numbers admitted to the hospital). Information from these analyses can be used to support the formulation of evacuation plans and other mitigation activities and estimate damage and cleanup costs.

Section 2 of this report provides a detailed description of the methodologies developed for this analysis. Results and discussion are presented in Section 3, while Section 4 discusses the detailed background information on health criteria used in the analysis. Concluding remarks and potential future work are highlighted in Section 5.

Appendix A presents the input and output files from the SLAB accidental chemical release model, along with an explanation of model input parameters. Best-fit parameter values for time vs. potential impacts (such as persons, hospital beds, geographical areas affected) for four regions are presented in Appendix B.

2 DESCRIPTION OF METHODOLOGIES

In general, the major steps of a chemical accident analysis consist of (1) constructing the source term/release scenario, (2) characterizing the range of possible environmental conditions, (3) conducting chemical accidental release modeling, (4) performing impact (consequence) analysis, and (5) implementing mitigation measures as needed, as shown in Figure 1.

To estimate potential impacts statistically for a site of interest, chemical accidental release modeling is performed to exercise all possible scenarios: combinations of chemical release amounts and meteorological conditions. It is impractical, albeit not impossible, to simulate the accidental release model for a combination of many different chemical release rates and several years' worth of hourly meteorological data (i.e., hundreds of thousands of scenarios or more in total). Accordingly, it is reasonable to reduce the myriad of all possible scenarios into a manageable number of scenarios. In sum, although the detailed aspects of postulated hypothetical scenarios cannot be known, this proposed approach encompasses the potential range of toxic chemical releases and meteorological conditions by applying probability distributions for both the source term and the meteorology.

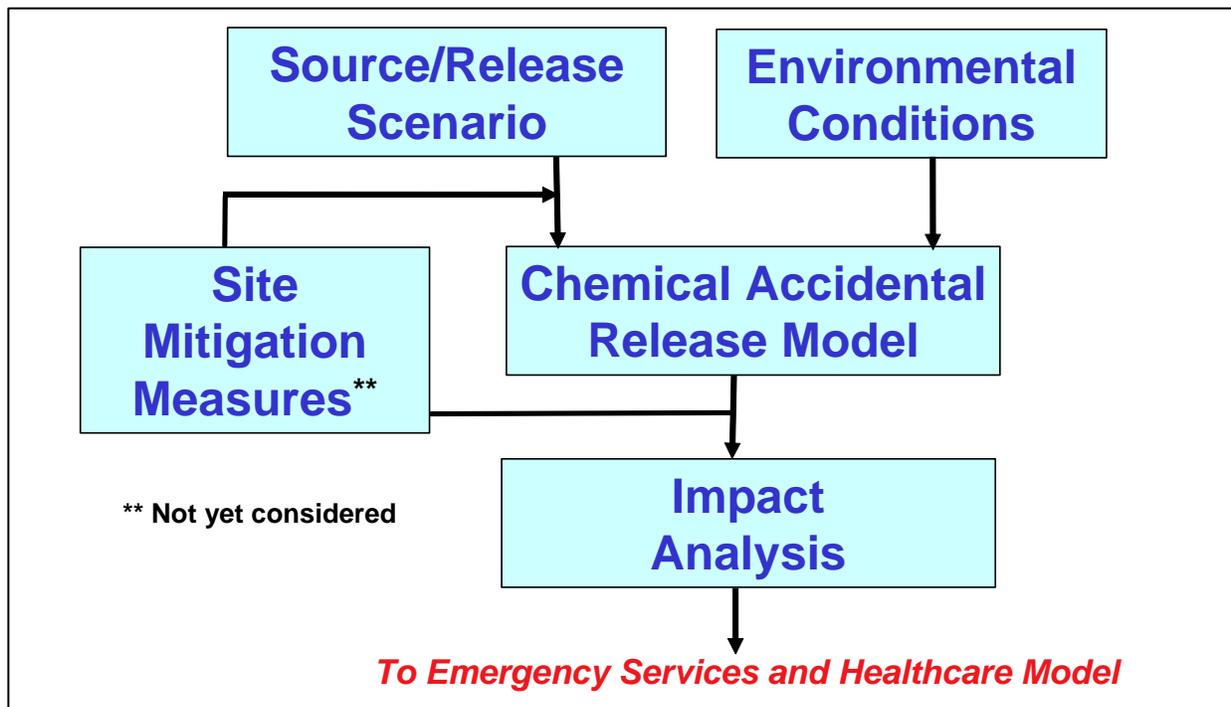


FIGURE 1 Major Components of Chemical Accident Analysis

First, all possible source terms and release conditions (e.g., release amounts, durations of release, release heights, sizes of tank rupture) are identified. For convenience, all possible release amounts (called “source terms”) are classified into four or five groups, and a release condition is determined that would produce the highest impacts. Then, meteorological conditions that are representative of the region of interest are identified. For this analysis, hourly meteorological conditions for several years are summarized into representative meteorological conditions, called the STAR (STability Array) summaries, which are widely used in long-term air quality modeling analysis. A total of about 2,000 scenarios, which are combinations of four or five source release groups and about 400 representative meteorological conditions, are simulated by using an accidental chemical release model (e.g., SLAB). On the basis of given health criteria, plume footprints¹ estimated from the model are overlaid on population and hospital bed distribution data to evaluate the potential impacts. Regression curves obtained from potential impacts are input to an emergency services and healthcare model to aid in impact analysis and emergency planning.

In general, there are some site mitigation measures in place at industrial facilities. Examples include passive barriers, such as dikes around storage tanks, or active barriers, such as spray curtains that spray water steam onto a vapor cloud and either knock down a significant portion of the cloud or dilute the cloud to make it buoyant near the release point before it becomes full-blown. Site mitigation measures are not considered in this analysis so that any errors are on the side of overestimating potential impacts.

The output of the analysis is a statistical distribution of potential impacts (persons, hospital beds, and areas affected) for a given toxic chemical and region. This information is used to support chemical scenario modeling for the Critical Infrastructure Protection/Decision Support System (CIP/DSS) project, which uses Monte Carlo sampling in dynamic simulation models to characterize the resources and demands for interdependent infrastructure services impacted by an event over time.

The systems dynamics methodology was used to construct simulation models of dynamic systems. It was developed at Argonne National Laboratory (Argonne) by using Vensim (Ventana Systems, Inc. 2008) and incorporating the results of probabilistic assessments of the potential impacts that could result from a large-scale release of chlorine in an urban setting.

The project activities are described in Section 2.1, and one chemical of interest — chlorine — is discussed in Section 2.2. The methodology used to develop chemical release source terms is discussed in Section 2.3, and meteorological data are summarized in Section 2.4. Models that are widely used in evaluating accidental chemical releases are presented in Section 2.5, and model input parameters are included in Section 2.6. The health criteria used to estimate footprints are discussed in Section 2.7, and SLAB model outputs and footprint estimation are provided in Section 2.8. The methodology used for impact (or consequence)

¹ A footprint represents an overhead view of the area where the ground-level pollutant concentration is predicted to exceed the level of concern (i.e., health criteria) at some time after a release begins.

analysis is discussed in Section 2.9, and a summary of calculation procedures is included in Section 2.10.

2.1 PROJECT ACTIVITIES

The U.S. Congress passed a series of laws intended to minimize the likelihood and consequences of catastrophic chemical accidents. The EPA established the Risk Management Program, which took effect in June 1999; it requires certain chemical facilities that use certain flammable and hazardous toxic substances to develop a Risk Management Program and to submit summary reports to the government every five years. A substantive risk management plan (RMP) must contain four basic elements as follows:

1. Management system (to oversee implementation of the overall program),
2. Hazard assessment (to assess potential off-site exposures),
3. Prevention program (to develop accident prevention procedures), and
4. Emergency response program (to require emergency planning for public areas).

Approximately 15,000 facility reports have been received to date, and these contain significant information on each facility's accident history, accident prevention program, and the potential consequences of hypothetical accidental chemical releases. These data have been assembled into a searchable computerized database called RMP*Info. (Argonne has a copy of the full RMP*Info database received through the U.S. Department of Defense [DoD] for the year 2002.)

The current National Chemical model simulates the stocks and flows of chlorine within the four U.S. Bureau of the Census (Census) Regions (Northeast, South, West, and Midwest), which represent the contiguous Lower 48 States, Alaska, and Hawaii (see Figure 2). A regional approach was applied in the systems dynamics model that uses state-level data aggregated to a lower number of Census Regions.

The overall goal of the chemical release scenario evaluation is to provide a flexible modeling framework for studying large-scale chemical releases of toxic chemicals, such as chlorine, ammonia, sulfur dioxide, and hydrogen fluoride, in a metropolitan area. These chemicals have been identified to be most commonly used and stored in large quantities throughout the United States, as shown in Table 1. However, this report addresses only chlorine releases; other chemicals may be addressed in follow-on work.

The tasks of this project were as follows:

1. Determine which metropolitan areas within each Census Region are most at risk from a worst-case release of chlorine by examining the numbers of people who are identified in the EPA RMP database as being potentially subject to off-site exposure.

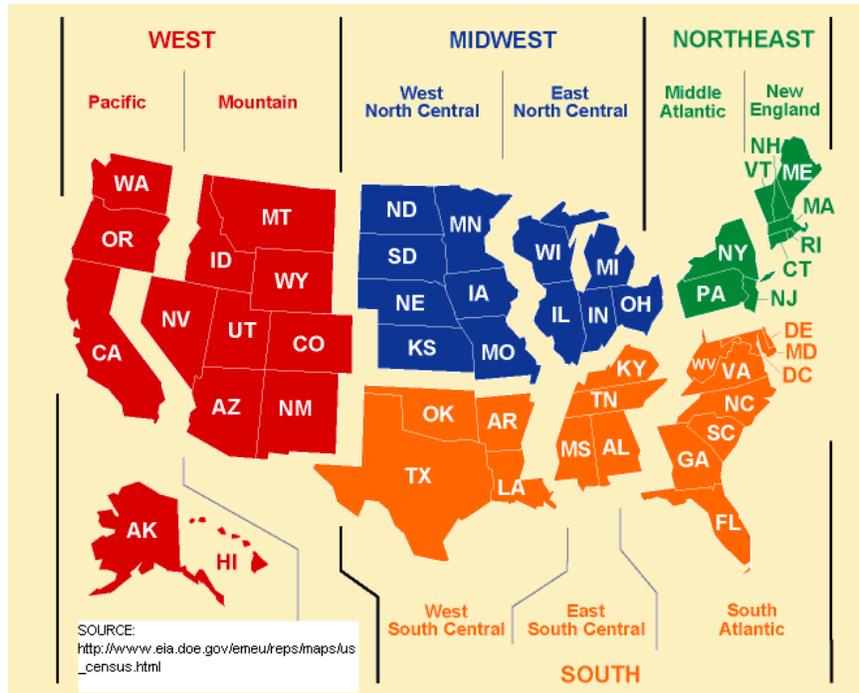


FIGURE 2 Map Indicating the U.S. Census Regions and Districts (Source: EIA 2000)

TABLE 1 Frequency Distribution of Top 10 RMP Chemicals

Chemical	Number of Processes	Percentage of Total
Ammonia (anhydrous)	8,343	32.5
Chlorine	4,682	18.3
Flammable mixtures	2,830	11.0
Propane	1,707	6.7
Sulfur dioxide	768	3.0
Ammonia (aqueous 20% or more concentration)	519	2.0
Butane	482	1.9
Formaldehyde	358	1.4
Isobutane	344	1.3
Hydrogen fluoride	315	1.2

Source: Belke (2000).

2. By using EPA RMP data, determine which production plants (or chemical storage facilities, etc.) for each of the four identified chemicals are located near metropolitan areas. The RMP data would be used to screen potential release locations and to develop an initial source term database.
3. Determine probabilistic distributions of potential worst-case source terms for chlorine for the appropriate metropolitan area. This effort would take the form of an Access database and would be based on developing frequency histograms for the amount of chemical released.
4. By using estimates of the number of potential impacts (e.g., persons [fatalities and injuries], hospital beds occupied, geographical areas affected) on the basis of the calculated chemical concentrations and population exposure within a given metropolitan area, incorporate these results into a systems dynamics modeling framework for the chemical industry.

A series of Microsoft Access queries (Figure 3) was developed to determine which metropolitan areas would have the largest potentially affected population within each Census Region. The results of the Access queries were then sorted to determine the potentially affected population as a function of facility type and location (Figure 4). The actual location for toxic gas dispersion calculations was taken to be the facility within each Census Region for which the largest number of people could be adversely affected by a catastrophic chlorine release.

Four metropolitan areas were selected for examination, each located within one of the four Census Regions. A single facility within each metropolitan area was used as the postulated release point for the probabilistic source terms.

2.2 CHEMICAL OF INTEREST: CHLORINE

2.2.1 Physical and Chemical Properties

At room temperature, chlorine is a diatomic greenish-yellow noncombustible gas and has a strong, pungent, and suffocating odor (ATSDR 2006). Chlorine gas is 2.5 times heavier than air and may collect in low-lying areas. It is a strong oxidizing agent and is not flammable, but it can react explosively or form explosive compounds with many common substances, such as acetylene, turpentine, ether, ammonia, fuel gas, hydrogen, and finely divided metals. Under increased pressure or temperatures lower than -34°C (-29°F), it turns to a clear, amber-colored liquid.

Chlorine is widely stored and used in many chemical plants and industrial facilities. It is generally shipped in steel cylinders as a compressed liquefied gas under its own vapor pressure. Upon accidental release, the liquid pressure immediately drops to ambient pressure, resulting in sudden vaporization of some or all of the liquid, a process that is termed “adiabatic flash.” Chlorine can expand as much as 460 times. The chlorine cloud generally forms a two-phase flow

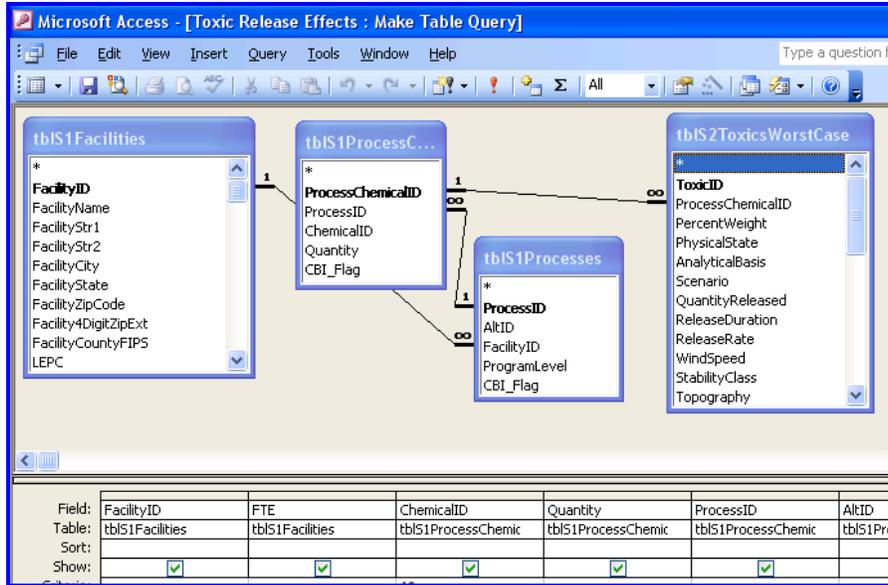


FIGURE 3 Example Access Query to Determine Potentially Affected Population

Quantity	ProcessID	AltID	QuantityReleased	ResidentialPopulation
1999999	35994	Repackaging/Hypo Manufact	180000	12000000
999999	2247	Repackaging/Hypo Manufact	180000	12000000
1999999	28447	Repackaging/Hypo Manufact	180000	12000000
720000	8127	Wastewater Disinfection	180000	10740000
900000	36505		180000	8050000
900000	37122		180000	8050000
540000	24701		180000	8050000
180000	30598	chlorine	180000	4574197
180000	9911	chlorine	180000	4574197
180000	24423	chlorine	180000	4574197
180000	6262	Storage	180000	4530000
900000	37343	Storage	180000	4530000
180000	33769	Storage	180000	4530000
720000	8951		180000	4400000
180000	5883	Ferric Chloride System	180000	4300000
1100000	10145	Dispersants	180000	4200000
1100000	37062	Dispersants	180000	4200000
180000	9587	Storage	180000	3960000
900000	37440	Storage	180000	3960000

FIGURE 4 Example Data Showing the Affected Population as a Function of Facility Type

of gas and aerosol. The presence of aerosols tends to keep the emitted cloud cooler (by vaporization) while it is being transported downwind. Aerosols also make the cloud heavier than air at distances further downwind than it would be without aerosols.

Chlorine is only slightly soluble in water, but on contact with moisture (either in air, water, or soil), it forms hypochlorous acid (HClO) and hydrochloric acid (HCl). The unstable HClO readily decomposes, forming oxygen free radicals. Because of these reactions, water substantially enhances chlorine's oxidizing and corrosive effects. A brief summary of selected physical properties of chlorine is presented in the adjoining text box.

Physical Properties of Chlorine (Cl ₂ ; CAS RN: 7782-50-5)	
Property	Value
Description	Yellowish-green gas at room temperature; clear amber-colored liquid under pressure or cold temperatures
Molecular weight	70.9 daltons
Melting point	-101°C (-150°F)
Boiling point	-34°C (-29°F)
Gas density	2.5 (air = 1)
Specific gravity	1.56 at boiling point (water = 1)
Solubility in water	0.7% at 20°C (68°F)
Vapor pressure	5,168 mm mercury (Hg) at 20°C (68°F)
Source: ATSDR (2006).	

2.2.2 Environmental Fate

Chlorine absorbs some wavelengths of ultraviolet and visible sunlight and undergoes rapid chemical reactions in the atmosphere. The atmospheric half-life and lifetime of chlorine resulting from these reactions are estimated to be about 10 min and 14 min, respectively. The chlorine atoms produced will then react with organic compounds (mainly alkanes in polluted urban areas) to form hydrogen chloride and organochlorine compounds (AG-DEWR 2005). When released into air, chlorine will react with moisture to form HClO and HCl, which are removed from the atmosphere by rainfall (ATSDR 2006). In water, HClO formed from reaction with water breaks down rapidly. The HCl also breaks down; its breakdown products will lower the pH of the water (that is, make it more acidic). Since chlorine is a gas, it is rarely found in soil. If released to soil, chlorine will react with moisture to form HClO and HCl. These compounds can react with other substances found in soil. There is no potential for the bioaccumulation or bioconcentration of chlorine in the food chain.

2.2.3 Health Effects

Chlorine gas is irritating and corrosive to the eyes, skin, and respiratory tract (ATSDR 2006). The effects depend on how much and for how long you are exposed to it. Exposure to low concentrations of chlorine gas (1 to 10 parts per million [ppm]) may cause a sore throat, coughing, and eye and skin irritation. Exposure to higher levels could cause burning of the eyes and skin, rapid breathing, narrowing of the bronchi, wheezing, blue coloring of the skin, accumulation of fluid in the lungs, and pain in the lung region. In high concentrations, chlorine can act as an asphyxiant (especially in poorly ventilated, enclosed, or low-lying areas, because chlorine is heavier than air) and cause respiratory distress, chest pain, loss of breath (leading to death), vomiting, filling of the lungs with fluid (pulmonary edema), and pneumonia. Exposure to even higher levels can produce severe eye and skin burns, lung collapse, and death.

Frostbite can result when the skin comes in contact with liquefied chlorine. The U.S. Department of Health and Human Services (DHHS), the International Agency for Research on Cancer (IARC), and the EPA have not classified chlorine as to its carcinogenicity.

Most exposures to chlorine occur by inhalation (ATSDR 2006). Chlorine's odor or irritant properties are discernible to most individuals at 0.32 ppm, which is lower than the permissible exposure limit (PEL) of 1 ppm as a "ceiling" limit (i.e., exposure limit that a worker shall at no time exceed, as set by the Occupational Safety and Health Administration [OSHA]). The National Institute for Occupational Safety and Health (NIOSH) immediately dangerous to life or health (IDLH) concentration — defined as the maximum exposure concentration of a given chemical in the workplace from which one could escape within 30 minutes without experiencing any escape-impairing symptoms or any irreversible health effects — was set at 10 ppm. Health criteria used in the analysis and their background information are discussed in general in Section 2.7 and in detail in Section 4.

2.2.4 Applications and Uses

Chlorine is produced commercially by electrolysis of sodium chloride brine. It is among the 10 chemicals manufactured in the highest volumes in the United States, with 1998 production in excess of 14 million tons (ATSDR 2006).

Chlorine is widely used in a number of industrial applications. Its largest use is in the production of chlorinated organics, including polyvinyl chloride (PVC) and other hazardous chemicals like perchloroethylene and trichloroethylene, which accounted for 76% of national chlorine consumption in 1995 (Lewis 2002). The production of PVC accounts for about one-third of national chlorine consumption. Use of chlorine for water purification processes, disinfectants, and drinking water and wastewater treatment accounts for 2–4%. Use for bleaching of paper in pulp and paper mills is also common.

Chlorine gas, a pulmonary (choking) agent, was first used as a chemical warfare agent in World War I. Its first large-scale use as a chemical agent was on April 22, 1915, when the Germans released chlorine gas against the Allied positions at Ypres, Belgium, to break the deadlock of trench warfare. Over 5,000 casualties resulted. After that attack, chlorine gas was used by both sides. As recently as in early 2007, car bombs laced with poisonous gases (chlorine in these cases), so-called "chemical dirty bombs," exploded in Iraq and resulted in many civilian casualties and injuries.

2.3 SOURCE TERMS

For the analysis, probabilistic source terms were developed on the basis of the EPA's database in RMP*Info. The worst-case release amounts of chlorine were determined as a function of facility type (production, repackaging, storage, water treatment, etc.) and Census Region and then binned into five representative release ranges. The frequency distributions of

these representative release ranges are shown in Table 2 for chlorine production facilities and in Table 3 for water treatment facilities.

After the variation in frequency distribution as a function of facility type was studied, a composite frequency distribution was developed on the basis of all facility types (Table 4). Average release amounts within each release bin were determined by simply summing the actual release quantities and then dividing that sum by the number of records (Table 5). The values in Tables 4 and 5 were used as inputs for toxic gas dispersion calculations.

2.4 METEOROLOGICAL CONDITIONS

Dispersion of the chemical releases in the atmosphere, either routinely from stacks or accidentally from storage tanks/pipelines, depends strongly on weather conditions, in particular

TABLE 2 Potential Source Term of a Worst-case Scenario Release of Chlorine from a Chlorine Production Facility by Region

Quantity Released (lb)	Percent of Total			
	Region 1	Region 2	Region 3	Region 4
0 to 1,000	0.0	1.0	43.5	5.9
1,001 to 10,000	33.3	32.3	0.0	44.1
10,001 to 100,000	0.0	4.2	0.0	2.9
100,001 to 1,000,000	60.0	58.3	56.5	47.1
Over 1,000,000	6.7	4.2	0.0	0.0

Source: EPA (1999b), Kleindorfer et al. (2000).

TABLE 3 Potential Source Term of a Worst-case Scenario Release of Chlorine from Water Treatment by Region

Quantity Released (lb)	Percent of Total			
	Region 1	Region 2	Region 3	Region 4
0 to 1,000	4.3	1.9	2.7	2.9
1,001 to 10,000	94.6	94.9	91.5	89.9
10,001 to 100,000	0.8	1.6	4.9	2.5
100,001 to 1,000,000	0.4	1.6	0.9	4.7
Over 1,000,000	0.0	0.0	0.0	0.0

Source: EPA (1999b), Kleindorfer et al. (2000).

TABLE 4 Potential Source Term of a Worst-case Scenario Release of Chlorine from All Sources by Region

Quantity Released (lb)	Percent of Total			
	Region 1	Region 2	Region 3	Region 4
0 to 1,000	2.6	3.0	3.6	3.0
1,001 to 10,000	84.7	85.3	81.1	80.6
10,001 to 100,000	1.8	2.1	5.5	2.7
100,001 to 1,000,000	10.4	9.4	9.8	13.6
Over 1,000,000	0.5	0.1	0.0	0.0

Source: EPA (1999b), Kleindorfer et al. (2000).

TABLE 5 Average Release Amount for the Potential Source Term of a Worst-case Scenario Release of Chlorine from All Sources by Region

Quantity Released (lb)	Average Value (lb)			
	Region 1	Region 2	Region 3	Region 4
0 to 1,000	200	200	200	200
1,001 to 10,000	2,000	2,000	2,000	2,000
10,001 to 100,000	30,000	40,000	40,000	30,000
100,001 to 1,000,000	200,000	200,000	200,000	200,000
Over 1,000,000	1,200,000	1,200,000	0	0

Source: EPA (1999b), Kleindorfer et al. (2000).

wind speed and direction and atmospheric stability. The Bhopal chemical disaster starkly demonstrated worst-case meteorological conditions: Light winds and stable atmospheres severely limited dilutions by atmospheric turbulence. The lower atmosphere, which is about 2,000–3,000 m from the ground, is the region where accidental releases would occur and life would be affected.

The EPA recommends the use of 5 years' worth of representative meteorological data when estimating concentrations with an air quality model. The underlying rationale for this recommendation is that 5 years' worth of hourly surface meteorological data would cover most possible combinations of meteorological conditions that could occur at the site of interest. However, the use of several years' worth of hourly meteorological data (~tens of thousands of hours) in combination with several source term release groups is impractical (albeit not impossible) for performing chemical accidental release modeling. Therefore, these data are summarized into a manageable number of representative meteorological conditions, which are called the STAR summaries and which still represent the general features of the spectrum of all possible meteorological conditions. The STAR summaries are widely used in long-term air

quality models (e.g., Industrial Source Complex-Long Term [ISCLT3]), radiological dispersion models (e.g., Clean Air Act Assessment Package-1988 [CAP-88]), and risk analyses.

The STAR summaries are a tabulation of the three-way joint frequency of occurrence of wind-speed and wind-direction categories, classified according to stability categories. For this analysis, six wind speed categories, 16 wind direction categories, and seven stability² classes were constructed on the basis of hourly surface meteorological data in the “Hourly U.S. Weather Observations 1990–1995” (HUSWO) database (NCDC 1997) (see Figure 5). This database includes wind speed and direction, ambient temperature, relative humidity, and cloud layer data (e.g., cloud cover and ceiling height). By using the Pasquill-Gifford stability classification scheme, the atmospheric stability class, which is a derived parameter rather than a directly measured parameter, was estimated on the basis of wind speed, cloud layer data (in daytime and at night), and solar elevation (in daytime) by the PCRAMMET program (EPA 1999a).

Wind speeds are classified into six categories defined in terms of meters-per-second ranges: 0–1.8, 1.8–3.3, 3.3–5.4, 5.4–8.5, 8.5–11.1, and >11.1 m/s, which are represented as 1.5, 2.5, 4.3, 6.8, 9.5, and 12.5 m/s, respectively. The 16 standard 22.5° wind direction sectors, which begin at north and move clockwise to end at north-northwest, are used in the analysis. The Pasquill-Gifford stability classes include: A (very unstable), B (moderately unstable), C (slightly

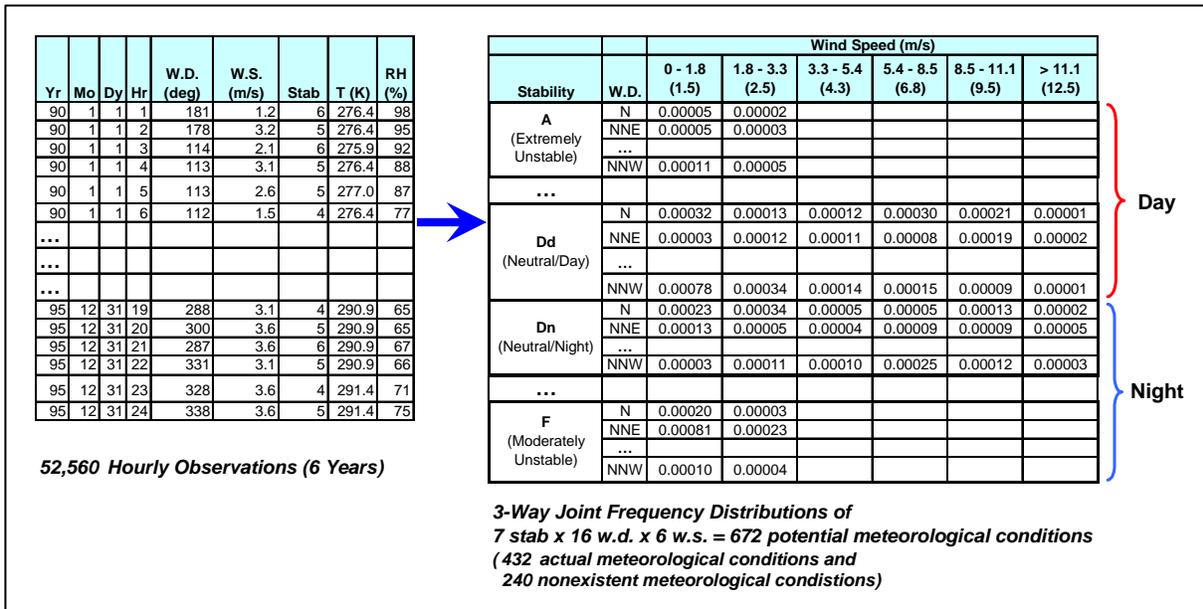


FIGURE 5 Conversion of Hourly Meteorological Data into STAR Summary Format (Source: NCDC 1997)

² Stability is a measure of the amount of turbulence in the atmosphere; the more turbulent the air, the more quickly a pollutant cloud is diluted.

stable), Dd (neutral/day), Dn (neutral/night), E (slightly stable), and F (moderately stable).³ In general, A-stability conditions occur in low winds with high incoming levels of solar radiation. E-stability and F-stability conditions arise on clear nights with little wind. D-stability class conditions occur with lower and higher wind speeds and greater cloud cover. A refinement of this method includes surface roughness height in the classification scheme, where increased roughness shifts more cases toward the neutral D-stability class conditions. For simplicity, this refinement is not exercised in this study. A total of 672 ($6 \times 16 \times 7$) combinations of representative meteorological conditions are possible, but a maximum of 432 meteorological conditions can realistically exist.⁴

As a sample graphical representation of a three-way joint frequency distribution, wind roses by stability class for Region 2 are presented in Figure 6. A segment on each spoke of the wind roses corresponds to one of a maximum of 432 meteorological conditions. From these wind roses, it can be concluded that the predominant wind direction for the site is from the southeast, and nearly half of the time the atmosphere is classified as being in the neutral stability class (Dd + Dn). In addition, as the atmospheric classification moves further away from D stability class (e.g., to A or F stability class), the wind speed lowers (see dotted lines in wind roses).

Corresponding to each representative meteorological condition, the minimum, average, and maximum values of ambient temperatures and relative humidity are also summarized. These are also inputs to the chemical accidental release model.

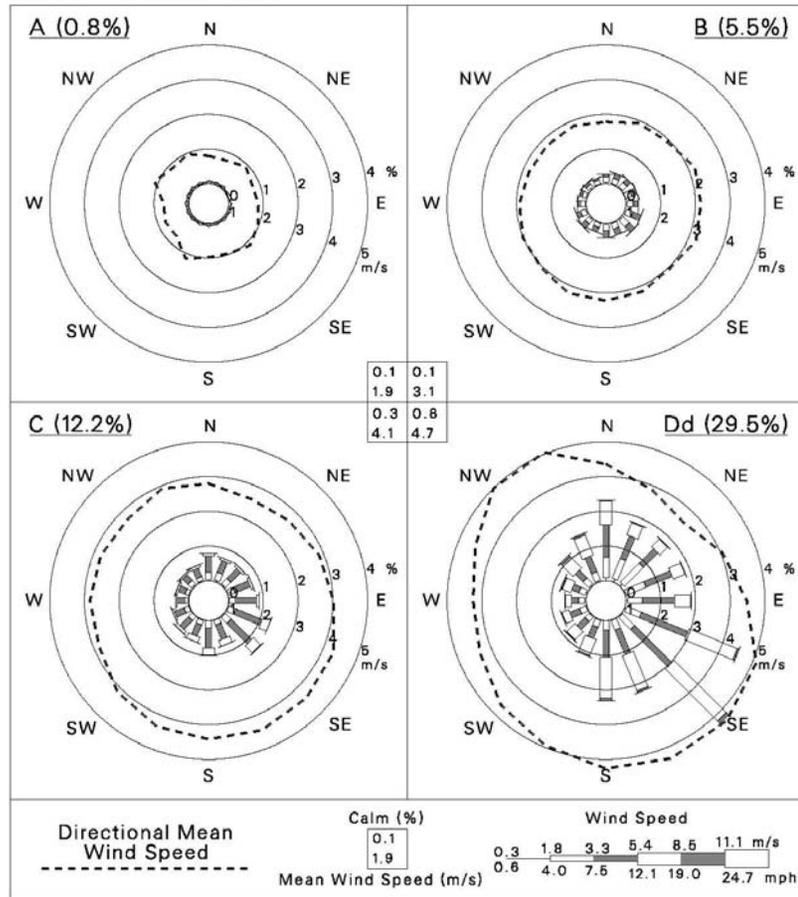
2.5 CHEMICAL RELEASE AND DISPERSION MODELS

A few tens of analytical or numerical chemical accidental release models are available. Some of them are proprietary, and a handful are available in the public domain. The following is a brief description and summary of the advantages and disadvantages of selected chemical accident models available in the public domain. Except for hydrogen fluoride in the HGSYSTEM model, most of the accidental release models do not account for chemical reactions or for the by-products of combustion (e.g., smoke). Except for the Hazard Prediction and Assessment Capability (HPAC) model, accidental release models assume that the terrain under a

³ The PCRAMMET program calculates D stability only, which is in turn classified into Dd (neutral/day) and Dn (neutral/night) on the basis of sunrise and sunset times for the region of interest. Stability classes of A, B, C, and Dd occur during daytime hours, while those of Dn, E, and F occur during nighttime hours. When numbers of persons affected are being counted, footprints estimated from the accident release model for daytime and nighttime stability are placed on the daytime and nighttime population distribution data, respectively.

⁴ Some combinations of wind speed and stability class are nonexistent. For example, A-stability (very unstable) or F-stability (stable) conditions can exist only at lower wind speeds. At high winds, atmospheric vertical temperature structure tends to be dry adiabatic lapse rate (i.e., neutral [D stability]). For this reason, it is sometimes unrealistic to use the Monte Carlo simulation for sampling meteorological data represented by frequency distribution data. In other words, realistically incompatible combinations of meteorological parameters can be elected (e.g., high wind speed and A stability). Another option for summarizing the representative meteorological conditions is to select a few percentage points of the hourly meteorological data by using the random generator.

Region : 2
 Anem. Ht : 6 m
 Period : 1990 - 1995



Region : 2
 Anem. Ht : 6 m
 Period : 1990 - 1995

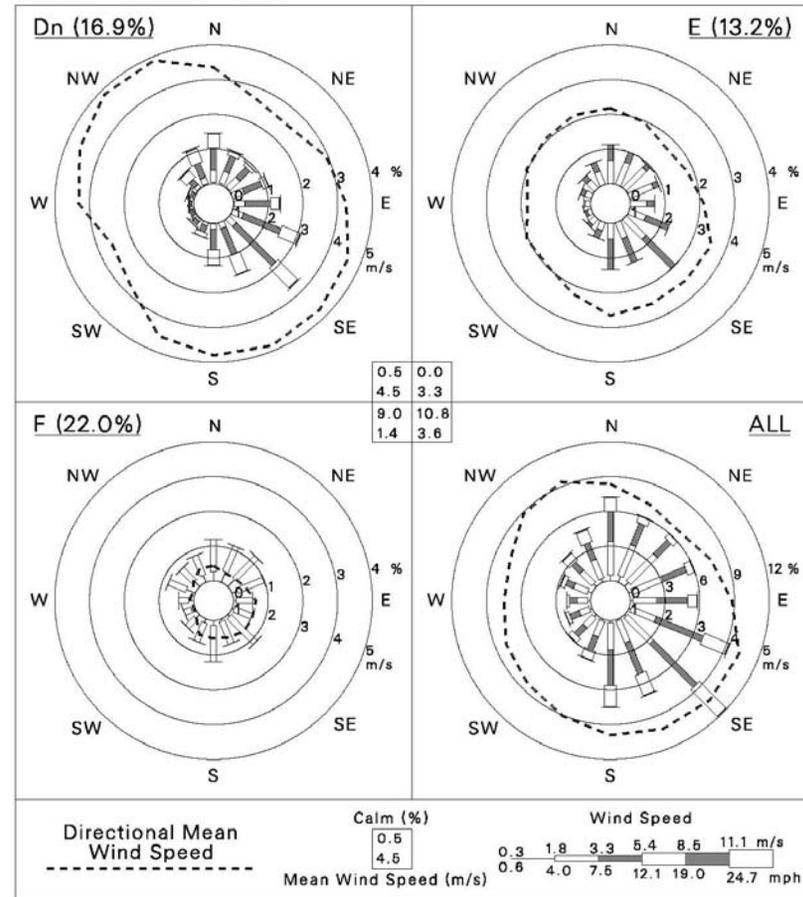


FIGURE 6 Wind Roses at the 6-m (20-ft) Level for Region 2 by Stability Classes A–F, 1990–1995 (Source: NCDC 1997). The positions of the spokes show the direction from which the wind is blowing, and the length of the segments on each spoke indicate the percentage of the time in the wind speed categories shown in the lower right. A segment on each spoke corresponds to one of more than 400 representative meteorological conditions.

dispersing gas cloud is flat and free of obstacles, such as buildings or trees,⁵ and they assume uniform wind fields (i.e., wind speed and direction are constant at any given height) throughout the area of a chemical release.

2.5.1 AFTOX

AFTOX (Air Force TOXic Chemical Dispersion Model) is a PC-based, Gaussian puff/plume model that estimates concentrations downwind from accidental chemical releases for neutrally buoyant releases (Kunkel 1991). It was developed as a result of the U.S. Air Force's (USAF's) need to update its toxic corridor prediction capability in case of accidental releases, and it has been thoroughly evaluated and refined against more than 240 test cases and field studies. The model is designed to handle releases that are continuous, of finite duration, or instantaneous; in the form of liquid or gas; occur either at the surface or at an elevation; and are from point or area sources. The program also contains an option for continuous heated plumes from stacks. It contains a library of 129 chemicals but may be run for other chemicals as well. The model can be applied to a wide range of accidental release scenarios, process analyses, and emergency response planning for highly toxic industrial chemicals. For each release, AFTOX assumes the plume distribution is Gaussian in the downwind and crosswind directions. The model uses Pasquill-Gifford dispersion coefficients with modifications to account for a user-specified averaging time. Outputs consist of concentration contour plots and toxic corridors, concentrations at specified locations, and maximum concentrations at a given elevation and time.

2.5.2 ALOHA

ALOHA[®] (Areal LOcations of Hazardous Atmospheres) was developed by the National Oceanic and Atmospheric Administration (NOAA) and the EPA's Chemical Emergency Preparedness and Prevention Office (CEPPO) (EPA and NOAA 2006). It is a PC-based, menu-driven model with a graphical user interface (GUI). ALOHA is a user-friendly source-term model⁶ that estimates rates of chemical releases from broken gas pipes, leaking tanks, and evaporating puddles, for which the model can simulate the dispersion of both neutrally buoyant and heavier-than-air gases as well as direct sources. ALOHA can simulate key hazards — toxicity, flammability, thermal radiation (heat), and overpressure (explosion blast force) — related to chemical releases that result in toxic gas dispersions, fires, and/or explosions. The model has an extensive chemical library for about 1,000 common hazardous chemicals.

⁵ Wind flowing around large buildings or tall trees forms eddies and changes direction and speed, significantly altering a cloud's shape and movement. When the models lack detailed obstacle information, they generally cannot handle the situation because of extensive data input needs and the enormous amounts of computational time required, although the detailed model is available. However, surface roughness corresponding to obstacles input by the user implicitly accounts for the effects of large obstacles, which are approximately represented by increased dispersion while the plume direction is maintained along with the wind.

⁶ Models that can determine release conditions and estimate the amount and duration of release on the basis of given storage and accident conditions (e.g., chemical name, storage tank type/volume/temperature, size and location of rupture opening) are called source-term models.

Model outputs are in both text and graphic form. They include “threat zone” plots of the area downwind of the release, where concentrations may exceed a user-set threshold level, as well as plots of source strength (release rates), concentrations at any location of special concern, and doses over time. In addition to user-defined meteorological data, ALOHA can accept weather data transmitted from portable weather monitoring stations and can plot threat zones on electronic maps displayed in MARPLOT[®], a companion mapping application. Its unique feature is to predict indoor concentrations given building type or air exchange rates of the building of interest. ALOHA is designed especially for use by people responding to chemical accidents under high-pressure emergency situations, as well as for emergency response, planning, training, and academic purposes. The heavy gas dispersion calculations used in ALOHA are based on those used in the DEGADIS model (Spicer and Havens 1989), which is discussed next. ALOHA is a closely faithful representation of DEGADIS model dynamics, which adopt simplified numerical procedures in view of the model’s common use in emergency response. However, ALOHA will not estimate downwind concentrations at distances further than 10 km (6 mi) from the release point, and therefore, very long footprints are truncated at 10 km. In the case of footprints larger than 10 km, another model should be used.

2.5.3 DEGADIS

DEGADIS (Dense GAs DISpersion) is a PC-based dense-gas dispersion model developed for the U.S. Coast Guard and EPA by Havens and Spicer at the University of Arkansas (Spicer and Havens 1989). DEGADIS is ideal for determining toxic endpoint distances and distances to lower flammability limits (LFLs) for certain toxic and flammable chemicals in accordance with EPA’s Risk Management Program requirements (EPA 1999b). DEGADIS can be used as a refined modeling approach to estimate short-term ambient concentrations (1-hour or less averaging times) and the expected area of exposure to concentrations above specified threshold values for toxic chemical releases. Its range of applicability includes continuous, instantaneous, finite-duration, and time-variant releases; negatively buoyant and neutrally buoyant releases; ground-level, low-momentum area releases; and ground-level or elevated and upwardly directed stack releases of gases or aerosols. DEGADIS describes the dispersion processes that accompany the ensuing gravity-driven flow and entrainment of the gas into the boundary layer. DEGADIS makes no provision for processes that occur in high-velocity releases, as is the case with releases from pressure relief valves.

Chemical property data must be input by the user, although the model does contain such data for a few selected chemicals. The model contains no modules for source calculations or release characterization. Input required includes the emission rate; release area and release duration; chemical characteristics; stack parameters; and meteorological data. Output results are provided in tabular form, including plume centerline information (such as elevation, mole fraction, concentration, density, temperature, and σ_y and σ_z values) at each downwind distance; off-centerline distances to two specified concentration values at a specified receptor height at each downwind distance; and concentration vs. time histories for finite-duration releases. No graphical representations are provided. To draw concentration isopleths, users can use the off-centerline distances to two specified concentration values at a specified receptor height at each downwind distance.

2.5.4 HGSYTEM

The HGSYTEM model was developed by Shell with the sponsorship of industry groups (Post 1994a,b). HGSYTEM is a collection of computer programs designed to predict the source term and subsequent dispersion of accidental chemical releases, with an emphasis on denser-than-air (dense gas) behavior. HGSYTEM, a PC-based software package, consists of mathematical models for estimating one or more consecutive phases between spillage and near-field and far-field dispersion of a chemical. The pollutant can be either a two-phase, multicomponent mixture of nonreactive compounds or hydrogen fluoride with chemical reactions. The model packages include the database program (generates physical properties), source-term models (estimates releases from pressurized vessel or from evaporating liquid pool), near-field models (high-momentum jet dispersion model or dispersion of instantaneous heavy gas releases), far-field models (heavy gas dispersion or passive Gaussian dispersions), and utility programs (postprocessors for modeling results or contour plots). HGSYTEM can handle steady-state, finite-duration, instantaneous, and time-dependent releases, depending on the individual model used. The models can be run consecutively, as the relevant data are passed from one model to the next by using link files. HGSYTEM is a source-term model and contains postprocessors that can be used to extract modeling results for graphic display. It can be used as a refined model to estimate short-term ambient concentrations (1-hour or less averaging times) for the area of toxic exposures for chemical releases (nonreactive chemicals or hydrogen fluoride) and for the area for flammable nonreactive gases. Although HGSYTEM is a source-term model, it requires detailed information about storage conditions and parameters for accidental release modeling.

2.5.5 HPAC

The Hazard Prediction and Assessment Capability (HPAC) model, which was developed by the Defense Threat Reduction Agency (DTRA), is designed primarily to simulate nuclear, biological, and chemical (NBC) accidental releases (DTRA 2004). The latest version of the model includes some industrial chemicals and is currently considered one of the top-of-the-line models. HPAC is a Gaussian puff model that uses a second-order closure model for treatment of the turbulence component and models the atmospheric dispersion of vapors, particles, or liquid droplets from multiple sources by using arbitrary meteorological inputs, which range from a single surface wind speed and direction up to four-dimensional gridded wind and temperature-field inputs.

The HPAC automated software system provides the means to accurately predict the effects of hazardous material released into the atmosphere and its impact on civilian and military populations. The system uses integrated source terms, high-resolution weather forecasts, and atmospheric transport and dispersion analyses to model hazard areas produced by military or terrorist incidents and industrial accidents.

The HPAC system is a forward-deployable, counterproliferation/counterforce collateral-effects assessment tool that is available by license for government, government-related, or academic use. It provides the means to accurately predict the effects of hazardous material

releases into the atmosphere and the impacts on civilian and military populations. It models NBC, radiological, and high-explosive collateral effects resulting from conventional weapons strikes against enemy WMD production and storage facilities. The HPAC system also predicts downwind hazard areas resulting from a nuclear weapon strike or reactor accident, and it has the capability to model NBC weapons strikes or accidental releases. HPAC uses physical and empirical algorithms for agents released from explosive dissemination, sprayers, bombs, artillery shells, etc.

Relevant real-world hazard prediction requires timely and accurate weather data in the area of concern. The HPAC system gives the user easy access to forecasted and real-time weather (observational) data by using a variety of DTRA-supported meteorological data server systems. The HPAC system also has embedded climatology or historical weather data for use when one is planning for incidents beyond the normal time associated with credible weather forecast data. Data on 1-km terrain areas and supporting wind-flow models calculate the local wind fields in the area of concern. Other weather sources are also available upon request to DTRA.

The HPAC system can also provide probabilistic calculations. The hazard area feature estimates the weather uncertainty and turbulence effects on possible plume trajectories and calculates the areas of hazard impact and the degree of confidence of the prediction.

5.2.6 SLAB

The SLAB model was developed by Don Ermak of Lawrence Livermore National Laboratory (Ermak 1990) with support from the U.S. Department of Energy (DOE), the USAF Engineering and Services Center, and the American Petroleum Institute (API). Like DEGADIS, SLAB is also ideal for determining toxic endpoint distances and distances to LFLs for certain toxic and flammable chemicals, as required by EPA's Risk Management Program (EPA 1999b). The SLAB model, a PC-based dispersion model of denser-than-air releases, can be used as a refined model to estimate spatial and temporal distribution of short-term ambient concentrations (e.g., 1-hour or less averaging times) and the expected area of exposure to concentrations above specified threshold values for toxic chemical releases. SLAB can model continuous, finite-duration, and instantaneous releases from four types of releases: a ground-level evaporating pool, an elevated horizontal jet, a stack or elevated vertical jet, and an instantaneous volume source. All sources except the evaporating pool may be characterized as aerosols. The model can simulate multiple sets of meteorological conditions in a single run, but it does not accept any type of real-time meteorological data. The SLAB model is a non-source-term model; it is different from ALOHA or HGSYSTEM in that the user specifies release conditions and it has no chemical database, although some chemical properties are available in the user's guide. Data are input directly into the model from an external file. Input data parameters are divided into five categories: source type, source properties, spill properties, field properties, and standard meteorological parameters. The model does not generate any type of graphical output but rather provides modeling results in tabular form. These results include input data; instantaneous, spatially averaged cloud parameters; time-averaged cloud parameters; and time-averaged concentration values at the plume centerline and at five off-centerline distances at four user-

specified heights and at the height of the plume, which can be used to construct the contours for a specified threshold level.

Among its limitations, the SLAB model assumes a uniform wind field, and it does not consider wind shifts and terrain steering effects, as do most chemical accidental release models except HPAC. Also, the model does not use the mixing height, defined as the overall depth of the turbulent boundary layer, under which released materials are vigorously mixed. Mixing height plays a significant role at receptors further downwind, especially for elevated releases. However, the SLAB model was selected for this analysis because of its minimal data requirements, ease of use, and fast computational speeds, which were needed to conduct several thousand runs. Key input parameters to the SLAB model are discussed next in Section 2.6.

2.6 SLAB MODEL INPUT PARAMETERS

Along with chemical release mass and representative meteorological conditions, many other parameters are input to the model. About 30 input parameters are required to run it. These parameters include the following:

- Source type (e.g., horizontal jet release or evaporating pool release),
- Source properties (e.g., molecular weight and boiling point temperature of source material, initial liquid mass fraction),
- Spill properties (e.g., mass source rate, source area, release duration, release height),
- Field parameters (e.g., concentration, averaging time, maximum downwind distance), and
- Meteorological parameters (e.g., surface roughness, height, wind speed, ambient temperature, relative humidity, atmospheric stability).

Samples of the SLAB input file along with a brief explanation of all parameters used in the model are provided in Appendix A. The selection of key input parameters is discussed in the following paragraphs.

Depending on their physical properties (e.g., vapor pressure or boiling point) and prerelease storage conditions, hazardous chemicals can be emitted from a container as a liquid, a vapor, or both. Many industrial chemicals, such as chlorine or ammonia, which are gases under normal pressures and temperatures (i.e., normal boiling point is well below ambient temperature), are stored in the liquid phase via pressure to save space in the containment vessels at stationary locations or in transit. When a rupture or broken valve causes a sudden pressure loss in a tank of liquefied gas, the liquid boils violently (“flash-boil”), the tank contents foam up, and the tank fills with a mixture of gas and fine liquid droplets (called aerosol). When such a two-phase mixture escapes from the container, the release is called a “two-phase flow,” and the

release rate can be significantly greater than that for a purely gaseous release. The two-phase mixture that escapes into the atmosphere may behave like a heavy gas cloud. The cloud is heavy, in part because it is initially cold and therefore denser than it would be at ambient temperatures and also because it consists of a two-phase mixture. While traveling with the wind, the tiny aerosol droplets that are mixed into the cloud weigh the cloud down and make it denser than a pure gas cloud, and the evaporation of the droplets cools the cloud.

A gas that has a molecular weight greater than that of air (the average molecular weight of air is about 29 kg/kg-mol) will form a heavy gas cloud if enough is released. Gases such as anhydrous ammonia that are lighter than air at room temperature but that are stored in a cryogenic (low-temperature) state can also form heavy gas clouds. If the density of a gas cloud is substantially greater than the density of the air (the density of air is about 1.1 kg/m³), the cloud is considered to be heavy.

When a gas that is heavier than air is released, it initially behaves very differently from a neutrally buoyant gas. The heavy gas will first “slump,” or sink, because it is heavier than the surrounding air. As the gas cloud hugs the ground, gravity makes it spread like a pancake; this can cause some of the vapor to travel upwind of its release point. Further downwind, as the cloud becomes more dilute via the entrainment of ambient air and its density approaches that of air, it begins behaving like a neutrally buoyant gas. This phase takes place when the concentration of heavy gas in the surrounding air drops below about 1% (10,000 ppm). For many small releases, this stage will occur within the first few meters. For large releases, it may happen much further downwind. For example, chlorine behaves as a heavy gas over a long distance (tens of miles), but ammonia becomes a passive plume after traveling only a few miles as a heavy gas.

For this analysis, horizontal jet release from pressurized tanks with two-phase flows was assumed in order to produce the maximum impacts (IDSPL = 2; input variable used in the code). In the model, the horizontal jet release is an area source with a source plane that is perpendicular to the ambient wind direction and source velocity pointing directly downwind. The center of the jet is located at $x = 1$ m, $y = 0$ m, and $z =$ release height. Release height from the tank was assumed to be 1 m from the ground ($HS = 1$ m) (Moser 1996). The temperature of the source material is the property of the material after it has fully expanded. When the source material is stored as a liquid under pressure and forms a two-phase liquid droplet-vapor mixture upon release, the source temperature is the boiling point temperature ($TS = 239.1$ K).

For two-phase pressurized liquid jet, the source area (AS) is the area of the source after it has flashed and formed a liquid droplet-vapor mixture of the pure substance. To estimate the source area, the area of the actual rupture or opening is needed. Having this measurement first provides the source duration of the release. To be consistent with EPA’s RMP analysis, the continuous source duration of the release was assumed to be 10 min ($TSD = 600$ s) (EPA 1999b). The SLAB model is a non-source-term model, so the rupture opening diameter was approximated by using the source-term model ALOHA (EPA and NOAA 2006). By assuming that all materials in the tank would be emptied within 10 minutes, the rupture opening diameter was estimated by trial and error, and the regression line is of the following form:

$$D = 0.3488 \times (M/2000)^{0.4998}$$

where D = rupture opening diameter (in.) and M = amount of material released (lb).

The concentration averaging time (TAV) is the appropriate averaging time for the safety standard of interest. For a single toxic material, there are generally a number of health criteria levels of interest, each corresponding to a different exposure time. For example, the acute exposure guideline levels (AEGs) that are discussed in Section 2.7 are given for exposure periods of 10, 30, and 60 minutes and 4 and 8 hours. In this case, SLAB would have to be run five times, with each run having a different value of TAV corresponding to the appropriate duration of exposure.

The correct averaging time is not based solely upon the release scenario but rather on the length and intensity of exposure for the population (or distance from the source) of concern. The duration (time) of exposure is a function of the release time, the size of the release, meteorological conditions, and the distance of the point of exposure from the source. In order to evaluate the effects of exposure at a given distance from the source, several health criteria should be considered, because the hazardous health impact of a particular agent can be strongly dependent on several factors, including the maximum concentration received, the duration of the exposure, the integrated dose to the individual, or (in general) some combination of these factors. In this study, for example, if it was estimated that a population was exposed for a 1-h period, health criteria for 10-min, 30-min, and 60-min exposures were used to generate plume footprints. It was found that most of the time, the plume that was generated when assuming an averaging time of 10 minutes had the largest footprint; therefore, the 10-minute averaging time (TAV = 600 s) was assumed for simplicity.

The EPA's RMP guidance provides a method to estimate distances to endpoints for toxic substances that range from 0.2 km (0.1 mi) to 40 km (25 mi)⁷ (EPA 1999b). Some models can simulate up to this distance, while others cannot. One commonly used model, ALOHA, has an artificial distance cutoff of 10 km (6 mi) (i.e., any scenario that would result in an endpoint distance beyond 6 mi is reported as "greater than 6 mi"). In the modeling run for this study, a maximum downwind distance for estimating contaminant plume concentrations is arbitrarily set at 100 km (XFFM = 100,000 m). However, a maximum downwind distance cutoff of 50 km (31 mi) is used when the footprint is constructed, considering that the major metropolitan areas in the United States have a size comparable to 50 km (31 mi).

Surface roughness (ZO) determines the degree of air turbulence over which a vapor cloud is passing. Surface roughness height depends on the size and number of roughness elements. In general, surface roughness height is about one-tenth of the physical obstacle height. Surface roughness height, ranging from less than a millimeter for ice and mud flats to several meters in

⁷ The following is a statement extracted from EPA (1999b). "EPA recognizes that modeling results at such large distances are highly uncertain. Almost no experimental data or data from accidents are available at such large distances to compare to modeling results. Most data are reported for distances well under 10 miles. Modeling uncertainties are likely to increase as distances increase because conditions (e.g., atmospheric stability, wind speed, surface roughness) are not likely to remain constant over large distances. Thus, at large distances (e.g., greater than about 6 to 10 miles), the modeling results should be viewed as very coarse estimates of consequence distances. EPA believes, however, that the results, even at large distances, can provide useful information for comparison purposes."

urban areas with high-rise buildings, is used to characterize the averaged effects of surface features on the wind flow. When roughness height and wind speed increase, the level of turbulence in the atmosphere generally increases. When all else is equal, a footprint will be longest for a smaller ground roughness value. For this analysis, the surface roughness height is assumed to be 1 m, a value that is representative of the land use typical of urban areas and industrial complexes (Moser 1996). In reality, condensed vapors in a toxic cloud may fall to the ground to form a pool, which, in turn, would be volatilized to the atmosphere. However, for the analysis, it was conservatively assumed that all release materials are airborne.

For this analysis, average values of ambient temperature and relative humidity were input to the SLAB model because the boiling point of chlorine (-34°C [-29°F]) is much lower than typical ambient temperature. However, for chemicals with boiling points around ambient temperature (e.g., 19.5°C [67.2°F] for hydrogen fluoride [HF] or 10.4°C [50.7°F] for ethylene oxide [$\text{C}_2\text{H}_4\text{O}$]), maximum ambient temperatures should be selected to estimate conservative maximum impacts.

2.7 HEALTH CRITERIA

To estimate a footprint, a threshold concentration of an airborne pollutant must be identified. It is usually the concentration above which the gas may pose a specific hazard level to people, termed the “level of concern” (LOC).

In this study, the LOC concept was applied to estimate how many persons, hospital beds, and geographical areas could be affected by hypothetical accidental chemical releases. The LOC levels for chlorine were based on AEGLs. AEGLs are developed by workgroups of federal agency and private industry scientists under the National Advisory Committee (NAC). They are intended to describe the risk to humans resulting from once-in-a-lifetime, or rare, exposure to airborne chemicals. The NAC for AEGLs is developing these guidelines to help both national and local authorities, as well as private companies, deal with emergencies involving spills or other catastrophic exposures.

After AEGL values are drafted and approved by vote by the NAC, they are considered “proposed” and are published in the *Federal Register* for review and public comment (EPA 2007). Once public comments have been addressed and the NAC committee again votes on the specific values, they are considered “interim” and are submitted to the National Research Council (NRC) AEGL subcommittee for review and comment. When concurrence with the NRC subcommittee is reached, the AEGL values are considered “final” and are published by the NRC. As of April 2007, the NAC had completed 31 final, 99 interim, and 64 proposed AEGL reports for a total of 194 chemicals (EPA 2007)

The AEGL values are developed for exposure times of 10, 30, and 60 minutes and 4 and 8 hours, and for three effect categories. Definitions are as follows:

- AEGL-1 is the airborne concentration of a substance above which it is predicted that the general population, including susceptible individuals, could

experience notable discomfort, irritation, or certain asymptomatic nonsensory effects. However, the effects are not disabling and are transient and reversible upon cessation of exposure.

- AEGL-2 is the airborne concentration of a substance above which it is predicted that the general population, including susceptible individuals, could experience irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape.
- AEGL-3 is the airborne concentration of a substance above which it is predicted that the general population, including susceptible individuals, could experience life-threatening health effects or death.

The AEGL-1 levels are based on no observed adverse effect levels (NOAELs) in human populations where possible (NRC 2001). If no studies are available with multiple exposure levels and an identified NOAEL, a lowest-observed adverse effect level (LOAEL) is used as the starting point for the guideline level. Uncertainty factors of 1, 3, or 10 are generally used to ensure that the guidelines are protective. Uncertainty factors are used to account for interspecies variability, intraspecies variability, use of LOAEL data when no NOAEL level is available, and other database deficiencies.

The AEGLs are the guidelines of choice because of the thorough level of data review required of federal and private scientists for their development, which also makes for a lengthy development process. When AEGL values are not available for specific chemicals, Emergency Response Planning Guideline (ERPG) values may also be useful. These values are developed by the ERPG committee of the American Industrial Hygiene Association (AIHA). ERPGs are defined for a 1-hour averaging time with three-tiered guideline levels similar to those for AEGLs. As of 2006, ERPG values for 125 chemicals are available, and about seven chemicals are added each year (AIHA 2007).

Temporary emergency exposure limit (TEEL) values are developed by an interagency workgroup, the Subcommittee on Consequence Assessment and Protective Actions (SCAPA) (2007) and funded by DOE. TEEL values are developed for chemicals for which AEGL values have not yet been developed and are based on a complex hierarchy of sources, including occupational 8-h time-weighted averages (TWAs), short-term exposure limits (STELs), and ceiling limits that are appropriately adjusted, or adjustments of primary toxicological data, such as 50% lethality concentrations (LC₅₀) (Craig 1995; DOE 2007). The methodology for TEEL development is refined often, and all changes are reviewed and voted on by SCAPA, which is composed of both governmental and industrial scientists. When AEGL or ERPG values become available, the TEEL values are superseded by the new values. TEELs have been developed for several thousand chemical compounds, so this large database is very valuable in the absence of other information. However, compilations of primary toxicology data are used as a data source (not the primary literature), so errors could be introduced if these data were reported inaccurately. TEELs are only developed for exposure durations of 1 hour. An additional TEEL value, TEEL-0, has been developed and is defined as the threshold concentration below which most people will experience no appreciable risk of health effects.

For this study, the final AEGL values for chlorine were used as LOCs, and three additional health impact levels were used in the analysis as follows:

- LC_{LO}: lethal concentration, low. The lowest concentration to cause death in test animals.
- LC₅₀: The level of concentration of a toxicant that will kill 50% of the organisms being tested.
- LC₁₀₀: The level of concentration of a toxicant that will kill all of the organisms being tested.

These levels were used to help estimate the level of emergency and hospital service that would be required by victims receiving large doses from accidental chemical releases. The values of the six health criteria for chlorine for different exposure lengths are listed in Table 6.

Detailed information on the derivation of chlorine health criteria and on emergency planning as it depends on health criteria is provided in Section 4.

2.8 MODEL OUTPUTS AND FOOTPRINT ESTIMATION

The SLAB output file contains several types of information:

- Problem description (various input parameters used by the code, definition of the problem to be solved);

TABLE 6 Health Criteria for Chlorine

Health Criteria	Air Concentration (ppm)				
	10 min ^a	30 min	60 min	4 h	8 h
AEGL-1	0.50	0.50	0.50	0.50	0.50
AEGL-2	2.8	2.8	2.0	1.0	0.71
AEGL-3	50	28	20	10	7.1
LC _{LO}	740	- ^b	300	-	-
LC ₅₀	1,100	-	450	-	-
LC ₁₀₀	1,600	-	640	-	-

^a Used in the analysis.

^b Not estimated but can be estimated using the formula: = $[(\text{Reference Toxicity Value})^2 \times (\text{Averaging Time of Interest}) / (\text{Reference Averaging Time})]^{1/2}$.

Source: EPA (2007).

- Instantaneous, spatially averaged cloud properties (results of the dispersion calculation phase of the simulation); and
- Time-averaged volume fractions.

A SLAB output file for one scenario is presented in Appendix A-3.

To determine the area of the plume footprint at a specified concentration (i.e., health criterion), the footprints are estimated on the basis of concentration outputs from the SLAB model. The SLAB model generates the concentrations for a given averaging time at downwind and crosswind locations. First, the maximum downwind distance exceeding a given health criteria level is found, then maximum crosswind width at each downwind distance is estimated. In these calculations, linear interpolations between the two concentrations and distances are employed. Then, by connecting downwind and crosswind points, the footprints can be constructed (as shown in Figure 7). These, in turn, are overlaid onto population and hospital bed distribution data to estimate potential impacts. Note that the plume concentrations at the ground level are used for the analysis. Footprints of the intermediate plumes at different times after the release were approximated by using the “downwind distance” and “time of maximum concentration” in output files from the SLAB model.

A crude approximation for total area impacted at a specified concentration (footprint area) is widely used by assuming it to be an ellipse (estimated with downwind distance and maximum width of a footprint). In this analysis, the footprint area was estimated by the following equation (Beyer 1991):

$$\text{Area} = | (x_1y_2 + x_2y_3 + \dots + x_{n-1}y_n + x_ny_1) - (y_1x_2 + y_2x_3 + \dots + y_{n-1}x_n + y_nx_1) | / 2$$

where (x_i, y_i) = coordinates of a contour.

2.9 IMPACT (CONSEQUENCE) ANALYSIS

To develop the “cumulative frequency or time vs. impacts” footprint plots, chemical accidental release modeling was performed for about 2,000 scenarios, which were combinations of four or five accidental release groups (source term) and more than 400 representative meteorological conditions. Each scenario was exercised for six health criteria, resulting in a total of more than 10,000 runs processed to develop the cumulative distributions of impacts. For example, Figure 7 illustrates a scenario for the three health criteria. A footprint for each run was overlaid on population and hospital bed distribution data to count the numbers of persons and hospital beds affected during and after the passage of the toxic plume.

To count persons affected, the population distribution database, *U.S.A. Day-Night & Indoor-Outdoor Population Database* (developed by Los Alamos National Laboratory) was used (LANL 2003). This database is provided for population distributions for day/indoors, day/outdoors, night/indoors, and night/outdoors cases on about a 200-m² cell (its size is a little different by latitude) over the entire United States. Footprints associated with daytime and

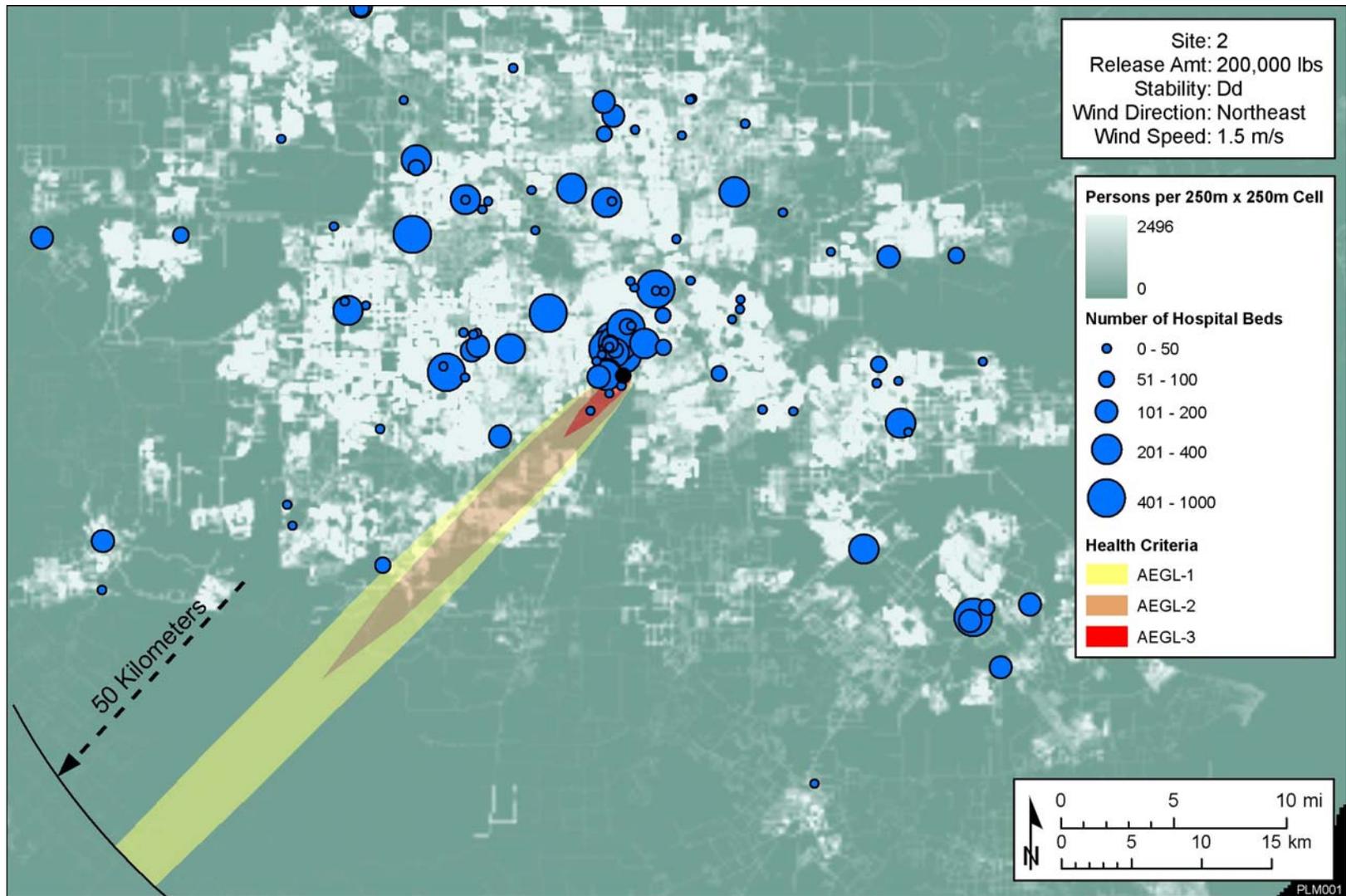


FIGURE 7 Plume Footprints over Population and Hospital Bed Distribution Data for a Scenario (Release Amount of 20,000 lb and one Meteorological Condition) for Region 2

nighttime meteorological conditions that depend on atmospheric stability classes were placed on daytime and nighttime population distribution data, respectively. To count hospital beds affected, *Homeland Security Initiative Program (HSIP) Gold Data* was used (NGA 2004). Population and hospital bed data within a radius of 50 km from the point of accidental release were included in the analysis.

The five types of impacts analyzed for this analysis are as follows:

1. Persons affected, typical case (TC);
2. Persons affected, typical case with shelter-in-place option (TC-SIP);
3. Persons affected, worst case (WC);
4. Hospital beds affected (HB); and
5. Areas affected (AR).

For persons affected, typical and worst cases were analyzed. The typical case considered reduced impacts for the indoor population, which result from the dampening effect of building structures against sudden changes in the concentrations of toxic gas outdoors. The worst case assumed that all exposed individuals were outdoors. Note that the number of persons affected for the worst case (rather than for the typical case) should be used to estimate the number of persons to be evacuated,⁸ because persons affected for the typical case were counted by considering reduced impacts for persons staying indoors.

Two principal responses to emergency situations are often employed: evacuation and sheltering. For chemical accidental releases, the shelter-in-place (SIP) option is the more prevalent response to reduce exposures, because once a release has occurred, there is rarely time to organize and execute an evacuation. For incidents that involve toxic materials, evacuations are most often conducted when a release has not yet occurred but there is a strong possibility for a large release. Ordering an evacuation is one of the most painstaking decisions during the emergency because an inappropriate decision can result in mistrust of public authorities, which can lead the public to take incorrect and unsafe actions.

To estimate indoor pollutant concentration, the building's *air exchange rate* — that is, the number of times per hour that the volume of air within the building is completely replaced by new outdoor air when doors and windows are closed (usually expressed as number of air changes

⁸ In real atmospheres, the wind rarely blows constantly from any one direction. As it shifts direction, it will blow a pollutant cloud in a new direction. In particular, wind direction is generally least predictable when wind speed is low. To account for variability in wind direction, some models introduce “uncertainty lines” (or “ladybug lines”) around the footprint to enclose the region within which the gas cloud is expected to remain about 95% of the time. The wider the zone between the lines, the less predictable the wind direction and the more likely it is to change substantially. Other factors, such as wind speed, also greatly influence the size and shape of a dispersing pollutant cloud. Accordingly, the modeling results presented in this report (i.e., under the assumption that wind direction and wind speed are constant until the incident is over) should be interpreted in that context.

per hour [ACH]) — is needed. Typically, the ACH for existing homes averages between 1 and 2. Newer construction tends to be tighter, with the number of exchanges that are <1 being common. The American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) recommends that the ACH for buildings be kept within the range of 0.5 to 1.0 complete changes to maintain indoor air quality. For this analysis, an ACH of 1 is used for the typical case, and an ACH of 0.25 is assumed for the SIP option. (For SIP, the air exchanges are reduced by actions such as taping doors and windows.) In general, as the air exchange rate rises, infiltration into buildings and buildup of indoor chemical concentration and consequent exposure dose will be faster.

Our analysis uses average reduction-in-casualty ratios for indoor to outdoor populations for liquefied gas (Brown et al. 2000), as follows:

TC (ACH = 1): 2.6 for daytime and 5.6 for nighttime

TC-SIP (ACH = 0.25): 6.3 for daytime and 22.0 for nighttime.

The impacts were estimated by calculating a footprint area in the same manner as that used for the outdoor concentrations, with all buildings kept at the same ACH. It was assumed that SIP would reduce the numbers of people affected rather than the degree to which those people were affected (i.e., the exposures are not lowered; instead, a percentage of the individuals exposed are assumed to have zero exposure because of the protection afforded by the shelter). Values among different relative hazards determined by release type and threshold concentrations in Brown et al. (2000) were selected to produce the highest impacts. Calculation procedures are as follows: If 800 persons indoors and 200 persons outdoors were within an AEGL-3 footprint at night, a total of 1,000 persons would be affected for the worst case and 343 ($800/5.6 + 200$) persons would be affected for the typical case. In addition, the numbers of hospital beds and geographic areas rendered unusable during and after the passage of the toxic plume were estimated for various times after the release.

Output results for the typical and worst cases were normalized to a population of 1 million within a 50-km radius of the release point. To estimate the total numbers of persons affected, output results should be multiplied by the ratio of the total population of the city of interest to 1 million within a 50-km radius of the release point. Output results for hospital beds affected were presented as a percentage of total hospital beds. To estimate the total numbers of hospital beds affected, procedures similar to those used to estimate numbers of persons affected were employed.

In constructing STAR summaries, a wind direction for a single hourly dataset is assigned to one of the sixteen 22.5° directional sectors (e.g., 78.75 to 101.25° from the north for an east wind). However, the plume centerline can be anywhere within a 22.5° sector. Population counts for a single scenario are made once by assuming the plume centerline to be on the center of the 22.5° sector. In other words, there was no rotation made of the footprint within a sector, which assumes that population distribution within a 22.5° sector is relatively uniform. However, hospital bed counts are made by rotating the footprint every 0.75° in a given 22.5° sector to avoid missing the highest impacts.

In general, as the health criterion concentration rises, the footprint becomes smaller, as shown in Figure 8. In other words, the AEGL-3 footprint is a subset of the AEGL-2 footprint, which in turn is a subset of the AEGL-1 footprint. For this analysis, nonoverlapped portions of each health criterion are reported (e.g., the AEGL-1 portion excludes the overlapped portions with the AEGL-2 footprint [the blue-filled area in Figure 8]). This approach avoids double-counting the individuals affected.

2.10 SUMMARY OF CALCULATION PROCEDURES

The general procedures from data preparation to consequence analysis are summarized as follows:

1. The release source terms (e.g., four to five groups) and representative meteorological conditions (maximum 432; STAR summaries) are combined to develop the scenarios (approximately 2,000), which represent the general features of the spectrum of all possible accidental release incidents for a given region. A composite frequency is calculated for each scenario, which is the product from multiplying a release source term frequency by a meteorological condition frequency.
2. The SLAB accidental release model is run for all scenarios, and the footprints for given health criteria (i.e., AEGL-1 to AEGL-3, LCLO, LC50, and LC100) are constructed by using the concentration levels at downwind and crosswind distances, which are outputs of the SLAB model.

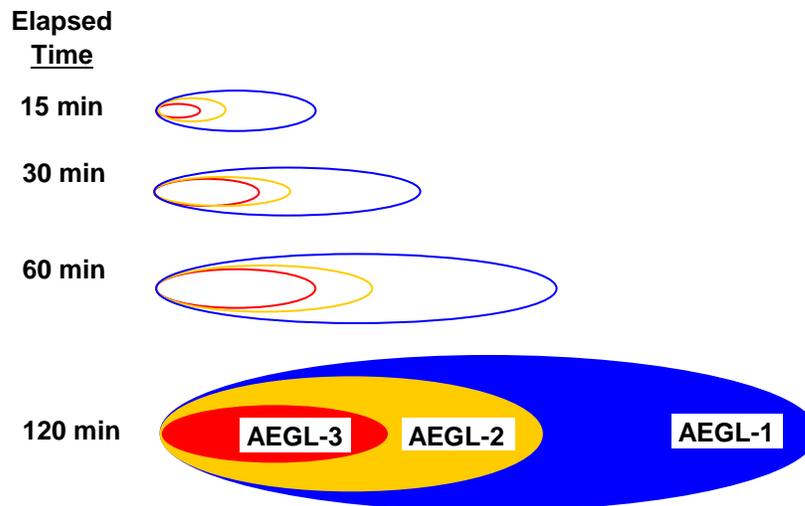


FIGURE 8 Time Series of Footprints for a Scenario

3. These footprints are overlaid onto population and hospital bed distribution data to count the numbers of persons and hospital beds affected during and after the passage of the toxic cloud at given times after the release (e.g., 15, 30, 120 minutes).
4. For indoor impacts, the reduction ratio is applied to outdoor impacts of the typical case and typical case with SIP options.
5. All scenarios are sorted in ascending order of impacts (e.g., numbers of persons affected), and composite frequencies of each scenario are added successively, from the lowest to the highest, to determine cumulative frequencies.
6. For selected cumulative frequencies (e.g., 1%, 5%, 10%, 25%, 50%, 75%, 90%, 95%, 99%, and 100%), the impacts' values for developing best-fit regression curves are found.

3 RESULTS AND DISCUSSION

As described in the previous chapter, combinations of four or five source-term groups (ranging from 200 lb to more than 1 million lb) and representative meteorological conditions (about 400 conditions) were simulated for six different health criteria by using the SLAB chemical release model to develop statistical distributions of potential impacts associated with accidental chemical releases (i.e., chlorine in this analysis). Modeling results from these scenarios (a total of about 2,000 scenarios) capture the general features of the spectrum of all possible accident scenarios that would occur at the site of interest. Depending on the atmospheric stability classes, meteorological conditions are classified into day or night, and modeling footprints are overlaid onto corresponding day or night population distribution data. The analysis is conducted within a radius of 50 km from the release point.

Figure 9 shows the sample curves, which incorporate modeling results from about 2,000 scenarios for Region 2 for cumulative frequency vs. persons affected (normalized to a population of 1 million); worst case (WC, assumes that everyone is outdoors); and health effects AEGL-1 to AEGL-3 (health criteria levels 1–3 [HC1–3]). It is of note that these curves are final results at the time after all impacts have occurred (i.e., about 3–5 hours after the release). From this plot, it is concluded that if an accident occurred within the region of interest, about 70% of the time, fewer than 20 persons would experience life-threatening health effects, and about 30% of the time, more than 20 persons would experience life-threatening health effects (AEGL-3) (denoted by dotted arrow). Also, 30% of the time, less than one person would experience health effects at the AEGL-3 level. These plots provide not only worst-case impact values (values at 100% cumulative frequency) but also values at all other cumulative frequencies. This information allows the stakeholders (i.e., government regulators, facility owner/operators, local concerned citizens, emergency responders) to make reasonable and informed decisions in terms of plant design, siting issues, volumes of toxic chemicals to be stored onsite, emergency response planning, etc.

Figure 10 illustrates the results for persons affected at health criterion level 1 (HC1 or AEGL-1) at different times post-release (i.e., as the toxic plume moves downwind). The figure shows that the swift changes in cumulative distribution occur in the earlier stages, but that the 60-minute cumulative distribution approximates that for the final results (3–5 hours post-release).

To aid decision making in emergency planning for situations when a heavy cloud is moving downwind, impact calculations were also made at intermediate times (e.g., at 15-, 30-, 45-, 60-, and 120-minute intervals) after the release. Figure 11 shows time vs. persons affected at 10 selected cumulative frequencies (i.e., 1%, 5%, 10%, 25%, 50%, 75%, 90%, 95%, 99%, and 100%), which are marked as arrows in Figures 9 and 10. These modeling results are input to emergency services and health care models and need to be in mathematical regression format for Monte Carlo simulations.

Cl₂; Region 2; Worst Case; AEGL-1 to AEGL-3

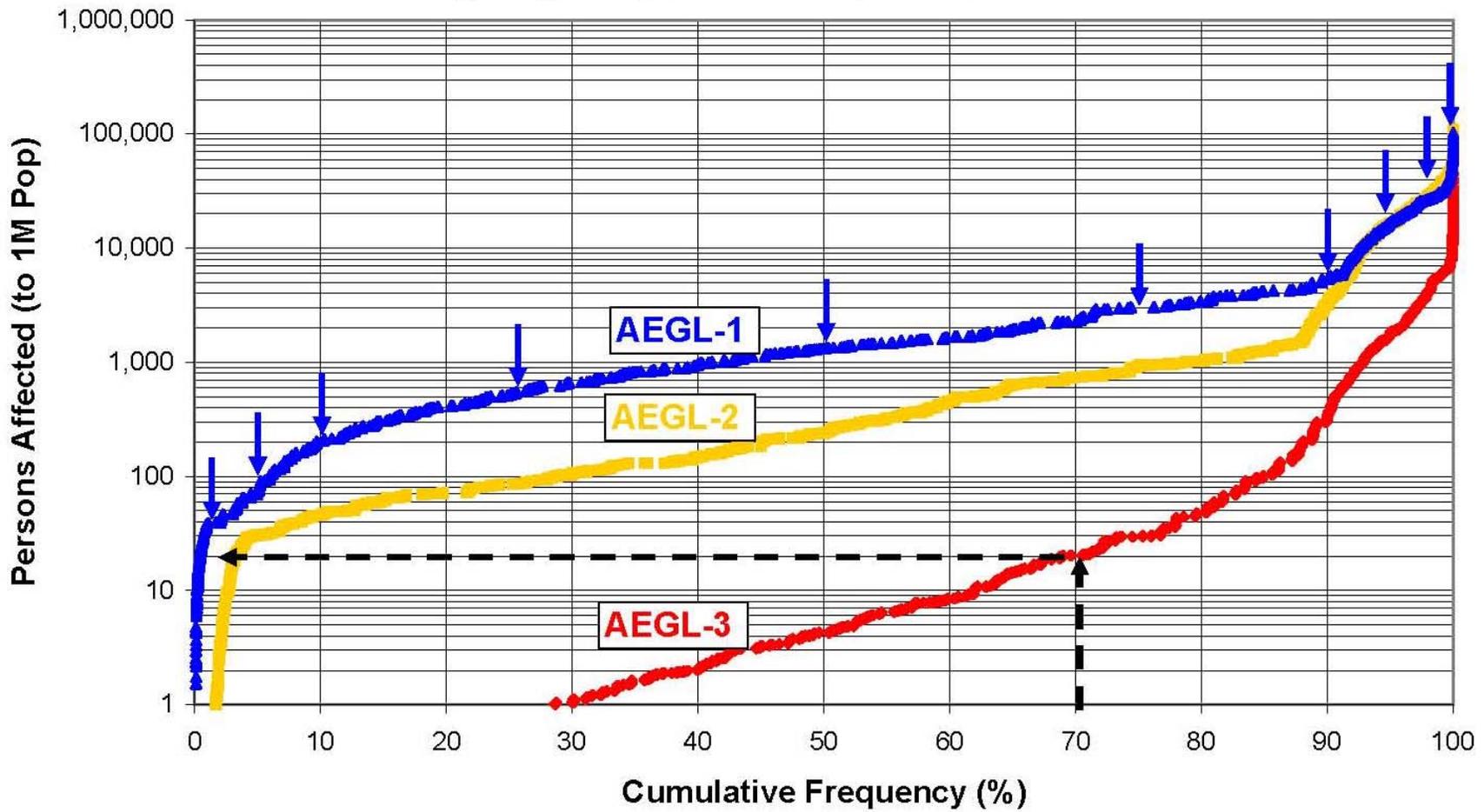


FIGURE 9 Cumulative Frequency vs. Normalized (to a Population of 1 Million) Persons Affected by Chlorine for Region 2, Worst Case, AEGL-1 to AEGL-3

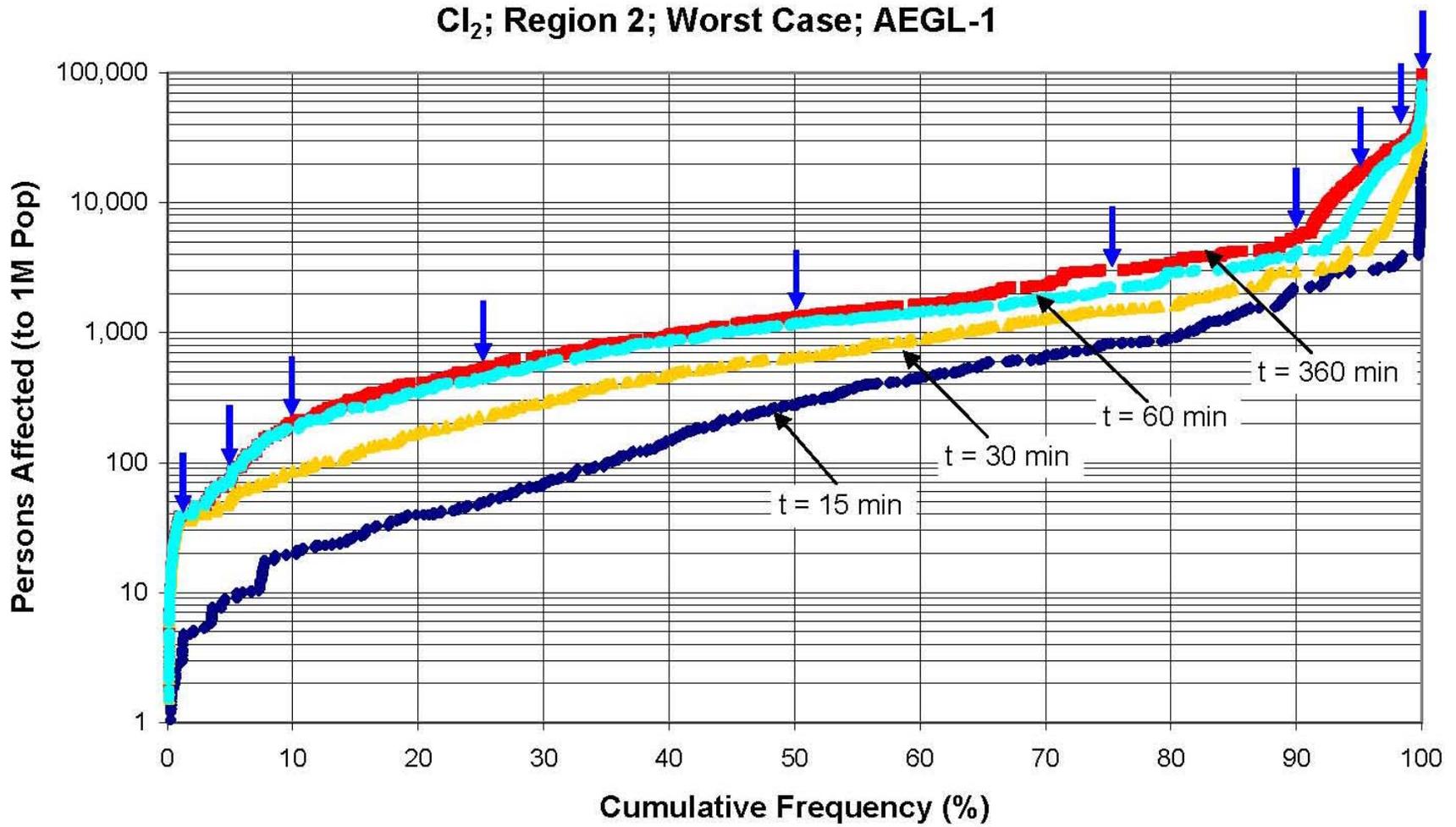


FIGURE 10 Cumulative Frequency vs. Normalized (to a Population of 1 Million) Persons Affected by Chlorine over Time for Region 2, Worst Case, AEGL-1

Chemical	Region	Type of Impact	Health Criteria	Anem. Height (m)	Shelter-In-Place	Cumulative	$Y = A (1 - \exp [-X/X_0])$			
Cl ₂	2	Worst Case	AEGL-1	6	NO	NO	where: X = time (min) Y = persons affected (to 1M pop)			
Parameter	1%	5%	10%	25%	50%	75%	90%	95%	99%	100%
A	39.3	71.4	210.6	532.2	1,338.8	3,077.3	5,344.3	17,362.9	31,166.7	103,830.6
X ₀	24.0	26.7	38.7	39.7	38.1	43.2	41.3	64.7	33.0	37.2
r ²	0.9879	0.9924	0.9937	0.9948	0.9976	0.9988	0.9983	0.9972	0.9952	0.9990

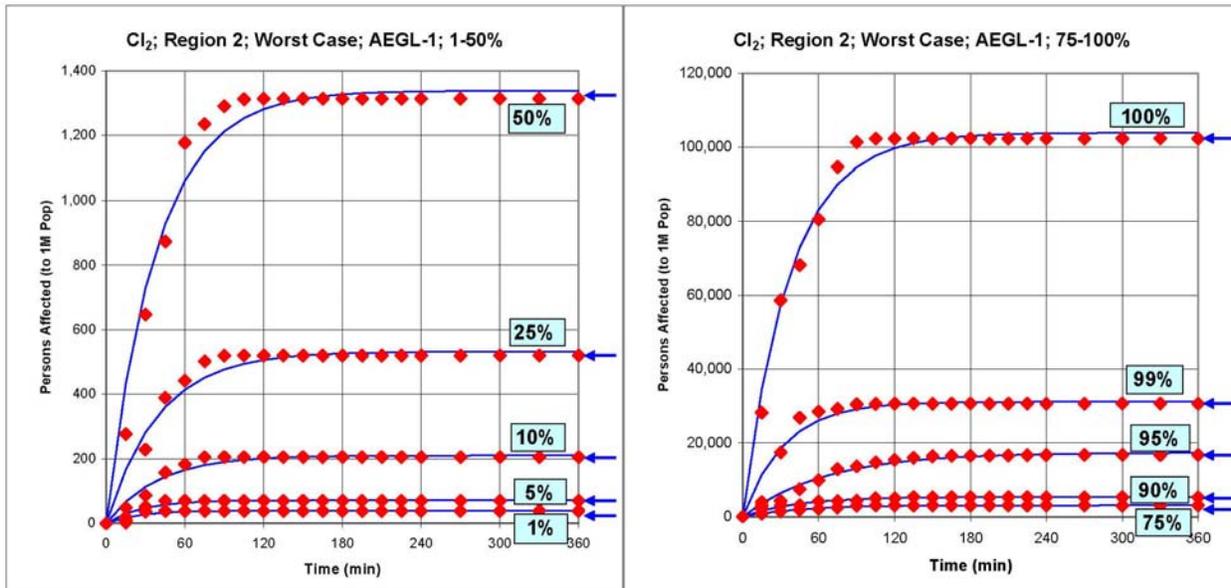


FIGURE 11 Time vs. Persons Affected (Normalized to a Population of 1 Million) by Cumulative Frequencies for Region 2, Worst Case, AEGL-1 (Note: Tabulated results can be found in Table B.2-3.)

Note that a scenario for a cumulative frequency at one time is not necessarily the same as that for other times. For example, a scenario for 90% cumulative frequency at $t = 15$ min is not necessarily the same as that at $t = 30$ min. In the model, results from all scenarios at $t = 15$ min are sorted in ascending order of impacts affected and by select values for cumulative percent of interest. The same process is applied at different times. Figure 11 suggests that all impacts have occurred by about 2 hours post-release (see 100% cumulative frequency regression curve), because one highly improbable (i.e., incredible) accident with the highest impacts (i.e., having a relatively long and wide footprint for unstable atmosphere and a wind speed of 2–3 m/s with the largest source release) is complete at 2 hours after the release. However, many other large incidents with large releases are still progressing at 2 hours after the release, which is reflected at other cumulative frequencies (e.g., 95% or 99%).

The following regression curve is well-fitted to time-series impact data (see Figure 11):

$$Y = A [1 - \exp (-X/X_0)]$$

where Y = impacts (e.g., number of persons affected), A = amplitude, X = time (min), and X_o = relaxation coefficient. Given estimated impact values (e.g., persons affected) with time, optimal values of amplitude A and relaxation coefficient X_o can be found by using the Excel Solver Tool. Maximum impact values after the event is over can be used as initial estimates for the amplitude. An initial estimate for relaxation coefficients (X_o), which determine how fast the regression curve arrives to the final value, can be determined by trial and error while the shape of the graph is reviewed. Depending on the initial estimates, many different sets of parameter values can be possible. Accordingly, the optimal values can be judged on the basis of correlation coefficients and the degree of agreement between impact data and regression curves.

Figure 11 is a plot of time vs. persons affected by cumulative frequency for Region 2, worst case, and health criterion 1 (AEGL-1). From these regression curves, it can be interpreted that if an accident occurs, at 2 hours after the release, definitely fewer than 100,000 persons are affected (see 100% cumulative frequency curve); 25% of the time, fewer than 400 persons are affected; and 75% of the time, more than 400 persons are affected (see 25% cumulative frequency curve). For one region, 30 spreadsheets (5 types of impacts \times 6 health criteria as described in Sections 2.7 and 2.9), one of which is similar to Figure 11, were provided. These regression curve data were input to the systems dynamics model for further calculations.

To determine which parameters input to the SLAB model generate the largest impacts, the largest footprints were examined. In the event of an actual accidental release, the quantity of the chemical that is released (i.e., the number of pounds released) is the most important parameter in the model.

Wind speed is relatively lower (mostly 1.5 or 2.5 m/s) when the highest impacts occur. In general, when the wind blows more strongly, the toxic cloud is spread out and diluted faster, so that the footprint area is smaller. When all else is equal, lowering the wind speed increases the footprint length. Note that a wind speed of 1.5 m/s is widely used as the worst-case wind speed, as it is in the RMP. The higher impacts occur when the wind blows toward areas with the highest population densities.

In general, the more unstable the atmosphere, the more likely is the existence of turbulence, and the more rapidly a dispersing gas mixes with the air around it. When all else is equal, a shorter footprint results when the atmosphere is less stable (e.g., Class A at daytime) because the pollutant is diluted more quickly to below the LOC. Typically, Class F, the most stable class, is considered the worst-case stability class. However, a maximum downwind distance cutoff of 50 km is assumed even though the plumes under stable conditions may continue to move beyond 50 km. Accordingly, footprints under unstable conditions are wider than those under stable conditions up to 50 km from the release point and lead to higher impacts. However, these results are valid for numbers of persons and hospital beds affected because population density and hospitals are generally sparse at 50 km beyond metropolitan centers.

Ambient temperature and relative humidity affect the plume's rise and fall by their influence on ambient air density; they are generally less important than the other parameters described above. Higher impacts occur when the temperature is higher. If the ambient temperature is higher than the release temperature, the released plume tends to be denser than the

ambient air (although this result also depends on the molecular weight of the released chemical), and the plume may descend. Conversely, if the release temperature is higher than the ambient temperature, the plume may tend to ascend. Moving the vertical location of a plume can have large effects on impacts, especially in the near-field where gradients are the largest. The relative humidity can affect the dynamics of elevated jet releases. Varying the humidity can result in altering the plume height above the ground. Lower relative humidity values will result in estimates of longer footprints.

In conclusion, this study finds that the highest impacts occur when all or most of the following conditions are met: (1) the release is large, (2) the wind speeds are lower, (3) the wind direction is toward the area with a higher population density, (4) the atmosphere is unstable, (5) the ambient temperature is higher than average, and (6) the relative humidity is lower than average.

Valuable conclusions reached through this analysis include the following:

- The number of affected people as a function of time increases exponentially to an asymptote.
 - The asymptote and exponential decay constant increase with the frequency of occurrence.
- Rapid plume movement may limit the effectiveness of potential response measures.
 - Significant numbers of people are affected in the first 15–60 min.
 - Response measures that activate quickly (i.e., local area sirens, SIP) may be most effective.
- Median (50% frequency) values are much lower than worst-case (100%) values.
 - The numbers of people affected increase by many orders of magnitude as 100% frequency is approached.
 - Focusing on a worst-case chemical release scenario may not be representative of the overall risk.

4 OUTCOMES OF ACUTE CHLORINE EXPOSURES: IMMEDIATE AND DELAYED EFFECTS AND USE OF HOSPITAL RESOURCES

4.1 INTRODUCTION

Chlorine is a strongly irritating gas stored in many locations across the United States. It is also regularly transported. Accidental releases of chlorine can result in minor to severe injury to the respiratory tract of exposed individuals, and, if exposure levels are high enough, in immediate or delayed death.

This section summarizes the available data on acute exposures to chlorine and describes recommended assumptions on use of hospital resources for an exposed population. In addition, for those injured through exposure to chlorine, recommended assumptions on numbers of delayed fatalities and length of hospital stay are given. This work is intended to aid in emergency planning in the event of a large spill of chlorine.

4.2 ACUTE TOXICITY DATA

Chlorine gas exerts its irritant effect by forming damaging hydrochloric and hypochlorous acids on contact with moist surfaces, such as the respiratory tract, lung, and eyes (NRC 2004). The odor threshold for chlorine ranges from about 0.2 to 0.4 ppm, and nuisance irritation responses (itching or burning of the eyes, nose, or throat) are observed at concentrations of 0 to 2 ppm for durations of 30 to 120 minutes.

Nonlethal Exposures. The Committee on Toxicology of the National Research Council developed AEGLs for many acutely hazardous chemicals, including chlorine. These levels are based on available data from human exposures and animal studies, and they are developed by subcommittees composed of qualified scientists primarily from government regulatory agencies, industry, academia, and professional organizations.

AEGLs are developed for three different health effect levels, from mild effects to potentially life threatening. For each health effect level, there are five exposure durations (i.e., 10 and 30 minutes and 1, 4, and 8 hours) with corresponding air concentrations. In this document, only the 10-minute and 1-hour values are presented, as these were considered the most relevant for accidental releases (i.e., exposure durations are unlikely to be longer than 1 hour).

Extensive documentation for the chlorine AEGL levels is available (NRC 2004). The definitions for the various AEGL health effect levels and the corresponding concentrations for chlorine are as follows:

- AEGL-1 is the airborne concentration (expressed as ppm or mg/m³) of a substance above which it is predicted that the general population, including susceptible individuals, could experience notable discomfort, irritation, or

certain asymptomatic nonsensory effects. However, the effects are not disabling and are transient and reversible upon cessation of exposure.

- *AEGL-1 value for chlorine is 0.5 ppm for all exposure durations.*
- AEGL-2 is the airborne concentration (expressed as ppm or mg/m³) of a substance above which it is predicted that the general population, including susceptible individuals, could experience irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape.
 - *AEGL-2 values for chlorine are 2.8 ppm for 10 minutes and 2.0 ppm for 1 hour.*
- AEGL-3 is the airborne concentration (expressed as ppm or mg/m³) of a substance above which it is predicted that the general population, including susceptible individuals, could experience life-threatening health effects or death.
 - *AEGL-3 values for chlorine are 50 ppm for 10 minutes and 20 ppm for 1 hour.*

For chlorine, the AEGL documentation states that the AEGL-1 value was derived from human data showing no observed adverse effect at 0.5 ppm for 1 hour (NRC 2004). This is considered the threshold for mild effects (itching and discomfort in the nose and respiratory tract, burning of the eyes).

The AEGL-2 value of 2 ppm for 1 hour was also derived from human data; in the studies, subjects experienced irritation and changes in pulmonary function tests. These types of effects might cause a victim to seek medical attention, but the individual would be unlikely to be admitted to the hospital.

The AEGL-3 value was based on animal lowest lethal concentration data because, although accidental deaths have occurred in humans, documentation of the exposure levels was inadequate for deriving the AEGL-3 (lethality threshold) value. The NRC committee used an experimentally determined “no deaths” concentration of 213 ppm for rats and modified it with an uncertainty factor of 10 to account for animal-to-human extrapolation and to be protective of more-sensitive individuals (e.g., asthmatics). This resulted in the AEGL-3 value of 20 ppm for 1 hour.

4.2.1 Potentially Lethal Levels

In order to characterize potential health effects occurring at concentrations greater than the AEGL-3 value, primary toxicity data can be used. These are concentrations that have resulted in death in experimental animals, and they are generally reported as concentrations lethal to a given percent of the exposed animals (e.g., LC₅₀ is lethal to 50% of the exposed population), or the lowest lethal concentrations for exposed animals (LC_{LO}). The following is a list of such primary toxicity values as given in the AEGL documentation for chlorine (NRC 2004):

Dog LC ₅₀ :	650 ppm (mg/m ³) for 30 minutes (Underhill 1920)
Dog LC ₉₂ :	900–2,000 ppm for 30 minutes (Underhill 1920; deaths within three days)
Rat LC ₅₀ :	5,500 ppm (mg/m ³) for 5 minutes
	1,946 ppm for 10 minutes
	700 ppm for 30 minutes
	1,000 ppm for 1 hour
	455 ppm for 1 hour
	293 ppm for 1 hour (Back et al. 1972 as cited in NRC 2004; study design flawed)
	250 ppm for 7.3 hours (data from 1940)
	63 ppm for >16 hours (data from 1940)
Mouse LC ₅₀ :	1,057 ppm for 10 minutes
	676 ppm for 10 minutes (data from 1942)
	628 ppm for 10 minutes (data from 1941)
	302 ppm for 10 minutes
	290 ppm for 10 minutes
	1,000 ppm for 28 minutes (data from 1940)
	504 ppm for 30 minutes
	127 ppm for 30 minutes
	170 ppm for 55 minutes
	137 ppm for 1 hour (Back et al. 1972 as cited in NRC 2004, study design flawed)
	250 ppm for 7.3 hours (data from 1940)
	63 ppm for >16 hours (data from 1940)

Review of these data by the AEGL committee showed that the mouse was not a good model, because mice experienced delayed deaths, which did not match human responses. The committee also found that the older data from the 1940s was questionable. Finally, the authors of Back et al. (1972) reported a 20–30% loss of chlorine in the exposure chambers, so their reported LC₅₀ values were lower than the actual values.

An estimate of the human LC_{LO} level of 430 ppm for 30 minutes (ATSDR 2006) was also published. The primary source for the data was not provided. This value corresponds to a 1-hour concentration of approximately 300 ppm (see “Time-Scaling” section below for methodology).

The dog LC₅₀ of 650 ppm for 30 minutes (Underhill 1920) and the lowest reliable rat LC₅₀ of 455 ppm for 1 hour (Zwart and Woutersen 1988) are quite comparable when the 650 ppm value is adjusted to 460 ppm to represent a 1-hour exposure (see “Time-Scaling” section below). The LC₅₀ value for use in this report is rounded down to 450 ppm to be protective.

The only available LC₁₀₀ value is a range given for dogs. The lower end of the dog LC₁₀₀ range is 900 ppm for 30 minutes. This corresponds to a level of 640 ppm for 1 hour.

4.2.2 Time Scaling

Time scaling is a procedure used to adapt primary toxicity data (e.g., LC₅₀ values) from the experimental exposure times to apply to other exposure times of interest. A common assumption in early toxicology work was that the effects of exposures to chemicals were dependent on the total dose, and the time over which the dose was delivered was not important. For example, it was assumed that a concentration of 30 ppm inhaled over 30 minutes would result in the same effects as a concentration of 15 ppm inhaled over 60 minutes. This linearity assumption on the effects of exposures is referred to as Haber's Law. However, it has been found experimentally that there are many chemicals for which this law does not apply, especially direct-acting irritant chemicals such as chlorine. For these chemicals, high doses for short times often cause more damage than the equivalent dose received at a lower concentration but over a longer time period.

The NRC AEGL committee considers chemical-specific data in scaling toxicity values, and it uses an exponential scaling equation to convert between various exposure durations (NRC 2001). The relationship between exposure duration and concentration can be expressed by the equation $C^n \times t = k$, where C equals exposure concentration, t equals exposure time, k equals a constant, and n represents a chemical-specific, and even a toxic-endpoint-specific, exponent. When $n = 1$, this equation simplifies to the linear equation described as Haber's Law.

The above equation can be manipulated to allow the concentration for a certain exposure duration to be converted to the concentration for a different exposure duration (time-scaling). For example, for deriving a 10-minute value from a 1-hour value, the following equation is used:

$$10\text{-min value} = [(60\text{-min value})^n \times (60 \text{ min}/10 \text{ min})]^{1/n}$$

A summary of the chlorine concentrations for 10-minute and 1-hour exposures that correspond to the various AEGL values and primary toxicity values deemed most applicable to human exposures is given in Table 7. Where time-scaling was required, it was done assuming an "n" value of 2 for chlorine. The NRC AEGL documentation discusses data supporting the use of $n = 2$.

TABLE 7 Summary of Significant Chlorine Exposure Concentrations

Impact Category	Chlorine Conc. for 10-min Exposure	Chlorine Conc. for 1-h Exposure
AEGL-1	0.5	0.5
AEGL-2	2.8	2.0
AEGL-3	50	20
LC _{LO}	740	300
LC ₅₀	1,100	450
LC ₁₀₀	1,600	640

Source: NRC (2004).

4.3 SUGGESTED LEVELS FOR HOSPITAL RESOURCE USE CATEGORIES

One goal for this project was to develop a method for estimating the numbers of exposed individuals who would require various levels of hospital services. Three levels of hospital service were defined: treat and release, treat and admit, and admission to intensive care unit (ICU). Populations exposed to increasing concentrations of chlorine were assumed to require increasing levels of hospital services. The hospital services concentration ranges below were developed by assuming that the victims were transported to the hospital within about 2 hours of the exposure and that the effects (e.g., severe injury or death) had occurred by the time of arrival at the hospital. Chlorine exposures sometimes result in delayed effects and deaths; assumptions for estimating numbers of delayed effects are discussed in Section 4.4.

It should be noted that there is considerable individual variability in response to chlorine exposures in the general population, depending on factors like existing respiratory conditions, age, behavior during the exposure, and others. Therefore, it is expected that most people exposed within the given concentration ranges would have the predicted outcome, but there are always more and less sensitive individuals within a population.

It was assumed that a reasonable concentration range corresponding to treat and release would be chlorine levels between the AEGL-1 and AEGL-2 values. AEGL-1 is the threshold for reversible effects, including effects such as mild irritation, headache, or odor detection. The AEGL-2 is the threshold for serious and possibly irreversible effects. Therefore, it is unlikely that persons exposed to concentrations lower than the AEGL-2 value would require hospitalization.

The concentration range corresponding to treat and admit was assumed to correspond to the levels between the AEGL-2 and the AEGL-3 value. AEGL-3 is the threshold for possibly life-threatening effects. Persons exposed to levels within this concentration range might require hospitalization but would be unlikely to require ICU services.

The concentration range corresponding to ICU services was assumed to correspond to levels between the AEGL-3 and the LC_{LO} value. This group would be likely to have serious adverse respiratory effects requiring ICU services from the exposure, but deaths would still be unlikely.

Outcomes of exposures to concentrations higher than the LC_{LO} value are concentration-dependent and somewhat more difficult to predict, because the more sensitive individuals would die within a short time from the exposure, but many individuals would eventually recover. An algorithm was developed that assumed higher percentages of dead on arrival (DOA) cases with increasing chlorine concentrations. It was assumed that in the population exposed in the range between the LC_{LO} and the LC_{50} values, 25% of the individuals would be DOA, and 75% would require ICU services. For the population exposed in the range between the LC_{50} and the LC_{100} values, 75% of the individuals would be DOA, and 25% would require ICU services. It was assumed that all individuals exposed at a concentration higher than the LC_{100} value would be DOA.

Table 8 summarizes the assumptions on hospital resource use based on exposure concentration ranges. One additional category of hospital resource use would be by individuals termed “worried well,” (i.e., individuals who either were not exposed at all or were exposed at a level too low to cause adverse health effects but who request medical examination to ensure that they are not injured). These individuals would be added to the treat and release category. However, no accurate method exists to estimate the number of worried well individuals who would report to the emergency room in the event of a large chemical release. The number would likely be most influenced by media coverage of the occurrence.

4.4 DELAYED EFFECTS AND HOSPITAL LENGTH OF STAY

Another goal of this project was to estimate the outcome of hospitalization for injured patients (measured by release or delayed death), as well as the length of stay in the hospital. These estimates were based on the published literature, as well as on professional judgment. The literature used is summarized in Table 9.

Delayed fatalities are defined as patients who initially survive and are admitted to the ICU within about 2 hours of the exposure but then die after some time in the ICU. Weedon et al. (1940) observed 50% death within 53 minutes at 1,000 ppm in rats, 50% death within 438 min (7.3 h) at 240 ppm, and time to 50% lethality greater than 16 hours at a concentration of 63 ppm. Additionally, Withers and Lees (1985) estimated a medical treatment factor of 0.9 for the general population, meaning that receipt of medical care results in survival of 90% of those admitted to the ICU. These observations led to the following assumptions regarding the expected number of delayed deaths:

- For those admitted from the highest exposure category (LC_{50} to LC_{100}): Assume that 10% are delayed deaths (based on medical treatment factor).

TABLE 8 Summary of Hospitalization Resource Use Categories Based on Exposure Concentration Ranges

Exposure Concentration Range	Hospitalization Resource Use Category			
	Treat/Release	Treat/Admit	ICU	DOA
Between AEGL-1 and AEGL-2	100%			
Between AEGL-2 and AEGL-3		100%		
Between AEGL-3 and LC_{LO}			100%	
Between LC_{LO} and LC_{50}			75%	25%
Between LC_{50} and LC_{100}			25%	75%
Higher than LC_{100}				100%

TABLE 9 Studies Supporting Assumptions for Delayed Deaths and Length of Hospital Stay

Study	Data	Symptoms	Discussion
Underhill et al. (1920)	% Lethality: 0% at 50–250 ppm; 6% at 400–500 ppm; 20% at 500–600 ppm; 43% at 600–700 ppm; 87% at 800–900 ppm; 92% at 900–2,000 ppm. Calculated LC ₅₀ = 650 ppm (for 30 min; equivalent to 460 ppm for 1 h, assuming n = 2).	Excitation, respiratory irritation, labored breathing. Some delayed deaths (longer than 3 days after exposure?) as a result of bronchopneumonia following subsidence of acute pulmonary edema in all exposure groups (1/9 in 50–250 ppm group).	112 male and female dogs, 30-min exposures, chlorine concentrations from 50 to 2,000 ppm. Reported fatalities that occurred within 3 d of exposure.
Weedon et al. (1940)	Time to LC ₅₀ : 53 min at 1,000 ppm; 438 min (7.3 h) at 240 ppm; >960 min (>16 h) at 63 ppm		Groups of eight rats exposed to 63, 240, or 1,000 ppm for 16 h or until death.
Withers and Lees (1985)	Gave references for percents of general population in various vulnerability categories: About 9% older than 70 yr, 9% less than 5 yr, 8% less than 9 yr; 2% with respiratory disease, heart trouble, restricted mobility or blind (overall 28% “vulnerable”). Also gave reference for assumption that at 50% lethal concentration of chlorine for general population, 100% lethality would occur in vulnerable population.	Gave medical treatment factor of 0.9 for general population and 0.7 for vulnerable populations (e.g., for general population, medical care will result in 90% of delayed deaths becoming recoveries).	Need to also consider level of activity and effect on inhalation rate. Most animal lethality data (including Underhill) are for resting animals, so same concentration could result in higher lethality in humans walking at 4 mph (e.g., if one is trying to escape, the inhalation rate is about 5 times higher).
Zwart and Wouterson (1988)	LC ₅₀ values for 1 h (disregard one very high value) – about 460 to 800 ppm. LC ₀₁ and irreversible damage threshold at 288 ppm (1 h) (estimated)	At higher concentrations: restlessness; eye and nasal irritation; labored breathing; reduced respiratory rate; and nose, larynx, and tracheal damage. At lower concentrations: lung lesions (including monocuclear inflammatory cells, squamous metaplasia of bronchiolar epithelium, and edema). Hyperplasia of the larynx and trachea resolved by 14 d post-exposure in survivors.	Rats exposed to 322–5,793 ppm for 5 min to 1 h. Observed for 14 d; mortalities occurred during exposure and up to 1 wk after exposure.

- For those admitted from the LC_{LO} to LC_{50} category: Assume that 4% die (for exposure at a similar concentration, it took more than 7 hours for 50% mortality to occur, whereas the modeled exposures would take place over only up to 1 hour).
- For those admitted from the AEGL-3 to LC_{LO} category: Assume that 0.75% die (professional judgment).

These are somewhat conservative professional judgments based on the above data sources, since the Weedon et al. (1940) data seem to indicate that the 1,000-ppm concentration would need to be sustained for 53 minutes for 50% death to occur, whereas we use a considerably lower concentration (450 ppm) as the LC_{50} for a 1-hour exposure. However, conservatism is warranted because the basis for the 10% delayed death rate with medical care cited by Withers and Lees (1985) is anecdotal (from World War I use) and not tied to concentration levels.

The time spent in the ICU before delayed deaths occur was also estimated on the basis of the Weedon et al. (1940) reference and professional judgment, as follows:

- For delayed deaths from the highest exposure category (LC_{50} to LC_{100}) and the LC_{LO} to LC_{50} category: Assume death occurs within 1 day of admittance.
- For delayed deaths from the AEGL-3 to LC_{LO} category: Assume death occurs within 1 week of admittance.

Finally, length of hospital stay and need for long-term follow-up care was estimated. Zwart and Wouterson (1988) observed an irreversible damage level of 288 ppm for 1-hour exposures (equivalent to about 700 ppm for 10-minute exposures). This likely means permanent decreased lung function occurs at lower exposures and brain damage and/or the need for a ventilator occurs at the highest exposure levels. The assumptions were as follows:

- For the 90% of the highest exposure category patients eventually discharged from the ICU, assume an average of 2 weeks in the hospital (1 week in ICU and 1 week in wards), and 50% requiring long-term care.
- For the 96% of the LC_{LO} to LC_{50} category patients eventually discharged from the ICU, assume an average of 1 week in hospital (3 days in ICU and 4 days in wards), and 25% requiring long-term care.
- For the 99.25% of the AEGL-3 to LC_{LO} category patients eventually discharged from the ICU, assume an average of 4 days in hospital (1 day in ICU and 3 days in wards), and 2% requiring long-term care.

Figure 12 illustrates the above assumptions on delayed deaths and length of ICU and hospital stay.

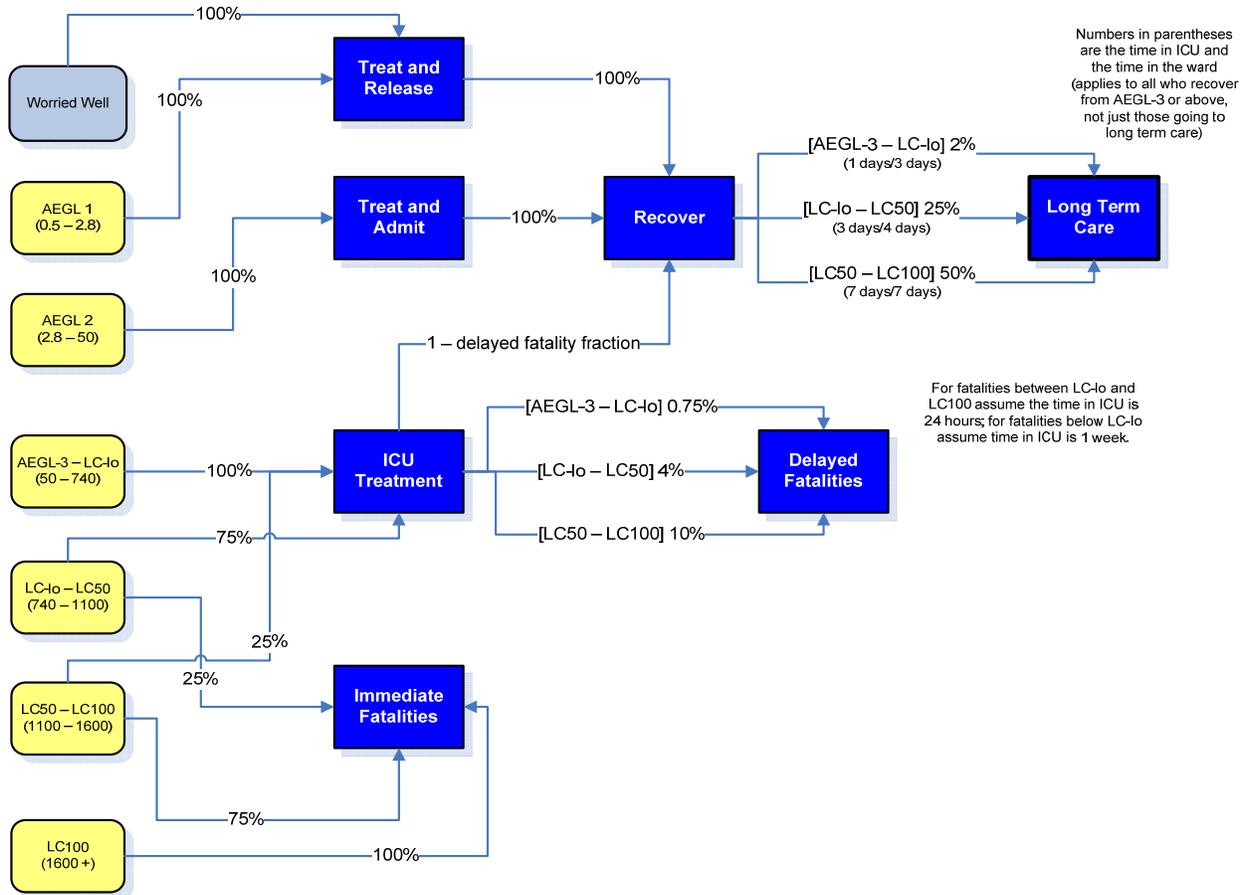


FIGURE 12 Hospital Resource Utilization Diagram for Varying Chlorine Exposure Levels (Source: LeClaire 2006).

The rationale and assumptions provided in this document allow reasonable estimation (based on chlorine toxicity data) to be made of the expected number of deaths and the use of hospital resources in the event of a chlorine spill involving the exposure of a large population.

5 CONCLUDING REMARKS AND FUTURE WORK

A methodology has been proposed to estimate the statistical impacts of human and infrastructure features (such as hospital beds and geographical areas) in the event of chemical releases triggered by terrorist attacks, human mishaps, or catastrophic accidents. In this analysis, chlorine was selected because it would have high impacts because of its toxicity and ubiquitous use in the United States. In this analysis, all possible combinations (tens of thousands of possible scenarios) of chemical release groups and hourly meteorological conditions were reduced to a manageable number of scenarios (i.e., a total of about 2,000 scenarios from four or five release groups and representative meteorological conditions [maximum 432]). Footprints for given health criteria (e.g., AEGL-1) were estimated from the SLAB chemical release model and were overlaid onto population and hospital bed distribution data to estimate potential impacts. Statistical results from accident release modeling followed by impact analysis were presented in this report and were input to emergency services and healthcare models for additional processing.

In many applications, accidental release modeling analysis for a single facility is limited to scenarios for the release of the highest volume of inventory with two meteorological conditions: (1) worst-case release scenario (e.g., Class F stability and a wind speed of 1.5 m/s with a catastrophic release of the entire chemical inventory) and (2) alternative release scenario (i.e., a more realistic or more likely to occur scenario, such as Class D stability and a wind speed of 3 m/s with a realistic and most likely failure event). However, to delineate a more realistic probability distribution of potential impacts, the methodology used in this analysis can also be applied by using the STAR summaries from historical meteorological data and several source terms (e.g., from 5 to 10 groups), which can be developed on the basis of statistical distribution of storage volumes with time. These statistical distributions of impacts can help the facility's stakeholders formulate appropriate safety and security plans and make reasonable and informed decisions.

The current study is limited to chlorine. In future work, other widely used chemicals such as anhydrous ammonia and hydrogen fluoride, can be included in the analysis. In addition, potential impacts associated with the implementation of mitigative measures (e.g., active barriers such as water spray curtains) can be exercised.

6 REFERENCES

- AG-DEWR (Australian Government-Department of the Environment and Water Resources), 2005, *Chlorine Fact Sheet*. Available at <http://www.npi.gov.au/database/substance-info/profiles/20.html#environmentaleffects>. Accessed July 2007.
- AIHA (American Industrial Hygiene Association), 2007, *Current AIHA ERPGs (2007)*. Available at <http://www.aiha.org/1documents/Committees/ERP-erpglevels.pdf>. Accessed July 2007.
- ATSDR (Agency for Toxic Substances and Disease Registry), 1999, *Industrial Chemicals and Terrorism: Human Health Threat Analysis, Mitigation and Prevention*. Available at <http://www.mipt.org/pdf/industrialchemicalsandterrorism.pdf>. Accessed June 2006.
- ATSDR, 2006, *Medical Management Guidelines (MMGs) for Chlorine (Cl₂)*. Available at <http://www.atsdr.cdc.gov/MHMI/mmg172.html>. Accessed April 26, 2006.
- Back, K.C., et al., 1972, *Reclassification of Materials Listed as Transportation Health Hazards*, Report TSA-20-72-3, Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Dayton, Ohio.
- Belke, J.C., 2000, *Chemical Accident Risks in U.S. Industry – A Preliminary Analysis of Accident Risk Data from U.S. Hazardous Chemical Facilities*,” U.S. Environmental Protection Agency, Chemical Emergency Preparedness and Prevention Office, Washington, D.C., Sept. 25. Available at <http://www.epa.gov/swercepp/pubs/stockholmpaper.pdf>. Accessed Oct. 2006.
- Beyer, W.H., 1991, *CRC Standard Mathematical Tables and Formulae*, 29th Edition, CRC Press, Boca Raton, Fla.
- Brown, D.F., et al., 2000, *A National Risk Assessment for Selected Hazardous Materials in Transportation*, ANL/DIS-01-1, Argonne National Laboratory, Argonne, Ill., Dec.
- Craig, D.K., et al., 1995, “Alternative Guideline Limits for Chemicals without ERPGs,” *Amer. Ind. Hyg. Assoc. J.* 56:919–925.
- DOE (U.S. Department of Energy), 2007, *Rev. 22A of AEGLs, ERPGs and TEELs for Chemicals of Concern (5/2007)*. Available at <http://www.atlantl.com/DOE/teels/teel.html>. Accessed Aug. 6, 2007.
- DTRA (Defense Threat Reduction Agency), 2004, *Hazard Prediction & Assessment Capability (HPAC) 4.04 Users Manual*, Ft. Belvoir, Va., April.
- EIA (Energy Information Administration), 2000, *U.S. Census Regions and Divisions*, June 14. Available at http://www.eia.doe.gov/emeu/reps/maps/us_census.html. Accessed May 27, 2008.

EPA (U.S. Environmental Protection Agency), 1999a, *PCRAMMET User's Guide*, EPA-454/B-96-001, Office of Air Quality Planning and Standards, Research Triangle Park, N.C., June. Available at <http://www.epa.gov/scram001/userg/relat/pcramtd.pdf>. Accessed May 2005.

EPA, 1999b, *Risk Management Program Guidance for Offsite Consequence Analysis*, EPA 550-B-99-009, Office of Solid Waste and Emergency Response, Chemical Emergency Preparedness and Prevention Office, April. Available at [http://yosemite.epa.gov/oswer/ceppoweb.nsf/vwResourcesByFilename/oca-all.PDF/\\$File/oca-all.PDF](http://yosemite.epa.gov/oswer/ceppoweb.nsf/vwResourcesByFilename/oca-all.PDF/$File/oca-all.PDF). Accessed May 2005.

EPA, 2007, *Acute Exposure Guideline Levels (AEGLs)*. Available at <http://www.epa.gov/oppt/aegl/pubs/process.htm>, last updated April 25, 2007. Accessed August 2007.

EPA and NOAA (National Oceanic and Atmospheric Administration), 2006, *ALOHA[®], Areal Locations of Hazardous Atmospheres, User's Manual*, EPA, Washington, D.C., and NOAA, Seattle, Wash., Feb. Available at http://www.epa.gov/ceppo/comeo/pubs/ALOHA_User_Manual_Feb2006.pdf. Accessed April 20, 2006.

Ermak, D.L., 1990, *User's Manual for SLAB: An Atmospheric Dispersion Model for Denser-Than-Air Releases*, UCRL-MA-105607, University of California, Lawrence Livermore National Laboratory, Livermore, Calif., June.

Grimaldi, J.V., and G. Gugliotta, 2001, "Chemical Plants Are Feared as Targets; Views Differ on Ways to Avert Catastrophe," *The Washington Post*, Dec. 16.

Hartmann, H., 2006, personal communication from Hartmann (Argonne National Laboratory, Argonne, Ill.) to M. Samsa (Argonne National Laboratory, Argonne, Ill.), Jan. 20.

HSC (Homeland Security Council), 2005, *National Planning Scenarios: Created for Use in National, Federal, State, and Local Homeland Security Preparedness Activities, Version 20.1 DRAFT*, April. Available at <http://media.washingtonpost.com/wp-srv/nation/nationalsecurity/earlywarning/NationalPlanningScenariosApril2005.pdf>. Accessed July 25, 2007.

Kleindorfer, P., et al., 2000, *Epidemiology and the U.S. Chemical Industry: Preliminary Results from RMP*Info*, Center for Risk Management and Decision Processes, Wharton School, University of Pennsylvania, March 6. Available at <http://www.acusafe.com/Talks-Paper/accident-epidemiology.pdf>. Accessed May 27, 2008.

Kunkel, B.A., 1991, *AFTOX 4.0 – The Air Force Toxic Chemical Dispersion Model – A User's Guide*, PL-TR-91-2119, Environmental Research Papers, No. 1083, Phillips Laboratory, Hanscom Air Force Base, Mass., May 8.

LANL (Los Alamos National Laboratory), 2003, *U.S.A. Day-Night & Indoor-Outdoor Population Database, v. 2.1*, LA-UR-03-8389, Los Alamos, N.M.

LeClaire, R., 2006, personal communication from R. LeClaire (Los Alamos National Laboratory, Los Alamos, N.M.), to H. Hartmann (Argonne National Laboratory, Argonne, Ill.), Jan. 31.

Leonnig, C.D., and S.S. Hsu, 2001, "Fearing Attack, Blue Plains Ceases Toxic Chemical Use," *The Washington Post*, Nov. 10.

Lewis, S., 2002, *The Safe Hometowns Guide – How to Do a Community Reassessment of Chemical Site Safety and Security after September 11, 2001*, A Publication of the Safe Hometowns Initiative. Available at <http://www.safehometowns.org/safehometowns.pdf>. Accessed April 26, 2005.

Moser, J.H., 1996, *A Guidance Manual for Modeling Hypothetical Accidental Releases to the Atmosphere*, API Publication 4628, prepared by James Moser Research, Inc., Cypress, Texas, for the American Petroleum Institute, Washington, D.C., Nov.

NCDC (National Climatic Data Center), 1997, *Hourly United States Weather Observations 1990–1995 (HUSWO)*, Asheville, N.C., Oct.

NGA (National Geospatial-Intelligence Agency), 2004, *Homeland Security Initiative Program (HSIP) Gold Data*, released Dec. 2.

NRC (National Research Council), 2001, *Standing Operating Procedures for Developing Acute Exposure Guideline Levels for Hazardous Chemicals*, Subcommittee on Acute Exposure Guideline Levels, Committee on Toxicology, National Academies Press, Washington, D.C. Available at <http://www.epa.gov/opptintr/aegl/pubs/sop.pdf>. Accessed Aug. 6, 2007.

NRC, 2004, *Acute Exposure Guideline Values for Selected Chemicals, Vol. 4*, National Academies Press. Available at <http://www.nap.edu/books/0309091470/html/14.html>. Accessed May 21, 2008.

Pianin, E., 2002, "Study Assesses Risk of Attack on Chemical Plant," *The Washington Post*, March 12.

Post, L., 1994a, *HGSYSTEM 3.0 User's Manual*, TNER 94.058, Shell Research Limited, Thornton Research Centre, Chester, United Kingdom.

Post, L. (editor), 1994b, *HGSYSTEM 3.0 Technical Reference Manual*, TNER 94.059, Shell Research Limited, Thornton Research Centre, Chester, United Kingdom.

Purvis, M., and M. Herman, 2005, *Needless Risk: Oil Refineries and Hazard Reduction*, Penn Environment Research & Policy Center, Aug. Available at <http://www.pennenvironment.org/reports/needlessrisk05.pdf>. Accessed Sept. 21, 2006.

RMS (Risk Management Solutions), 2004, "Today's 10 Greatest Risks," *Risk & Insurance*, J. Roberts (editor-in-chief), April 15. Available at http://www.rms.com/Publications/10GreatestUSCats_R&I_041504.pdf#search=%22%22today's%2010%20greatest%20risks%22%22. Accessed Aug. 24, 2005.

SCAPA (Subcommittee on Consequence Assessment and Protective Actions), 2007, *Protective Action Criteria for Chemicals — TEEL Values Including AEGLs and ERPGs*. Available at <http://orise.orau.gov/emi/scapa/teels.htm>. Accessed July 25, 2007.

Spicer, T., and J. Havens, 1989, *User's Guide for the DEGADIS 2.1 Dense Gas Dispersion Model*, EPA-450/4-89-019, U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, N.C., Nov.

Underhill, F.P., 1920, *The Lethal War Gases: Physiology and Experimental Treatment*, Yale University Press, New Haven, Conn., p. 20.

Ventana Systems, Inc., 2008, *Vensim® from Ventana Systems, Inc.* Available at <http://www.vensim.com/>.

Weedon, F.R., A. Hartzell, and C. Setterstrom, 1940, "Toxicity of Ammonia, Chlorine, Hydrogen Cyanide, Hydrogen Sulphide, and Sulphur Dioxide Gases, V: Animals," *Cornell University Contributions* 11, Ithaca, N.Y., Boyce Thompson Institute for Plant Research, Inc., pp. 365–385.

Withers, R.M.J., and F.P. Lees, 1985, "The Assessment of Major Hazards: The Lethal Toxicity of Chlorine, Part 2: Model of Toxicity to Man," *J. of Hazard. Mater.* 12:283–302.

Zwart, A., and R.A. Woutersen, 1988, "Acute Inhalation Toxicity of Chlorine in Rats and Mice: Time-Concentration-Mortality Relationships and Effects on Respiration," *J. of Hazard. Mater.* 19:195–208.

APPENDIX A:
SLAB SAMPLE INPUT/OUTPUT FILES

APPENDIX A: SLAB SAMPLE INPUT/OUTPUT FILES

For all simulated accidents, chlorine stored under pressure is assumed to be released by producing a two-phase (liquid droplet-vapor mixture), horizontal jet source. The release is of a finite duration (10 minutes) when the SLAB dispersion calculation is used.

The input/output data file for one scenario among approximately 2,000 scenarios is presented. For this scenario, the release amount is 200 lb, and meteorological conditions⁹ include a wind speed of 1.5 m/s and a stability class of "A." The sample input to SLAB for the chlorine release described above is given in Tables A-1 and A-2, and selected values are described briefly below. The output from SLAB is given in Table A-3. The determination of parameter values is discussed in Section 2.6.

- Line 1: IDSPL is the spill source type. IDSPL = 2 for a horizontal jet release.
- Line 2: NCALC is a numerical substep parameter. The code developer recommends using NCALC = 1. However, NCALC can be increased if numerical stability problems are encountered.
- Line 3: WMS is the molecular weight of chlorine in kg/mole; WMS = 0.070906.
- Line 4: CPS is the specific heat at constant pressure, taken from a table in the SLAB *User's Manual* (Ermak 1990). CPS = 498.1.
- Line 5: TBP is the boiling point of chlorine; TBP = 239.1 K.
- Line 6: CMEDO is the liquid mass fraction, which was estimated to be 0.80 by using source property data and storage temperature.
- Lines 7–9: DHE = 287,840, CPSL = 926.3, and RHOSL = 1,574 are, respectively, the heat of vaporization at 293 K (J/kg), the specific heat of liquid chlorine (J/kg/K), and the liquid density (kg/m³). Their values are taken from Table 2 of the SLAB *User's Manual* (Ermak 1990).
- Lines 10–11: SPB and SPC are parameters that go into the formula for the saturated vapor pressure of chlorine:

$$P_s = P_a \times \exp(\text{SPA} - \text{SPB}/(\text{T} + \text{SPC}))$$

where P is the saturated vapor pressure, P_a is the ambient pressure (= 1.01 × 10⁵ N/m²), a value for SPA is specified in the code, and the values of SPB (1978) and SPC (−27.01) are given in the *User's Manual*. T is the ambient temperature (K).

⁹ Wind direction is not used in the SLAB run, but the resulting plume will be rotated along with wind direction to count the population and hospital beds affected.

- Lines 12–17: These specify spill parameters, which have already been discussed in detail above. TS is the temperature of the released material (TS = 239.1 K). QS is the rate of release (QS = 0.15 kg/s). AS is the effective area of the source (AS = 0.006 m²), which is estimated on the basis of the actual area of tank rupture. TSD is the duration of release (TSD = 600 s). QTIS is zero except in the case of a puff release. HS is the height of release (HS = 1 m).
- Line 18: TAV is the exposure time. As recommended in the *User's Manual*, its value is set to the value that is appropriate for the LOC under consideration. In this case, that value is 600 s (see Section 2.6).
- Line 19: XFFM is the maximum downwind extent of the calculation. It may be necessary to determine this by trial and error. A value of 100 km should be adequate for many applications. However, cutoff distance for impact analysis is limited to 50 km from the release point (see Section 2.6).
- Lines 20–23: ZP(I) allows the user to specify up to four heights at which the concentration is calculated as a function of downwind distance.
- Lines 24–29: These allow the user to specify meteorological conditions. ZO is the surface roughness length, which is set to 1 m for an urban area. ZA is the height at which the wind speed is measured (6 m). UA is the wind speed at height ZA (1.5 m/s). TA is the ambient temperature (302.6 K). RH is the relative humidity (47.6%). STAB is the stability class (1 or A).
- Line 30: TER < 0 terminates the run.

TABLE A-1 Sample SLAB Input – Chlorine Release for Release Amount of 200 lb and Meteorological Conditions (Release Type = Two-Phase, Horizontal-Jet Release; Wind Direction = North; Wind Speed = 1.5 m/s; Stability Class = A)

Line No.	Value	Input Parameter	Input Parameter Description
1	2	IDSPL	Spill source type
2	1	NCALC	Numerical substep parameter
3	0.070906	WMS	Molecular weight of source material (kg)
4	498.1	CPS	Vapor heat capacity at constant pressure (J/kg-K)
5	239.1	TBP	Boiling point temperature (K)
6	0.80	CMEDO	Initial liquid mass fraction
7	287840.	DHE	Heat of vaporization (J/kg)
8	926.3	CPSL	Liquid heat capacity (J/kg-K)
9	1574.	RHOSL	Liquid density of source material (kg/m ³)
10	1978.34	SPB	SPB saturation pressure constant
11	-27.01	SPC	Saturation pressure constant
12	239.10	TS	Temperature of source material (K)
13	0.15	QS	Mass source rate (kg/s)
14	0.0006	AS	Source area (m ²)
15	600.	TSD	Continuous source duration (s)
16	0.	QTIS	Instantaneous source mass (kg)
17	1.	HS	Source height (m)
18	600.	TAV	Concentration averaging time (s)
19	100000.	XFFM	Maximum downwind distance (m)
20	0.	ZP(1)	1 st height of concentration calculation (m)
21	0.	ZP(2)	2 nd height of concentration calculation (m)
22	0.	ZP(3)	3 rd height of concentration calculation (m)
23	0.	ZP(4)	4 th height of concentration calculation (m)
24	1.00000	ZO	Surface roughness height (m)
25	6.00	ZA	Ambient measurement height (m)
26	1.50	UA	Ambient wind speed (m/s)
27	302.6	TA	Ambient temperature (K)
28	47.6	RH	Relative humidity (percent)
29	1.	STAB	Stability class values
30	-1.	TER	Termination indicator

TABLE A-2 Sample SLAB Input File^a

```
2
1
.070906
498.1
239.1
.80
287840.
926.3
1574.
1978.34
-27.01
239.10
.15
.0006
600.
0.
1.
600.
100000.
0.
0.
0.
0.
1.00000
6.00
1.50
302.6
47.6
1.
-1.
```

^a See Table A-1 for description of each parameter.

TABLE A-3 Sample SLAB Output File

problem input

```

idspl =      2
ncalc =      1
wms  =   .070906
cps  =   498.10
tbp  =   239.10
cmed0 =   .80
dhe  =  287840.
cpsl =   926.30
rhosl = 1574.00
spb  =  1978.34
spc  =   -27.01
ts   =   239.10
qs   =   .15
as   =   .00
tsd  =   600.
qtis =   .00
hs   =   1.00
tav  =   600.00
xffm = 100000.00
zp(1) =   .00
zp(2) =   .00
zp(3) =   .00
zp(4) =   .00
z0   =  1.000000
za   =   6.00
ua   =   1.50
ta   =   302.60
rh   =   47.60
stab =   1.00

```

release gas properties

molecular weight of source gas (kg)	- wms = 7.0906E-02
vapor heat capacity, const. p. (j/kg-k)	- cps = 4.9810E+02
temperature of source gas (k)	- ts = 2.3910E+02
density of source gas (kg/m3)	- rhos = 3.6140E+00
boiling point temperature	- tbp = 2.3910E+02
liquid mass fraction	- cmed0= 8.0000E-01
liquid heat capacity (j/kg-k)	- cpsl = 9.2630E+02
heat of vaporization (j/kg)	- dhe = 2.8784E+05
liquid source density (kg/m3)	- rhosl= 1.5740E+03
saturation pressure constant	- spa = 9.3278E+00
saturation pressure constant (k)	- spb = 1.9783E+03
saturation pressure constant (k)	- spc = -2.7010E+01

TABLE A-3 (Cont.)

spill characteristics

spill type	- idspl=	2
mass source rate (kg/s)	- qs =	1.5000E-01
continuous source duration (s)	- tsd =	6.0000E+02
continuous source mass (kg)	- qtcs =	9.0000E+01
instantaneous source mass (kg)	- qtis =	0.0000E+00
source area (m2)	- as =	6.0000E-04
vertical vapor velocity (m/s)	- ws =	0.0000E+00
source half width (m)	- bs =	1.2247E-02
source height (m)	- hs =	1.0000E+00
horizontal vapor velocity (m/s)	- us =	1.3962E+01

field parameters

concentration averaging time (s)	- tav =	6.0000E+02
mixing layer height (m)	- hmx =	8.3200E+03
maximum downwind distance (m)	- xffm =	1.0000E+05
concentration measurement height (m)	- zp(1)=	0.0000E+00
	- zp(2)=	0.0000E+00
	- zp(3)=	0.0000E+00
	- zp(4)=	0.0000E+00

ambient meteorological properties

molecular weight of ambient air (kg)	- wmae =	2.8735E-02
heat capacity of ambient air at const p. (j/kg-k)	- cpaa =	1.0167E+03
density of ambient air (kg/m3)	- rhoa =	1.1573E+00
ambient measurement height (m)	- za =	6.0000E+00
ambient atmospheric pressure (pa=n/m2=j/m3)	- pa =	1.0133E+05
ambient wind speed (m/s)	- ua =	1.5000E+00
ambient temperature (k)	- ta =	3.0260E+02
relative humidity (percent)	- rh =	4.7600E+01
ambient friction velocity (m/s)	- uastr =	5.0473E-01
atmospheric stability class value	- stab =	1.0000E+00
inverse monin-obukhov length (1/m)	- ala =	-8.7500E-02
surface roughness height (m)	- z0 =	1.0000E+00

additional parameters

sub-step multiplier	- ncalc =	1
number of calculational sub-steps	- nssm =	3
acceleration of gravity (m/s2)	- grav =	9.8067E+00
gas constant (j/mol- k)	- rr =	8.3143E+00
von karman constant	- xk =	4.1000E-01

TABLE A-3 (Cont.)

1

instantaneous spatially averaged cloud parameters

x	zc	h	bb	b	bbx	bx	cv	rho	t	u	ua
1.00E+00	1.00E+00	2.45E-02	1.22E-02	1.10E-02	0.00E+00	0.00E+00	1.00E+00	1.79E+01	2.39E+02	1.40E+01	1.73E-01
1.03E+00	1.00E+00	2.58E-02	1.29E-02	1.15E-02	3.12E-02	3.12E-02	9.85E-01	1.64E+01	2.37E+02	1.39E+01	1.73E-01
1.06E+00	1.00E+00	2.74E-02	1.37E-02	1.22E-02	7.05E-02	7.05E-02	9.65E-01	1.48E+01	2.36E+02	1.38E+01	1.73E-01
1.10E+00	1.00E+00	2.95E-02	1.47E-02	1.30E-02	1.20E-01	1.20E-01	9.38E-01	1.30E+01	2.34E+02	1.36E+01	1.73E-01
1.15E+00	9.99E-01	3.23E-02	1.62E-02	1.41E-02	1.82E-01	1.82E-01	9.01E-01	1.12E+01	2.31E+02	1.34E+01	1.73E-01
1.22E+00	9.99E-01	3.64E-02	1.82E-02	1.56E-02	2.61E-01	2.61E-01	8.49E-01	9.34E+00	2.28E+02	1.30E+01	1.74E-01
1.30E+00	9.98E-01	4.24E-02	2.12E-02	1.78E-02	3.59E-01	3.59E-01	7.74E-01	7.48E+00	2.24E+02	1.25E+01	1.74E-01
1.40E+00	9.96E-01	5.24E-02	2.62E-02	2.12E-02	4.84E-01	4.83E-01	6.65E-01	5.69E+00	2.20E+02	1.15E+01	1.75E-01
1.53E+00	9.93E-01	7.10E-02	3.55E-02	2.67E-02	6.40E-01	6.40E-01	5.15E-01	4.11E+00	2.16E+02	1.00E+01	1.76E-01
1.69E+00	9.87E-01	1.09E-01	5.46E-02	3.61E-02	8.37E-01	8.37E-01	3.42E-01	2.92E+00	2.11E+02	7.68E+00	1.78E-01
1.90E+00	9.76E-01	1.87E-01	9.37E-02	5.07E-02	1.08E+00	1.08E+00	1.98E-01	2.21E+00	2.08E+02	5.12E+00	1.82E-01
2.16E+00	9.50E-01	4.09E-01	2.04E-01	8.18E-02	1.40E+00	1.40E+00	9.61E-02	1.53E+00	2.66E+02	2.83E+00	1.97E-01
2.48E+00	8.90E-01	9.40E-01	4.70E-01	1.26E-01	1.79E+00	1.79E+00	4.02E-02	1.31E+00	2.85E+02	1.39E+00	2.31E-01
2.90E+00	7.41E-01	2.25E+00	1.13E+00	2.12E-01	2.28E+00	2.28E+00	1.56E-02	1.22E+00	2.95E+02	6.46E-01	3.77E-01
3.41E+00	5.43E-01	3.02E+00	1.77E+00	3.16E-01	2.91E+00	2.91E+00	8.41E-03	1.19E+00	2.99E+02	5.77E-01	4.99E-01
4.06E+00	4.19E-01	3.67E+00	2.36E+00	3.97E-01	3.69E+00	3.69E+00	4.82E-03	1.17E+00	3.01E+02	6.26E-01	5.96E-01
4.88E+00	3.46E-01	4.36E+00	2.91E+00	4.61E-01	4.68E+00	4.68E+00	2.92E-03	1.17E+00	3.02E+02	7.05E-01	6.91E-01
5.91E+00	2.99E-01	5.18E+00	3.43E+00	5.09E-01	5.92E+00	5.92E+00	1.85E-03	1.16E+00	3.02E+02	7.98E-01	7.91E-01
7.21E+00	2.67E-01	6.14E+00	3.94E+00	5.45E-01	7.48E+00	7.48E+00	1.21E-03	1.16E+00	3.02E+02	8.99E-01	8.95E-01
8.84E+00	2.45E-01	7.22E+00	4.52E+00	5.79E-01	9.45E+00	9.45E+00	8.05E-04	1.16E+00	3.02E+02	9.99E-01	9.98E-01
1.09E+01	2.28E-01	8.49E+00	5.18E+00	6.09E-01	1.19E+01	1.19E+01	5.42E-04	1.16E+00	3.02E+02	1.10E+00	1.10E+00
1.35E+01	2.15E-01	9.99E+00	5.92E+00	6.34E-01	1.51E+01	1.51E+01	3.67E-04	1.16E+00	3.03E+02	1.21E+00	1.21E+00
1.67E+01	2.05E-01	1.17E+01	6.88E+00	6.65E-01	1.90E+01	1.90E+01	2.49E-04	1.16E+00	3.03E+02	1.31E+00	1.31E+00
2.09E+01	1.97E-01	1.37E+01	8.00E+00	6.91E-01	2.39E+01	2.39E+01	1.69E-04	1.16E+00	3.03E+02	1.42E+00	1.42E+00
2.60E+01	1.91E-01	1.61E+01	9.31E+00	7.13E-01	3.02E+01	3.02E+01	1.15E-04	1.16E+00	3.03E+02	1.53E+00	1.53E+00
3.25E+01	1.86E-01	1.91E+01	1.09E+01	7.31E-01	3.80E+01	3.80E+01	7.74E-05	1.16E+00	3.03E+02	1.64E+00	1.64E+00
4.07E+01	1.82E-01	2.26E+01	1.27E+01	7.46E-01	4.79E+01	4.79E+01	5.21E-05	1.16E+00	3.03E+02	1.75E+00	1.75E+00
5.10E+01	1.80E-01	2.68E+01	1.50E+01	7.58E-01	6.03E+01	6.03E+01	3.50E-05	1.16E+00	3.03E+02	1.86E+00	1.87E+00
6.40E+01	1.77E-01	3.18E+01	1.78E+01	7.68E-01	7.59E+01	7.59E+01	2.34E-05	1.16E+00	3.03E+02	1.98E+00	1.98E+00
8.03E+01	1.75E-01	3.78E+01	2.13E+01	7.75E-01	9.56E+01	9.56E+01	1.56E-05	1.16E+00	3.03E+02	2.09E+00	2.09E+00
1.01E+02	1.74E-01	4.50E+01	2.56E+01	7.81E-01	1.20E+02	1.20E+02	1.04E-05	1.16E+00	3.03E+02	2.21E+00	2.21E+00
1.27E+02	1.73E-01	5.36E+01	3.08E+01	7.86E-01	1.52E+02	1.52E+02	6.85E-06	1.16E+00	3.03E+02	2.32E+00	2.32E+00
1.59E+02	1.72E-01	6.38E+01	3.74E+01	7.90E-01	1.91E+02	1.91E+02	4.53E-06	1.16E+00	3.03E+02	2.43E+00	2.43E+00
2.00E+02	1.72E-01	7.60E+01	4.56E+01	7.93E-01	2.40E+02	2.40E+02	2.98E-06	1.16E+00	3.03E+02	2.54E+00	2.54E+00
2.52E+02	1.71E-01	9.06E+01	5.57E+01	7.95E-01	3.03E+02	3.03E+02	1.96E-06	1.16E+00	3.03E+02	2.65E+00	2.65E+00
3.17E+02	1.71E-01	1.08E+02	6.83E+01	7.96E-01	3.81E+02	3.81E+02	1.29E-06	1.16E+00	3.03E+02	2.76E+00	2.76E+00
3.99E+02	1.71E-01	1.29E+02	8.39E+01	7.98E-01	4.80E+02	4.80E+02	8.47E-07	1.16E+00	3.03E+02	2.87E+00	2.87E+00
5.02E+02	1.70E-01	1.54E+02	1.03E+02	7.99E-01	6.04E+02	6.04E+02	5.57E-07	1.16E+00	3.03E+02	2.98E+00	2.98E+00
6.32E+02	1.70E-01	1.83E+02	1.27E+02	7.99E-01	7.60E+02	7.60E+02	3.66E-07	1.16E+00	3.03E+02	3.08E+00	3.09E+00
7.95E+02	1.70E-01	2.18E+02	1.56E+02	8.00E-01	9.57E+02	9.57E+02	2.41E-07	1.16E+00	3.03E+02	3.19E+00	3.19E+00
1.01E+03	1.70E-01	2.69E+02	1.93E+02	8.00E-01	1.00E+03	9.57E+02	1.51E-07	1.16E+00	3.03E+02	3.32E+00	3.32E+00
1.28E+03	1.70E-01	3.31E+02	2.39E+02	8.01E-01	1.06E+03	9.57E+02	9.41E-08	1.16E+00	3.03E+02	3.44E+00	3.44E+00

TABLE A-3 (Cont.)

1.64E+03	1.70E-01	4.06E+02	2.97E+02	8.01E-01	1.13E+03	9.57E+02	5.79E-08	1.16E+00	3.03E+02	3.56E+00	3.56E+00
2.10E+03	1.70E-01	4.97E+02	3.68E+02	8.01E-01	1.22E+03	9.57E+02	3.53E-08	1.16E+00	3.03E+02	3.68E+00	3.68E+00
2.71E+03	1.70E-01	6.08E+02	4.56E+02	8.01E-01	1.33E+03	9.57E+02	2.14E-08	1.16E+00	3.03E+02	3.79E+00	3.79E+00
3.49E+03	1.70E-01	7.42E+02	5.62E+02	8.02E-01	1.47E+03	9.57E+02	1.29E-08	1.16E+00	3.03E+02	3.90E+00	3.90E+00
4.51E+03	1.70E-01	9.04E+02	6.90E+02	8.02E-01	1.64E+03	9.57E+02	7.70E-09	1.16E+00	3.03E+02	4.01E+00	4.01E+00
5.82E+03	1.70E-01	1.10E+03	8.43E+02	8.02E-01	1.85E+03	9.57E+02	4.59E-09	1.16E+00	3.03E+02	4.12E+00	4.12E+00
7.52E+03	1.69E-01	1.33E+03	1.02E+03	8.03E-01	2.11E+03	9.57E+02	2.73E-09	1.16E+00	3.03E+02	4.22E+00	4.22E+00
9.71E+03	1.69E-01	1.61E+03	1.23E+03	8.03E-01	2.43E+03	9.58E+02	1.63E-09	1.16E+00	3.03E+02	4.32E+00	4.32E+00
1.25E+04	1.69E-01	1.94E+03	1.48E+03	8.04E-01	2.83E+03	9.58E+02	9.70E-10	1.16E+00	3.03E+02	4.42E+00	4.42E+00
1.62E+04	1.69E-01	2.32E+03	1.76E+03	8.04E-01	3.31E+03	9.58E+02	5.80E-10	1.16E+00	3.03E+02	4.51E+00	4.51E+00
2.08E+04	1.69E-01	2.77E+03	2.09E+03	8.05E-01	3.90E+03	9.58E+02	3.49E-10	1.16E+00	3.03E+02	4.60E+00	4.60E+00
2.68E+04	1.69E-01	3.28E+03	2.47E+03	8.06E-01	4.62E+03	9.58E+02	2.11E-10	1.16E+00	3.03E+02	4.67E+00	4.67E+00
3.44E+04	1.68E-01	3.84E+03	2.90E+03	8.07E-01	5.49E+03	9.59E+02	1.29E-10	1.16E+00	3.03E+02	4.75E+00	4.75E+00
4.41E+04	1.68E-01	4.46E+03	3.39E+03	8.08E-01	6.56E+03	9.59E+02	7.96E-11	1.16E+00	3.03E+02	4.81E+00	4.81E+00
5.66E+04	1.67E-01	5.10E+03	3.94E+03	8.10E-01	7.86E+03	9.60E+02	4.98E-11	1.16E+00	3.03E+02	4.86E+00	4.86E+00
7.24E+04	1.67E-01	5.76E+03	4.58E+03	8.13E-01	9.44E+03	9.61E+02	3.17E-11	1.16E+00	3.03E+02	4.91E+00	4.91E+00
9.24E+04	1.66E-01	6.38E+03	5.30E+03	8.17E-01	1.14E+04	9.62E+02	2.05E-11	1.16E+00	3.03E+02	4.95E+00	4.95E+00
1.18E+05	1.64E-01	6.94E+03	6.11E+03	8.22E-01	1.37E+04	9.63E+02	1.36E-11	1.16E+00	3.03E+02	4.98E+00	4.98E+00
1.50E+05	1.63E-01	7.39E+03	7.05E+03	8.29E-01	1.66E+04	9.65E+02	9.12E-12	1.16E+00	3.03E+02	5.00E+00	5.00E+00

TABLE A-3 (Cont.)

1

x	cm	cmv	cmda	cmw	cmwv	wc	vg	ug	w	v	vx
1.00E+00	1.00E+00	2.00E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.11E+00	8.01E-02	0.00E+00
1.03E+00	9.94E-01	2.05E-01	6.14E-03	8.02E-05	1.64E-05	-1.70E-02	0.00E+00	0.00E+00	5.30E-01	8.67E-02	2.85E-01
1.06E+00	9.86E-01	2.12E-01	1.42E-02	1.86E-04	1.53E-05	-3.81E-02	0.00E+00	0.00E+00	5.52E-01	9.50E-02	2.85E-01
1.10E+00	9.74E-01	2.20E-01	2.56E-02	3.34E-04	1.42E-05	-6.44E-02	0.00E+00	0.00E+00	5.84E-01	1.06E-01	2.85E-01
1.15E+00	9.58E-01	2.29E-01	4.19E-02	5.48E-04	1.28E-05	-9.69E-02	0.00E+00	0.00E+00	6.33E-01	1.20E-01	2.85E-01
1.22E+00	9.33E-01	2.41E-01	6.64E-02	8.68E-04	1.14E-05	-1.37E-01	0.00E+00	0.00E+00	7.11E-01	1.40E-01	2.85E-01
1.30E+00	8.94E-01	2.57E-01	1.05E-01	1.37E-03	9.90E-06	-1.84E-01	0.00E+00	0.00E+00	8.40E-01	1.67E-01	2.85E-01
1.40E+00	8.30E-01	2.78E-01	1.67E-01	2.19E-03	8.35E-06	-2.37E-01	0.00E+00	0.00E+00	1.06E+00	2.02E-01	2.85E-01
1.53E+00	7.24E-01	3.06E-01	2.72E-01	3.56E-03	6.92E-06	-2.89E-01	0.00E+00	0.00E+00	1.38E+00	2.41E-01	2.85E-01
1.69E+00	5.62E-01	3.42E-01	4.33E-01	5.65E-03	5.81E-06	-3.29E-01	0.00E+00	0.00E+00	1.67E+00	2.60E-01	2.85E-01
1.90E+00	3.78E-01	3.78E-01	6.14E-01	8.02E-03	5.17E-06	-3.62E-01	0.00E+00	0.00E+00	1.63E+00	2.26E-01	2.85E-01
2.16E+00	2.08E-01	2.08E-01	7.82E-01	1.02E-02	1.87E-03	-3.66E-01	0.00E+00	0.00E+00	1.83E+00	1.75E-01	2.86E-01
2.48E+00	9.38E-02	9.38E-02	8.95E-01	1.17E-02	8.48E-03	-3.48E-01	0.00E+00	0.00E+00	1.85E+00	9.31E-02	2.88E-01
2.90E+00	3.76E-02	3.76E-02	9.50E-01	1.24E-02	1.24E-02	-2.80E-01	4.26E-01	0.00E+00	1.27E+00	4.95E-02	3.03E-01
3.41E+00	2.05E-02	2.05E-02	9.67E-01	1.26E-02	1.26E-02	-1.60E-01	5.22E-01	0.00E+00	9.38E-01	5.88E-02	3.12E-01
4.06E+00	1.18E-02	1.18E-02	9.75E-01	1.27E-02	1.27E-02	-8.05E-02	4.54E-01	0.00E+00	8.53E-01	6.98E-02	3.21E-01
4.88E+00	7.18E-03	7.18E-03	9.80E-01	1.28E-02	1.28E-02	-4.40E-02	3.70E-01	0.00E+00	8.06E-01	8.09E-02	3.32E-01
5.91E+00	4.55E-03	4.55E-03	9.83E-01	1.28E-02	1.28E-02	-2.61E-02	2.99E-01	0.00E+00	7.72E-01	9.25E-02	3.45E-01
7.21E+00	2.98E-03	2.98E-03	9.84E-01	1.29E-02	1.29E-02	-1.65E-02	2.43E-01	0.00E+00	7.46E-01	1.05E-01	3.58E-01
8.84E+00	1.98E-03	1.98E-03	9.85E-01	1.29E-02	1.29E-02	-1.07E-02	1.98E-01	0.00E+00	7.25E-01	1.17E-01	3.70E-01
1.09E+01	1.34E-03	1.34E-03	9.86E-01	1.29E-02	1.29E-02	-7.07E-03	1.61E-01	0.00E+00	7.08E-01	1.29E-01	3.81E-01
1.35E+01	9.06E-04	9.06E-04	9.86E-01	1.29E-02	1.29E-02	-4.75E-03	1.31E-01	0.00E+00	6.92E-01	1.41E-01	3.92E-01
1.67E+01	6.15E-04	6.15E-04	9.86E-01	1.29E-02	1.29E-02	-3.15E-03	1.06E-01	0.00E+00	6.79E-01	1.53E-01	4.01E-01
2.09E+01	4.17E-04	4.17E-04	9.87E-01	1.29E-02	1.29E-02	-2.10E-03	8.54E-02	0.00E+00	6.66E-01	1.65E-01	4.10E-01
2.60E+01	2.83E-04	2.83E-04	9.87E-01	1.29E-02	1.29E-02	-1.40E-03	6.85E-02	0.00E+00	6.54E-01	1.78E-01	4.19E-01
3.25E+01	1.91E-04	1.91E-04	9.87E-01	1.29E-02	1.29E-02	-9.36E-04	5.47E-02	0.00E+00	6.41E-01	1.90E-01	4.26E-01
4.07E+01	1.29E-04	1.29E-04	9.87E-01	1.29E-02	1.29E-02	-6.22E-04	4.35E-02	0.00E+00	6.29E-01	2.03E-01	4.34E-01
5.10E+01	8.63E-05	8.63E-05	9.87E-01	1.29E-02	1.29E-02	-4.12E-04	3.45E-02	0.00E+00	6.17E-01	2.16E-01	4.41E-01
6.40E+01	5.77E-05	5.77E-05	9.87E-01	1.29E-02	1.29E-02	-2.71E-04	2.72E-02	0.00E+00	6.04E-01	2.28E-01	4.47E-01
8.03E+01	3.85E-05	3.85E-05	9.87E-01	1.29E-02	1.29E-02	-1.77E-04	2.14E-02	0.00E+00	5.91E-01	2.40E-01	4.54E-01
1.01E+02	2.55E-05	2.55E-05	9.87E-01	1.29E-02	1.29E-02	-1.14E-04	1.68E-02	0.00E+00	5.78E-01	2.52E-01	4.60E-01
1.27E+02	1.69E-05	1.69E-05	9.87E-01	1.29E-02	1.29E-02	-7.34E-05	1.31E-02	0.00E+00	5.65E-01	2.64E-01	4.66E-01
1.59E+02	1.12E-05	1.12E-05	9.87E-01	1.29E-02	1.29E-02	-4.68E-05	1.02E-02	0.00E+00	5.52E-01	2.75E-01	4.72E-01
2.00E+02	7.36E-06	7.36E-06	9.87E-01	1.29E-02	1.29E-02	-2.97E-05	7.88E-03	0.00E+00	5.39E-01	2.85E-01	4.79E-01
2.52E+02	4.84E-06	4.84E-06	9.87E-01	1.29E-02	1.29E-02	-1.87E-05	6.10E-03	0.00E+00	5.26E-01	2.95E-01	4.85E-01
3.17E+02	3.18E-06	3.18E-06	9.87E-01	1.29E-02	1.29E-02	-1.17E-05	4.70E-03	0.00E+00	5.13E-01	3.04E-01	4.91E-01
3.99E+02	2.09E-06	2.09E-06	9.87E-01	1.29E-02	1.29E-02	-7.34E-06	3.61E-03	0.00E+00	5.00E-01	3.11E-01	4.98E-01
5.02E+02	1.37E-06	1.37E-06	9.87E-01	1.29E-02	1.29E-02	-4.59E-06	2.78E-03	0.00E+00	4.87E-01	3.17E-01	5.05E-01
6.32E+02	9.03E-07	9.03E-07	9.87E-01	1.29E-02	1.29E-02	-2.89E-06	2.15E-03	0.00E+00	4.75E-01	3.22E-01	5.12E-01
7.95E+02	5.95E-07	5.95E-07	9.87E-01	1.29E-02	1.29E-02	-1.85E-06	1.70E-03	2.77E-04	4.62E-01	3.25E-01	5.19E-01
1.01E+03	3.74E-07	3.74E-07	9.87E-01	1.29E-02	1.29E-02	-1.17E-06	1.29E-03	2.14E-04	4.47E-01	3.27E-01	4.06E-01
1.28E+03	2.32E-07	2.32E-07	9.87E-01	1.29E-02	1.29E-02	-7.27E-07	9.84E-04	1.71E-04	4.33E-01	3.27E-01	4.04E-01
1.64E+03	1.43E-07	1.43E-07	9.87E-01	1.29E-02	1.29E-02	-5.02E-07	8.34E-04	1.62E-04	4.18E-01	3.23E-01	4.02E-01
2.10E+03	8.71E-08	8.71E-08	9.87E-01	1.29E-02	1.29E-02	-3.98E-07	8.07E-04	1.83E-04	4.03E-01	3.17E-01	3.98E-01
2.71E+03	5.27E-08	5.27E-08	9.87E-01	1.29E-02	1.29E-02	-3.28E-07	8.08E-04	2.14E-04	3.89E-01	3.07E-01	3.94E-01

TABLE A-3 (Cont.)

3.49E+03	3.17E-08	3.17E-08	9.87E-01	1.29E-02	1.29E-02	-2.44E-07	7.25E-04	2.17E-04	3.73E-01	2.95E-01	3.88E-01
4.51E+03	1.90E-08	1.90E-08	9.87E-01	1.29E-02	1.29E-02	-2.36E-07	8.38E-04	2.93E-04	3.58E-01	2.80E-01	3.82E-01
5.82E+03	1.13E-08	1.13E-08	9.87E-01	1.29E-02	1.29E-02	-2.38E-07	1.00E-03	3.97E-04	3.41E-01	2.64E-01	3.74E-01
7.52E+03	6.75E-09	6.75E-09	9.87E-01	1.29E-02	1.29E-02	-2.47E-07	1.23E-03	5.35E-04	3.24E-01	2.47E-01	3.66E-01
9.71E+03	4.02E-09	4.02E-09	9.87E-01	1.29E-02	1.29E-02	-1.94E-07	1.15E-03	5.24E-04	3.06E-01	2.29E-01	3.57E-01
1.25E+04	2.39E-09	2.39E-09	9.87E-01	1.29E-02	1.29E-02	-1.70E-07	1.19E-03	5.73E-04	2.86E-01	2.11E-01	3.48E-01
1.62E+04	1.43E-09	1.43E-09	9.87E-01	1.29E-02	1.29E-02	-1.64E-07	1.35E-03	6.80E-04	2.65E-01	1.93E-01	3.38E-01
2.08E+04	8.60E-10	8.60E-10	9.87E-01	1.29E-02	1.29E-02	-1.67E-07	1.62E-03	8.42E-04	2.42E-01	1.76E-01	3.28E-01
2.68E+04	5.20E-10	5.20E-10	9.87E-01	1.29E-02	1.29E-02	-1.76E-07	2.01E-03	1.06E-03	2.17E-01	1.60E-01	3.17E-01
3.44E+04	3.18E-10	3.18E-10	9.87E-01	1.29E-02	1.29E-02	-1.88E-07	2.52E-03	1.34E-03	1.91E-01	1.45E-01	3.07E-01
4.41E+04	1.96E-10	1.96E-10	9.87E-01	1.29E-02	1.29E-02	-2.01E-07	3.19E-03	1.68E-03	1.64E-01	1.30E-01	2.96E-01
5.66E+04	1.23E-10	1.23E-10	9.87E-01	1.29E-02	1.29E-02	-2.16E-07	4.05E-03	2.09E-03	1.35E-01	1.17E-01	2.86E-01
7.24E+04	7.82E-11	7.82E-11	9.87E-01	1.29E-02	1.29E-02	-2.32E-07	5.11E-03	2.58E-03	1.07E-01	1.05E-01	2.76E-01
9.24E+04	5.07E-11	5.07E-11	9.87E-01	1.29E-02	1.29E-02	-2.47E-07	6.41E-03	3.14E-03	8.11E-02	9.34E-02	2.67E-01
1.18E+05	3.34E-11	3.34E-11	9.87E-01	1.29E-02	1.29E-02	-2.60E-07	7.97E-03	3.78E-03	5.77E-02	8.32E-02	2.59E-01
1.50E+05	2.25E-11	2.25E-11	9.87E-01	1.29E-02	1.29E-02	-2.70E-07	9.79E-03	4.47E-03	3.87E-02	7.39E-02	2.53E-01

TABLE A-3 (Cont.)

1

time averaged (tav = 600. s) volume concentration: concentration contour parameters

$$c(x,y,z,t) = cc(x) * (\text{erf}(xa)-\text{erf}(xb)) * (\text{erf}(ya)-\text{erf}(yb)) * (\exp(-za*za)+\exp(-zb*zb))$$

c(x,y,z,t) = concentration (volume fraction) at (x,y,z,t)
 x = downwind distance (m)
 y = crosswind horizontal distance (m)
 z = height (m)
 t = time (s)

erf = error function
 xa = (x-xc+bx)/(sr2*betax)
 xb = (x-xc-bx)/(sr2*betax)
 ya = (y+b)/(sr2*betac)
 yb = (y-b)/(sr2*betac)
 exp = exponential function
 za = (z-zc)/(sr2*sig)
 zb = (z+zc)/(sr2*sig)
 sr2 = sqrt(2.0)

x	cc(x)	b(x)	betac(x)	zc(x)	sig(x)	t	xc(t)	bx(t)	betax(t)
1.00E+00	0.00E+00	1.10E-02	3.08E-03	1.00E+00	7.07E-03	0.00E+00	1.00E+00	0.00E+00	0.00E+00
1.03E+00	3.80E-01	1.15E-02	3.31E-03	1.00E+00	7.44E-03	3.53E-03	1.03E+00	3.12E-02	2.55E-04
1.06E+00	3.75E-01	1.22E-02	3.60E-03	1.00E+00	7.90E-03	8.24E-03	1.06E+00	7.05E-02	5.76E-04
1.10E+00	3.67E-01	1.30E-02	4.00E-03	1.00E+00	8.51E-03	1.42E-02	1.10E+00	1.20E-01	9.79E-04
1.15E+00	3.57E-01	1.41E-02	4.54E-03	9.99E-01	9.33E-03	2.19E-02	1.15E+00	1.82E-01	1.49E-03
1.22E+00	3.41E-01	1.56E-02	5.35E-03	9.99E-01	1.05E-02	3.17E-02	1.22E+00	2.61E-01	2.13E-03
1.30E+00	3.18E-01	1.78E-02	6.64E-03	9.98E-01	1.22E-02	4.46E-02	1.30E+00	3.59E-01	2.93E-03
1.40E+00	2.84E-01	2.12E-02	8.91E-03	9.96E-01	1.51E-02	6.17E-02	1.40E+00	4.83E-01	3.95E-03
1.53E+00	2.37E-01	2.67E-02	1.35E-02	9.93E-01	2.05E-02	8.58E-02	1.53E+00	6.40E-01	5.23E-03
1.69E+00	1.79E-01	3.61E-02	2.36E-02	9.87E-01	3.15E-02	1.23E-01	1.69E+00	8.37E-01	6.83E-03
1.90E+00	1.26E-01	5.07E-02	4.55E-02	9.76E-01	5.41E-02	1.89E-01	1.90E+00	1.08E+00	8.86E-03
2.16E+00	8.29E-02	8.18E-02	1.08E-01	9.50E-01	1.18E-01	3.26E-01	2.16E+00	1.40E+00	1.14E-02
2.48E+00	5.18E-02	1.26E-01	2.61E-01	8.90E-01	2.71E-01	6.66E-01	2.48E+00	1.79E+00	1.46E-02
2.90E+00	2.13E-02	2.12E-01	6.39E-01	7.41E-01	8.73E-01	1.56E+00	2.90E+00	2.28E+00	1.86E-02
3.41E+00	1.00E-02	3.16E-01	1.01E+00	5.43E-01	1.43E+00	3.37E+00	3.41E+00	2.91E+00	2.37E-02
4.06E+00	5.66E-03	3.97E-01	1.36E+00	4.19E-01	1.87E+00	5.54E+00	4.06E+00	3.69E+00	3.01E-02
4.88E+00	3.55E-03	4.61E-01	1.70E+00	3.46E-01	2.32E+00	8.01E+00	4.88E+00	4.68E+00	3.82E-02
5.91E+00	2.39E-03	5.09E-01	2.05E+00	2.99E-01	2.82E+00	1.08E+01	5.91E+00	5.92E+00	4.83E-02
7.21E+00	1.70E-03	5.45E-01	2.43E+00	2.67E-01	3.39E+00	1.38E+01	7.21E+00	7.48E+00	6.11E-02
8.84E+00	1.26E-03	5.79E-01	2.90E+00	2.45E-01	4.03E+00	1.72E+01	8.84E+00	9.45E+00	7.72E-02
1.09E+01	9.55E-04	6.09E-01	3.47E+00	2.28E-01	4.77E+00	2.12E+01	1.09E+01	1.19E+01	9.74E-02
1.35E+01	7.44E-04	6.34E-01	4.18E+00	2.15E-01	5.64E+00	2.56E+01	1.35E+01	1.51E+01	1.23E-01
1.67E+01	5.85E-04	6.65E-01	5.11E+00	2.05E-01	6.62E+00	3.08E+01	1.67E+01	1.90E+01	1.55E-01
2.09E+01	4.65E-04	6.91E-01	6.25E+00	1.97E-01	7.79E+00	3.68E+01	2.09E+01	2.39E+01	1.95E-01
2.60E+01	3.73E-04	7.13E-01	7.66E+00	1.91E-01	9.21E+00	4.38E+01	2.60E+01	3.02E+01	2.46E-01

TABLE A-3 (Cont.)

3.25E+01	3.02E-04	7.31E-01	9.42E+00	1.86E-01	1.09E+01	5.21E+01	3.25E+01	3.80E+01	3.10E-01
4.07E+01	2.45E-04	7.46E-01	1.16E+01	1.82E-01	1.29E+01	6.17E+01	4.07E+01	4.79E+01	3.91E-01
5.10E+01	2.00E-04	7.58E-01	1.44E+01	1.80E-01	1.54E+01	7.31E+01	5.10E+01	6.03E+01	4.92E-01
6.40E+01	1.64E-04	7.68E-01	1.78E+01	1.77E-01	1.83E+01	8.66E+01	6.40E+01	7.59E+01	6.20E-01
8.03E+01	1.34E-04	7.75E-01	2.22E+01	1.75E-01	2.17E+01	1.03E+02	8.03E+01	9.56E+01	7.81E-01
1.01E+02	1.10E-04	7.81E-01	2.76E+01	1.74E-01	2.59E+01	1.22E+02	1.01E+02	1.20E+02	9.83E-01
1.27E+02	8.99E-05	7.86E-01	3.43E+01	1.73E-01	3.08E+01	1.45E+02	1.27E+02	1.52E+02	1.24E+00
1.59E+02	7.36E-05	7.90E-01	4.28E+01	1.72E-01	3.68E+01	1.72E+02	1.59E+02	1.91E+02	1.56E+00
2.00E+02	6.02E-05	7.93E-01	5.34E+01	1.72E-01	4.38E+01	2.05E+02	2.00E+02	2.40E+02	1.96E+00
2.52E+02	4.93E-05	7.95E-01	6.66E+01	1.71E-01	5.22E+01	2.45E+02	2.52E+02	3.03E+02	2.47E+00
3.17E+02	4.03E-05	7.96E-01	8.30E+01	1.71E-01	6.23E+01	2.93E+02	3.17E+02	3.81E+02	3.11E+00
3.99E+02	3.29E-05	7.98E-01	1.03E+02	1.71E-01	7.42E+01	3.51E+02	3.99E+02	4.80E+02	3.92E+00
5.02E+02	2.69E-05	7.99E-01	1.29E+02	1.70E-01	8.85E+01	4.22E+02	5.02E+02	6.04E+02	4.93E+00
6.32E+02	2.19E-05	7.99E-01	1.60E+02	1.70E-01	1.06E+02	5.07E+02	6.32E+02	7.60E+02	6.21E+00
7.95E+02	1.79E-05	8.00E-01	1.98E+02	1.70E-01	1.26E+02	6.11E+02	7.95E+02	9.57E+02	7.82E+00
1.01E+03	1.46E-05	8.00E-01	2.46E+02	1.70E-01	1.55E+02	6.64E+02	1.01E+03	9.57E+02	1.74E+02
1.28E+03	1.19E-05	8.01E-01	3.07E+02	1.70E-01	1.91E+02	7.46E+02	1.28E+03	9.57E+02	2.63E+02
1.64E+03	9.77E-06	8.01E-01	3.82E+02	1.70E-01	2.34E+02	8.48E+02	1.64E+03	9.57E+02	3.48E+02
2.10E+03	8.00E-06	8.01E-01	4.76E+02	1.70E-01	2.87E+02	9.76E+02	2.10E+03	9.57E+02	4.37E+02
2.71E+03	6.56E-06	8.01E-01	5.91E+02	1.70E-01	3.51E+02	1.14E+03	2.71E+03	9.57E+02	5.35E+02
3.49E+03	5.38E-06	8.02E-01	7.30E+02	1.70E-01	4.28E+02	1.34E+03	3.49E+03	9.57E+02	6.44E+02
4.51E+03	4.42E-06	8.02E-01	8.98E+02	1.70E-01	5.22E+02	1.60E+03	4.51E+03	9.57E+02	7.70E+02
5.82E+03	3.64E-06	8.02E-01	1.10E+03	1.70E-01	6.35E+02	1.92E+03	5.82E+03	9.57E+02	9.16E+02
7.52E+03	3.00E-06	8.03E-01	1.33E+03	1.69E-01	7.69E+02	2.33E+03	7.52E+03	9.57E+02	1.09E+03
9.71E+03	2.48E-06	8.03E-01	1.61E+03	1.69E-01	9.30E+02	2.84E+03	9.71E+03	9.58E+02	1.29E+03
1.25E+04	2.06E-06	8.04E-01	1.93E+03	1.69E-01	1.12E+03	3.49E+03	1.25E+04	9.58E+02	1.54E+03
1.62E+04	1.72E-06	8.04E-01	2.31E+03	1.69E-01	1.34E+03	4.30E+03	1.62E+04	9.58E+02	1.83E+03
2.08E+04	1.44E-06	8.05E-01	2.73E+03	1.69E-01	1.60E+03	5.32E+03	2.08E+04	9.58E+02	2.18E+03
2.68E+04	1.22E-06	8.06E-01	3.22E+03	1.69E-01	1.89E+03	6.60E+03	2.68E+04	9.58E+02	2.61E+03
3.44E+04	1.04E-06	8.07E-01	3.78E+03	1.68E-01	2.22E+03	8.22E+03	3.44E+04	9.59E+02	3.12E+03
4.41E+04	8.90E-07	8.08E-01	4.42E+03	1.68E-01	2.57E+03	1.03E+04	4.41E+04	9.59E+02	3.75E+03
5.66E+04	7.74E-07	8.10E-01	5.14E+03	1.67E-01	2.95E+03	1.28E+04	5.66E+04	9.60E+02	4.50E+03
7.24E+04	6.83E-07	8.13E-01	5.96E+03	1.67E-01	3.32E+03	1.61E+04	7.24E+04	9.61E+02	5.42E+03
9.24E+04	6.11E-07	8.17E-01	6.88E+03	1.66E-01	3.68E+03	2.01E+04	9.24E+04	9.62E+02	6.53E+03
1.18E+05	5.56E-07	8.22E-01	7.92E+03	1.64E-01	4.00E+03	2.52E+04	1.18E+05	9.63E+02	7.90E+03
1.50E+05	5.15E-07	8.29E-01	9.09E+03	1.63E-01	4.27E+03	3.17E+04	1.50E+05	9.65E+02	9.56E+03

TABLE A-3 (Cont.)

1

time averaged (tav = 600. s) volume concentration: concentration in the z = .00 plane.

downwind distance x (m)	time of max conc (s)	cloud duration (s)	effective half width bbc (m)	average concentration (volume fraction) at (x,y,z)					
				y/bbc=	y/bbc=	y/bbc=	y/bbc=	y/bbc=	y/bbc=
				0.0	0.5	1.0	1.5	2.0	2.5
1.00E+00	3.00E+02	6.00E+02	1.22E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.03E+00	3.00E+02	6.00E+02	1.29E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.06E+00	3.00E+02	6.00E+02	1.37E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.10E+00	3.00E+02	6.00E+02	1.47E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.15E+00	3.00E+02	6.00E+02	1.62E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.22E+00	3.00E+02	6.00E+02	1.82E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.30E+00	3.00E+02	6.00E+02	2.12E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.40E+00	3.00E+02	6.00E+02	2.62E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.53E+00	3.00E+02	6.00E+02	3.55E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.69E+00	3.00E+02	6.00E+02	5.46E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.90E+00	3.00E+02	6.00E+02	9.37E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2.16E+00	3.00E+02	6.00E+02	2.04E-01	2.96E-15	2.05E-15	6.70E-16	1.00E-16	6.70E-18	1.94E-19
2.48E+00	3.01E+02	6.00E+02	4.70E-01	7.08E-04	4.87E-04	1.58E-04	2.42E-05	1.72E-06	5.67E-08
2.90E+00	3.01E+02	6.00E+02	1.13E+00	3.09E-02	2.12E-02	6.90E-03	1.06E-03	7.62E-05	2.58E-06
3.41E+00	3.01E+02	6.00E+02	1.78E+00	1.81E-02	1.25E-02	4.05E-03	6.21E-04	4.48E-05	1.52E-06
4.06E+00	3.01E+02	6.00E+02	2.39E+00	1.00E-02	6.90E-03	2.24E-03	3.43E-04	2.48E-05	8.44E-07
4.88E+00	3.01E+02	6.00E+02	2.98E+00	5.86E-03	4.03E-03	1.31E-03	2.00E-04	1.45E-05	4.93E-07
5.91E+00	3.02E+02	6.00E+02	3.58E+00	3.57E-03	2.45E-03	7.96E-04	1.22E-04	8.83E-06	3.02E-07
7.21E+00	3.02E+02	6.00E+02	4.24E+00	2.23E-03	1.53E-03	4.98E-04	7.64E-05	5.53E-06	1.89E-07
8.84E+00	3.03E+02	6.00E+02	5.05E+00	1.42E-03	9.77E-04	3.17E-04	4.86E-05	3.52E-06	1.20E-07
1.09E+01	3.04E+02	6.00E+02	6.05E+00	9.10E-04	6.25E-04	2.03E-04	3.11E-05	2.25E-06	7.71E-08
1.35E+01	3.05E+02	6.00E+02	7.27E+00	5.84E-04	4.01E-04	1.30E-04	2.00E-05	1.45E-06	4.95E-08
1.67E+01	3.06E+02	6.00E+02	8.87E+00	3.76E-04	2.59E-04	8.39E-05	1.29E-05	9.32E-07	3.18E-08
2.09E+01	3.07E+02	6.00E+02	1.08E+01	2.42E-04	1.66E-04	5.40E-05	8.27E-06	5.99E-07	2.05E-08
2.60E+01	3.09E+02	6.00E+02	1.33E+01	1.55E-04	1.07E-04	3.46E-05	5.31E-06	3.84E-07	1.31E-08
3.25E+01	3.12E+02	6.00E+02	1.63E+01	9.92E-05	6.82E-05	2.21E-05	3.40E-06	2.46E-07	8.42E-09
4.07E+01	3.15E+02	6.00E+02	2.02E+01	6.35E-05	4.36E-05	1.42E-05	2.17E-06	1.57E-07	5.40E-09
5.10E+01	3.19E+02	6.00E+02	2.49E+01	4.06E-05	2.79E-05	9.05E-06	1.39E-06	1.01E-07	3.42E-09
6.40E+01	3.24E+02	6.00E+02	3.09E+01	2.59E-05	1.78E-05	5.79E-06	8.88E-07	6.43E-08	2.21E-09
8.03E+01	3.30E+02	6.00E+02	3.84E+01	1.66E-05	1.14E-05	3.70E-06	5.68E-07	4.11E-08	1.42E-09
1.01E+02	3.38E+02	6.00E+02	4.77E+01	1.06E-05	7.30E-06	2.37E-06	3.64E-07	2.63E-08	9.10E-10
1.27E+02	3.48E+02	6.00E+02	5.95E+01	6.81E-06	4.68E-06	1.52E-06	2.33E-07	1.69E-08	5.78E-10
1.59E+02	3.60E+02	6.00E+02	7.41E+01	4.37E-06	3.01E-06	9.76E-07	1.50E-07	1.08E-08	3.72E-10
2.00E+02	3.75E+02	6.00E+02	9.24E+01	2.81E-06	1.93E-06	6.28E-07	9.63E-08	6.98E-09	2.34E-10
2.52E+02	3.95E+02	6.00E+02	1.15E+02	1.81E-06	1.25E-06	4.05E-07	6.21E-08	4.49E-09	1.53E-10
3.17E+02	4.19E+02	6.00E+02	1.44E+02	1.17E-06	8.06E-07	2.62E-07	4.01E-08	2.91E-09	1.00E-10
3.99E+02	4.50E+02	6.00E+02	1.79E+02	7.59E-07	5.22E-07	1.69E-07	2.60E-08	1.88E-09	6.61E-11
5.02E+02	4.89E+02	6.00E+02	2.23E+02	4.93E-07	3.39E-07	1.10E-07	1.69E-08	1.22E-09	4.15E-11
6.32E+02	5.38E+02	6.00E+02	2.77E+02	3.21E-07	2.21E-07	7.17E-08	1.10E-08	7.94E-10	2.88E-11
7.95E+02	6.00E+02	6.00E+02	3.43E+02	2.09E-07	1.44E-07	4.67E-08	7.16E-09	5.19E-10	1.94E-11

TABLE A-3 (Cont.)

1.01E+03	6.64E+02	6.05E+02	4.26E+02	1.25E-07	8.58E-08	2.79E-08	4.27E-09	3.10E-10	1.15E-11
1.28E+03	7.46E+02	6.17E+02	5.31E+02	7.69E-08	5.28E-08	1.72E-08	2.63E-09	1.91E-10	6.60E-12
1.64E+03	8.48E+02	6.36E+02	6.62E+02	4.75E-08	3.27E-08	1.06E-08	1.63E-09	1.18E-10	3.39E-12
2.10E+03	9.76E+02	6.64E+02	8.24E+02	2.94E-08	2.02E-08	6.57E-09	1.01E-09	7.32E-11	2.61E-12
2.71E+03	1.14E+03	7.03E+02	1.02E+03	1.83E-08	1.26E-08	4.08E-09	6.25E-10	4.53E-11	2.01E-12
3.49E+03	1.34E+03	7.53E+02	1.26E+03	1.13E-08	7.80E-09	2.53E-09	3.88E-10	2.82E-11	7.72E-13
4.51E+03	1.60E+03	8.18E+02	1.56E+03	7.04E-09	4.84E-09	1.57E-09	2.41E-10	1.74E-11	5.89E-13
5.82E+03	1.92E+03	8.99E+02	1.90E+03	4.36E-09	3.00E-09	9.73E-10	1.49E-10	1.09E-11	4.46E-13
7.52E+03	2.33E+03	1.00E+03	2.31E+03	2.69E-09	1.85E-09	6.01E-10	9.22E-11	6.69E-12	3.35E-13
9.71E+03	2.84E+03	1.13E+03	2.79E+03	1.66E-09	1.14E-09	3.70E-10	5.68E-11	4.10E-12	2.49E-13
1.25E+04	3.49E+03	1.28E+03	3.35E+03	1.02E-09	7.00E-10	2.27E-10	3.48E-11	2.47E-12	0.00E+00
1.62E+04	4.30E+03	1.47E+03	3.99E+03	6.24E-10	4.29E-10	1.39E-10	2.13E-11	1.54E-12	0.00E+00
2.08E+04	5.32E+03	1.70E+03	4.73E+03	3.82E-10	2.63E-10	8.54E-11	1.31E-11	9.22E-13	0.00E+00
2.68E+04	6.60E+03	1.98E+03	5.58E+03	2.35E-10	1.62E-10	5.25E-11	8.05E-12	5.98E-13	0.00E+00
3.44E+04	8.22E+03	2.32E+03	6.55E+03	1.45E-10	1.00E-10	3.25E-11	4.97E-12	3.82E-13	0.00E+00
4.41E+04	1.03E+04	2.73E+03	7.66E+03	9.07E-11	6.24E-11	2.02E-11	3.09E-12	2.22E-13	0.00E+00
5.66E+04	1.28E+04	3.23E+03	8.91E+03	5.72E-11	3.93E-11	1.28E-11	1.97E-12	1.49E-13	0.00E+00
7.24E+04	1.61E+04	3.84E+03	1.03E+04	3.67E-11	2.52E-11	8.18E-12	1.25E-12	9.03E-14	0.00E+00
9.24E+04	2.01E+04	4.59E+03	1.19E+04	2.39E-11	1.64E-11	5.33E-12	8.19E-13	6.01E-14	0.00E+00
1.18E+05	2.52E+04	5.51E+03	1.37E+04	1.59E-11	1.09E-11	3.54E-12	5.42E-13	3.99E-14	0.00E+00
1.50E+05	3.17E+04	6.64E+03	1.57E+04	1.07E-11	7.38E-12	2.39E-12	3.65E-13	2.64E-14	0.00E+00

TABLE A-3 (Cont.)

1

time averaged (tav = 600. s) volume concentration: maximum concentration (volume fraction) along centerline.

downwind distance x (m)	height z (m)	maximum concentration c(x,0,z)	time of max conc (s)	cloud duration (s)
1.00E+00	1.00E+00	1.00E+00	3.00E+02	6.00E+02
1.03E+00	1.00E+00	1.00E+00	3.00E+02	6.00E+02
1.06E+00	1.00E+00	1.00E+00	3.00E+02	6.00E+02
1.10E+00	1.00E+00	1.00E+00	3.00E+02	6.00E+02
1.15E+00	9.99E-01	1.00E+00	3.00E+02	6.00E+02
1.22E+00	9.99E-01	1.00E+00	3.00E+02	6.00E+02
1.30E+00	9.98E-01	1.00E+00	3.00E+02	6.00E+02
1.40E+00	9.96E-01	1.00E+00	3.00E+02	6.00E+02
1.53E+00	9.93E-01	9.01E-01	3.00E+02	6.00E+02
1.69E+00	9.87E-01	6.24E-01	3.00E+02	6.00E+02
1.90E+00	9.76E-01	3.71E-01	3.00E+02	6.00E+02
2.16E+00	9.50E-01	1.83E-01	3.00E+02	6.00E+02
2.48E+00	8.90E-01	7.68E-02	3.01E+02	6.00E+02
2.90E+00	0.00E+00	3.09E-02	3.01E+02	6.00E+02
3.41E+00	0.00E+00	1.81E-02	3.01E+02	6.00E+02
4.06E+00	0.00E+00	1.00E-02	3.01E+02	6.00E+02
4.88E+00	0.00E+00	5.86E-03	3.01E+02	6.00E+02
5.91E+00	0.00E+00	3.57E-03	3.02E+02	6.00E+02
7.21E+00	0.00E+00	2.23E-03	3.02E+02	6.00E+02
8.84E+00	0.00E+00	1.42E-03	3.03E+02	6.00E+02
1.09E+01	0.00E+00	9.10E-04	3.04E+02	6.00E+02
1.35E+01	0.00E+00	5.84E-04	3.05E+02	6.00E+02
1.67E+01	0.00E+00	3.76E-04	3.06E+02	6.00E+02
2.09E+01	0.00E+00	2.42E-04	3.07E+02	6.00E+02
2.60E+01	0.00E+00	1.55E-04	3.09E+02	6.00E+02
3.25E+01	0.00E+00	9.92E-05	3.12E+02	6.00E+02
4.07E+01	0.00E+00	6.35E-05	3.15E+02	6.00E+02
5.10E+01	0.00E+00	4.06E-05	3.19E+02	6.00E+02
6.40E+01	0.00E+00	2.59E-05	3.24E+02	6.00E+02
8.03E+01	0.00E+00	1.66E-05	3.30E+02	6.00E+02
1.01E+02	0.00E+00	1.06E-05	3.38E+02	6.00E+02
1.27E+02	0.00E+00	6.81E-06	3.48E+02	6.00E+02
1.59E+02	0.00E+00	4.37E-06	3.60E+02	6.00E+02
2.00E+02	0.00E+00	2.81E-06	3.75E+02	6.00E+02
2.52E+02	0.00E+00	1.81E-06	3.95E+02	6.00E+02
3.17E+02	0.00E+00	1.17E-06	4.19E+02	6.00E+02
3.99E+02	0.00E+00	7.59E-07	4.50E+02	6.00E+02
5.02E+02	0.00E+00	4.93E-07	4.89E+02	6.00E+02
6.32E+02	0.00E+00	3.21E-07	5.38E+02	6.00E+02
7.95E+02	0.00E+00	2.09E-07	6.00E+02	6.00E+02

TABLE A-3 (Cont.)

1.01E+03	0.00E+00	1.25E-07	6.64E+02	6.05E+02
1.28E+03	0.00E+00	7.69E-08	7.46E+02	6.17E+02
1.64E+03	0.00E+00	4.75E-08	8.48E+02	6.36E+02
2.10E+03	0.00E+00	2.94E-08	9.76E+02	6.64E+02
2.71E+03	0.00E+00	1.83E-08	1.14E+03	7.03E+02
3.49E+03	0.00E+00	1.13E-08	1.34E+03	7.53E+02
4.51E+03	0.00E+00	7.04E-09	1.60E+03	8.18E+02
5.82E+03	0.00E+00	4.36E-09	1.92E+03	8.99E+02
7.52E+03	0.00E+00	2.69E-09	2.33E+03	1.00E+03
9.71E+03	0.00E+00	1.66E-09	2.84E+03	1.13E+03
1.25E+04	0.00E+00	1.02E-09	3.49E+03	1.28E+03
1.62E+04	0.00E+00	6.24E-10	4.30E+03	1.47E+03
2.08E+04	0.00E+00	3.82E-10	5.32E+03	1.70E+03
2.68E+04	0.00E+00	2.35E-10	6.60E+03	1.98E+03
3.44E+04	0.00E+00	1.45E-10	8.22E+03	2.32E+03
4.41E+04	0.00E+00	9.07E-11	1.03E+04	2.73E+03
5.66E+04	0.00E+00	5.72E-11	1.28E+04	3.23E+03
7.24E+04	0.00E+00	3.67E-11	1.61E+04	3.84E+03
9.24E+04	0.00E+00	2.39E-11	2.01E+04	4.59E+03
1.18E+05	0.00E+00	1.59E-11	2.52E+04	5.51E+03
1.50E+05	0.00E+00	1.07E-11	3.17E+04	6.64E+03

APPENDIX B:
STATISTICAL RESULTS OF IMPACTS ANALYSIS

APPENDIX B:**STATISTICAL RESULTS OF IMPACTS ANALYSIS**

The tables on the following pages show the best-fit parameter values for time as compared to various impacts by selected cumulative frequencies and by health criteria for the four Census regions:

B.1 Region 1

- B.1.1 Typical Case
- B.1.2 Typical Case with Shelter-in-Place (SIP) Option
- B.1.3 Worst Case
- B.1.4 Hospital Beds
- B.1.5 Areas

B.2 Region 2

- B.2.1 Typical Case
- B.2.2 Typical Case with Shelter-in-Place (SIP) Option
- B.2.3 Worst Case (refers to Figure 11 in the main text)
- B.2.4 Hospital Beds
- B.2.5 Areas

B.3 Region 3

- B.3.1 Typical Case
- B.3.2 Typical Case with Shelter-in-Place (SIP) Option
- B.3.3 Worst Case
- B.3.4 Hospital Beds
- B.3.5 Areas

B.4 Region 4

- B.4.1 Typical Case
- B.4.2 Typical Case with Shelter-in-Place (SIP) Option
- B.4.3 Worst Case
- B.4.4 Hospital Beds
- B.4.5 Areas

TABLE B.1-1 Best-fit Parameter Values for Time vs. Persons Affected (Normalized to a Population of 1 Million) by Selected Cumulative Frequencies and by Health Criteria for Typical Case in Region 1 (Chemical = Chlorine; Anemometer Height = 6 m)

Health Criteria	Parameter ^a	Cumulative Frequency (%)									
		1	5	10	25	50	75	90	95	99	100
AEGL-1	A	- ^b	-	-	3.5	107.3	245.9	1,394.8	3,680.9	11,262.9	93,070.4
	X _o	-	-	-	32.2	49.7	26.6	60.9	53.4	41.8	43.3
	r ²	-	-	-	0.9901	0.9922	0.9998	0.9948	0.9938	0.9947	0.9980
AEGL-2	A	-	-	-	-	1.6	15.5	917.1	2,799.2	8,420.5	70,789.4
	X _o	-	-	-	-	21.6	25.3	61.0	49.4	42.4	27.8
	r ²	-	-	-	-	0.9985	0.9960	0.9891	0.9954	0.9970	0.9997
AEGL-3	A	-	-	-	-	-	-	0.7	111.1	508.7	15,898.2
	X _o	-	-	-	-	-	-	27.6	33.0	19.1	24.9
	r ²	-	-	-	-	-	-	0.9933	0.9964	0.9999	0.9994
LC _{LO}	A	-	-	-	-	-	-	-	-	3.0	479.7
	X _o	-	-	-	-	-	-	-	-	17.9	14.8
	r ²	-	-	-	-	-	-	-	-	0.9957	0.9984
LC ₅₀	A	-	-	-	-	-	-	-	-	0.4	315.2
	X _o	-	-	-	-	-	-	-	-	15.4	25.1
	r ²	-	-	-	-	-	-	-	-	0.9980	0.9941
LC ₁₀₀	A	-	-	-	-	-	-	-	-	0.1	262.0
	X _o	-	-	-	-	-	-	-	-	24.1	19.7
	r ²	-	-	-	-	-	-	-	-	0.9828	0.9932

^a Equation for regression curve: $Y = A(1 - \exp[-X/X_o])$
 where: X = time (min) and
 Y = persons affected (normalized to a population of 1 million).

Parameter: A = amplitude,
 X_o = relaxation coefficient (min), and
 r = correlation coefficient.

^b Hyphen means not applicable.

TABLE B.1-2 Best-fit Parameter Values for Time vs. Persons Affected (Normalized to a Population of 1 Million) by Selected Cumulative Frequencies and by Health Criteria for Typical SIP Case in Region 1 (Chemical = Chlorine; Anemometer Height = 6 m)

Health Criteria	Parameter ^a	Cumulative Frequency (%)									
		1	5	10	25	50	75	90	95	99	100
AEGL-1	A	- ^b	-	-	1.3	35.8	90.0	461.7	1,434.5	6,263.9	51,507.5
	X _o	-	-	-	34.2	43.9	28.4	50.5	52.9	45.1	43.3
	r ²	-	-	-	0.9909	0.9928	0.9996	0.9982	0.9947	0.9940	0.9980
AEGL-2	A	-	-	-	-	0.5	5.2	310.7	1,125.0	3,421.2	39,176.6
	X _o	-	-	-	-	20.6	22.8	57.6	45.1	36.9	27.8
	r ²	-	-	-	-	0.9984	0.9975	0.9899	0.9943	0.9953	0.9997
AEGL-3	A	-	-	-	-	-	-	0.3	39.2	226.3	8,798.5
	X _o	-	-	-	-	-	-	35.4	27.2	24.4	24.9
	r ²	-	-	-	-	-	-	0.9898	0.9956	0.9995	0.9994
LC _{Lo}	A	-	-	-	-	-	-	-	-	1.0	265.5
	X _o	-	-	-	-	-	-	-	-	17.3	14.8
	r ²	-	-	-	-	-	-	-	-	0.9964	0.9984
LC ₅₀	A	-	-	-	-	-	-	-	-	0.1	104.3
	X _o	-	-	-	-	-	-	-	-	1.4	22.9
	r ²	-	-	-	-	-	-	-	-	1.0000	0.9971
LC ₁₀₀	A	-	-	-	-	-	-	-	-	-	86.6
	X _o	-	-	-	-	-	-	-	-	-	16.5
	r ²	-	-	-	-	-	-	-	-	-	0.9972

^a Equation for regression curve: $Y = A(1 - \exp[-X/X_o])$
 where: X = time (min) and
 Y = persons affected (normalized to a population of 1 million).

Parameter: A = amplitude,
 X_o = relaxation coefficient (min), and
 r = correlation coefficient.

^b Hyphen means not applicable.

TABLE B.1-3 Best-fit Parameter Values for Time vs. Persons Affected (Normalized to a Population of 1 Million) by Selected Cumulative Frequencies and by Health Criteria for Worst Case in Region 1 (Chemical = Chlorine; Anemometer Height = 6 m)

Health Criteria	Parameter ^a	Cumulative Frequency (%)									
		1	5	10	25	50	75	90	95	99	100
AEGL-1	A	- ^b	-	-	16.7	432.4	1,048.0	6,792.6	15,236.9	37,775.8	206,301.2
	X _o	-	-	-	30.6	52.8	26.4	72.5	64.9	34.8	43.3
	r ²	-	-	-	0.9891	0.9918	0.9999	0.9932	0.9945	0.9927	0.9980
AEGL-2	A	-	-	-	-	5.1	58.7	3,572.7	10,432.4	35,473.8	156,912.8
	X _o	-	-	-	-	22.1	21.8	55.2	57.5	37.8	27.8
	r ²	-	-	-	-	0.9976	0.9971	0.9905	0.9969	0.9956	0.9997
AEGL-3	A	-	-	-	-	-	-	3.3	423.3	2,341.1	49,430.2
	X _o	-	-	-	-	-	-	26.9	32.2	23.9	47.7
	r ²	-	-	-	-	-	-	0.9934	0.9976	0.9995	0.9992
LC _{LO}	A	-	-	-	-	-	-	-	-	15.6	1,681.1
	X _o	-	-	-	-	-	-	-	-	18.5	23.2
	r ²	-	-	-	-	-	-	-	-	0.9951	0.9976
LC ₅₀	A	-	-	-	-	-	-	-	-	1.9	1,615.7
	X _o	-	-	-	-	-	-	-	-	16.4	25.3
	r ²	-	-	-	-	-	-	-	-	0.9993	0.9937
LC ₁₀₀	A	-	-	-	-	-	-	-	-	0.5	1,346.1
	X _o	-	-	-	-	-	-	-	-	17.3	22.0
	r ²	-	-	-	-	-	-	-	-	0.9964	0.9887

^a Equation for regression curve: $Y = A(1 - \exp[-X/X_o])$
 where: X = time (min) and
 Y = persons affected (normalized to a population of 1 million).

Parameter: A = amplitude,
 X_o = relaxation coefficient (min), and
 r = correlation coefficient.

^b Hyphen means not applicable.

TABLE B.1-4 Best-fit Parameter Values for Time vs. Hospital Beds Affected (as a Percentage of Total Hospital Beds) by Selected Cumulative Frequencies and by Health Criteria in Region 1 (Chemical = Chlorine; Anemometer Height = 6 m)

Health Criteria	Parameter ^a	Cumulative Frequency (%)									
		1	5	10	25	50	75	90	95	99	100
AEGL-1	A	- ^b	-	-	-	-	0.5	1.3	2.7	5.8	17.7
	X _o	-	-	-	-	-	57.4	48.5	49.9	32.1	23.4
	r ²	-	-	-	-	-	0.9889	0.9959	0.9949	0.9953	0.9998
AEGL-2	A	-	-	-	-	-	-	0.7	2.9	8.1	21.1
	X _o	-	-	-	-	-	-	53.0	57.9	28.2	25.0
	r ²	-	-	-	-	-	-	0.9850	0.9932	0.9919	0.9996
AEGL-3	A	-	-	-	-	-	-	-	-	0.7	13.8
	X _o	-	-	-	-	-	-	-	-	24.1	38.8
	r ²	-	-	-	-	-	-	-	-	0.9918	0.9971
LC _{LO}	A	-	-	-	-	-	-	-	-	-	0.7
	X _o	-	-	-	-	-	-	-	-	-	1.3
	r ²	-	-	-	-	-	-	-	-	-	1.0000
LC ₅₀	A	-	-	-	-	-	-	-	-	-	0.7
	X _o	-	-	-	-	-	-	-	-	-	24.1
	r ²	-	-	-	-	-	-	-	-	-	0.9828
LC ₁₀₀	A	-	-	-	-	-	-	-	-	-	-
	X _o	-	-	-	-	-	-	-	-	-	-
	r ²	-	-	-	-	-	-	-	-	-	-

^a Equation for regression curve: $Y = A(1 - \exp[-X/X_o])$
 where: X = time (min) and
 Y = hospital beds affected (as a percentage of total hospital beds).

Parameter: A = amplitude,
 X_o = relaxation coefficient (min), and
 r = correlation coefficient.

^b Hyphen means not applicable.

TABLE B.1-5 Best-fit Parameter Values for Time vs. Areas Affected (in m²) by Selected Cumulative Frequencies and by Health Criteria in Region 1 (Chemical = Chlorine; Anemometer Height = 6 m)

Health Criteria	Parameter ^a	Cumulative Frequency (%)									
		1	5	10	25	50	75	90	95	99	100
AEGL-1	A	9.7E+04	7.6E+05	8.7E+05	1.2E+06	1.6E+06	3.7E+06	7.0E+07	1.1E+08	1.3E+08	2.7E+08
	X _o	17.6	33.1	24.1	17.9	11.4	29.0	147.1	54.0	47.2	49.5
	r ²	0.9962	0.9923	0.9906	0.9965	0.9999	0.9989	0.9828	0.9766	0.9905	0.9957
AEGL-2	A	1.7E+04	1.3E+05	1.7E+05	2.0E+05	3.5E+05	8.2E+05	2.5E+07	4.0E+07	1.1E+08	2.5E+08
	X _o	7.4	10.3	9.9	3.5	4.3	12.6	61.8	39.0	90.0	93.0
	r ²	1.0000	0.9998	0.9999	1.0000	1.0000	0.9994	0.9905	0.9944	0.9952	0.9900
AEGL-3	A	8.0E+02	5.6E+03	8.7E+03	9.0E+03	1.6E+04	5.1E+04	1.6E+06	2.5E+06	1.2E+07	6.0E+07
	X _o	2.7	1.0	2.1	2.0	2.0	2.7	18.5	12.5	34.4	60.1
	r ²	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9950	0.9995	0.9946	0.9947
LC _{LO}	A	1.9E+01	1.2E+02	1.9E+02	2.0E+02	3.6E+02	1.0E+03	3.3E+04	6.4E+04	3.9E+05	2.3E+06
	X _o	8.0	1.3	3.3	1.1	1.4	3.1	10.7	3.3	15.9	22.3
	r ²	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9998	1.0000	0.9977	0.9961
LC ₅₀	A	1.2E+01	7.7E+01	1.2E+02	1.2E+02	2.2E+02	6.2E+02	2.1E+04	4.1E+04	2.4E+05	1.6E+06
	X _o	8.2	1.2	1.3	1.1	1.2	1.2	11.5	3.6	4.0	20.3
	r ²	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9996	1.0000	1.0000	0.9950
LC ₁₀₀	A	2.2E+01	1.5E+02	2.3E+02	2.4E+02	4.2E+02	1.1E+03	4.4E+04	8.4E+04	5.5E+05	3.9E+06
	X _o	1.4	0.8	1.3	1.5	1.4	1.0	1.0	1.0	3.5	16.7
	r ²	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9979

^a Equation for regression curve: $Y = A(1 - \exp[-X/X_o])$
 where: X = time (min) and
 Y = areas affected (m²).

Parameter: A = amplitude,
 X_o = relaxation coefficient (min), and
 r = correlation coefficient.

TABLE B.2-1 Best-fit Parameter Values for Time vs. Persons Affected (Normalized to a Population of 1 Million) by Selected Cumulative Frequencies and by Health Criteria for Typical Case in Region 2 (Chemical = Chlorine; Anemometer Height = 6 m)

Health Criteria	Parameter ^a	Cumulative Frequency (%)									
		1	5	10	25	50	75	90	95	99	100
AEGL-1	A	11.7	21.5	57.1	148.1	343.0	834.1	1,794.6	4,120.0	14,073.6	46,841.8
	X _o	29.8	31.2	42.4	42.3	35.0	35.8	31.3	41.7	35.1	37.2
	r ²	0.9897	0.9930	0.9923	0.9938	0.9985	0.9997	0.9904	0.9994	0.9951	0.9990
AEGL-2	A	0.1	9.2	13.9	26.1	74.6	218.3	1,016.9	4,719.7	12,089.0	49,265.5
	X _o	2.5	19.0	15.8	14.5	19.8	22.8	45.1	68.9	32.6	37.1
	r ²	1.0000	0.9943	0.9977	0.9992	0.9988	0.9995	0.9990	0.9992	0.9973	0.9989
AEGL-3	A	- ^b	-	0.1	0.2	1.6	6.5	91.8	525.9	1,556.7	25,698.0
	X _o	-	-	1.4	1.2	1.2	6.7	18.3	25.9	10.3	29.6
	r ²	-	-	1.0000	1.0000	1.0000	1.0000	0.9984	0.9987	0.9999	0.9993
LC _{LO}	A	-	-	-	-	0.1	0.1	1.5	11.4	50.4	1,907.4
	X _o	-	-	-	-	1.4	1.4	16.1	13.4	12.6	11.7
	r ²	-	-	-	-	1.0000	1.0000	0.9976	0.9991	0.9996	0.9996
LC ₅₀	A	-	-	-	-	-	0.1	0.4	7.1	42.5	1,718.2
	X _o	-	-	-	-	-	1.4	1.3	9.6	12.7	15.8
	r ²	-	-	-	-	-	1.0000	1.0000	0.9999	0.9997	0.9978
LC ₁₀₀	A	-	-	-	-	0.1	0.2	1.2	13.1	78.2	1,770.1
	X _o	-	-	-	-	1.4	1.2	1.1	3.1	8.4	12.3
	r ²	-	-	-	-	1.0000	1.0000	1.0000	1.0000	1.0000	0.9994

^a Equation for regression curve: $Y = A(1 - \exp[-X/X_o])$
 where: X = time (min) and
 Y = persons affected (normalized to a population of 1 million).

Parameter: A = amplitude,
 X_o = relaxation coefficient (min), and
 r = correlation coefficient.

^b Hyphen means not applicable.

TABLE B.2-2 Best-fit Parameter Values for Time vs. Persons Affected (Normalized to a Population of 1 Million) by Selected Cumulative Frequencies and by Health Criteria for Typical SIP Case in Region 2 (Chemical = Chlorine; Anemometer Height = 6 m)

Health Criteria	Parameter ^a	Cumulative Frequency (%)									
		1	5	10	25	50	75	90	95	99	100
AEGL-1	A	3.9	10.1	23.2	59.8	150.8	374.1	797.8	1,615.9	7,788.7	25,923.4
	X _o	29.6	36.9	46.0	44.5	41.0	29.3	12.8	31.2	35.1	37.2
	r ²	0.9898	0.9917	0.9915	0.9915	0.9987	0.9990	0.9998	0.9987	0.9951	0.9990
AEGL-2	A	- ^b	3.2	5.4	10.6	32.6	89.1	455.8	1,653.8	6,690.4	27,264.7
	X _o	-	18.9	17.2	15.7	20.5	23.0	37.0	55.0	32.6	37.1
	r ²	-	0.9945	0.9966	0.9987	0.9988	1.0000	0.9988	0.9995	0.9973	0.9989
AEGL-3	A	-	-	-	0.1	0.8	2.7	37.8	215.4	853.5	14,221.9
	X _o	-	-	-	1.4	1.3	8.6	21.7	27.1	10.1	29.6
	r ²	-	-	-	1.0000	1.0000	0.9999	0.9978	0.9990	0.9997	0.9993
LC _{LO}	A	-	-	-	-	-	0.1	0.6	4.2	23.3	1,055.6
	X _o	-	-	-	-	-	1.4	12.0	11.5	11.7	11.7
	r ²	-	-	-	-	-	1.0000	0.9995	0.9996	0.9996	0.9996
LC ₅₀	A	-	-	-	-	-	0.1	0.2	3.0	14.4	950.9
	X _o	-	-	-	-	-	1.4	1.2	9.8	9.2	15.8
	r ²	-	-	-	-	-	1.0000	1.0000	0.9999	0.9999	0.9978
LC ₁₀₀	A	-	-	-	-	0.1	0.1	0.5	5.7	26.1	979.6
	X _o	-	-	-	-	1.4	1.4	1.3	3.7	5.0	12.3
	r ²	-	-	-	-	1.0000	1.0000	1.0000	1.0000	1.0000	0.9994

^a Equation for regression curve: $Y = A(1 - \exp[-X/X_o])$
 where: X = time (min) and
 Y = persons affected (normalized to a population of 1 million).

Parameter: A = amplitude,
 X_o = relaxation coefficient (min), and
 r = correlation coefficient.

^b Hyphen means not applicable.

TABLE B.2-3 Best-fit Parameter Values for Time vs. Persons Affected (Normalized to a Population of 1 Million) by Selected Cumulative Frequencies and by Health Criteria for Worst Case in Region 2 (Chemical = Chlorine; Anemometer Height = 6 m)

Health Criteria	Parameter ^a	Cumulative Frequency (%)									
		1	5	10	25	50	75	90	95	99	100
AEGL-1	A	39.3	71.4	210.6	532.2	1,338.8	3,077.3	5,344.3	17,362.9	31,166.7	103,830.6
	X _o	24.0	26.7	38.7	39.7	38.1	43.2	41.3	64.7	33.0	37.2
	r ²	0.9879	0.9924	0.9937	0.9948	0.9976	0.9988	0.9983	0.9972	0.9952	0.9990
AEGL-2	A	0.1	30.7	45.4	85.1	240.4	920.8	3,280.3	16,967.0	34,650.6	109,202.8
	X _o	1.4	16.3	11.7	11.1	17.4	25.5	47.1	62.6	47.7	37.1
	r ²	1.0000	0.9973	0.9996	0.9997	0.9987	0.9987	0.9975	0.9955	0.9987	0.9989
AEGL-3	A	0.1	0.1	0.2	0.7	4.3	30.1	339.1	1,804.1	5,929.5	56,962.3
	X _o	1.4	1.4	1.2	1.3	1.2	9.1	16.4	24.5	30.3	29.6
	r ²	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999	0.9990	0.9989	0.9987	0.9993
LC _{LO}	A	- ^b	-	-	0.1	0.1	0.4	4.3	40.8	232.4	4,227.9
	X _o	-	-	-	1.4	1.4	1.3	14.7	12.7	15.2	11.7
	r ²	-	-	-	1.0000	1.0000	1.0000	0.9985	0.9993	0.9982	0.9996
LC ₅₀	A	-	-	-	-	0.1	0.3	1.0	26.4	158.5	3,808.7
	X _o	-	-	-	-	1.4	1.1	1.4	11.9	11.3	15.8
	r ²	-	-	-	-	1.0000	1.0000	1.0000	0.9995	0.9997	0.9978
LC ₁₀₀	A	-	0.1	0.1	0.1	0.3	0.5	3.6	41.6	316.7	3,923.7
	X _o	-	1.4	1.4	1.4	1.1	1.3	1.3	1.4	6.6	12.3
	r ²	-	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9994

^a Equation for regression curve: $Y = A(1 - \exp[-X/X_o])$
 where: X = time (min) and
 Y = persons affected (normalized to a population of 1 million).

Parameter: A = amplitude,
 X_o = relaxation coefficient (min), and
 r = correlation coefficient.

^b Hyphen means not applicable.

TABLE B.2-4 Best-fit Parameter Values for Time vs. Hospital Beds Affected (as a Percentage of Total Hospital Beds) by Selected Cumulative Frequencies and by Health Criteria in Region 2 (Chemical = Chlorine; Anemometer Height = 6 m)

Health Criteria	Parameter ^a	Cumulative Frequency (%)									
		1	5	10	25	50	75	90	95	99	100
AEGL-1	A	- ^b	-	-	-	0.3	3.3	7.9	9.3	13.3	19.0
	X _o	-	-	-	-	41.9	21.2	1.4	1.4	1.5	10.8
	r ²	-	-	-	-	0.9688	0.9996	1.0000	1.0000	1.0000	0.9992
AEGL-2	A	-	-	-	-	-	4.0	8.0	12.3	13.7	26.9
	X _o	-	-	-	-	-	34.6	19.7	11.8	6.5	1.5
	r ²	-	-	-	-	-	0.9923	0.9998	0.9996	1.0000	1.0000
AEGL-3	A	-	-	-	-	-	-	-	2.9	15.9	29.6
	X _o	-	-	-	-	-	-	-	35.6	8.5	6.5
	r ²	-	-	-	-	-	-	-	0.9951	0.9995	1.0000
LC _{LO}	A	-	-	-	-	-	-	-	-	-	18.2
	X _o	-	-	-	-	-	-	-	-	-	14.0
	r ²	-	-	-	-	-	-	-	-	-	0.9988
LC ₅₀	A	-	-	-	-	-	-	-	-	-	15.2
	X _o	-	-	-	-	-	-	-	-	-	11.7
	r ²	-	-	-	-	-	-	-	-	-	0.9996
LC ₁₀₀	A	-	-	-	-	-	-	-	-	-	26.7
	X _o	-	-	-	-	-	-	-	-	-	19.2
	r ²	-	-	-	-	-	-	-	-	-	0.9940

^a Equation for regression curve: $Y = A(1 - \exp[-X/X_o])$
 where: X = time (min) and
 Y = hospital beds affected (as a percentage of total hospital beds).

Parameter: A = amplitude,
 X_o = relaxation coefficient (min), and
 r = correlation coefficient.

^b Hyphen means not applicable.

TABLE B.2-5 Best-fit Parameter Values for Time vs. Areas Affected (in m²) by Selected Cumulative Frequencies and by Health Criteria in Region 2 (Chemical = Chlorine; Anemometer Height = 6 m)

Health Criteria	Parameter ^a	Cumulative Frequency (%)									
		1	5	10	25	50	75	90	95	99	100
AEGL-1	A	1.5E+05	6.7E+05	1.0E+06	1.3E+06	2.5E+06	7.3E+06	6.3E+07	1.2E+08	1.3E+08	2.8E+08
	X _o	24.1	31.6	37.9	24.5	33.5	55.8	221.0	92.6	47.5	53.4
	r ²	0.9828	0.9891	0.9877	0.9913	0.9970	0.9934	0.9676	0.9857	0.9899	0.9960
AEGL-2	A	2.6E+04	1.3E+05	2.0E+05	2.2E+05	5.4E+05	1.9E+06	1.2E+07	4.2E+07	1.3E+08	2.5E+08
	X _o	21.8	10.5	14.4	6.3	14.0	27.9	56.7	53.6	127.8	98.1
	r ²	0.9893	0.9998	0.9986	1.0000	0.9989	0.9949	0.9863	0.9942	0.9955	0.9888
AEGL-3	A	1.2E+03	5.9E+03	8.9E+03	1.1E+04	2.6E+04	1.3E+05	8.0E+05	2.8E+06	1.4E+07	6.2E+07
	X _o	15.4	9.2	2.7	2.3	4.6	3.8	18.4	16.7	39.0	60.8
	r ²	0.9981	0.9999	1.0000	1.0000	1.0000	1.0000	0.9951	0.9992	0.9955	0.9948
LC _{LO}	A	2.6E+01	1.3E+02	2.0E+02	2.4E+02	5.5E+02	2.7E+03	2.2E+04	8.7E+04	4.7E+05	2.4E+06
	X _o	24.1	7.5	2.8	3.1	4.5	4.0	18.9	10.2	17.7	22.4
	r ²	0.9828	1.0000	1.0000	1.0000	1.0000	1.0000	0.9945	0.9998	0.9960	0.9962
LC ₅₀	A	1.6E+01	8.0E+01	1.3E+02	1.6E+02	3.4E+02	1.6E+03	1.4E+04	5.7E+04	3.4E+05	1.7E+06
	X _o	24.1	7.1	3.1	3.0	4.1	3.6	18.8	10.7	11.2	20.5
	r ²	0.9828	1.0000	1.0000	1.0000	1.0000	1.0000	0.9945	0.9998	0.9997	0.9948
LC ₁₀₀	A	2.8E+01	1.6E+02	2.4E+02	3.0E+02	6.0E+02	2.3E+03	2.7E+04	1.3E+05	8.0E+05	4.0E+06
	X _o	1.3	0.7	1.1	1.5	1.2	1.0	1.0	1.0	11.7	16.8
	r ²	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9996	0.9980

^a Equation for regression curve: $Y = A(1 - \exp[-X/X_o])$
 where: X = time (min) and
 Y = areas affected (m²).

Parameter: A = amplitude,
 X_o = relaxation coefficient (min), and
 r = correlation coefficient.

TABLE B.3-1 Best-fit Parameter Values for Time vs. Persons Affected (Normalized to a Population of 1 Million) by Selected Cumulative Frequencies and by Health Criteria for Typical Case in Region 3 (Chemical = Chlorine; Anemometer Height = 9 m)

Health Criteria	Parameter ^a	Cumulative Frequency (%)									
		1	5	10	25	50	75	90	95	99	100
AEGL-1	A	3.4	43.5	60.4	89.6	203.3	414.7	1,699.4	5,419.9	15,083.7	25,245.5
	X _o	38.6	62.1	56.4	46.8	57.1	52.8	139.1	93.9	72.3	40.3
	r ²	0.9879	0.9737	0.9814	0.9891	0.9948	0.9971	0.9983	0.9935	0.9948	0.9955
AEGL-2	A	- ^b	0.9	3.1	9.8	37.3	113.5	963.9	3,227.4	6,428.0	15,722.9
	X _o	-	18.5	22.5	28.0	27.7	33.9	66.3	75.7	51.2	58.2
	r ²	-	0.9950	0.9912	0.9930	0.9959	0.9977	0.9944	0.9975	0.9960	0.9985
AEGL-3	A	-	-	-	-	0.3	2.8	93.9	278.0	831.1	1,418.3
	X _o	-	-	-	-	1.1	14.0	31.8	38.5	38.6	11.4
	r ²	-	-	-	-	1.0000	0.9988	0.9942	0.9987	0.9983	1.0000
LC _{LO}	A	-	-	-	-	-	-	0.8	7.0	21.9	117.2
	X _o	-	-	-	-	-	-	17.8	17.7	12.0	10.7
	r ²	-	-	-	-	-	-	0.9959	0.9959	0.9998	0.9998
LC ₅₀	A	-	-	-	-	-	-	0.5	3.3	14.3	39.1
	X _o	-	-	-	-	-	-	13.4	12.0	10.7	4.1
	r ²	-	-	-	-	-	-	0.9991	0.9995	0.9998	1.0000
LC ₁₀₀	A	-	-	-	-	-	-	0.4	4.1	39.0	111.8
	X _o	-	-	-	-	-	-	1.3	5.0	13.2	1.2
	r ²	-	-	-	-	-	-	1.0000	1.0000	0.9992	1.0000

^a Equation for regression curve: $Y = A(1 - \exp[-X/X_o])$
 where: X = time (min) and
 Y = persons affected (normalized to a population of 1 million).

Parameter: A = amplitude,
 X_o = relaxation coefficient (min), and
 r = correlation coefficient.

^b Hyphen means not applicable.

TABLE B.3-2 Best-fit Parameter Values for Time vs. Persons Affected (Normalized to a Population of 1 Million) by Selected Cumulative Frequencies and by Health Criteria for Typical SIP Case in Region 3 (Chemical = Chlorine; Anemometer Height = 9 m)

Health Criteria	Parameter ^a	Cumulative Frequency (%)									
		1	5	10	25	50	75	90	95	99	100
AEGL-1	A	1.1	15.6	21.3	46.7	73.9	169.8	736.9	2,199.7	8,347.7	13,971.5
	X _o	38.5	64.6	57.6	59.3	47.7	56.6	125.7	77.0	72.3	40.3
	r ²	0.9876	0.9741	0.9820	0.9901	0.9975	0.9993	0.9973	0.9926	0.9948	0.9955
AEGL-2	A	- ^b	0.5	1.0	4.2	17.9	42.6	402.2	1,339.3	3,399.7	8,701.4
	X _o	-	20.8	20.8	31.3	30.5	30.3	73.1	66.8	46.6	58.2
	r ²	-	0.9911	0.9911	0.9939	0.9955	0.9985	0.9972	0.9977	0.9960	0.9985
AEGL-3	A	-	-	-	-	0.1	0.9	38.5	107.9	324.3	784.9
	X _o	-	-	-	-	1.4	6.8	32.9	31.4	26.7	11.4
	r ²	-	-	-	-	1.0000	1.0000	0.9951	0.9994	0.9988	1.0000
LC _{LO}	A	-	-	-	-	-	-	0.3	2.8	9.2	64.9
	X _o	-	-	-	-	-	-	18.5	16.5	10.7	10.7
	r ²	-	-	-	-	-	-	0.9950	0.9988	0.9998	0.9998
LC ₅₀	A	-	-	-	-	-	-	0.2	1.7	6.7	21.7
	X _o	-	-	-	-	-	-	15.4	12.4	10.6	4.2
	r ²	-	-	-	-	-	-	0.9980	0.9994	0.9998	1.0000
LC ₁₀₀	A	-	-	-	-	-	-	0.2	2.2	15.2	61.9
	X _o	-	-	-	-	-	-	1.2	4.9	9.4	1.2
	r ²	-	-	-	-	-	-	1.0000	1.0000	0.9999	1.0000

^a Equation for regression curve: $Y = A(1 - \exp[-X/X_o])$
 where: X = time (min) and
 Y = persons affected (normalized to a population of 1 million).

Parameter: A = amplitude,
 X_o = relaxation coefficient (min), and
 r = correlation coefficient.

^b Hyphen means not applicable.

TABLE B.3-3 Best-fit Parameter Values for Time vs. Persons Affected (Normalized to a Population of 1 Million) by Selected Cumulative Frequencies and by Health Criteria for Worst Case in Region 3 (Chemical = Chlorine; Anemometer Height = 9 m)

Health Criteria	Parameter ^a	Cumulative Frequency (%)									
		1	5	10	25	50	75	90	95	99	100
AEGL-1	A	11.7	133.5	153.9	243.8	754.6	1,737.6	5,923.4	23,687.3	34,490.2	55,613.7
	X _o	33.0	54.0	44.4	40.0	56.3	64.7	113.7	134.6	69.5	36.0
	r ²	0.9870	0.9763	0.9854	0.9925	0.9938	0.9971	0.9944	0.9935	0.9938	0.9938
AEGL-2	A	- ^b	3.0	11.2	33.1	92.9	493.8	3,640.5	10,209.2	28,117.5	64,298.5
	X _o	-	17.9	21.0	23.1	21.6	36.7	62.5	76.8	107.8	101.9
	r ²	-	0.9957	0.9908	0.9925	0.9975	0.9944	0.9909	0.9953	0.9986	0.9976
AEGL-3	A	-	-	-	-	1.4	12.5	311.2	877.3	3,496.4	6,871.2
	X _o	-	-	-	-	1.4	12.8	27.7	31.4	48.3	42.5
	r ²	-	-	-	-	1.0000	0.9993	0.9960	0.9966	0.9967	0.9952
LC ₁₀	A	-	-	-	-	-	-	3.4	19.2	76.0	259.9
	X _o	-	-	-	-	-	-	17.6	14.9	14.7	10.7
	r ²	-	-	-	-	-	-	0.9961	0.9983	0.9988	0.9998
LC ₅₀	A	-	-	-	-	-	-	1.6	9.8	56.5	149.6
	X _o	-	-	-	-	-	-	10.1	10.9	12.5	11.8
	r ²	-	-	-	-	-	-	0.9998	0.9997	0.9994	0.9996
LC ₁₀₀	A	-	-	-	-	-	-	1.7	13.8	162.3	433.0
	X _o	-	-	-	-	-	-	0.9	6.9	14.9	11.6
	r ²	-	-	-	-	-	-	1.0000	1.0000	0.9984	0.9996

^a Equation for regression curve: $Y = A(1 - \exp[-X/X_o])$
 where: X = time (min) and
 Y = persons affected (normalized to a population of 1 million).

Parameter: A = amplitude,
 X_o = relaxation coefficient (min), and
 r = correlation coefficient.

^b Hyphen means not applicable.

TABLE B.3-4 Best-fit Parameter Values for Time vs. Hospital Beds Affected (as a Percentage of Total Hospital Beds) by Selected Cumulative Frequencies and by Health Criteria in Region 3 (Chemical = Chlorine; Anemometer Height = 9 m)

Health Criteria	Parameter ^a	Cumulative Frequency (%)									
		1	5	10	25	50	75	90	95	99	100
AEGL-1	A	- ^b	-	-	-	-	0.8	2.0	2.4	6.2	11.4
	X _o	-	-	-	-	-	100.0	58.9	45.0	77.9	29.2
	r ²	-	-	-	-	-	0.8819	0.9822	0.9926	0.9927	0.9984
AEGL-2	A	-	-	-	-	-	-	1.8	2.3	3.8	11.6
	X _o	-	-	-	-	-	-	58.3	57.7	68.0	81.5
	r ²	-	-	-	-	-	-	0.9779	0.9805	0.9870	0.9844
AEGL-3	A	-	-	-	-	-	-	-	-	1.9	3.2
	X _o	-	-	-	-	-	-	-	-	37.6	13.5
	r ²	-	-	-	-	-	-	-	-	0.9889	0.9985
LC ₁₀	A	-	-	-	-	-	-	-	-	-	2.4
	X _o	-	-	-	-	-	-	-	-	-	24.1
	r ²	-	-	-	-	-	-	-	-	-	0.9828
LC ₅₀	A	-	-	-	-	-	-	-	-	-	-
	X _o	-	-	-	-	-	-	-	-	-	-
	r ²	-	-	-	-	-	-	-	-	-	-
LC ₁₀₀	A	-	-	-	-	-	-	-	-	-	-
	X _o	-	-	-	-	-	-	-	-	-	-
	r ²	-	-	-	-	-	-	-	-	-	-

^a Equation for regression curve: $Y = A(1 - \exp[-X/X_o])$
 where: X = time (min) and
 Y = hospital beds affected (as a percentage of total hospital beds).

Parameter: A = amplitude,
 X_o = relaxation coefficient (min), and
 r = correlation coefficient.

^b Hyphen means not applicable.

TABLE B.3-5 Best-fit Parameter Values for Time vs. Areas Affected (in m²) by Selected Cumulative Frequencies and by Health Criteria in Region 3 (Chemical = Chlorine; Anemometer Height = 9 m)

Health Criteria	Parameter ^a	Cumulative Frequency (%)									
		1	5	10	25	50	75	90	95	99	100
AEGL-1	A	1.3E+05	7.7E+05	1.1E+06	1.4E+06	3.0E+06	8.4E+06	6.4E+07	1.1E+08	1.3E+08	1.5E+08
	X _o	32.9	41.8	50.6	39.4	38.8	57.6	164.6	104.5	54.5	58.4
	r ²	0.9866	0.9866	0.9863	0.9900	0.9931	0.9884	0.9709	0.9781	0.9889	0.9910
AEGL-2	A	2.8E+04	1.3E+05	1.8E+05	2.6E+05	6.5E+05	2.5E+06	3.0E+07	5.6E+07	1.3E+08	1.5E+08
	X _o	33.0	20.3	19.4	14.5	17.5	30.2	103.4	87.4	140.6	165.4
	r ²	0.9882	0.9987	0.9939	0.9987	0.9965	0.9932	0.9866	0.9930	0.9900	0.9958
AEGL-3	A	1.5E+03	6.0E+03	9.5E+03	1.2E+04	4.2E+04	1.9E+05	1.8E+06	5.0E+06	1.5E+07	1.6E+07
	X _o	22.8	8.6	3.0	2.1	2.7	13.9	26.0	30.3	41.6	48.0
	r ²	0.9865	0.9999	1.0000	1.0000	1.0000	0.9989	0.9944	0.9962	0.9926	0.9941
LC _{LO}	A	3.3E+01	1.2E+02	2.4E+02	2.8E+02	9.0E+02	4.6E+03	4.6E+04	1.4E+05	5.1E+05	5.9E+05
	X _o	1.2	1.1	1.3	1.5	1.3	2.7	13.1	13.3	19.4	19.5
	r ²	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9992	0.9991	0.9943	0.9980
LC ₅₀	A	2.0E+01	8.2E+01	1.5E+02	1.8E+02	5.6E+02	2.6E+03	2.9E+04	8.9E+04	3.4E+05	4.0E+05
	X _o	1.3	1.3	0.8	0.6	1.3	2.1	9.6	13.3	17.9	17.8
	r ²	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999	0.9991	0.9957	0.9959
LC ₁₀₀	A	3.5E+01	1.8E+02	3.1E+02	3.5E+02	9.8E+02	3.7E+03	6.0E+04	2.2E+05	8.2E+05	9.7E+05
	X _o	1.3	0.6	1.5	1.5	1.0	1.0	1.0	3.9	9.2	11.7
	r ²	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999	0.9996

^a Equation for regression curve: $Y = A(1 - \exp[-X/X_o])$
 where: X = time (min) and
 Y = areas affected (m²).

Parameter: A = amplitude,
 X_o = relaxation coefficient (min), and
 r = correlation coefficient.

TABLE B.4-1 Best-fit Parameter Values for Time vs. Persons Affected (Normalized to a Population of 1 Million) by Selected Cumulative Frequencies and by Health Criteria for Typical Case in Region 4 (Chemical = Chlorine; Anemometer Height = 6 m)

Health Criteria	Parameter ^a	Cumulative Frequency (%)									
		1	5	10	25	50	75	90	95	99	100
AEGL-1	A	1.5	23.8	56.3	95.0	177.7	455.2	2,621.7	5,037.9	12,175.3	45,435.2
	X _o	23.0	31.3	32.8	23.4	22.4	37.1	54.9	40.7	34.6	44.2
	r ²	0.9859	0.9886	0.9917	0.9971	0.9999	0.9997	0.9943	0.9948	0.9948	0.9975
AEGL-2	A	0.1	0.2	0.9	5.2	34.0	93.3	2,093.5	4,996.5	10,363.8	20,578.8
	X _o	1.4	15.4	20.5	17.9	14.6	15.9	48.4	37.3	28.0	45.4
	r ²	1.0000	0.9980	0.9919	0.9957	0.9996	0.9995	0.9957	0.9963	0.9972	0.9994
AEGL-3	A	- ^b	-	-	-	0.3	1.4	149.8	293.4	867.4	1,856.2
	X _o	-	-	-	-	1.1	1.4	15.8	16.4	32.2	33.8
	r ²	-	-	-	-	1.0000	1.0000	0.9990	0.9998	0.9987	0.9975
LC _{LO}	A	-	-	-	-	-	-	0.4	5.2	32.1	74.5
	X _o	-	-	-	-	-	-	1.3	6.4	14.6	1.2
	r ²	-	-	-	-	-	-	1.0000	1.0000	0.9985	1.0000
LC ₅₀	A	-	-	-	-	-	-	0.3	2.9	13.8	85.3
	X _o	-	-	-	-	-	-	1.1	8.3	9.4	1.3
	r ²	-	-	-	-	-	-	1.0000	1.0000	0.9999	1.0000
LC ₁₀₀	A	-	-	-	-	-	-	0.8	4.0	21.5	78.9
	X _o	-	-	-	-	-	-	1.3	1.3	3.2	10.4
	r ²	-	-	-	-	-	-	1.0000	1.0000	1.0000	0.9998

^a Equation for regression curve: $Y = A(1 - \exp[-X/X_o])$
 where: X = time (min) and
 Y = persons affected (normalized to a population of 1 million).

Parameter: A = amplitude,
 X_o = relaxation coefficient (min), and
 r = correlation coefficient.

^b Hyphen means not applicable.

TABLE B.4-2 Best-fit Parameter Values for Time vs. Persons Affected (Normalized to a Population of 1 Million) by Selected Cumulative Frequencies and by Health Criteria for Typical SIP Case in Region 4 (Chemical = Chlorine; Anemometer Height = 6 m)

Health Criteria	Parameter ^a	Cumulative Frequency (%)									
		1	5	10	25	50	75	90	95	99	100
AEGL-1	A	0.8	8.9	23.1	39.6	84.3	191.0	1,002.2	2,521.0	6,741.7	25,144.9
	X _o	26.1	32.5	34.8	26.0	26.0	31.6	53.4	40.9	34.9	44.2
	r ²	0.9856	0.9899	0.9910	0.9979	0.9997	0.9999	0.9956	0.9934	0.9945	0.9975
AEGL-2	A	- ^b	0.1	0.4	2.5	14.7	40.3	831.9	2,076.9	5,574.7	11,388.8
	X _o	-	24.1	20.0	19.4	14.2	14.5	50.1	38.5	26.1	45.4
	r ²	-	0.9828	0.9927	0.9954	0.9996	0.9996	0.9972	0.9972	0.9968	0.9994
AEGL-3	A	-	-	-	-	0.1	0.7	56.6	132.0	336.9	675.7
	X _o	-	-	-	-	1.4	1.3	14.6	16.9	22.7	21.8
	r ²	-	-	-	-	1.0000	1.0000	0.9993	0.9998	0.9989	0.9986
LC _{LO}	A	-	-	-	-	-	-	0.2	2.3	11.8	41.2
	X _o	-	-	-	-	-	-	1.2	8.4	14.3	1.4
	r ²	-	-	-	-	-	-	1.0000	1.0000	0.9987	1.0000
LC ₅₀	A	-	-	-	-	-	-	0.1	1.3	5.9	47.2
	X _o	-	-	-	-	-	-	1.4	9.7	10.2	1.2
	r ²	-	-	-	-	-	-	1.0000	0.9999	0.9998	1.0000
LC ₁₀₀	A	-	-	-	-	-	-	0.3	1.9	8.3	32.1
	X _o	-	-	-	-	-	-	1.1	1.3	1.1	1.3
	r ²	-	-	-	-	-	-	1.0000	1.0000	1.0000	1.0000

^a Equation for regression curve: $Y = A(1 - \exp[-X/X_o])$
 where: X = time (min) and
 Y = persons affected (normalized to a population of 1 million).

Parameter: A = amplitude,
 X_o = relaxation coefficient (min), and
 r = correlation coefficient.

^b Hyphen means not applicable.

TABLE B.4-3 Best-fit Parameter Values for Time vs. Persons Affected (Normalized to a Population of 1 Million) by Selected Cumulative Frequencies and by Health Criteria for Worst Case in Region 4 (Chemical = Chlorine; Anemometer Height = 6 m)

Health Criteria	Parameter ^a	Cumulative Frequency (%)									
		1	5	10	25	50	75	90	95	99	100
AEGL-1	A	3.7	81.1	156.7	315.0	573.1	1,829.8	9,453.8	17,795.9	32,064.9	100,712.2
	X _o	23.2	26.5	27.9	22.6	18.6	41.9	55.7	48.2	33.6	44.2
	r ²	0.9854	0.9871	0.9929	0.9977	0.9997	0.9985	0.9939	0.9950	0.9949	0.9975
AEGL-2	A	0.3	0.7	2.2	18.9	98.1	397.4	7,940.8	17,000.2	29,799.5	64,851.7
	X _o	1.1	7.6	16.3	16.5	10.0	22.0	50.2	40.7	31.2	58.0
	r ²	1.0000	1.0000	0.9974	0.9972	0.9999	0.9987	0.9956	0.9967	0.9977	0.9988
AEGL-3	A	- ^b	-	-	0.2	0.8	5.4	437.8	857.3	3,920.9	9,571.1
	X _o	-	-	-	1.2	1.3	3.8	14.2	12.5	35.0	39.4
	r ²	-	-	-	1.0000	1.0000	1.0000	0.9995	0.9998	0.9970	0.9921
LC _{LO}	A	-	-	-	-	-	-	1.8	16.8	91.2	263.2
	X _o	-	-	-	-	-	-	6.8	6.3	11.0	12.8
	r ²	-	-	-	-	-	-	1.0000	1.0000	0.9997	0.9993
LC ₅₀	A	-	-	-	-	-	-	0.9	8.7	53.5	212.6
	X _o	-	-	-	-	-	-	1.3	6.6	9.6	6.8
	r ²	-	-	-	-	-	-	1.0000	1.0000	0.9999	1.0000
LC ₁₀₀	A	-	-	-	-	-	0.1	2.4	12.3	97.0	403.9
	X _o	-	-	-	-	-	1.4	1.1	1.3	0.3	11.4
	r ²	-	-	-	-	-	1.0000	1.0000	1.0000	1.0000	0.9997

^a Equation for regression curve: $Y = A(1 - \exp[-X/X_o])$
 where: X = time (min), and
 Y = persons affected (normalized to a population of 1 million).

Parameter: A = amplitude,
 X_o = relaxation coefficient (min) and
 r = correlation coefficient.

^b Hyphen means not applicable.

TABLE B.4-4 Best-fit Parameter Values for Time vs. Hospital Beds Affected (as a Percentage of Total Hospital Beds) by Selected Cumulative Frequencies and by Health Criteria in Region 4 (Chemical = Chlorine; Anemometer Height = 6 m)

Health Criteria	Parameter ^a	Cumulative Frequency (%)									
		1	5	10	25	50	75	90	95	99	100
AEGL-1	A	- ^b	-	-	-	-	-	2.1	3.5	7.9	15.8
	X _o	-	-	-	-	-	-	58.1	44.8	44.5	16.4
	r ²	-	-	-	-	-	-	0.9817	0.9934	0.9976	0.9988
AEGL-2	A	-	-	-	-	-	-	1.6	3.9	14.2	14.2
	X _o	-	-	-	-	-	-	53.5	41.5	51.6	11.2
	r ²	-	-	-	-	-	-	0.9798	0.9927	0.9967	0.9997
AEGL-3	A	-	-	-	-	-	-	-	-	1.6	5.9
	X _o	-	-	-	-	-	-	-	-	63.1	33.3
	r ²	-	-	-	-	-	-	-	-	0.9810	0.9874
LC ₁₀	A	-	-	-	-	-	-	-	-	-	-
	X _o	-	-	-	-	-	-	-	-	-	-
	r ²	-	-	-	-	-	-	-	-	-	-
LC ₅₀	A	-	-	-	-	-	-	-	-	-	-
	X _o	-	-	-	-	-	-	-	-	-	-
	r ²	-	-	-	-	-	-	-	-	-	-
LC ₁₀₀	A	-	-	-	-	-	-	-	-	-	-
	X _o	-	-	-	-	-	-	-	-	-	-
	r ²	-	-	-	-	-	-	-	-	-	-

^a Equation for regression curve: $Y = A(1 - \exp [-X/X_o])$
 where: X = time (min) and
 Y = hospital beds affected (as a percentage of total hospital beds).

Parameter: A = amplitude,
 X_o = relaxation coefficient (min), and
 r = correlation coefficient.

^b Hyphen means not applicable.

TABLE B.4-5 Best-fit Parameter Values for Time vs. Areas Affected (in m²) by Selected Cumulative Frequencies and by Health Criteria in Region 4 (Chemical = Chlorine; Anemometer Height = 6 m)

Health Criteria	Parameter ^a	Cumulative Frequency (%)									
		1	5	10	25	50	75	90	95	99	100
AEGL-1	A	8.8E+04	7.4E+05	8.3E+05	1.2E+06	1.6E+06	7.1E+06	1.0E+08	1.1E+08	1.3E+08	1.4E+08
	X _o	16.8	32.9	23.8	17.7	14.2	64.2	69.6	40.4	44.5	40.2
	r ²	0.9969	0.9924	0.9906	0.9968	0.9989	0.9924	0.9794	0.9895	0.9934	0.9950
AEGL-2	A	1.5E+04	1.3E+05	1.3E+05	1.9E+05	3.4E+05	1.8E+06	3.0E+07	4.4E+07	1.0E+08	1.3E+08
	X _o	4.3	10.0	5.0	2.8	6.3	28.7	41.7	51.2	84.4	128.6
	r ²	1.0000	0.9999	1.0000	1.0000	1.0000	0.9942	0.9940	0.9945	0.9929	0.9978
AEGL-3	A	6.8E+02	5.6E+03	6.0E+03	8.9E+03	1.6E+04	1.2E+05	1.6E+06	2.4E+06	1.2E+07	1.4E+07
	X _o	1.2	8.4	2.9	1.0	1.9	15.7	11.8	12.0	35.6	41.4
	r ²	1.0000	1.0000	1.0000	1.0000	1.0000	0.9978	0.9996	0.9996	0.9943	0.9958
LC _{LO}	A	1.6E+01	1.2E+02	1.3E+02	1.9E+02	3.5E+02	2.5E+03	3.4E+04	6.3E+04	3.8E+05	4.8E+05
	X _o	1.3	6.7	3.1	1.1	1.4	14.9	2.9	3.0	15.6	17.2
	r ²	1.0000	1.0000	1.0000	1.0000	1.0000	0.9983	1.0000	1.0000	0.9979	0.9965
LC ₅₀	A	1.0E+01	7.5E+01	8.6E+01	1.2E+02	2.2E+02	1.5E+03	2.1E+04	4.0E+04	2.4E+05	3.4E+05
	X _o	1.3	5.9	3.4	1.3	2.8	14.6	2.7	2.9	4.5	11.2
	r ²	1.0000	1.0000	1.0000	1.0000	1.0000	0.9985	1.0000	1.0000	1.0000	0.9997
LC ₁₀₀	A	1.6E+01	1.5E+02	1.7E+02	2.4E+02	4.1E+02	2.2E+03	4.5E+04	8.3E+04	5.4E+05	8.1E+05
	X _o	1.3	0.8	0.6	1.3	1.5	1.0	1.0	1.0	3.4	11.7
	r ²	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9996

^a Equation for regression curve: $Y = A(1 - \exp[-X/X_o])$
 where: X = time (min) and
 Y = areas affected (m²).

Parameter: A = amplitude,
 X_o = relaxation coefficient (min), and
 r = correlation coefficient.



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