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Chemical Hazards, Mitigation and Preparedness in Areas of High Seismic Risk: A Methodology for Estimating the Risk of Post-Earthquake Hazardous Materials Release

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Technical Report NCEER-96-0013

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NOTICE

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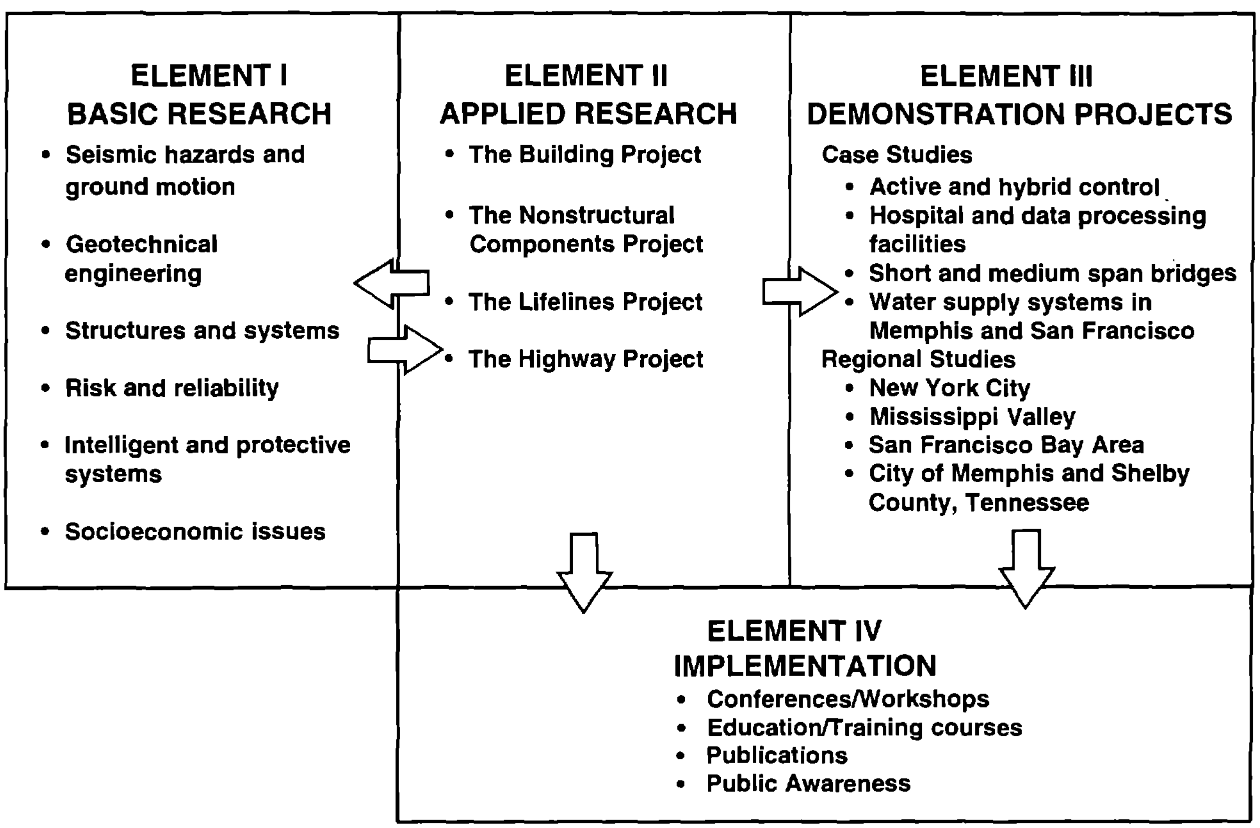
PREFACE

The National Center for Earthquake Engineering Research (NCEER) was established in 1986 to develop and disseminate new knowledge about earthquakes, earthquake-resistant design and seismic hazard mitigation procedures to minimize loss of life and property. The emphasis of the Center is on eastern and central United States *structures*, and *lifelines* throughout the country that may be exposed to any level of earthquake hazard.

NCEER's research is conducted under one of four Projects: the Building Project, the Nonstructural Components Project, and the Lifelines Project, all three of which are principally supported by the National Science Foundation, and the Highway Project which is primarily sponsored by the Federal Highway Administration.

The research and implementation plan in years six through ten (1991-1996) for the Building, Nonstructural Components, and Lifelines Projects comprises four interdependent elements, as shown in the figure below. Element I, Basic Research, is carried out to support projects in the Applied Research area. Element II, Applied Research, is the major focus of work for years six through ten for these three projects. Demonstration Projects under Element III have been planned to support the Applied Research projects and include individual case studies and regional studies. Element IV, Implementation, will result from activity in the Applied Research projects, and from Demonstration Projects.



Research tasks in the **Lifeline Project** evaluate seismic performance of lifeline systems, and recommend and implement measures for mitigating the societal risk arising from their failures or disruption caused by earthquakes. Water delivery, crude oil transmission, gas pipelines, electric power and telecommunications systems are being studied. Regardless of the specific systems to be considered, research tasks focus on (1) seismic vulnerability and strengthening; (2) repair and restoration; (3) risk and reliability; (4) disaster planning; and (5) dissemination of research products.

The end products of the **Lifeline Project** will include technical reports, computer codes and manuals, design and retrofit guidelines, and recommended procedures for repair and restoration of seismically damaged systems. The **societal and economic impact program** constitutes one of the important areas of research in the **Lifeline Project**. The program involves identifying, quantifying, and analyzing the impacts earthquakes and other natural disasters have on the populations and socio-economic systems of impacted regions. The primary focus of this program is on the interaction between the social and economic system and the built physical environment which accommodates it. The major tasks are as follows:

1. Fundamental research concerning the built physical environment system.
2. Fundamental research concerning the social and economic system, including investigations of macro-economic impact, epidemiology of casualties, and housing reconstruction.
3. Specific research concerning the social and economic system such as the economics of non-structural component and lifeline failures, and the social consequences of lifeline failures.
4. Knowledge utilization research focused on professional and private acceptance of research results.

The purpose of the report is to demonstrate a pilot application of a methodology for estimating regional exposure to hazmat releases given an earthquake. Because of the rarity of such events, and the potentially grave consequences, the methodology provides guidance for mitigation, which would otherwise be lacking. The methodology is described and amply illustrated by the pilot application, which is for the Los Angeles basin, perhaps one of the highest risk areas in the U.S. for post-earthquake hazmat releases.

ABSTRACT

While recent earthquake disasters (1994 Northridge and 1995 Kobe) have produced few documented occurrences of hazardous materials release, failures in previous events, such as the release of chlorine gas from a chlorine repackaging facility in the 1987 Whittier Narrows earthquake (FEMA, 1987), indicate that even one such occurrence may place significant demands on limited emergency resources. Facilities that manufacture and store chemicals may be especially vulnerable to earthquake damage and subsequent hazardous materials release because of their high concentration of industrial type equipment which may or may not incorporate seismic resistant features. Furthermore, the ability of a community to respond to multiple incidents may be hampered by limited resources and lack of communication capability. It appears that the first significant step towards developing a constructive areawide response and mitigation program for chemical facilities is to be able to quantify the seismic risk potential of hazardous materials release and its effect on surrounding communities. Current reporting and permitting requirements may facilitate implementation of such an assessment; extensive chemical inventories are often collected locally, usually by the Fire Department.

The objective of this project was to develop a methodology that would enable local jurisdictions to determine the magnitude of the problem and identify areas most susceptible to earthquake-induced hazardous materials release. The generalized methodology, as developed, includes five major steps; inventory development, seismic hazard analysis, component vulnerability assessment, regional vulnerability assessment, and population risk assessment. The results enable local emergency managers to prepare for and mitigate potential earthquake-induced releases This report illustrates the application of the methodology for assessing the risk of earthquake-induced hazardous materials release and its impact on surrounding population. The methodology is demonstrated on the Los Angeles area using data from a survey conducted by the South Coast Air Quality Management District, limited to 22 facilities using ammonia and/or chlorine within Los Angeles County.

Results of the pilot application indicate that

- In a M 7.0 earthquake on the Newport-Inglewood Fault, as many as 133,000 people (2% of the total population in Los Angeles County) would be exposed to hazardous materials released from the 22 subject sources.
- From those 22 sources, over 20,000 people would suffer exposure to hazardous materials following a M 8+ event on the southern San Andreas fault
- Less than 7,000 people were estimated to suffer hazardous materials exposure in a simulation of the M 5.9 Whittier Narrows earthquake. (During the 1987 Whittier Narrows earthquake, a tank in the city of Santa Fe Springs ruptured and released 240 gallons of chlorine. The resulting plume, which drifted toward the city of Whittier, prompted the evacuation of some areas).

ACKNOWLEDGMENTS

This report documents work that was sponsored by the National Science Foundation (Grant No. ECE-8600292) and the National Center for Earthquake Engineering Research (Grant No. 926301A). The authors wish to thank Dr. William Anderson (NSF) and Professor M. Shinozuka (NCEER) for providing the initial guidance for this study. In addition, the authors would like to thank the following individuals who contributed to this study:

Mr. Robert Antonopolis (formerly of the South Coast Air Quality Management District) for help in developing the generic facility models used in this study.

Mr. Allan R. Porush of Dames & Moore for his help in developing the facility seismic vulnerability models.

Dr. Craig E. Taylor, of EQE International, Inc., for his advice on constructing the probabilistic plume models.

The work was performed in 1989, prior to much of the recent earthquake-related hazardous materials research (e.g., ABAG, 1991 and Selvaduray and Perkins, 1993). At that time, the authors were affiliated with the following companies or institutions;

- Hope Seligson and Ronald Eguchi - Dames & Moore, Los Angeles, California
- Kathleen Tierney - University of Southern California
- Kenneth Richmond - TRC Environmental Consultants

The authors would also like to thank USC, Dames & Moore and TRC Environmental Consultants for their part in helping to secure the research grants. This support is gratefully acknowledged.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

SECTION 1
INTRODUCTION

It is generally acknowledged that a major earthquake in an industrialized, densely populated area of the U.S. could lead to the release of hazardous chemicals. A large post-earthquake release would present a threat not only to residents in the immediate vicinity of the source, but also to those of surrounding communities. Affected areas would then face a range of emergency management problems. For example, a major earthquake is likely to seriously impair community emergency response capability, making it difficult to effectively deal with secondary emergencies such as hazardous materials releases and fires. Tasks which are normally problematic, such as warning the public about a toxic release and evacuating people from areas that are hazardous, would be much more difficult following a major earthquake. Further, communities are accustomed to responding to hazardous materials releases one at a time, while in an earthquake situation multiple accidents may occur simultaneously, greatly compounding resource problems.

Although there has never been a major incident involving hazardous materials in a U.S. earthquake, smaller releases have occurred in events that were moderate in size. A recent example is an accident at a chlorine repackaging facility in the 1987 Whittier Narrows Earthquake, in which nearly one ton of chlorine gas was released (FEMA, 1987). The research for this project combines seismic hazard analyses, findings from research on earthquake-related failures in industrial facilities, and data on airborne toxic releases to estimate the magnitude of the risk.

The main challenge in approaching this problem from a community perspective is to develop a risk assessment methodology that is sophisticated enough to provide the type of information needed for more effective hazard management, that is also cost-effective to apply on a regional basis. Conducting detailed seismic risk assessments and modeling potential failures in chemical facilities is very time consuming and expensive; few communities can afford to conduct such studies. The objective of this project is to develop a general method that would enable local jurisdictions to determine the magnitude of the problem and identify areas that are susceptible to earthquake-generated releases, yet would not be cumbersome and prohibitively expensive to apply.

Adding to the complexity of the problem, highly hazardous materials number in the thousands, and new products are constantly being developed. Before systematic analyses can be undertaken, it is necessary to determine which hazardous substances are likely to pose the biggest threat to the community in an earthquake. In this project, we have chosen to focus on two hazardous materials; chlorine and ammonia. These substances were selected because: (1) they are responsible for a number of fatalities and casualties in U.S. hazardous materials incidents; (2) they are present in large quantities in our study area, Greater Los Angeles; and (3) they form clouds that can spread to adjacent areas, thus presenting a hazard beyond the plant gates.

SECTION 2
METHODOLOGY

This risk assessment methodology as developed for this study is presented in Figure 2-1. As shown, the methodology has 5 major components, as briefly discussed below. Details on how the generalized methodology has been applied in the pilot application to Los Angeles County are presented in later sections.

The first step in the methodology entails the collection of hazardous materials inventory data. This data is often collected by local jurisdictions as part of permit or reporting requirements. Required data include facility location (e.g., address or latitude and longitude), material and quantity stored, and material usage (i.e., storage only, storage and processing, etc.). Data collected for the pilot application on 22 of the largest users of chlorine and anhydrous ammonia in the Greater Los Angeles area are discussed in Section 3.1. Facilities are further classified according to "generic" facility models - one for chemical processing facilities and one for chemical storage and transfer facilities. Section 3.2 describes these models.

The second major component of the methodology is the seismic hazard assessment. Modified Mercalli Intensity has been selected as the seismic hazard indicator for the models developed in this study. For each facility storing hazardous materials, a seismic hazard assessment must be performed to estimate strong ground shaking for a postulated earthquake scenario. Three scenarios have been selected for the pilot application; a M 7.0 on the Newport-Inglewood fault, a M 8+ on the southern San Andreas fault, and a M 5.9 simulation of the 1987 Whittier Narrows earthquake. Models used to develop regional ground shaking estimates for the pilot application are documented in Section 3.3.

Each modeled facility must be classified into one of the generic facility categories. For this study, the "generic" facility models have been developed to best reflect the characteristics of the 22 facilities included in the pilot test. Representative components have been selected, and for each of the "generic" facility models, component fragilities and associated failure probabilities have been developed through

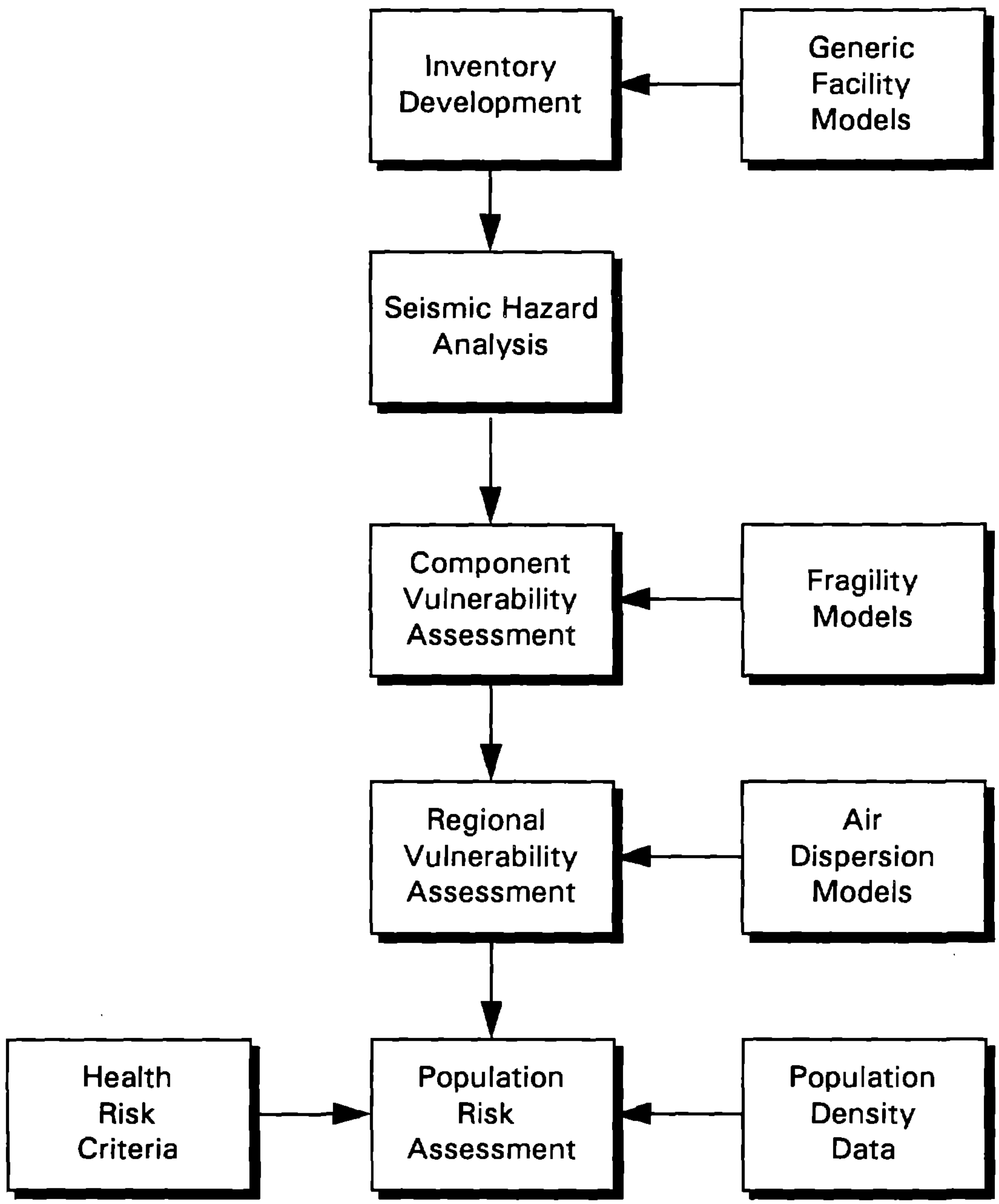


FIGURE 2-1 Methodology for Risk Assessment of Hazardous Materials Release During Earthquake

the use of a fault tree analysis. These models consider typical facility design, and determine likelihood of failure of various failure modes. The component fragility models may be combined with site-specific ground motions to estimate component and facility failure probabilities for a given earthquake scenario. Details on the component vulnerability assessment are furnished in Section 3.4.

To determine regional impacts of component or facility failure, the consequences of failure must be estimated. For each facility component with failure potential, resultant chemical plumes have been modeled using physical dispersion models. Section 3.5 provides details of the physical dispersion models used to represent the behavior of airborne chemicals, and the probabilistic models used to determine the location of plumes relative to population centers. The shape and extent of the airborne plume must be overlain onto exposed population to estimate the number of people likely to suffer exposure to potential hazardous materials clouds. The details of the population data are presented in Section 3.6

The models and methodology defined above are implemented in a computer program designed to determine overall risk to the population from earthquake-induced hazardous materials release. Section 3.7 describes the probabilistic approach used to aggregate this information in Program "Plume"; a computer program which computes the number of people exposed to a hazardous materials release given a specific earthquake in the Los Angeles area. Results of the trial run are discussed in Section 4.0.

The results and output from the methodology should enable the user to: (a) show which areas of the community are likely to have the most problems with airborne releases; (b) show how many people would be at risk from earthquake-generated accidents; and (c) assist emergency response agencies in preparing for such incidents. The illustrative application of these steps are presented in the following sections.

SECTION 3

APPLICATION OF RISK ASSESSMENT METHODOLOGY

To illustrate the application of the risk assessment methodology, a pilot study of the Los Angeles area has been performed. The following sections describe data collection and development, including development of a model computer program to calculate population exposure to earthquake-generated hazardous materials release.

3.1 HAZARDOUS MATERIAL INVENTORY - DESCRIPTION OF FACILITIES

The group of facilities examined in this study includes twenty-two of the largest users of chlorine and anhydrous ammonia in the greater Los Angeles area. Users include petroleum refineries, chemical manufacturers, and wastewater treatment plants. Although the methodology as developed calls for data obtained from inventories prepared under state and federal laws, these data were actually obtained from a survey conducted by the South Coast Air Quality Management District (AQMD).

These facilities store and use varying amounts of chemicals, and are dispersed throughout the study area. Figure 3-1 shows the locations relative to the Los Angeles - Orange County border. Major cities are also noted on the figure. Facilities have been divided into three facility types based on chemical usage: chlorine storage facilities, ammonia storage facilities, and ammonia processing facilities. Chlorine storage amounts range from 4 to 1000 tons, while ammonia storage varies from 2 to 206 tons. Table 3-1 indicates the usage of each facility, and the amount of each chemical stored on-site.

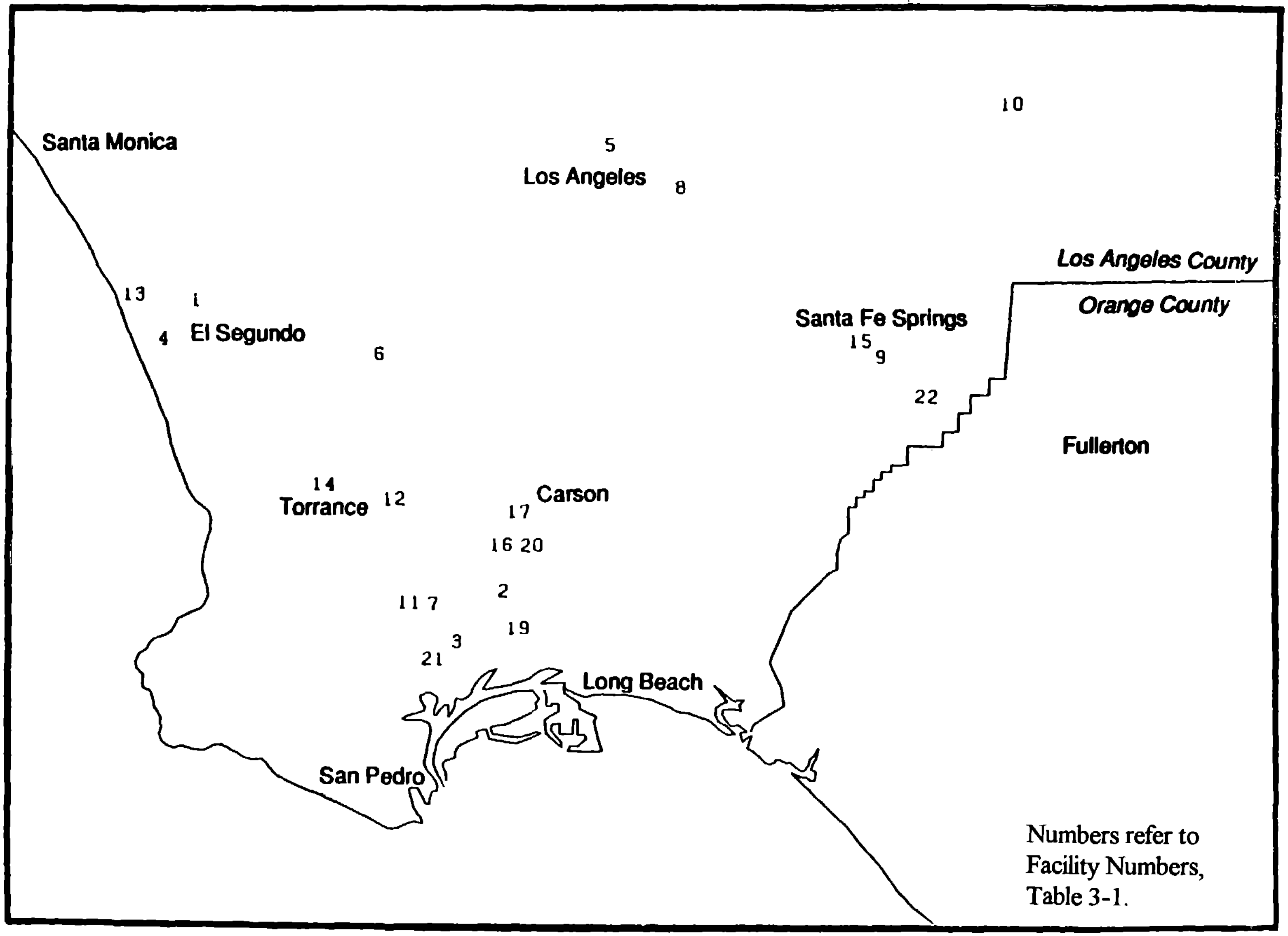


FIGURE 3-1 Hazardous Materials Source Locations in Los Angeles County

TABLE 3-1 Chemical Facility Use and Storage - Los Angeles County

Facility	Facility Type			Chemical Storage	
	Chlorine Storage	Ammonia Storage	Ammonia Processing	Chlorine (Tons)	Ammonia (Tons)
1	x		x	4	40
2	x		x	32	57
3	x		x	8	26
4	x		x	12	206
5	x			180	
6	x			5	
7	x		x	10	15
8	x			450	
9	x			5	
10		x			26
11	x			454	
12	x	x		1000	14
13	x			25	
14	x		x	20	15
15	x	x		270	1
16	x			90	
17	x			48	
18		x			26
19	x		x	10	10
20	x			6	
21	x	x		24	2
22		x			100
Total	19	6	7	2653 Tons	538 Tons

3.2 "GENERIC" MODELS OF CHEMICAL FACILITIES

"Generic" facility models were developed for reasons of economy and efficiency. It was assumed that facilities that perform the same function have more or less the same components, allowing for analysis by facility type, rather than on an individual facility basis. This method is particularly applicable to the Los Angeles area, where the range of facilities is somewhat limited. Facilities are generally comprised of the same components and follow similar process operations, using gaseous toxic chemicals as reactants in the manufacturing process. Examples include plants using chlorine gas as a reactant to form chlorinated hydrocarbons, and plants using hydrogen fluoride as a reactant to form freons.

The two basic models used in this study are the chemical processing model (Figure 3-2), and the storage and transfer model. Components of the processing model that are subject to failure include the: (1) pressurized storage vessel; (2) exothermic reactor; (3) piping; and (4) separator/regenerator. The storage and transfer model is simply a subset of the processing model, consisting of a storage vessel and associated piping.

While information about the number of vessels and their sizes was given for facilities engaged in storage and transfer only, determining the sizes of the various components at processing plants were less straightforward. Available data on the quantity of chemicals stored were limited to a total for the facility; i.e., there was no breakdown of information regarding the amount residing in the various vessels. Developing a method for determining the size of the various components based on the total amount of the chemical stored at the facility was essential. It was believed that the simplest way to do this would be to take an "average" facility, determine the component sizes, and somehow extrapolate this to other facilities with varying amounts of storage.

The starting point for this method was the typical design of an ammonia processing plant with one 90-ton rail car of ammonia storage. Such a facility would require an exothermic reactor 10 feet in diameter and 12 feet in height, and a separator vessel 3 feet in diameter and 6 feet in height. Since

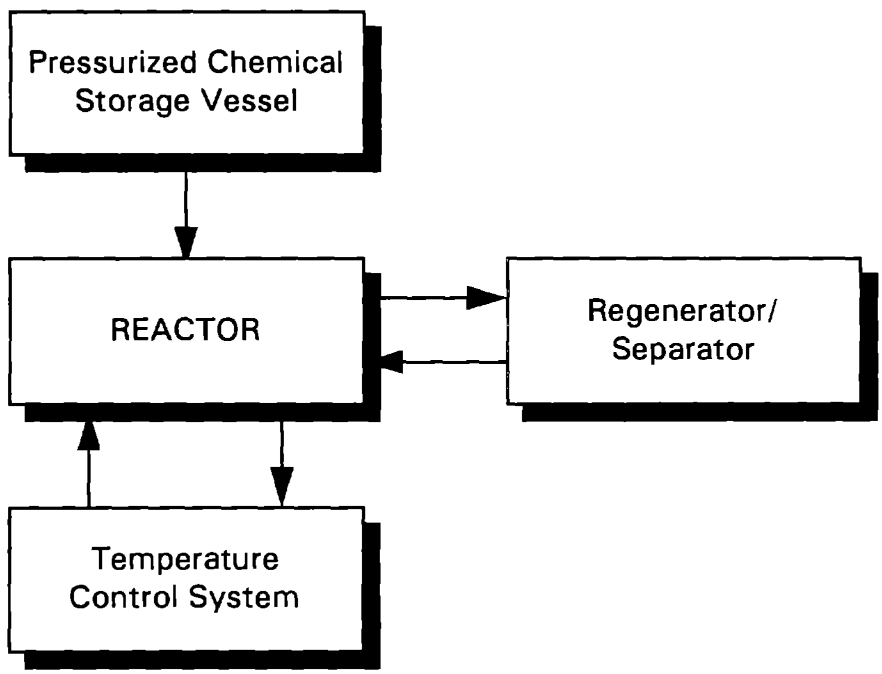


FIGURE 3-2 Simple Flowchart of Chemical Processing Facility

the density of anhydrous ammonia is known, it is possible to calculate the volume, in tons, of both the reactor and the separator. The reactor would hold up to 18 tons of ammonia, while the separator would hold slightly less than 1 ton.

This typical design can be used with an industry "rule-of-thumb" (Antonopolis, 1989) to determine the size of reactors and separators for facilities with varying numbers and sizes of storage vessels. The rule-of-thumb is as follows:

$$V2 = V1 \times (S2/S1)^{0.6}$$

where: V2 = Volume of the vessel under consideration

V1 = Volume of the corresponding vessel in the typical facility

S2 = Total amount stored at the facility under consideration

S1 = Total amount stored at the typical facility (90 tons)

When this rule of thumb is applied to the ammonia processing plants, it is possible to determine the necessary volume of the reactor and separator vessels. Table 3-2 presents the breakdown of facilities as calculated by this equation. For simplicity, it would be optimal to choose one size vessel to represent all reactors, and one size for all separators. It was apparent from the calculations that the selection of a 20-ton vessel for the "generic" reactor and a 1-ton vessel for the "generic" separator would be a fairly safe assumption, since these vessels are only occasionally full, but are expected to be able to hold varying amounts of chemicals for processing at different capacities. Table 3-3 lists the assumed components at each facility, including the breakdown of storage into vessels of various sizes.

One additional assumption concerning facility components was made: piping was assumed to be three inches in diameter, a size common in many industrial uses. It was assumed that most piping at chemical storage and processing facilities would be similarly sized, and therefore that the overall impact of this assumption would be small.

TABLE 3-2 Calculated Reactor and Separator Vessel Sizes for Ammonia Processing Facilities

Facility	Amount Stored (Tons)	Reactor Size (Tons)	Separator Size (Tons)
1	40	11	0.5
2	57	14	0.6
3	26	9	0.4
4	206	30	1.3
7	15	6	0.3
14	15	6	0.3
19	10	5	0.2

TABLE 3-3 Assumed Facility Components

Facility	Ammonia Storage Vessels					Ammonia Processing Vessels		Chlorine Storage Vessels		
	1 Ton	20 Ton	50 Ton	100 Ton	200 Ton	Reactor 20 Ton	Separator 1 Ton	1 Ton	2 Ton	90 Ton
1		1				1	1		2	
2			1			1	1	32		
3		1				1	1	8		
4					1	1	1		6	
5										2
6								5		
7		1				1	1		5	
8										5
9								5		
10		1								
11								4		5
12		1								11
13								25		
14		1				1	1		10	
15	1									3
16										1
17								48		
18		1								
19		1				1	1		5	
20								6		
21	2							24		
22				1						

3.3 EARTHQUAKE SCENARIOS AND GROUND SHAKING ESTIMATES

3.3.1 Earthquake Scenarios

Three different earthquake scenarios were modeled for this project. Only damage due to ground shaking was considered, although alternative scenarios could be developed for other earthquake effects, such as fault rupture, liquefaction and other ground failures.

Scenario 1 is a Magnitude 7.0 event on the Newport-Inglewood fault. This fault was the source of the 1933 Long Beach earthquake (M 6.3), which caused 120 deaths and $41 million (1933 dollars) in damage. A major earthquake (M 7.0 or above) in the Newport-Inglewood Fault Zone would likely result in numerous fatalities and injuries, billions of dollars in damages, and severe disruption of economic activity at the local, regional, state and even national levels.

The San Andreas fault zone has long been recognized as the dominant seismotectonic feature in California. One of California's largest historic earthquakes, the 1857 Fort Tejon Earthquake, occurred along the San Andreas Fault in Southern California. With an estimated Magnitude of 8.3, this earthquake was felt throughout southern and central California, western Nevada, Arizona, and Northern Mexico - an area of over 135,000 square miles. Surface fault rupture extended for 360 - 400 kilometers. Scenario 2 is a Magnitude 8.3 earthquake on the San Andreas fault. This event involves 300 km of rupture along the Mojave, San Bernardino Mountain, and Coachella Valley segments of the fault. Such an event would be expected to cause high ground shaking levels throughout the Los Angeles Basin. As with the Newport-Inglewood event, losses and disruption would be significant.

Scenario 3 is a Magnitude 5.9 event - a simulation of the 1987 Whittier Narrows Earthquake. This earthquake, with localized strong ground shaking, caused few deaths and injuries, but produced losses exceeding $350 million. In addition, the earthquake caused a significant hazardous materials incident. A tank in the City of Santa Fe Springs ruptured and leaked 240 gallons of chlorine into the air. The resulting plume, which drifted through the industrial section of the city toward Whittier, prompted evacuation of some areas (FEMA, 1987).

3.3.2 Ground Shaking Estimates

For each of the 22 source facilities, latitude and longitude locations were estimated. Ground shaking intensities at each facility location were then computed for the three earthquake scenarios.

Peak ground accelerations (PGAs) were calculated at each location using a deterministic magnitude-distance attenuation relationship (Campbell, 1981). This attenuation relationship was derived from recorded strong ground shaking data from past earthquakes, and estimates site strong ground shaking as a function of earthquake magnitude and distance from the facility to the fault rupture segment.

Calculated PGAs were then converted to values of ground shaking intensity based on the Modified Mercalli Intensity (MMI) scale (Table 3-4) using a conversion equation developed by Trifunac (1976). Trifunac used regression analysis techniques to correlate 187 recorded strong ground shaking accelerograms with corresponding Modified Mercalli Intensity observations. These conversions yield MMI values equivalent to PGA values for sites located on "basement rock".

In order to account for variations in local ground conditions from "basement rock", MMI modifiers were added to the "basement rock" MMI values. These modifiers were based on Evernden and Thomson's (1985) site soil classifications and local soil information. Data on generalized local ground conditions for the study area were derived from published geologic maps, including maps generated by Tinsley and Fumal (1985), from their study of the areal variations in shaking response due to earthquakes in southern California. MMI values may vary with local ground conditions as much as one MMI unit for sites located the same distance from a given magnitude event. "Soft" (unconsolidated) soil sites show the largest response, adding up to one additional MMI unit, while "hard" (usually older, consolidated) soil or rock sites show the smallest response.

TABLE 3-4 Modified Mercalli Intensity Scale
(excerpt, abridged)

I-V	Not significant to structures.
VI	Felt by all; many are frightened and run outdoors. Some heavy furniture moves; a few instances of fallen plaster or damaged chimneys. Damage slight.
VII	Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motorcars.
VIII	Damage slight in specially designed structures; considerable in ordinary substantial buildings, with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Chimneys, factory stacks, columns, monuments, and walls fall. Heavy furniture overturned. Disturbs persons driving motorcars.
IX	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb; damage great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.
X	Some well-built wooden structures destroyed; most masonry and frame structures destroyed, along with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks.

Thus, for the earthquake scenarios modeled, strong ground motion estimates were generated which incorporate generalized local ground conditions, as well as regional ground shaking parameters. These intensities are listed in Table 3-5. Figure 3-3 shows the resulting shaking intensity map for Scenario 1 - a Magnitude 7.0 earthquake on the Newport-Inglewood Fault.

3.4 COMPONENT VULNERABILITY MODELS

3.4.1 Fault Tree Analysis

In determining the likelihood of damage or failure for complex systems such as chemical facilities, it is not possible to identify just one or two failure modes that could be sources for overall system failures. Instead, all conceivable failure modes must be identified, and their individual contributions to overall facility failure must be systematically combined. A method called fault tree analysis has been found useful for this kind of assessment. In fault tree analysis, Boolean techniques are used to model the interdependency of individual component failures. Cases where several failure modes must occur for some "fault" to occur are modeled using "AND gates." Cases where some "fault" can occur due to one or more failure modes are modeled using "OR gates"

The fault tree models for earthquake-generated failures and toxic releases for chemical processing facilities, and storage and transfer facilities are presented in Figures 3-4 and 3-5, respectively. Failures can stem from a number of sources, including power failures, earthquake damage to the systems that normally keep the processes under control, and damage to individual components and connections in the system.

3.4.2 Damage Models and Probabilities

Figure 3-6 illustrates generic earthquake damage curves for four types of chemical processing equipment: horizontal storage vessels, reactors, temperature control facilities, and feed controllers.

TABLE 3-5 Strong Ground Shaking Estimates (MMI) for Facility Sites

Facility Number	Scenario 1 Newport Inglewood M = 7.0	Scenario 2 San Andreas M = 8.3	Scenario 3 Whittier Elsinore M = 5.9
1	8.9	7.6	6.2
2	9.0	7.4	6.4
3	8.7	7.4	6.2
4	8.7	7.5	6.1
5	8.6	8.0	7.6
6	9.5	7.6	6.6
7	8.8	7.4	6.3
8	8.5	8.0	7.9
9	8.4	7.9	7.6
10	7.7	8.2	8.0
11	8.7	7.4	6.2
12	8.9	7.5	6.4
13	8.7	7.6	6.0
14	8.7	7.5	6.2
15	8.4	7.9	7.7
16	9.2	7.5	6.5
17	9.4	7.5	6.6
18	7.3	8.3	6.0
19	8.9	7.4	6.3
20	9.2	7.5	6.5
21	8.6	7.4	6.2
22	8.4	7.8	7.3

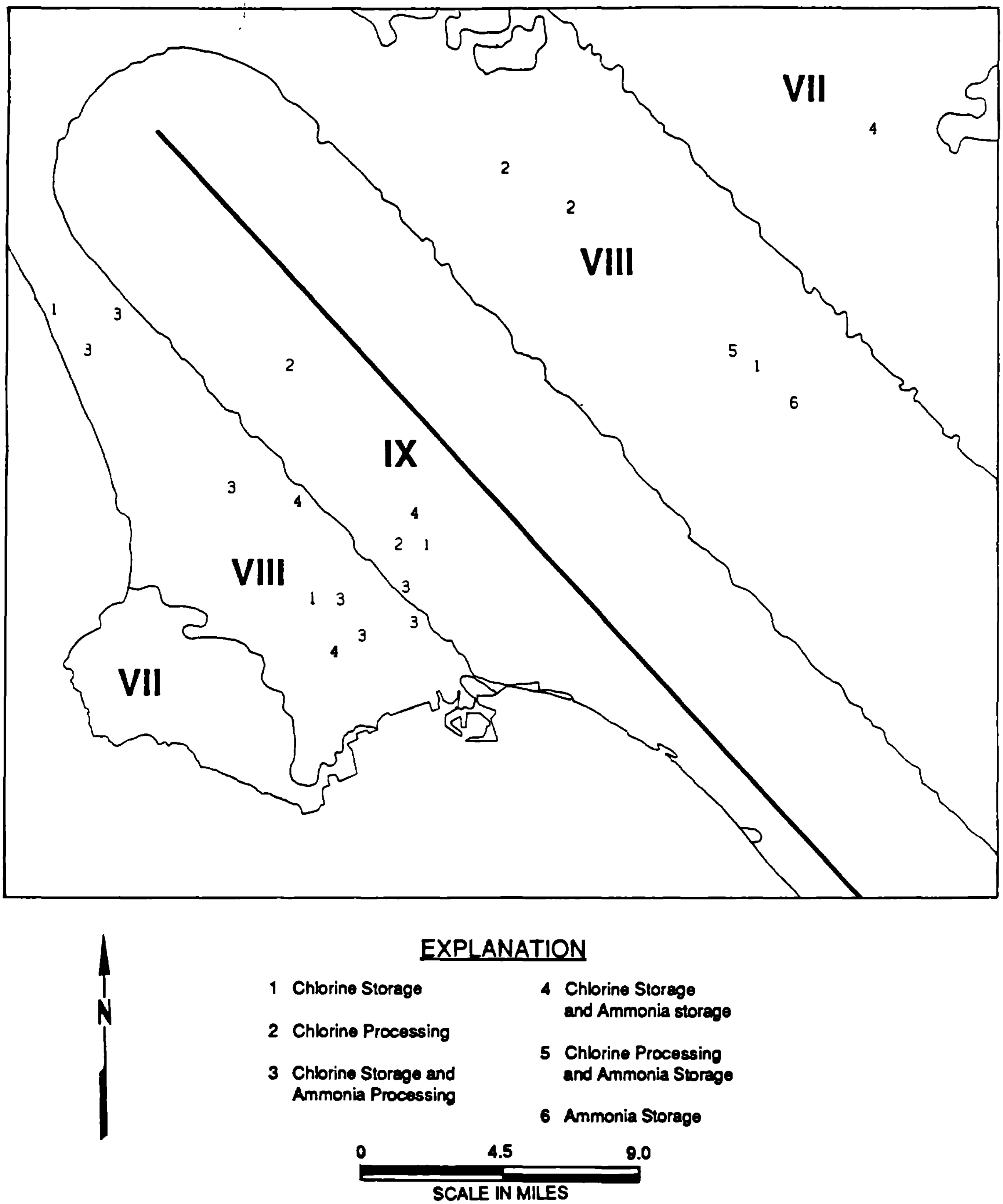


FIGURE 3-3 Shaking Intensity Map (Modified Mercalli Intensity) for a Magnitude 7.0 Earthquake on the Newport-Inglewood Fault with Site Locations

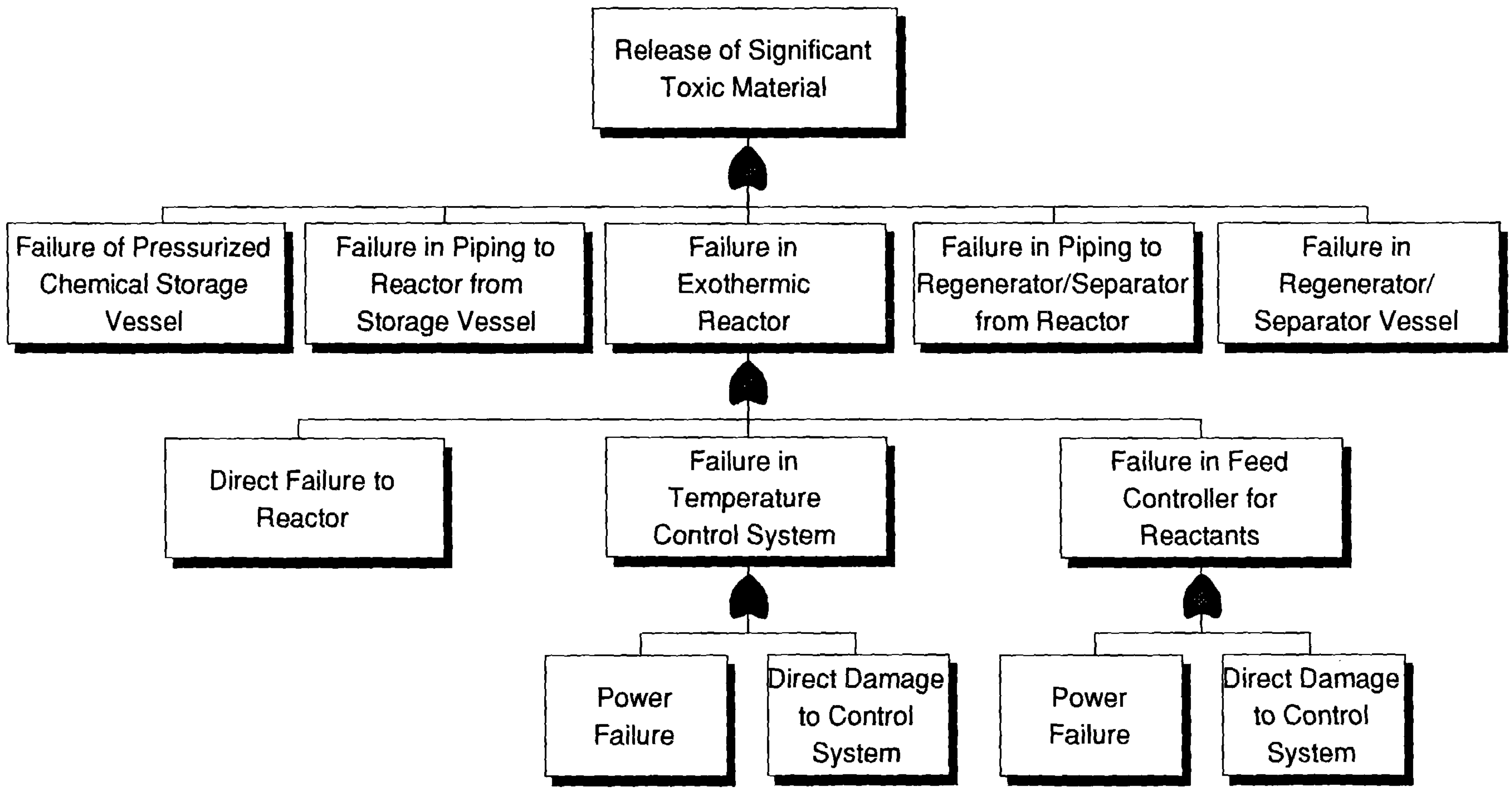


FIGURE 3-4 Fault Tree Model for Toxic Chemical Release for Chemical Processing Facilities

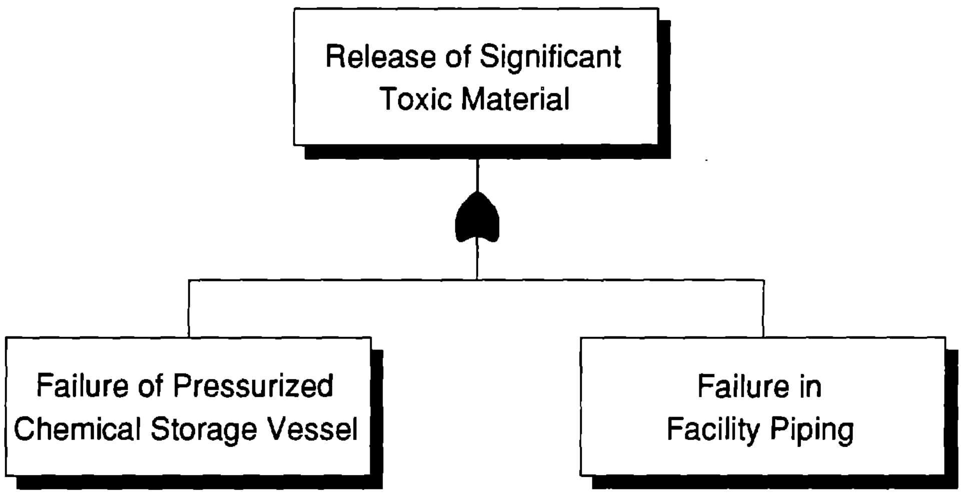


FIGURE 3-5 Fault Tree Model for Toxic Chemical Release for Storage and Transfer Facilities

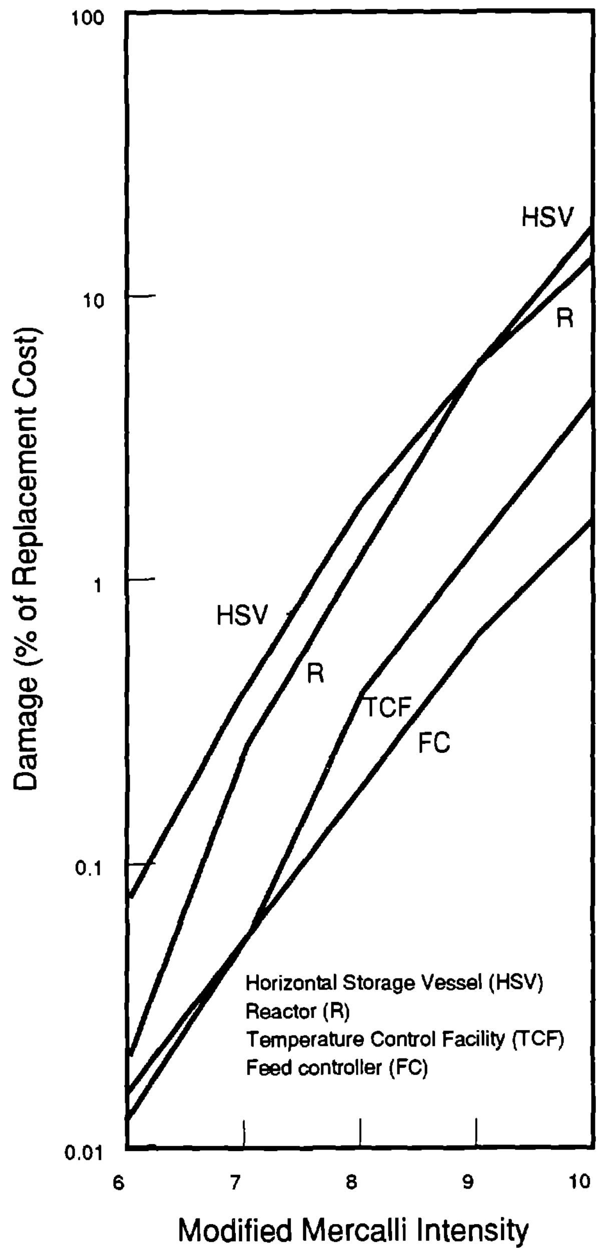


FIGURE 3-6 Earthquake Damage Curves for Chemical Processing Equipment

These components were selected because they are the components that typically contain large quantities of chemicals, which would be released in the event of a failure, and also because they are the components most vulnerable in the event of an earthquake. Because little data are available on the performance of all these components in actual earthquakes, expert judgments on the likelihood of damage and failure were elicited. This approach has been used extensively in seismic vulnerability analyses (see Applied Technology Council, 1985). Appendix A contains the Damage Probability Matrices used in developing the curves in Figure 3-6.

Figure 3-6 indicates that significant levels of damage would be expected for MMIs above IX. Of the four types of components, the most vulnerable are horizontal storage vessels and reactor vessels. The critical failure modes will likely involve failure of the piping that connects to vessels, rather than the failure of the vessels themselves.

Failure probabilities for each of the components that were listed in Figure 3-4 were estimated from the damage curves in Figure 3-6. Critical failure modes that could lead to an airborne release of a large quantity of hazardous material were identified and the probabilities of these failure modes actually occurring in an earthquake were estimated. The probability of the release of toxic material was estimated for each MMI level by integrating the individual probabilities for each component. In estimating the probability of failure for each component, a failure threshold of severe damage (see Tables A.1 through A.4 in Appendix A) was assumed. Figure 3-7 presents the product of that analysis, an integrated probability of failure fragility curve for a chemical processing facility. Significant failure probabilities are expected for ground shaking intensities above MMI IX. As shown in Figure 3-2, one-fourth of the facilities identified in this study are in the MMI IX zone for Scenario 1.

3.5 PLUME MODELING

3.5.1 Plume Dimensions

The size and shape of the area exposed to anhydrous ammonia (NH_3) or chlorine gas (Cl_2) following an earthquake-induced hazardous materials release were estimated through a chemical dispersion analysis.

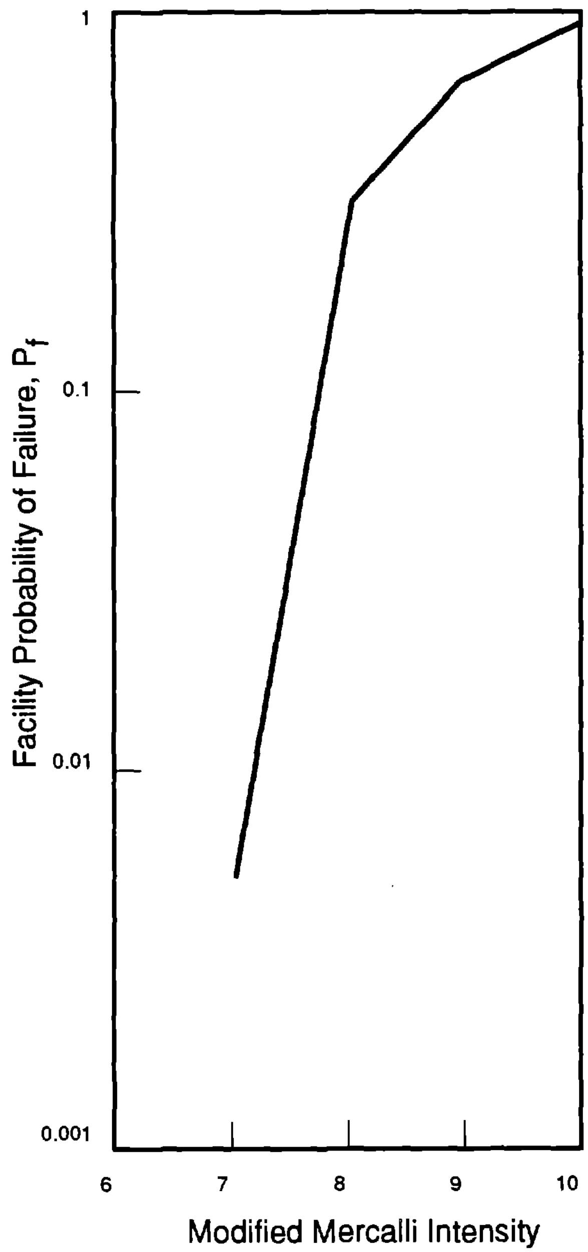


FIGURE 3-7 Earthquake Probability of Failure Curve for Chemical Processing Facilities

The results of this analysis yield a conservative estimate of the zone of vulnerability, or area in which specific health criteria may be exceeded, for a given release and meteorological condition. The complete text of the dispersion analysis report is contained in Appendix B.

Three accidental release modes were simulated in the dispersion analysis:

- an instantaneous release of NH_3 or Cl_2 from a catastrophic storage vessel failure,
- a continuous release of NH_3 or Cl_2 from an uncontrolled liquid line rupture, or
- a finite duration release of NH_3 or Cl_2 from a liquid line rupture where a supplementary control system or check-valve limits the release length to 5 minutes.

The dispersion of the resulting hazardous materials clouds were modeled using the SLAB dispersion model (Ermak, 1989), for various meteorological conditions typical of the Southern California Air Basin, as indicated in Table 3-6.

The range of wind velocities and stabilities considered are within those recommended by the U.S. EPA for screening purposes in urban areas (EPA, 1988). Temperatures and relative humidities used were based on climatological averages for downtown Los Angeles (NOAA, 1981).

In order to determine potential zones of vulnerability, it was necessary to establish health criteria or levels of concern for both Cl_2 and NH_3. The chemical-specific health criteria used were based on the Emergency Response Planning Guidelines (ERPGs) developed by a committee of the American Industrial Hygiene Association (AIHA). The criteria selected for this study was ERPG 3, "the maximum airborne concentration below which it is believed that nearly all individuals could be exposed for up to one hour without experiencing or developing life-threatening health effects." This exposure level is 20 ppm for Chlorine and 1000 ppm for Ammonia.

TABLE 3-6 Meteorological Scenarios Considered

Wind Speed (m/s)	Ambient Temperature (K)	Relative Humidity (%)	Pasquill Stability Class
1.5	297	53	B
1.5	297	53	C
3.0	297	53	C
6.0	297	53	C
1.5	292	63	D
3.0	292	63	D
6.0	292	63	D
1.5	286	74	E
3.0	286	74	E

For each meteorological condition and release mode, a zone of vulnerability or hazard footprint was determined. As a conservative estimate, the composite maximum width and length were taken to represent a generalized footprint for each release mode (i.e., the largest width and length from all meteorological conditions are used to define the exposure area for each release mode). These results are summarized in Table 3-7.

In general, vulnerability zones were larger under slightly stable (Pasquill stability class E) atmospheric conditions, and with slower wind speeds, although downwind extent (plume length) varied significantly with the size of the materials release.

3.5.2 Plume Position

Because it would be virtually impossible to account for all of the variables that influence the position of the hazardous materials plume, such as wind speed and direction, a probabilistic approach was taken for the determination of the likelihood that a given site will be within any hazardous material plume.

Although hazard footprints are sometimes irregular, varying from tear-drop shape to circular, hazardous materials plumes were modeled as ellipses. (The composite maximum plume dimensions, length and width, were converted to ellipse parameters a and b). This general model was deemed appropriate because it was able to capture most of the characteristics of the irregular footprints.

Given an elliptical plume pattern (see Figure 3-8), the plume will exist somewhere within a circle defined by sweeping the ellipse (fixed at the source) through a 360 degree arc. The plume's exact position within this circle is unknown. Only sites within this circle can be exposed to the chemical plume.

TABLE 3-7 Composite Maximum Footprint Length and Width

CASE	AMMONIA		CHLORINE	
	Length (m)	Width (m)	Length (m)	Width (m)
20 T Vessel Catastrophic Failure	928	372	4931	754
1 T Vessel Catastrophic Failure	181	90	980	194
3" Line 5 Min. Release	263	133	3286	760
3" Line Continuous Release	409	434	6016	1646

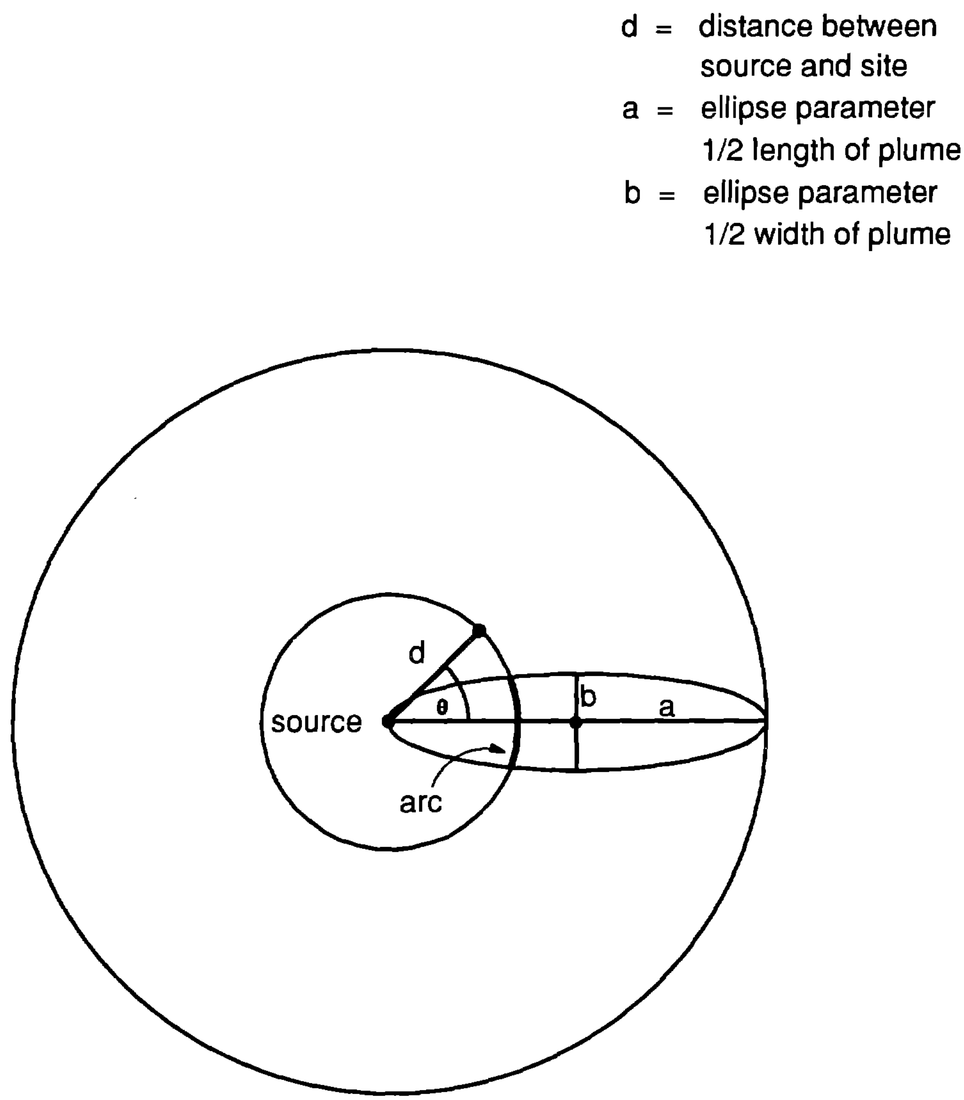


FIGURE 3-8 Elliptical Plume Model

If one draws a circle with the center at the source, and the radius equal to the distance from the source to the site, the site will be within the plume if it sits anywhere along the arc defined by the intersection of this circle and the plume (See Figure 3-8). Since the width of the plume, and hence the length of this arc, varies with the distance from the source, the probability of the site being located within the plume (on the arc) varies with distance from the source. Hence, this probability will depend on three factors; the parameters that define the plume (semi-axes a and b), and the distance, d, from the site to the source of the plume.

The following derivation yields the probability of the site being anywhere along the arc through the plume. The derivation begins by placing the plume such that the site lies somewhere along its edge (See Figure 3-9). If we drop a perpendicular from the site to the plume axis, the distance from the center of the plume to the point of intersection will be denoted as x. (The plume center will be taken as the origin for measuring x; x will be negative if located to the left of the plume center, positive to the right.) x is calculated as follows (a complete derivation of x is presented in Appendix C):

$$x = \frac{-a \pm a*\left(b^4 - b^2 + a^2 d^2\right)^{1/2}}{\left(a^2 - b^2\right)}$$

If Q (Theta), measured in radians, represents the angle between the plume axis and a line connecting the source to the site, then

$$cos\,\theta = (a + x) / d$$

The length of the arc through the plume, S, is calculated from

$$S = 2\theta d$$

and the probability, P, that the site is along this arc may be calculated as the ratio of the arc length to the circumference, C, of the circle with radius d:

$$P = \frac{S}{C} = \frac{2\theta d}{2\pi d} = \frac{\theta}{\pi}$$

d = distance between source and site
a = ellipse parameter 1/2 length of plume
b = ellipse parameter 1/2 width of plume

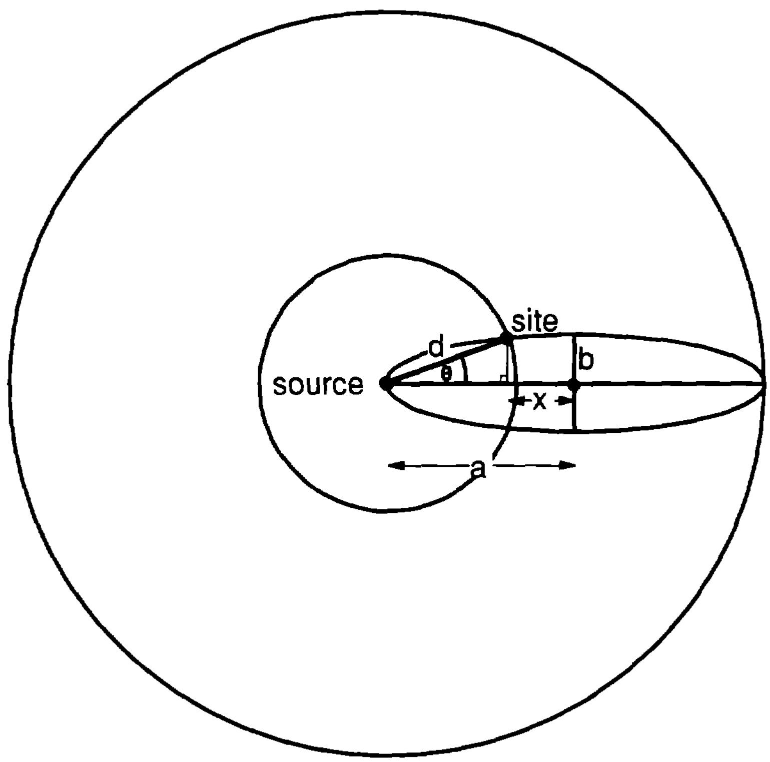


FIGURE 3-9 Model for Determining Site Exposure Probability

3.6 POPULATION DATA

Population data from the 1980 census was available for enumeration districts in the five counties in the Los Angeles basin: Los Angeles, Orange, Riverside, San Bernardino, and Ventura Counties. In these five counties, a total of 10,370 enumeration districts represent 11.5 million people. For each enumeration district, a population count is associated with a representative geographic point location. Table 3-8 provides a breakdown of enumeration districts and population by county.

3.7 PROGRAM "PLUME"

To get a true sense of the overall risk, it was important to somehow aggregate all the data and information collected in first six steps of the risk assessment methodology. The means by which this was accomplished was the development of a computer program. Program "Plume" was designed to take the collected information as input, and output the number of people exposed to hazardous chemicals in a given earthquake event.

3.7.1 Program Input

Hazardous materials source information input for the program includes:

- facility number
- facility location
- calculated strong ground shaking at each facility location for each of the three earthquake scenario events (see Table 3-5)
- chemical usage at each facility; chlorine storage, and/or ammonia storage or ammonia processing (see Table 3-1)
- number of storage vessels at each facility (see Table 3-3):
- standard sizes for ammonia storage vessels are 1-ton, 20-ton, 50-ton, 100-ton, 200-ton
- standard sizes for chlorine storage vessels are 1-ton, 2-ton and 90-ton.

TABLE 3-8 Enumeration District Information By County (1980 Census)

County	Total Population	Number of Enumeration Districts	Maximum District Population	Average District Population
Los Angeles	7,477,503	6,507	8,050	1,149
Orange	1,932,709	1,381	8,828	1,400
Riverside	663,166	989	5,774	671
San Bernardino	895,016	975	12,552	918
Ventura	529,174	518	5,418	1,022

Population data input includes:

- location of each enumeration district
- population associated with each enumeration district
- county within which each enumeration district is located.

Other information built into the program includes:

- ellipse parameters (a and b) for release plumes from various facility components:
  - at ammonia-handling facilities: 1-ton, 20-ton, 50-ton, 100- ton, and 200-ton storage vessels, 1-ton separator vessels, 20-ton reactor vessels, and 3-inch diameter piping
  - at chlorine storage facilities: 1-ton, 2-ton, and 90-ton storage vessels, and 3-inch diameter piping
- slopes and y-intercepts for the logarithmic determination of the probability of component failure in each failure mode, at various Modified Mercalli Intensity levels.

3.7.2 Program Calculations

A probabilistic approach forms the basis of Program "Plume". The general procedure used for calculating population exposure at a given site from a given hazardous materials source, for a given earthquake event is as follows:

1) Based on the ground shaking intensity (MMI) at the hazardous materials source, calculate the probability of failure in each failure mode for each facility component. Also note the resultant plume size if failure were to occur in each component.

2) For each population center, calculate the distance from hazardous materials source to the population site.

3) For each component at the source facility, check whether the population site could be located within the resultant plume if failure occurs.

4) If the distance to the population site is less than the length of the plume, calculate the probability that the plume will form over the site.

5) Aggregate these probabilities for all components at the source to find the total probability of exposure at the population center. Given a facility, source **j** of usage(s) **k** (chlorine storage, and/or ammonia storage and/or ammonia processing) with as many as **n** each of **i** different component types, **n(i)**, each failing in a characteristic failure mode (component types and failure modes will vary for different facility types - chlorine storage, ammonia storage, and ammonia processing facilities), and a population center (site) **m**, then:

$P_1(i,j)$ = probability of failure of component **i**, at source **j**

$P_2(i,j,m)$ = probability that site **m** is within the plume resulting from failure of component **i** at source **j**

$P_3(i,j,m)$ = probability of no exposure to hazardous materials at site **m** from a single component of type **i** at source **j**

$$= 1.0 - [P_1(i, j) * P_2(i, j,m)]$$

For sources with **n(i)** components of type **i**, this equation becomes

$$= \{1.0 - [P_1(i,j) * P_2(i, j,m)]\}^{n(i)}$$

$P_4(j,k,m)$ = probability that failure at source **j**, with facility usage **k**, causes exposure to hazardous materials at site **m**

$$= 1.0 - \Pi_i P_3(i,j,m)$$

$P_5(j,m)$ = the total probability of exposure to hazardous materials at site **m** due to a release at source **j**

$$= 1.0 - \Pi_k[1.0 - P_4(j,k,m)]$$

POPEXP(j,m) = total expected population exposed to hazardous materials at site **m** due to a release at source **j**

= $P_5(j,m)$ * (population at site m)

These values may be aggregated such that total exposure of each site from all sources is produced. For each site, **m**:

SPNEXP(m) = probability of no exposure at site **m** from all sources

= $1.0 - \Pi_j P_5(j,m)$

SPEXP(m) = total probability of exposure at site m from all sources

= 1.0 - SPNEXP(m)

SPOPEXP(m) = total expected population exposed at site m from all hazardous materials sources

= SPEXP(m) * (population at site m)

This procedure is used to calculate the exposure at each site from each source, and from all sources in each earthquake modeled. In our example, the exposure is further aggregated - exposure numbers are summed by county.

SECTION 4
RESULTS

This section introduces the results of the pilot application of the risk assessment methodology. Section 4.1 discusses the assumptions made and the limitations of the results. Section 4.2 presents the program output and associated results.

4.1 ASSUMPTIONS AND LIMITATIONS

This application of the methodology has been made for illustrative purposes. Simplifying assumptions have been made, and the information developed has certain limitations.

1. Only 22 sources within the city limits of Los Angeles have been included. Other sources certainly exist, and the inventory at sources, both identified and not identified, fluctuates over time.

2. Only sources of ammonia and chlorine have been included. Many other chemicals are dangerous, though perhaps not as commonly used. Different chemicals will have different health-safety effects and dispersion patterns. Each jurisdiction should identify those hazardous chemicals prevalent among their industrial sectors.

3. Only strong ground shaking hazards have been considered. Other related hazards that could generate a hazardous materials release include surface faulting, liquefaction, fire and building collapse.

4. Vulnerability models of "generic" facilities are representative of the "average" facility performance. Individual facility performance will vary depending on such factors as general facility conditions, quality of maintenance, age and quality of manufactured facility components, and site soil characteristics.

approach used for this project. Actual atmospheric conditions will certainly affect plume dispersion.

6. Population data were available on a point basis - a geographic point was assigned the population count of the surrounding area, but the actual dimensions of that area and density distribution within that area are unknown. Exposure was calculated by assuming that the population was concentrated at the point given.

7. Failures, as modeled, result from mechanical causes only. Failures caused by human error are not considered.

4.2 POPULATION EXPOSURE

Output from the computer analysis consisted of the number of people exposed to hazardous materials in each county, as a result of each earthquake modeled. Table 4-1 presents these population exposure numbers. In addition, for each scenario, the population centers with the largest exposure (approximately 20 enumeration districts) to each event have been identified and mapped.

Scenario 1: Newport-Inglewood Event

As a result of a M 7.0 earthquake on the Newport-Inglewood fault, 133,000 people would be exposed to hazardous materials released from the 22 subject sources. Of the more than 3000 enumeration districts affected by hazardous materials, only 1% have more than 500 people affected, 90% have fewer than 100 people affected, and 40% have fewer than 10 people affected. The maximum number of people exposed at any one site is approximately 1400. The 20 sites with the greatest number of people affected are plotted in Figure 4-1. Each site has more than 500 people affected. The people exposed at these sites comprise 12% of the total number of people subjected to hazardous release as a result of this earthquake.

TABLE 4-1 Population Exposure To Hazardous Materials By County

	County	Population Exposed	Total Population	Percent Exposed
Scenario 1: M 7.0 Newport/Inglewood Event	Los Angeles	132,509	7,477,503	1.800%
	Orange	491	1,932,709	0.030%
	Riverside	0	663,166	n/a
	San Bernardino	0	895,016	n/a
	Ventura	0	529,174	n/a
Scenario 2: M 8.3 San Andreas Event	Los Angeles	20,546	7,477,503	0.300%
	Orange	217	1,932,709	0.010%
	Riverside	0	663,166	n/a
	San Bernardino	0	895,016	n/a
	Ventura	0	529,174	n/a
Scenario 3: M 5.9 Whittier/Narrows Earthquake	Los Angeles	6,503	7,477,503	0.090%
	Orange	157	1,932,709	0.008%
	Riverside	0	663,166	n/a
	San Bernardino	0	895,016	n/a
	Ventura	0	529,174	n/a

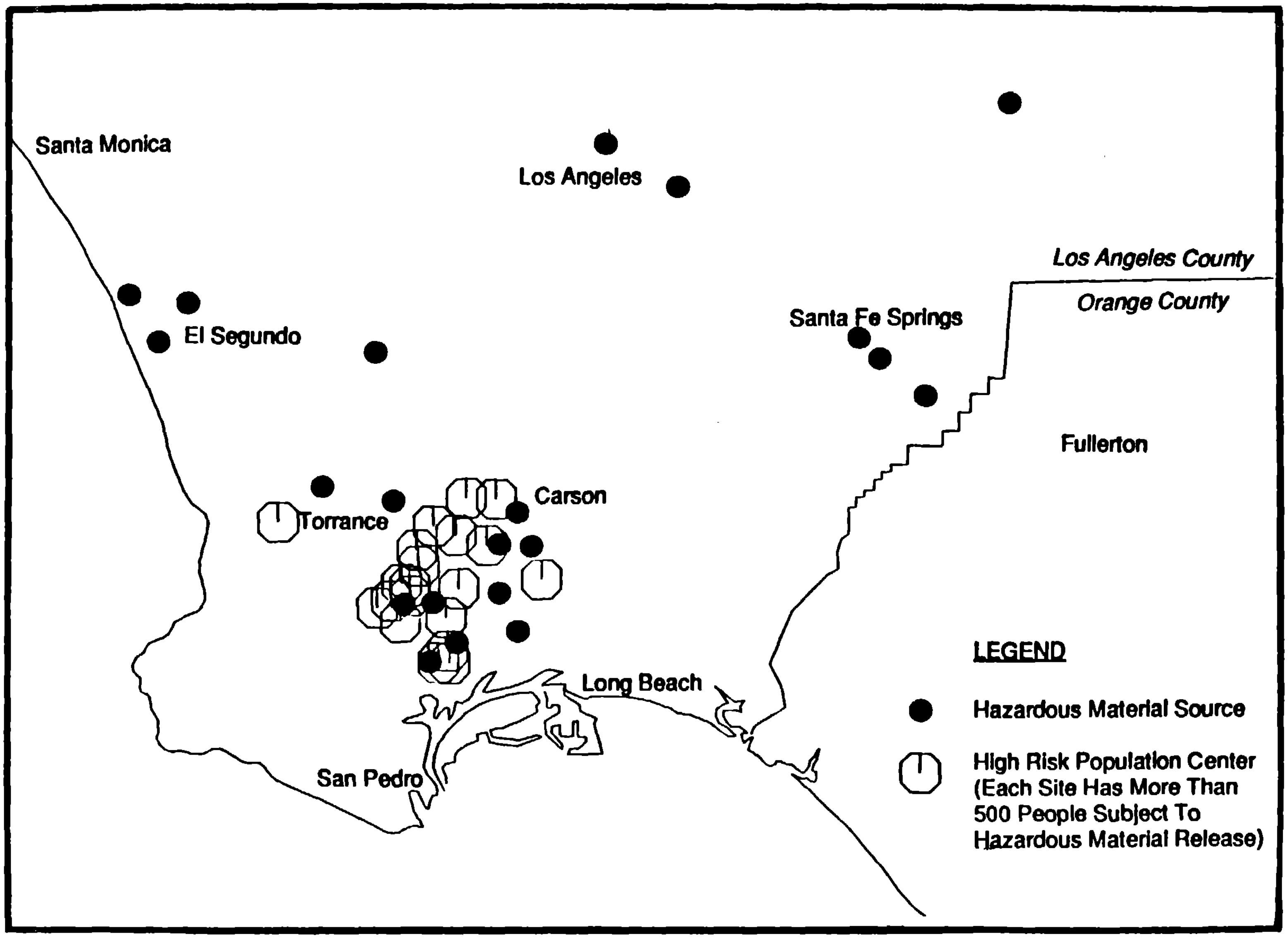


FIGURE 4-1 Population Centers with High Risk Potential from Hazardous Materials Release During a Magnitude 7.0 Earthquake on the Newport-Inglewood Fault

Scenario 2: San Andreas Event

From the listed sources, 20,763 people would suffer exposure to hazardous materials following a M 8.3 event on the San Andreas fault. The stricken population would be distributed among 2860 enumeration districts. Of these sites, 99.9% would have fewer than 100 people affected, and 81.5% would have fewer than 10 people affected. The most affected at one site would be only 211 people. All sites with more than 70 people (22 sites) affected by an earthquake-generated release are plotted in Figure 4-2 (9.5% of the affected population).

Scenario 3: Whittier-Narrows Event

In the smallest of the three events, 6660 people would be stricken by hazardous materials release. 1800 enumeration districts would be affected; 99.7% of these would have fewer than 25 people affected, and 75% would have fewer than 5 people affected. The largest number of people affected by the release at any one site is 57 people. 21 sites with 19 or more people stricken are plotted in Figure 4-3. These sites represent 7.8% of the total population affected as a result of this earthquake.

4.3 CONCLUSIONS

Hazardous materials release threats exist wherever hazardous materials are stored. Earthquake-induced releases are a very real possibility. Based on the 22 sources identified for this study, the most serious releases would occur not in the largest postulated earthquake, but in the earthquake causing the strongest ground shaking at the hazardous materials sources. This earthquake, the Magnitude 7.0 Newport-Inglewood event, would cause ground shaking of at least intensity 8.0 at all but two of the studied sources. In contrast, the M 8.3 San Andreas event causes MMI 8.0 or more at only 4 sites.

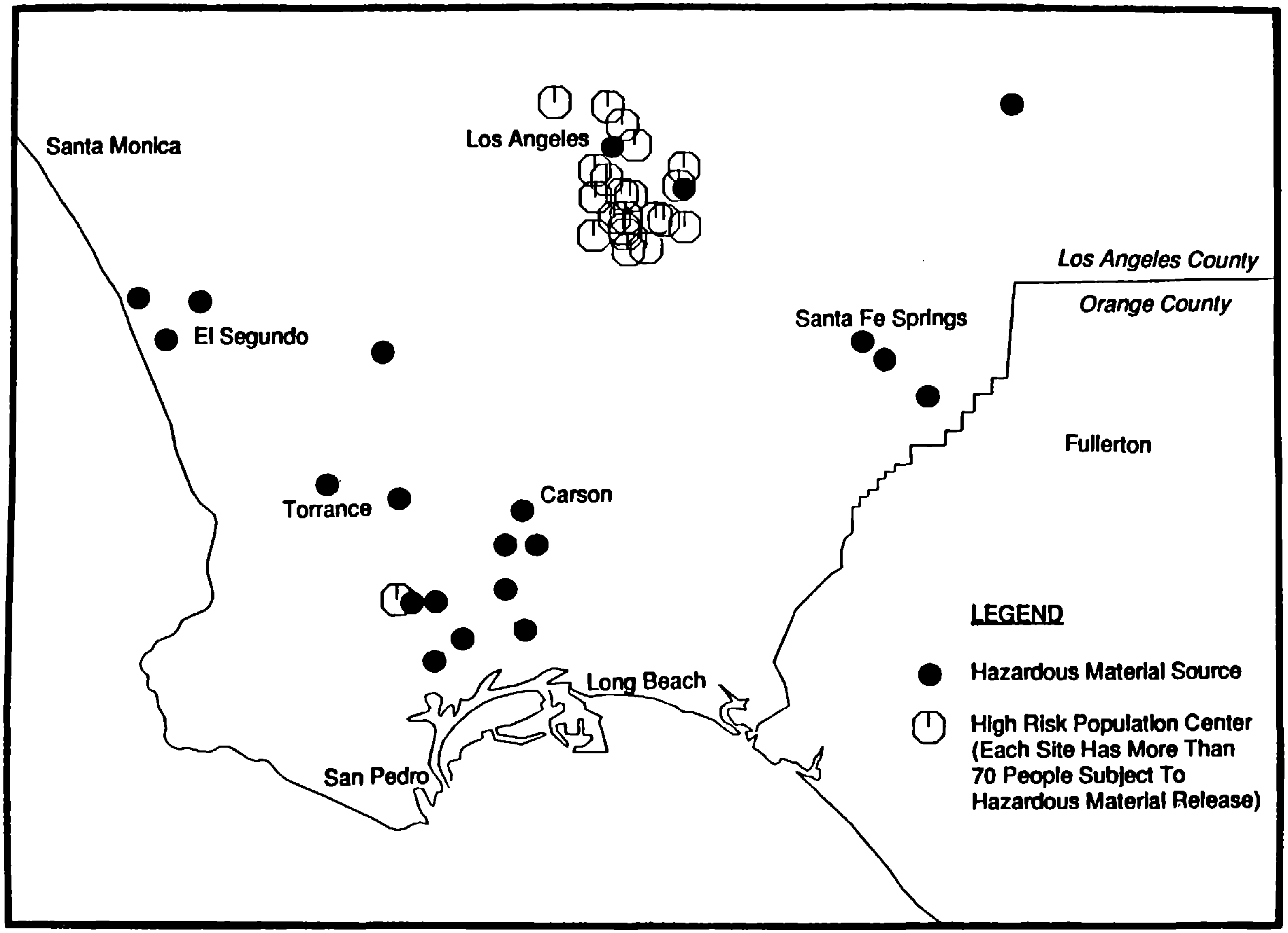


FIGURE 4-2 Population Centers with High Risk Potential from Hazardous Materials Release During a Magnitude 8.3 Earthquake on the San Andreas Fault

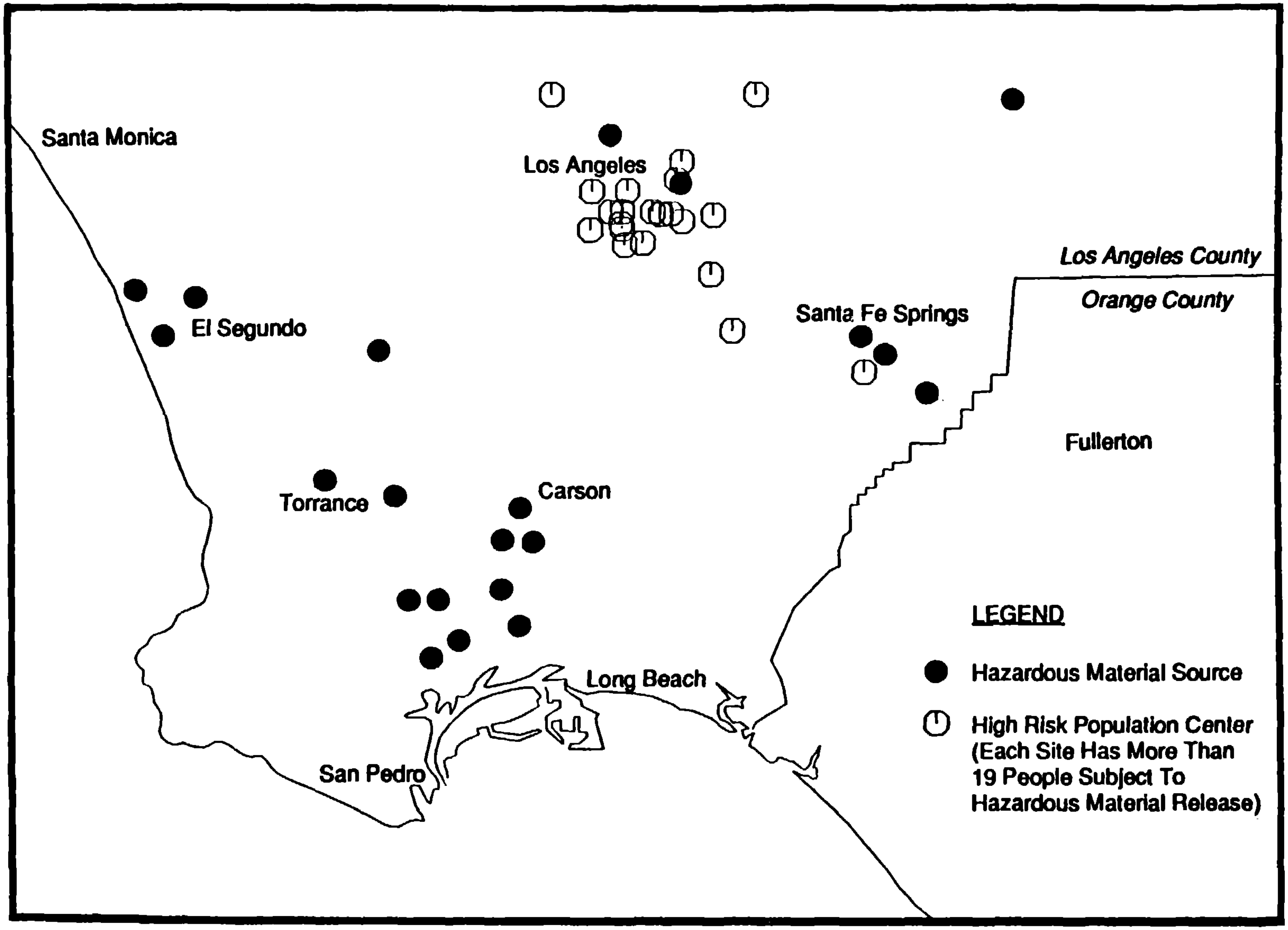


FIGURE 4-3 Population Centers with High Risk Potential from Hazardous Materials Release During a Magnitude 5.9 Whittier- Narrows Earthquake

One of the most serious hazardous materials threats is presented by the storage of large quantities of chlorine in areas expected to suffer strong ground shaking. Chlorine is stored in vessels as large as 90-ton rail cars, whose failure plumes can extend over 7 miles. The identification of chlorine as the major threat enables users to address this risk by concentrating efforts in improving performance of existing vessels, developing smaller safer vessels, or perhaps relocating storage facilities.

The failure models developed for use in this study are based on conservative assumptions regarding failure thresholds. Even with these conservative assumptions, the largest total expected population affected in any of the three scenarios is 133,000 or less than 2 percent of the total population of Los Angeles County. These estimates, however, do not include risks that may result from failure of chemical facilities in counties other than Los Angeles, or from chemicals other than ammonia or chlorine. A more complete analysis of risk must include these other facilities and chemicals.

4.4 FUTURE DIRECTIONS

Based on the results of the pilot application of the methodology, the following possible future directions have been identified:

1. Review recent earthquake performance (e.g., Northridge and Kobe) for application of lessons learned to the methodology. Models should be evaluated in light of earthquake experience data that was not available at the time of model development.

2. A significant amount of hazardous materials inventory data is collected by local jurisdictions, typically by the fire department. These databases should be examined, and guidelines for conversion or translation into an appropriate format developed.

3. Extension of facility models to a more diverse range of facility types. Currently, one model has been developed to represent "chemical processing facilities". Additional data on actual facility make-up needs to be collected to facilitate the development of a range of processing facility models.

4. Extend the assessment to additional hazardous chemicals which produce airborne clouds. The pilot application incorporated only two chemicals - ammonia and chlorine. For wider application, these models should be extended to additional chemicals or families of chemicals.

5. Fragility models which consider ground failure hazards such as settlement or liquefaction should be explored.

6. For emergency management applications, the population databases should be stored in such a way that database attributes are accessible. That is, information regarding population age or language requirements would be useful information for the planning or execution of potential evacuations.

SECTION 5

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APPENDIX A

DAMAGE PROBABILITY MATRICES FOR TYPICAL CHEMICAL STORAGE AND PROCESSING EQUIPMENT

TABLE A-1 Damage Probability Matrix for Horizontal Storage Vessels

DAMAGE STATE	DAMAGE RATIO (%)		MODIFIED MERCALLI INTENSITY (MMI)				
	RANGE	CENTRAL VALUE	VI	VII	VIII	IX	X
NONE	0 - 0.05	0	0.91	0.80	0.55	0.25	0.1
LIGHT	0.05 - 1.25	0.3	0.08	0.15	0.32	0.40	0.2
MODERATE	1.25 - 20	5	0.01	0.045	0.125	0.25	0.36
SEVERE	20 - 65	30	0	0.005	0.02	0.09	0.28
TOTAL	65 - 100	100	0	0	0.005	0.01	0.06
		Σ	1.0	1.0	1.0	1.0	1.0

Damage State Descriptions:

None - None or insignificant structural damage.

Light - Slight Movement of tank from support.

Moderate - Failure of some connected piping; repairable damage to the tank support system; moderate likelihood of release of tank contents.

Severe - Failure of most piping connections; tank support system completely failed; almost certain release of tank contents.

Total - Failure of all piping connections; tank support system completely failed; tank itself damaged (possible buckling); contents of tank released.

TABLE A-2 Damage Probability Matrix for Reactor Vessels

DAMAGE STATE	DAMAGE RATIO (%)		MODIFIED MERCALLI INTENSITY (MMI)				
	RANGE	CENTRAL VALUE	VI	VII	VIII	IX	X
NONE	0 - 0.05	0	0.93	0.81	0.5	0.25	0.1
LIGHT	0.05 - 1.25	0.3	0.07	0.15	0.35	0.35	0.2
MODERATE	1.25 - 20	5	0	0.04	0.14	0.3	0.44
SEVERE	20 - 65	30	0	0	0.01	0.09	0.21
TOTAL	65 - 100	100	0	0	0	0.01	0.05
		Σ	1.0	1.0	1.0	1.0	1.0

Damage State Descriptions:

None - None or insignificant structural damage.

Light - Minor buckling of some cross braces in support structure.

Moderate - Failure of some connected piping; repairable damage to the reactor support system; moderate likelihood of release of reactor contents.

Severe - Failure of most piping connections; reactor support system almost completely failed; almost certain release of reactor contents.

Total - Failure of all piping connections; reactor support system completely failed; reactor itself severely damaged (possible buckling and shearing); contents of reactor released.

TABLE A-3 Damage Probability Matrix for Feed Controller Units (Pump)

DAMAGE STATE	DAMAGE RATIO (%)		MODIFIED MERCALLI INTENSITY (MMI)				
	RANGE	CENTRAL VALUE	VI	VII	VIII	IX	X
NONE	0 - 0.05	0	0.96	0.9	0.75	0.6	0.35
LIGHT	0.05 - 1.25	0.3	0.04	0.095	0.23	0.3	0.4
MODERATE	1.25 - 20	5	0	0.005	0.02	0.10	0.245
SEVERE	20 - 65	30	0	0	0	0	0.005
TOTAL	65 - 100	100	0	0	0	0	0
		Σ	1.0	1.0	1.0	1.0	1.0

Damage State Descriptions:

None - None or insignificant structural damage.

Light - Possible movement of equipment; no damage to piping.

Moderate - Failure of some connected piping; equipment displaced with some internal damage; moderate chance of release of reactants.

Severe - Failure of most piping connections; equipment damaged; almost certain release of reactants.

Total - Failure of all piping connections; equipment damaged; reactants released.

TABLE A-4 Damage Probability Matrix for Temperature Control Facilities

DAMAGE STATE	DAMAGE RATIO (%)		MODIFIED MERCALLI INTENSITY (MMI)				
	RANGE	CENTRAL VALUE	VI	VII	VIII	IX	X
NONE	0 - 0.05	0	0.95	0.9	0.7	0.45	0.15
LIGHT	0.05 - 1.25	0.3	0.05	0.095	0.25	0.35	0.35
MODERATE	1.25 - 20	5	0	0.005	0.048	0.195	0.45
SEVERE	20 - 65	30	0	0	0.002	0.005	0.048
TOTAL	65 - 100	100	0	0	0	0	0.002
		Σ	1.0	1.0	1.0	1.0	1.0

Damage State Descriptions:

None - None or insignificant structural damage.

Light - No structural damage to building; light damage to nonstructural systems in building; no damage to mechanical or electrical equipment for temperature control systems.

Moderate - Minor structural damage to building; significant damage to nonstructural systems; some interruptable damage to mechanical and electrical equipment.

Severe - Major structural damage; structure unuseable because of extensive nonstructural damage; extensive damage to mechanical and electrical equipment; temperature control system completely down.

Total - Possible collapse of building; all internal systems severely damaged or down.

APPENDIX B

DISPERSION MODELING ANALYSIS HYPOTHETICAL CHLORINE AND AMMONIA RELEASES

by

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DISPERSION MODELING ANALYSIS
HYPOTHETICAL CHLORINE AND
AMMONIA REALEASES

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DISPERSION MODELING ANALYSIS
HYPOTHETICAL CHLORINE AND AMMONIA RELEASES

1.0 Introduction

A dispersion modeling analysis was conducted to determine the consequences of hypothetical releases of anhydrous ammonia (NH_3) and chlorine (Cl_2) that might be associated with a major earthquake in the South Coast Air Basin (SCAB). The consequence analysis was one component of an overall risk assessment methodology for estimating the potential risk and repercussions of post-earthquake releases of acutely hazardous materials. Dispersion modeling tools were applied to simulate the behavior of NH_3 and Cl_2 discharges over a wide range of potential release conditions. The objective of the dispersion modeling analysis was to provide a conservative estimate of the zone of vulnerability for a given accidental release and meteorological condition. The zone of vulnerability was determined as the maximum width and distance downwind that a specified level of concern (LOC) for NH_3 or Cl_2 may potentially be exceeded. The zone of vulnerability, number of people potentially affected, and probability of each hazardous release can be combined with the spatial distribution of individual facilities to provide the types of information that can aid emergency response planning. The probability of the failures occurring and the population likely affected were topics of other components of the overall risk assessment methodology.

The dispersion modeling methodologies that were applied depended in part on the mode and duration of the release, and hence the nature of the postulated accident. The two types of hypothetical accidents simulated were:

- a two-phase (vapor plus aerosol) jet discharged from a break in the liquid supply line to a storage vessel; and

- a two-phase aerosol cloud from a catastrophic rupture of the storage vessel.

These two types of failures were selected: based on an inventory of facilities using or storing NH_3 and Cl_2 in the SCAB, after consideration of seismic vulnerability, and based on experience gained through the preparation of Risk Management and Prevention Programs (RMPP) for individual facilities . Dispersion modeling simulations were conducted for a range of typical storage vessel sizes and for supply lines of different diameters. For the vessel failure case, it was assumed that the entire contents were instantaneously released. Both continuous and 5 minute discharges were simulated in the potential event of a line rupture.

The following sections describe the techniques applied for the estimation of zones of vulnerability for each potential release. Section 2.0 describes the dispersion modeling methodologies that were applied including the derivation of source terms and initial conditions, applicable dispersion models, and post-processing of model results. The health criteria used to assess the significance of predicted concentrations of NH_3 and Cl_2 are discussed in Section 3.0. The results of the dispersion modeling analysis are presented in Section 4.0.

2.0 Dispersion Modeling Methodology

Observations from field experiments (Wheatley, 1987) and experience from historical accidents (Kaiser and Walker, 1978), suggest that the majority of NH_3 releases from pressurized storage vessels produce either a two-phase jet or an aerosol cloud. Although less evidence has been obtained for Cl_2, a liquid phase release under pressure would also likely produce a significant aerosol fraction (Hanna and Drivas, 1987; AICHE, 1989). The presence of the aerosol and subsequent evaporation produce a cold, denser-than-air, plume. The simulation of dense gas clouds and two-phase jets, specification of initial conditions, estimation of discharge rates, selection of meteorological scenarios, and derivation of hazard footprints are discussed below.

2.1 Two-Phase Dispersion Models

The discharge of liquid phase NH_3 or Cl_2 from a storage vessel at elevated pressure and near ambient temperature would likely result in the formation of a denser-than-air aerosol. The pressurized liquid would flash to ambient pressure and some or all of the remaining liquid may atomize and become entrained in the plume. Close to the point of release a high velocity two-phase jet would be formed, followed further downwind by a plume dominated by buoyancy-induced spreading. Field experiments examining the release of NH_3 have shown that estimates of downwind concentrations were under-estimated when conventional dispersion modeling techniques were employed (Spicer, Havens, and Key, 1987). This was primarily attributed to an over-prediction of the vertical dispersion by the Gaussian models which do not consider the stable stratification and reduced vertical mixing of the dense gas cloud. In order to simulate such aerosol releases and the dispersion of denser-than-air clouds, the consequence analysis utilized a modeling system based on the SLAB dispersion model (Ermak, 1989).

This SLAB model was developed by Lawrence Livermore National Laboratory and is available in the public domain. The model has undergone extensive peer review since it's initial formulation (eg. Blewitt, et al. 1987; Ermak, et al. 1982, and Petersen, 1989) and has also been evaluated using a variety of field data. The initial portions of a release can be simulated by a steady state jet followed by a transient puff or continuous plume. The SLAB model incorporates the modules essential to simulate a denser-than-air aerosol releases, namely:

- turbulent growth due to a high momentum horizontal jet,
- buoyancy-induced gravity spreading which produces a wider and lower cloud,
- reduced turbulent mixing due to stable density stratification;
- thermodynamic effects due to aerosol formation, evaporation, and heating of the cloud by the ground, and
- physical effects due to normal atmospheric diffusion and advection.

The SLAB model numerically solves the coupled mass, energy, and momentum conservation equations to yield instantaneous ensemble averaged cloud or plume properties. These predictions are then post-processed within the code to predict time-averaged volume concentrations. The averaging routines take into consideration the effects of plume meander which varies with concentration averaging time, the possible finite duration of the release, and the length of the averaging time.

The SLAB model was applied in three basic modes during the present consequence analysis:

- an instantaneous release of a two-phase aerosol cloud due to a catastrophic NH_3 or Cl_2 storage vessel rupture,
- a continuous release of NH_3 or Cl_2 involving a high momentum two-phase horizontal jet due to an uncontrolled liquid line rupture, and
- a finite duration release due to a liquid line rupture, where a supplementary control system or check-valve limits the release to 5 minutes.

It was conservatively assumed that two-phase NH_3 or Cl_2 jets would be oriented horizontally downwind and would not be impeded by obstructions surrounding the release. All of the liquid phase was assumed to atomize and become entrained in the plume. Further, instantaneous releases were modeled assuming no initial dilution and no removal of droplets at the surface were considered for any of the releases.

2.2 Source Terms and Initial Conditions

Application of the SLAB model required estimates for mass emission rates and discharge conditions for each release simulated. For the catastrophic vessel failure, the entire contents were instantaneously released from an assumed initial cylindrical volume where the radius was twice the height. No initial dilution or entrainment of air was assumed. The initial density and liquid mass fractions of the instantaneous releases were as specified for the line rupture discussed below.

The initial density, velocities, liquid mass fraction, and mass emission rates for the two-phase jets resulting from a potential liquid line rupture were calculated using the suggestions of Fauske and Epstein (1987). It was assumed that the liquid Cl_2 and NH_3 were stored at saturation vapor pressure and near ambient temperature. The discharge rates for two-phase choked flow at equilibrium were estimated from:

$$Q = FA \frac{h_{vap}}{\frac{1}{\rho_v} - \frac{1}{\rho_l}} (T_o c_{pl})^{-1/2} \qquad \text{(eq. 1)}$$

where:

- Q = the total mass discharge rate (kg/s),
- A = the cross-sectional area of the pipe outlet (m^2),
- F = a factor to account for frictional losses for long pipes,
- c_{pl} = the specific heat of the liquid (J/(kg-°K)),
- ρ_v, ρ_l = the respective gas and liquid densities (kg/m^3),
- T_o = the storage temperature (°K), and
- h_{vap} = the latent heat of vaporization (J/kg).

After Fauske and Epstein (1987), based on the length of the pipe (L) and the pipe diameter (D), the factor to account for frictional losses was determined from the following table.

Variation of Factor F with Ratio L/D	
L/D	F
0	1.00
50	0.85
100	0.75
200	0.65
400	0.55

For the purposes of the present analysis, the break was assumed to occur at 20 feet from the storage vessel. Since, the variation in the factor (F) is relatively small when compared to other uncertainties in the analysis, this adhoc assumption is not expected to significantly affect the outcome of the analysis.

In addition to the mass emission rate, the SLAB model must also be initialized with estimates of the exit velocity, amount of aerosol, and mixture density. The specification of these quantities is important in determining the initial enthalpy of the mixture and hence the energy balance for calculations downstream of the point of release. For an all-liquid discharge, the mass fraction of the vapor component (α) was estimated from:

$$\alpha = c_{pl} \frac{T_o - T_{bp}}{h_{vap}} \qquad \text{(eq. 2)}$$

where:

α = initial mass fraction of NH_3 or Cl_2 vapor, and

T_{bp}= the boiling point temperature (°K).

For the pressurized storage vessels considered in the offsite consequence analysis application of Equation (2) resulted in an initial vapor mass fraction of 0.2 for storage temperatures of 292°K (mean annual temperature) for both Cl_2 and NH_3.

The initial jet mixture density was determined from:

$$\rho_{mix} = \frac{1}{\frac{\alpha}{\rho_v} - \frac{1-\alpha}{\rho_l}} \qquad \text{(eq. 3)}$$

where ρ_{mix} is the mixture density (kg/m^3). For the initial mass fractions above and assuming an initial mixture temperature near T_{bp}, the mixture density ranged from 4.2 to 17.9 kg/m^3, for NH_3 and Cl_2 respectively.

Exit velocities for the two-phase jet releases were also calculated using the methods outlined by Fauske and Epstein (1987) and the mass discharge rates obtained through Equation (1). Using the principle of conservation of momentum flux, the jet velocity at the end of the zone of depressurization was given by:

$$u_j = u_l + \frac{P(T_o) - P_a}{\rho_l u_l} \qquad \text{(eq. 4)}$$

where:

u_j = two-phase jet velocity (m/s),

u_l = initial liquid discharge velocity (m/s) determined from the mass discharge rate and the area of the release,

$P(T_o)$= tank pressure (Pa), and

P_a = atmospheric pressure (Pa).

Initial tank pressures were assumed to be determined by the saturation vapor pressure of NH_3 and Cl_2 at 292 °K.

2.3 Post-Processing

This section describes the manner in which the SLAB model output files were post-processed to produce the tabular and graphical presentations used in the consequence analysis. For each meteorological condition, release scenario, NH_3 and Cl_2 level of concern, and averaging time of concern a hazard footprint was determined. In the context of the present discussion the hazard footprint refers to the spatial extent where NH_3 or Cl_2 concentrations exceed a given health criteria. In addition to providing an indication of the shape and extent of the zone of vulnerability for a given release, these plots could also overlaid on demographical data to determine the degree of exposure and number of people potentially affected.

The SLAB model does not employ a fixed receptor grid, but provides plume or puff parameters and concentrations at downwind distances which are dependent on the numerical technique used to solve the model equations. Concentrations along a fixed receptor grid downwind and the downwind extent of the hazard footprints were determined through logarithmic interpolation of the model output files. This procedure assumes that the concentration follows a power law with downwind distance which was found to be a good approximation over short distance intervals based on plots of the model output data.

Crosswind concentrations were determined analytically using the model's crosswind profile function and the shape parameters which were included in the output file. Given the plume centerline concentration (c_{max}), the crosswind concentration was derived from:

$$c(y) = c_{max} \frac{erf\left(\frac{y+b}{\sqrt{2}\,\beta}\right) - erf\left(\frac{y-b}{\sqrt{2}\,\beta}\right)}{2erf\left(\frac{b}{\sqrt{2}\,\beta}\right)} \qquad \text{(eq. 5)}$$

where:

c(y)= concentration (ppm) at crosswind distance y (m),

erf= error function, and

b,ß= half-width parameters (m). The half width parameters are such that the crosswind profile is uniform when ß = 0, and approaches a Gaussian shape when ß >> b.

Crosswind hazard footprints were determined implicitly from Equation (5) by solving for the crosswind distance (y) that corresponds to a given level of concern. This calculation was performed at each downwind distance until a maximum crosswind width of a specified level was determined.

2.4 Selection of Meteorological Scenarios

The SLAB model was applied for a variety of meteorological conditions typical of the SCAB. For the purposes of dispersion modeling the hypothetical meteorological scenarios considered are indicated in the following table.

Meteorological Scenarios Considered			
Wind Speed (m/s)	Ambient Temp. (K)	Relative Humid. (%)	Pasquill Stab. Class
1.5	297	53	B
1.5	297	53	C
3.0	297	53	C
6.0	297	53	C
1.5	292	63	D
3.0	292	63	D
6.0	292	63	D
1.5	286	74	E
3.0	286	74	E

The range of wind velocities and atmospheric stratifications considered are within those recommended by the U. S. EPA for screening purposes in urban areas (EPA, 1988). Actual stability class, wind speed combinations were selected from joint frequency distributions prepared for downtown Los Angeles based on joint occurrences over 5 percent. Temperature and relative humidities used in the two-phase modeling were based on climatological averages from downtown Los Angeles (NOAA, 1981). Finally as suggested by Petersen (1989), a surface roughness of 0.5 m was used in the SLAB simulations as appropriate for large industrial complexes.

3.0 Levels of Concern

In order to determine potential zones of vulnerability, it was necessary to establish health criteria or levels of concern for both Cl_2 and NH_3. The chemical-specific health criteria used in the consequence analysis were based on the Emergency Response Planning Guidelines (ERPGs) developed by a committee of the American Industrial Hygiene Association (AIHA). A technique was also applied to adjust these health criteria to variable exposure periods to provide a more robust dose-response relationship.

As specified by the AIHA, ERPGs are based on three concentration levels:

ERPG 1 - Maximum airborne concentration below which it is believed that nearly all individuals could be exposed up to one hour without experiencing more than mild transient adverse health effects or without perceiving a clearly defined objectionable odor;

ERPG 2 - The maximum airborne concentration below which it is believed that nearly all individuals could be exposed for up to one hour without experiencing or developing irreversible or other serious health effects or symptoms which could impair an individual's ability to take protective action; and

ERPG 3 - The maximum airborne concentration below which it is believed that nearly all individuals could be exposed for up to one hour without experiencing or developing life-threatening health effects.

Above ERPG 2, symptoms which might be expected to impair an individual's ability to take protective action would include effects such as severe eye irritation, respiratory irritation or pronounced muscular weakness. For the purposes of the present analysis it was determined that the more useful levels were ERPG 2 and ERPG 3.

The ERPG levels are generally considered to be applicable for 30 to 60 minute exposure periods. The dispersion modeling analysis involved the simulation of transient and instantaneous discharges which would result in shorter exposures for receptors sufficiently close to the point of release. When downwind concentrations from such short-term events are averaged over 30 minutes to 1-hour to compare with the ERPGs, the zone of vulnerability may be understated. In order to derive levels of concern based on the ERPG levels, short-term health criteria were determined using the procedures for evaluating dose-response at variable durations of exposure, as developed by Withers and Lees (1985).

Following Withers and Lees, for both NH_3 and Cl_2 an equivalent toxic load can be described for different periods of exposure by the following relationship:

$$L^{*} = C_{avg}^{2} T \qquad \text{(eq. 6)}$$

where:

L^{*} = the toxic load (ppm^2-min),

C_{avg} = the time averaged concentration (ppm), and

T - the exposure period (min).

It was assumed that levels of vulnerability for different averaging periods can be obtained based on equivalent toxic loads. For ERPG levels based on a 30 minute exposure period, equivalent health criteria for 5 minutes were as follows:

Exposure Period	NH_3(ppm)		Cl_2(ppm)	
	ERPG-2	ERPG-3	ERPG-2	ERPG-3
30-60 min	200	1000	3	20
5 min	490	2500	7.5	50

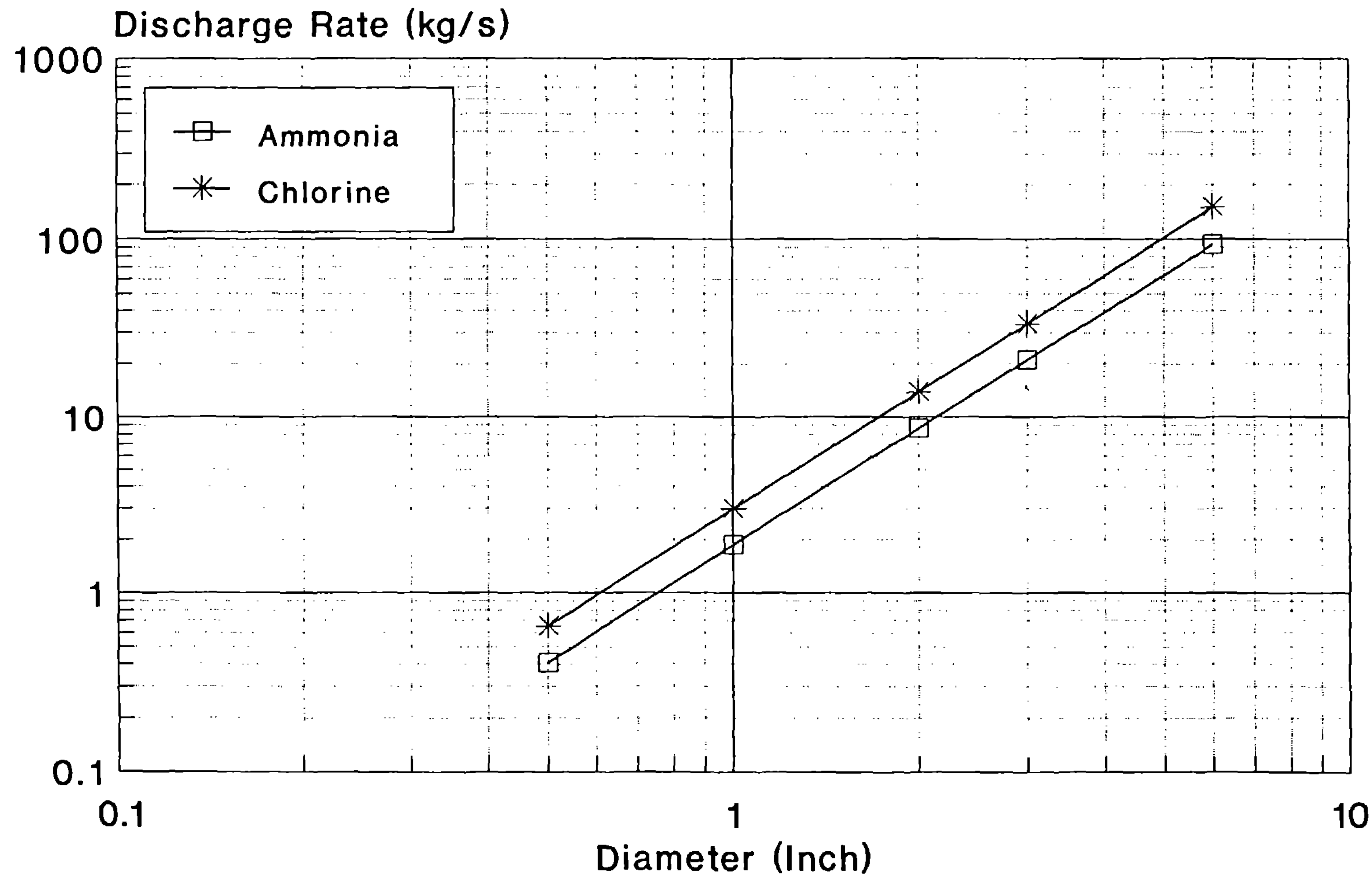
Vulnerability zones for the continuous release line rupture scenario were assessed using the unmodified ERPG levels. For the instantaneous tank failure and 5 minute line rupture cases, levels of concern were based on the equivalent 5 minute criteria. Test cases using shorter averaging periods did not produce significantly different results for the majority of the receptors affected.

4.0 Results

The dispersion modeling methodologies described in the previous sections were applied to simulate hypothetical releases of Cl_2 and NH_3, and to determine the spatial extent where health criteria for these acutely hazardous materials would be exceeded. Postulated complete failures of storage vessels were simulated over a range of capacities from 1 T to 90 T, for Cl_2, and from 1 T to 200 T, for NH_3. Ruptures or complete breaks in liquid supply or loading lines were simulated for diameters of 0.5 to 3 inches and 0.5 to 6 inches for Cl_2 and NH_3, respectively. For the line rupture cases, both continuous and 5 minute finite duration discharges were modeled. Levels of concern were based the AIHA's ERPG 2 & 3 values for 30 minutes to 1-hour exposures and adjusted to examine acute effects for 5 minute exposures. Criteria based on 5 minutes were used to address the more transient effects of exposure to the instantaneous and finite duration releases.

The calculated discharge rates for the line rupture case are displayed in Figure 4-1 as function of orifice or pipe diameter. For an equivalent diameter, the mass emission rates of Cl_2 were predicted to be slightly higher than NH_3. Emission rates increased at a rate somewhat higher than the square of diameter due to the reduction of frictional losses with large diameters.

Figure 4-1. Line Rupture Discharge Rates for Two-Phase Flow



Press = Saturated Vapor Press
Temp = 292 K
Break 20 ft from Tank

Hazard footprints for the entire range of accidents simulated by the SLAB model are presented in Attachment 1. Footprints are delineated by meteorological scenario, release condition, Cl_2 or NH_3, and levels of concern. For the later, 30 minute averaging times were used for the continuous discharges, and a 5 minute averaging time was used to address the 5 minute and instantaneous releases. Note, that in addition to the ERPG 2 & 3 levels, the estimated zone of vulnerability corresponding to the IDLH (Immediately Dangerous to Life and Health) level are also presented in the Attachment.

Figure 4-2 presents a typical hazard footprint for the case of a continuous discharge of Cl_2 from a 2 inch line. The outline of the zone of vulnerability is displayed for both the ERPG-2 and ERPG-3 levels. This contour plot was constructed using the composite maximum for all meteorological scenarios at each downwind distance. The shape of this zone was well described by an ellipse with the maximum width occurring almost midway along the maximum downwind extent. For this example, the spatial extent of the area exceeding the ERPG-2 level was approximately 10 times the area above the ERPG-3 criteria.

Figure's 4-3 to 4-6 summarize the predicted maximum downwind and crosswind extent where the Cl_2 and NH_3 levels of concern would be exceeded for the liquid line rupture case as functions of line diameter. The results for both a 5 minute and continuous release are presented. All results tended to well explained by a power as a function of rupture diameter. The vulnerability zones tended to be much larger for Cl_2 due to the more acutely toxic properties of this material. As expected, the hazard footprints of the continuous release encompassed a larger area than the 5 minute case. For both Cl_2 and NH_3, the maximum downwind and crosswind extent of the potential hazards ranged approximately an order of magnitude across the various pipe diameters used to initialize the model.

For most of the line rupture cases, the larger vulnerability zones were predicted under slightly stable (Pasquill stability class E) atmospheric conditions. The maximum crosswind extent of the hazard footprint invariably were found for the lower wind speed class (1.5 m/s), but the downwind extent in some case were predicted to be larger for the 3 m/s meteorological scenario. The later case was particularly prevalent in the instance of the 5 minute release.

Figure 4-7 displays the composite hazard footprint of a potential 50 T NH_3 vessel failure. The levels of concern contoured correspond to the ERPG 2 & 3 concentrations for NH_3, adjusted to 5 minutes based on the techniques discussed in Section 3. The shape of the vulnerability zone in this figure is typical of all the instantaneous releases simulated in the analysis and demonstrates the effect of buoyancy induced spreading close the source. Such effects were not as pronounced in the line rupture cases due to the high momentum jet associated with these SLAB model applications.

Figure 4–2. Composite Hazard Footprint, Continuous Cl2 Release, 2" Line Rupture

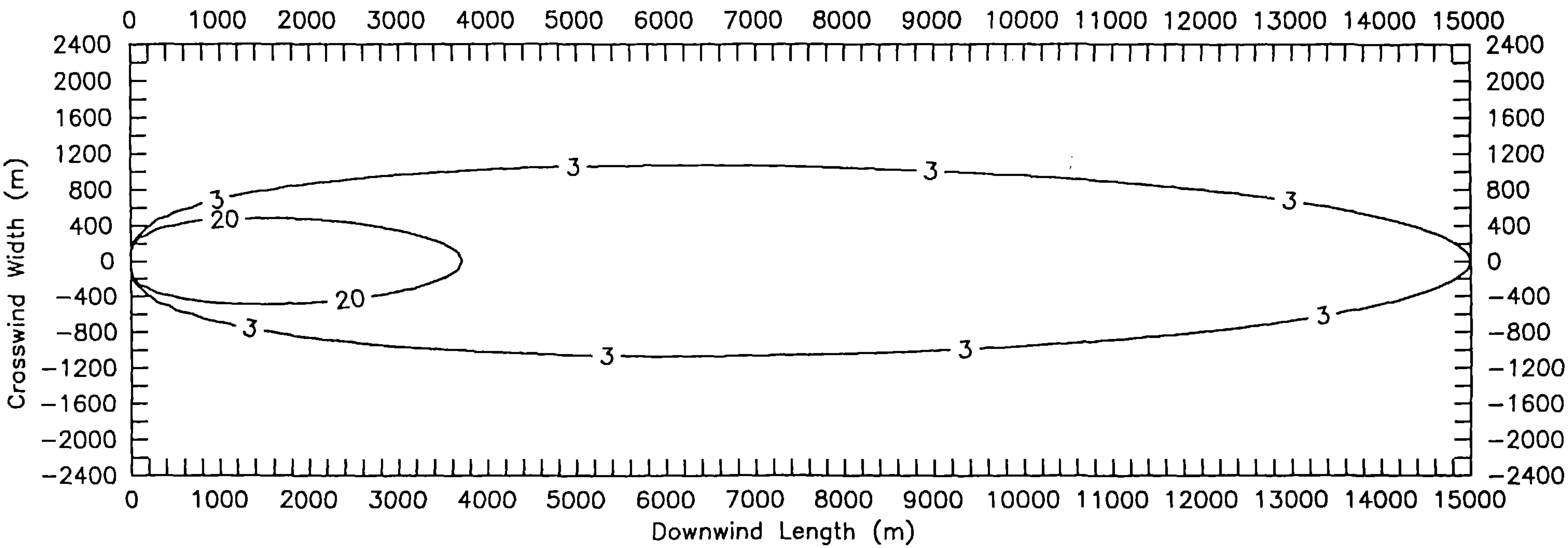


Figure 4-3. Line Rupture Hazard
Maximum Downwind Extent of
Concentrations Above the ERPG-2 Level

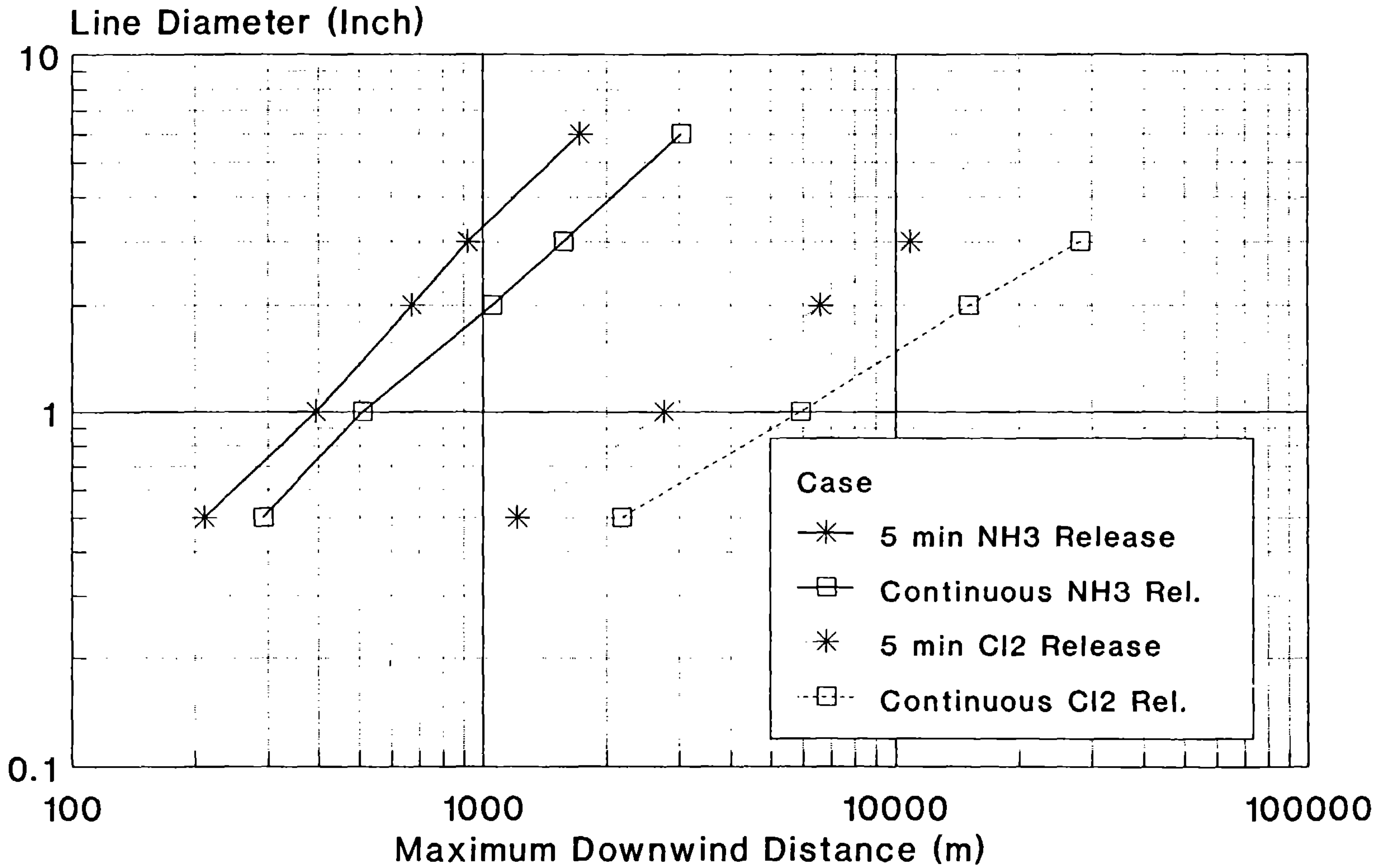


Figure 4-4. Line Rupture Hazard
Maximum Crosswind Extent of
Concentrations Above the ERPG-2 Level

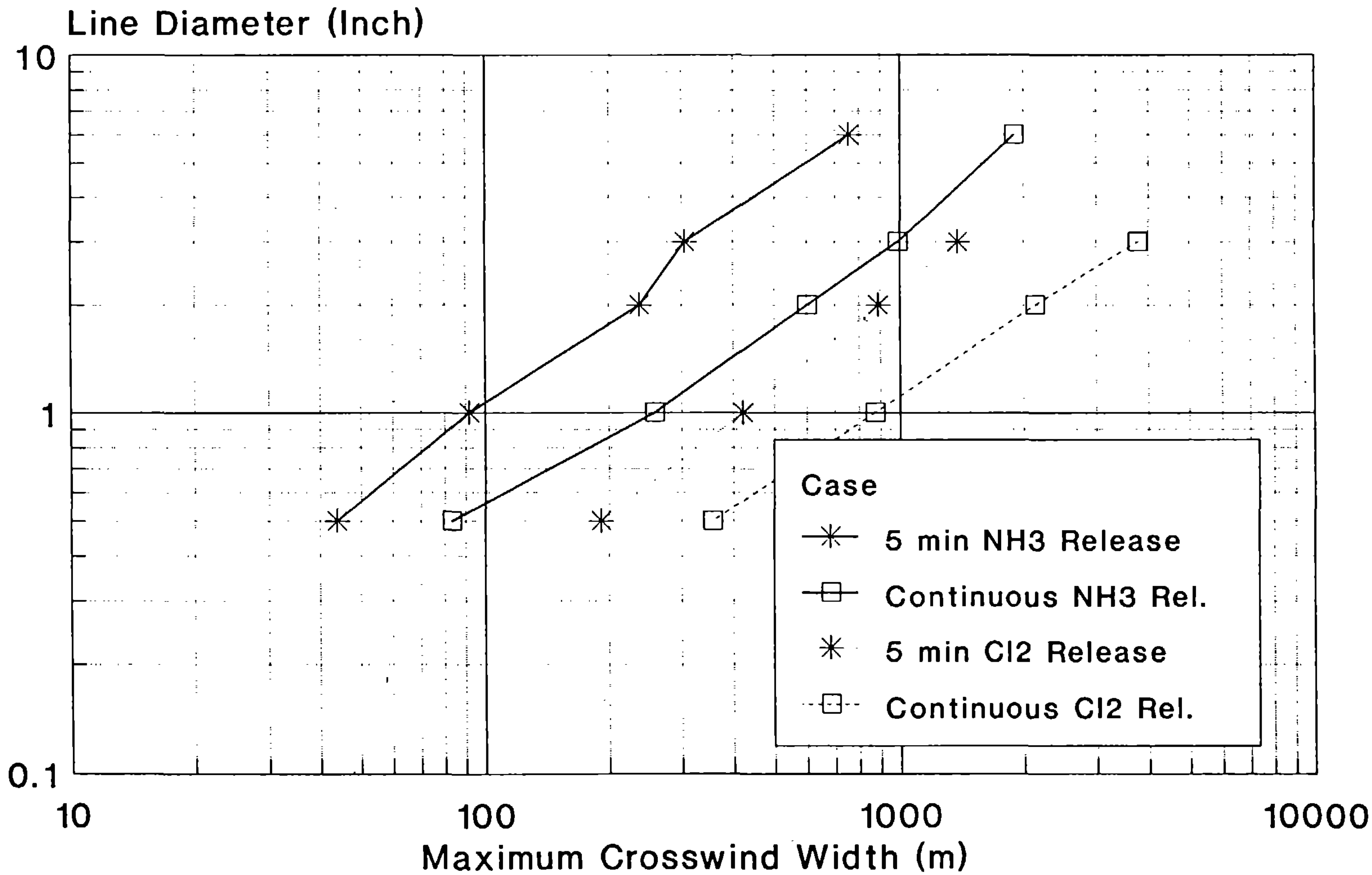


Figure 4-5. Line Rupture Hazard
Maximum Downwind Extent of
Concentrations Above the ERPG-3 Level

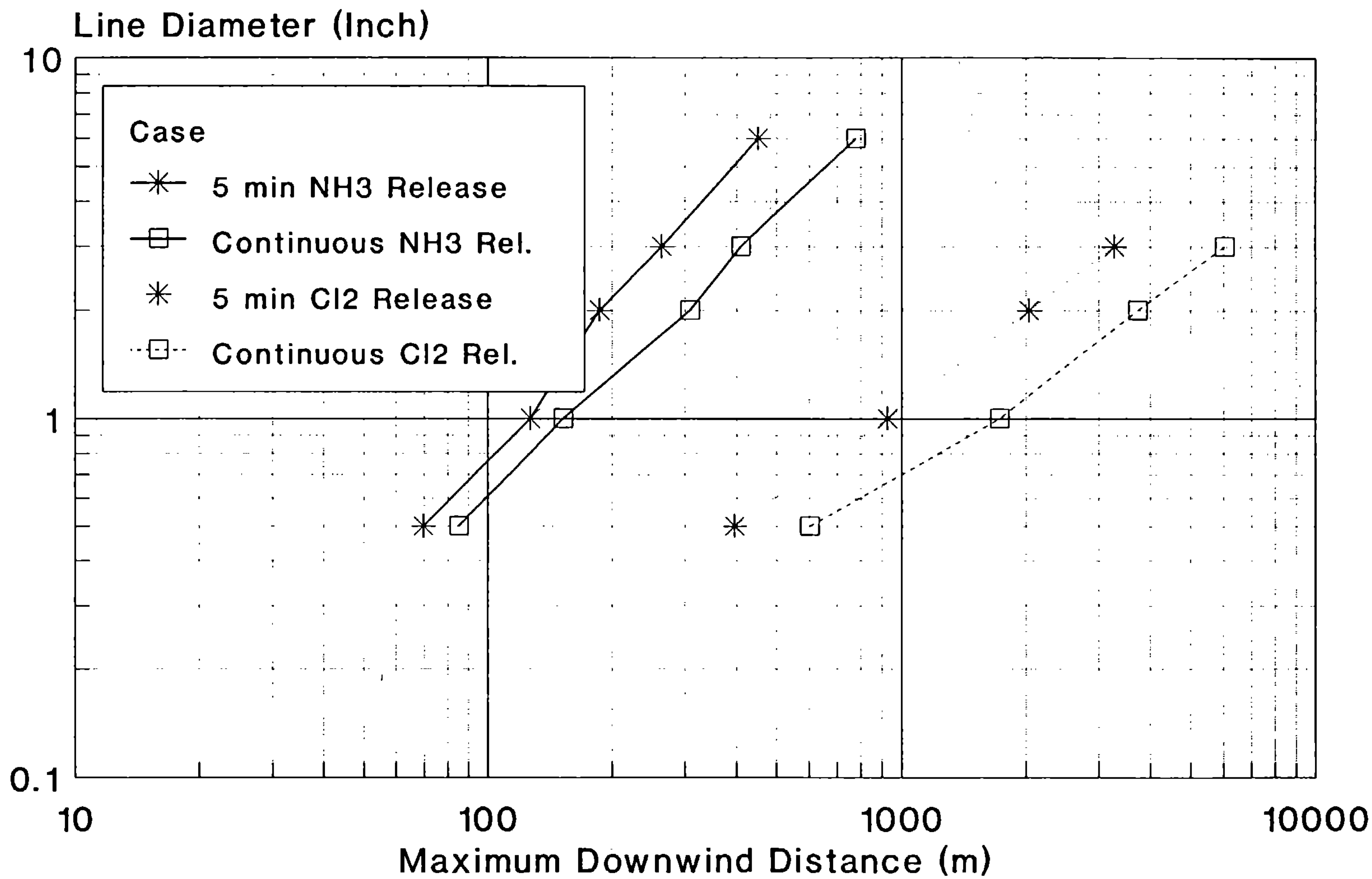


Figure 4-6. Line Rupture Hazard
Maximum Crosswind Extent of
Concentrations Above the ERPG-3 Level

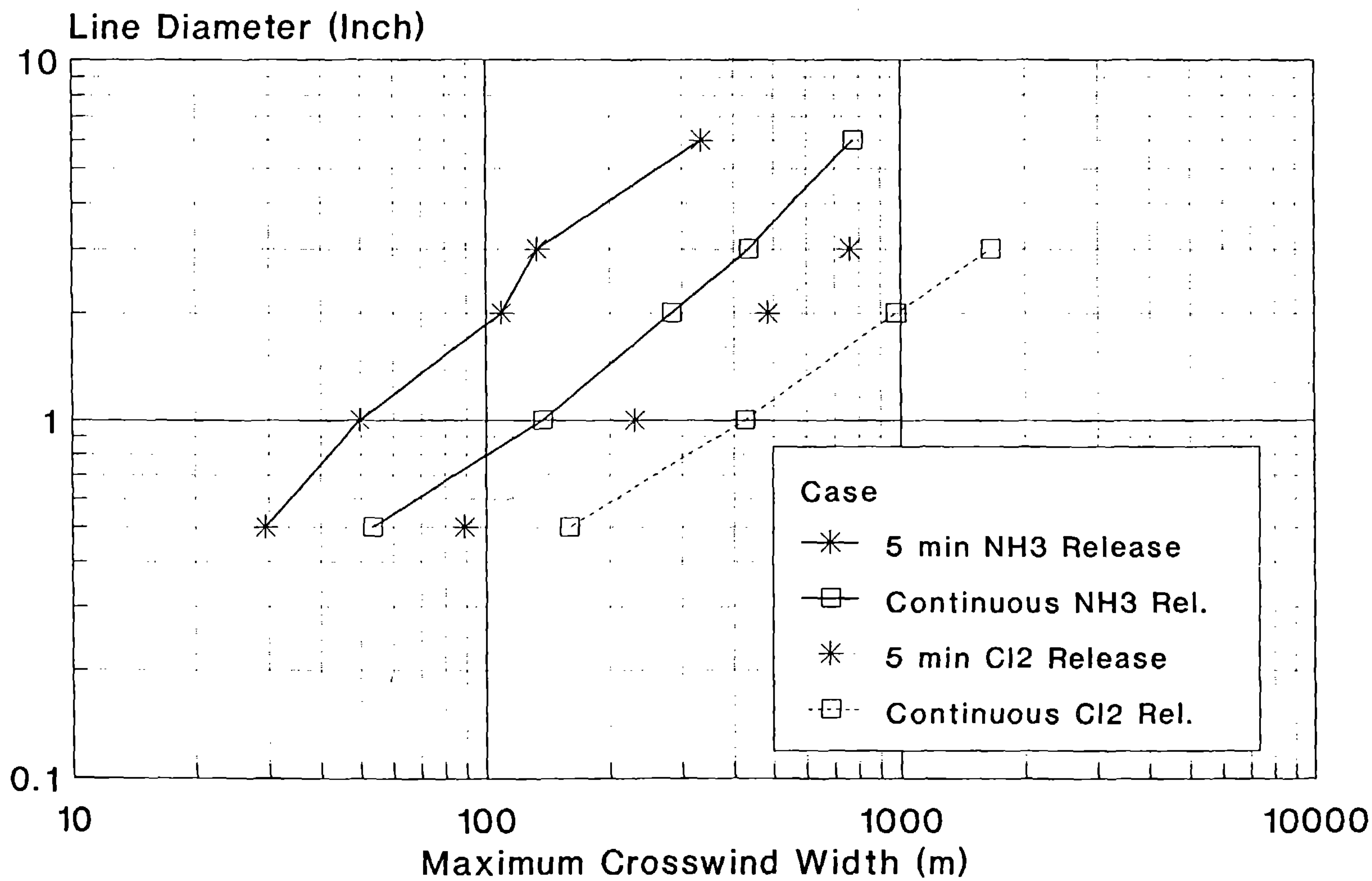
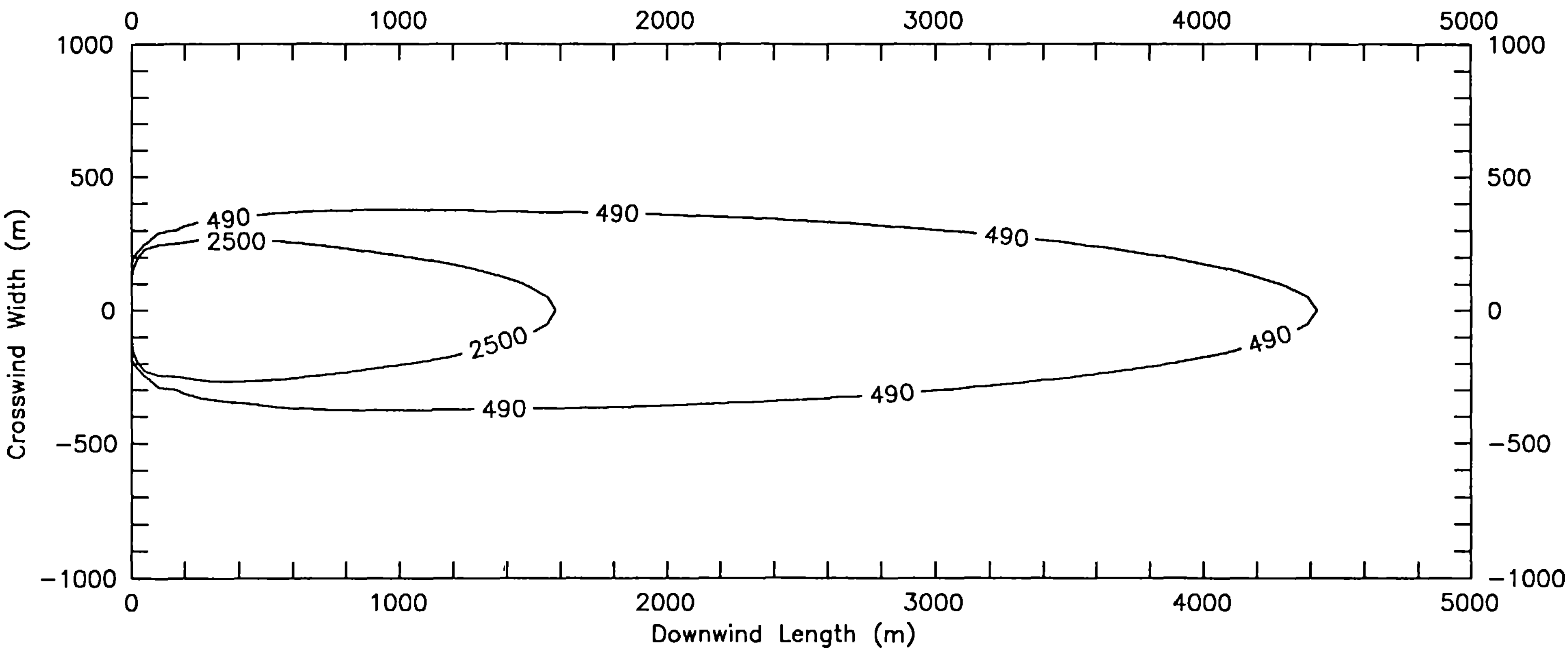


Figure 4–7. Composite Hazard Footprint, 50 T Ammonia Vessel Failure



The maximum composite downwind and crosswind extent of the predicted vulnerability zones for the vessel failure cases are indicated in Figures 4-8 to 4-11 for the 5 minute equivalent ERPG 2 & 3 levels of concern. The area affected by the simulated instantaneous releases were found to be power law functions of vessel capacity with the areas predicted above Cl_2 health criteria many times larger than the NH_3 vessel failures. Higher concentration predictions at receptors further downwind resulted when slightly stable atmospheric stratifications were simulated. Maximum crosswind widths were found to occur for the lower wind speed classes, but downwind extent varied depending on the size of the release. The larger releases extended further downwind under a 3 m/s wind speed. In some instances under light winds, buoyancy induced spreading and the resulting entrained air acted to dilute the clouds more than atmospheric turbulence.

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Figure 4-8. Catastrophic Vessel Failure
Maximum Downwind Extent of
Concentrations Above the ERPG-2 Level

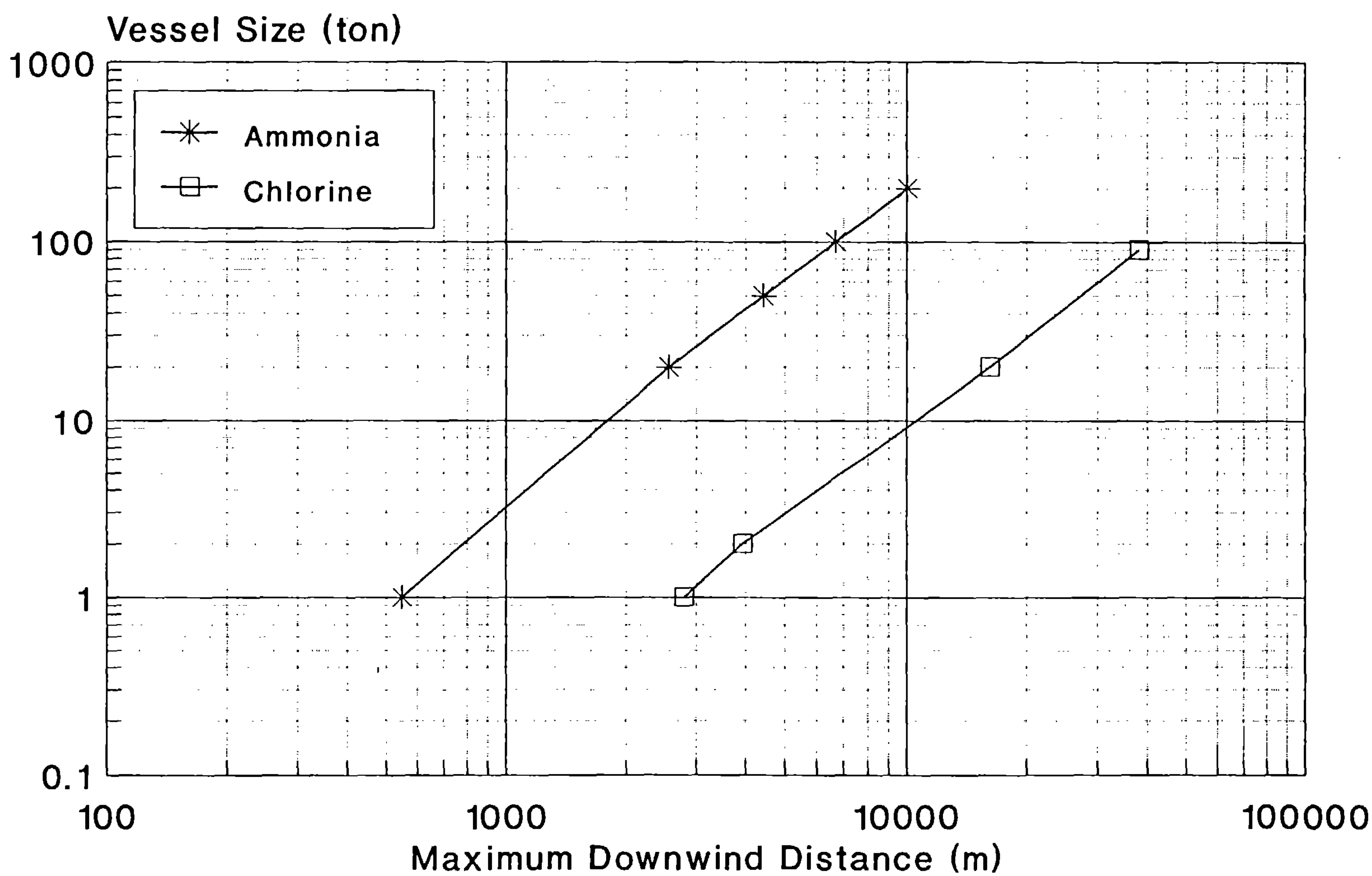


Figure 4-9. Catastrophic Vessel Failure
Maximum Crosswind Extent of
Concentrations Above the ERPG-2 Level

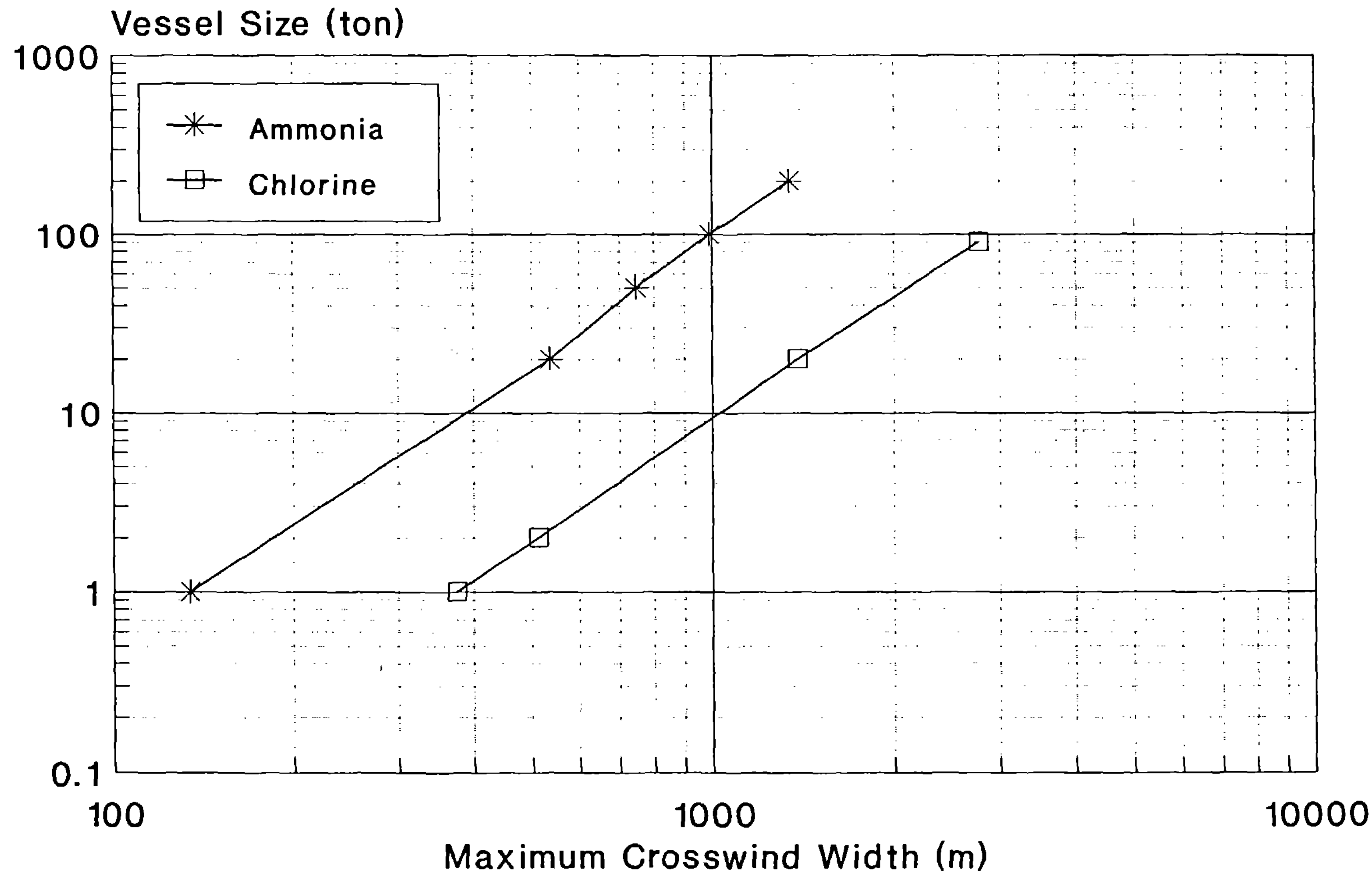


Figure 4-10. Catastrophic Vessel Failure
Maximum Downwind Extent of
Concentrations Above the ERPG-3 Level

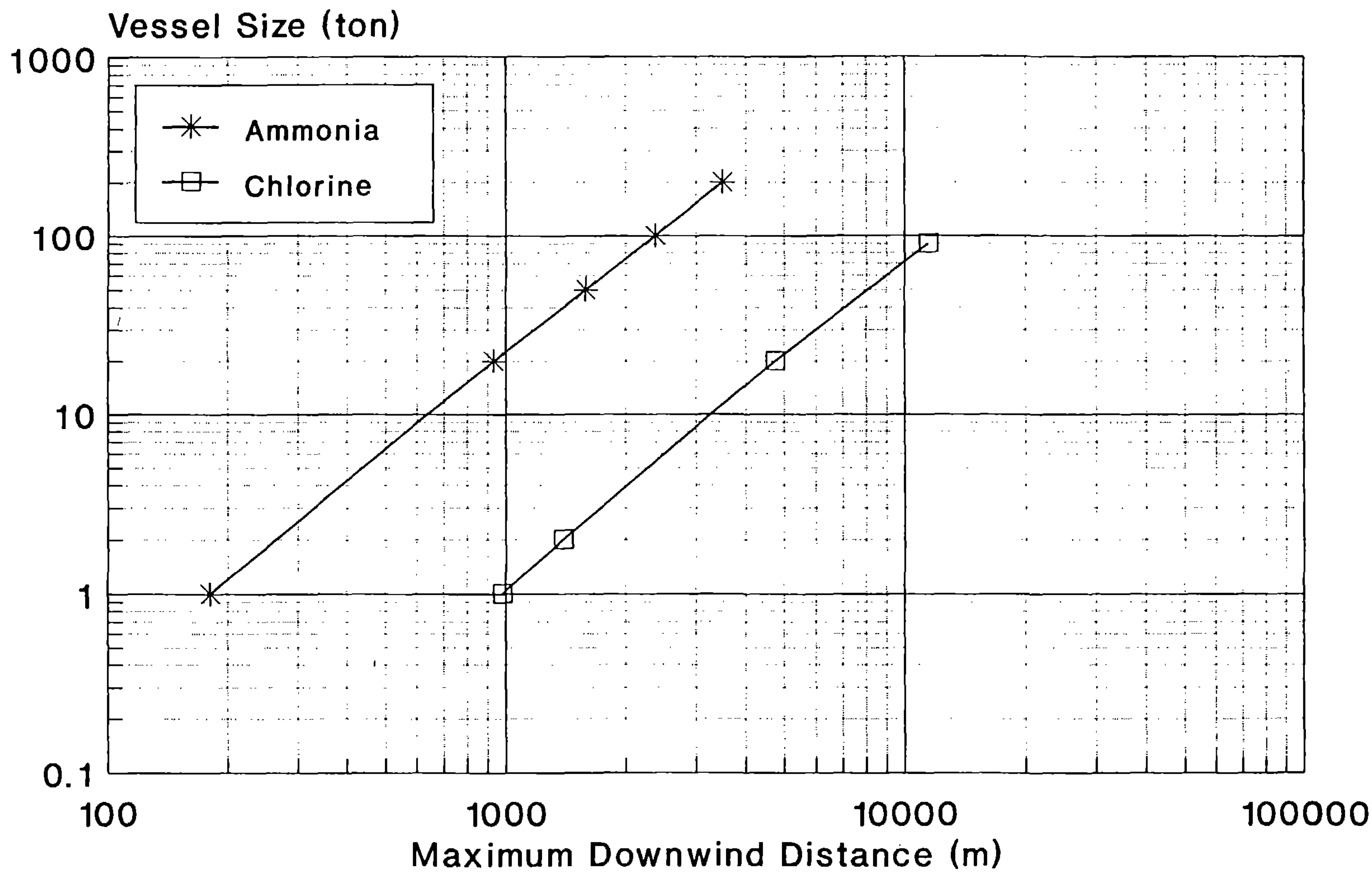
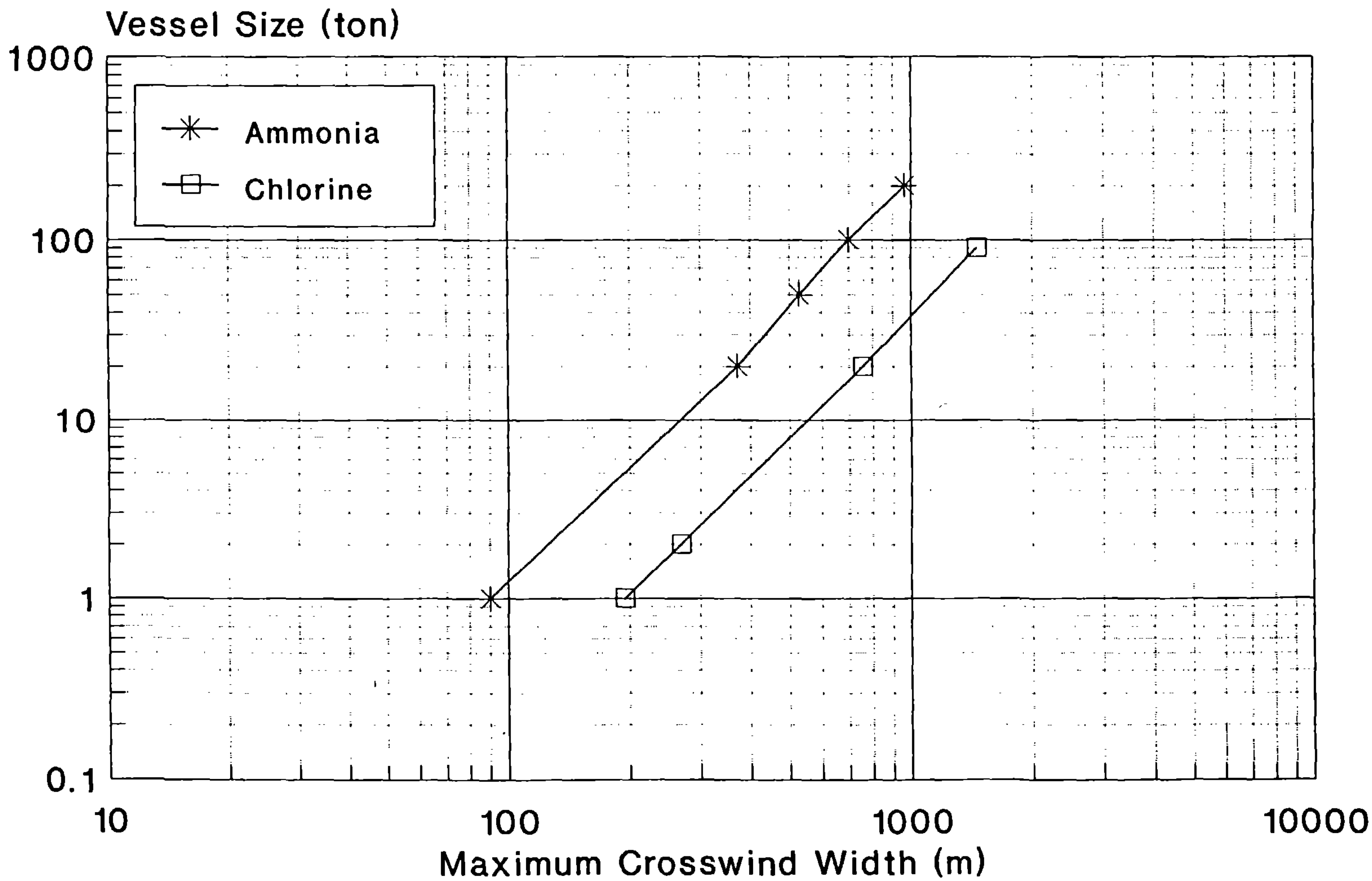


Figure 4-11. Catastrophic Vessel Failure
Maximum Crosswind Extent of
Concentrations Above the ERPG-3 Level



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Attachment 1. Hazard Footprints

Ammonia Hazard Footprints
Continuous Release, 1" Line Rupture
1800.(sec) Averaging Time

Met Scenario				ERPG-2(1)		IDLH(2)		ERPG-3(3)	
u (m/s)	temp (K)	rh (%)	ipas	x (m)	wid (m)	x (m)	wid (m)	x (m)	wid (m)
1.5	297.0	53.0	2	1.921E+02	1.246E+02	1.156E+02	9.880E+01	7.837E+01	8.031E+01
1.5	297.0	53.0	3	3.486E+02	1.643E+02	1.872E+02	1.251E+02	1.115E+02	9.937E+01
3.0	297.0	53.0	3	2.599E+02	9.338E+01	1.538E+02	7.424E+01	1.019E+02	6.173E+01
6.0	297.0	53.0	3	1.912E+02	5.044E+01	1.162E+02	4.065E+01	7.914E+01	3.557E+01
1.5	292.0	63.0	4	4.195E+02	2.011E+02	2.097E+02	1.493E+02	1.196E+02	1.153E+02
3.0	292.0	63.0	4	3.573E+02	1.137E+02	1.986E+02	8.745E+01	1.238E+02	7.089E+01
6.0	292.0	63.0	4	2.778E+02	6.335E+01	1.638E+02	4.863E+01	1.081E+02	4.064E+01
1.5	286.0	74.0	5	5.083E+02	2.565E+02	2.354E+02	1.845E+02	1.277E+02	1.374E+02
3.0	286.0	74.0	5	4.868E+02	1.473E+02	2.555E+02	1.098E+02	1.516E+02	8.661E+01
Composite Maximum				5.083E+02	2.565E+02	2.555E+02	1.845E+02	1.516E+02	1.374E+02

(1) Maximum extent that 200 ppm was exceeded.

(2) Maximum extent that 500 ppm was exceeded.

(3) Maximum extent that 1000 ppm was exceeded.

Ammonia Hazard Footprints
Continuous Release, 2" Line Rupture
1800.(sec) Averaging Time

Met Scenario				ERPG-2(1)		IDLH(2)		ERPG-3(3)	
u (m/s)	temp (K)	rh (%)	ipas	x (m)	wid (m)	x (m)	wid (m)	x (m)	wid (m)
1.5	297.0	53.0	2	4.526E+02	2.939E+02	2.752E+02	2.211E+02	1.826E+02	1.736E+02
1.5	297.0	53.0	3	8.047E+02	3.742E+02	4.036E+02	2.758E+02	2.279E+02	2.126E+02
3.0	297.0	53.0	3	6.169E+02	2.227E+02	3.685E+02	1.730E+02	2.411E+02	1.412E+02
6.0	297.0	53.0	3	4.296E+02	1.184E+02	2.633E+02	9.516E+01	1.815E+02	8.064E+01
1.5	292.0	63.0	4	8.516E+02	4.644E+02	3.900E+02	3.285E+02	2.097E+02	2.421E+02
3.0	292.0	63.0	4	8.045E+02	2.697E+02	4.381E+02	2.022E+02	2.679E+02	1.602E+02
6.0	292.0	63.0	4	6.265E+02	1.491E+02	3.695E+02	1.138E+02	2.450E+02	9.354E+01
1.5	286.0	74.0	5	9.255E+02	6.000E+02	3.924E+02	4.005E+02	2.043E+02	2.809E+02
3.0	286.0	74.0	5	1.053E+03	3.524E+02	5.325E+02	2.537E+02	3.065E+02	1.936E+02
Composite Maximum				1.053E+03	6.000E+02	5.325E+02	4.005E+02	3.065E+02	2.809E+02

(1) Maximum extent that 200 ppm was exceeded.

(2) Maximum extent that 500 ppm was exceeded.

(3) Maximum extent that 1000 ppm was exceeded.

Ammonia Hazard Footprints
Continuous Release, 3" Line Rupture
1800.(sec) Averaging Time

Met Scenario				ERPG-2(1)		IDLH(2)		ERPG-3(3)	
u (m/s)	temp (K)	rh (%)	ipas	x (m)	wid (m)	x (m)	wid (m)	x (m)	wid (m)
1.5	297.0	53.0	2	7.797E+02	4.756E+02	4.683E+02	3.491E+02	2.946E+02	2.679E+02
1.5	297.0	53.0	3	1.139E+03	4.757E+02	5.370E+02	3.425E+02	2.903E+02	2.630E+02
3.0	297.0	53.0	3	1.021E+03	3.528E+02	5.838E+02	2.662E+02	3.664E+02	2.124E+02
6.0	297.0	53.0	3	6.806E+02	1.627E+02	4.138E+02	1.243E+02	2.829E+02	1.034E+02
1.5	292.0	63.0	4	1.285E+03	7.437E+02	5.565E+02	5.124E+02	2.910E+02	3.667E+02
3.0	292.0	63.0	4	1.287E+03	4.409E+02	6.792E+02	3.243E+02	4.034E+02	2.532E+02
6.0	292.0	63.0	4	1.003E+03	2.434E+02	5.834E+02	1.830E+02	3.825E+02	1.474E+02
1.5	286.0	74.0	5	1.359E+03	9.884E+02	5.537E+02	6.377E+02	2.853E+02	4.336E+02
3.0	286.0	74.0	5	1.563E+03	4.924E+02	7.435E+02	3.372E+02	4.088E+02	2.493E+02
Composite Maximum				1.563E+03	9.884E+02	7.435E+02	6.377E+02	4.088E+02	4.336E+02

(1) Maximum extent that 200 ppm was exceeded.

(2) Maximum extent that 500 ppm was exceeded.

(3) Maximum extent that 1000 ppm was exceeded.

Ammonia Hazard Footprints
Continuous Release, 6" Line Rupture
1800.(sec) Averaging Time

Met Scenario				ERPG-2(1)		IDLH(2)		ERPG-3(3)	
u (m/s)	temp (K)	rh (%)	ipas	x (m)	wid (m)	x (m)	wid (m)	x (m)	wid (m)
1.5	297.0	53.0	2	1.328E+03	6.123E+02	7.024E+02	4.308E+02	4.123E+02	3.316E+02
1.5	297.0	53.0	3	2.884E+03	1.222E+03	1.235E+03	8.550E+02	6.343E+02	6.161E+02
3.0	297.0	53.0	3	2.437E+03	7.501E+02	1.285E+03	5.472E+02	7.543E+02	4.255E+02
6.0	297.0	53.0	3	1.624E+03	4.350E+02	9.855E+02	3.287E+02	6.653E+02	2.629E+02
1.5	292.0	63.0	4	2.830E+03	1.689E+03	1.126E+03	1.122E+03	5.683E+02	7.717E+02
3.0	292.0	63.0	4	2.729E+03	9.592E+02	1.288E+03	6.755E+02	6.991E+02	5.059E+02
6.0	292.0	63.0	4	2.234E+03	5.460E+02	1.236E+03	3.970E+02	7.742E+02	3.083E+02
1.5	286.0	74.0	5	2.687E+03	1.896E+03	1.010E+03	1.152E+03	4.989E+02	7.639E+02
3.0	286.0	74.0	5	3.023E+03	1.119E+03	1.278E+03	7.193E+02	6.524E+02	5.066E+02
Composite Maximum				3.023E+03	1.896E+03	1.288E+03	1.152E+03	7.742E+02	7.717E+02

(1) Maximum extent that 200 ppm was exceeded.

(2) Maximum extent that 500 ppm was exceeded.

(3) Maximum extent that 1000 ppm was exceeded.

Chlorine Hazard Footprints
Continuous Release, 1/2" Line Rupture
1800.(sec) Averaging Time

Met Scenario				ERPG-2(1)		ERPG-3(2)		IDLH(3)	
u (m/s)	temp (K)	rh (%)	ipas	x (m)	wid (m)	x (m)	wid (m)	x (m)	wid (m)
1.5	297.0	53.0	2	5.055E+02	1.473E+02	1.895E+02	6.891E+01	1.687E+02	6.377E+01
1.5	297.0	53.0	3	9.960E+02	1.943E+02	3.581E+02	9.901E+01	3.171E+02	9.242E+01
3.0	297.0	53.0	3	6.912E+02	1.202E+02	2.567E+02	5.502E+01	2.283E+02	5.070E+01
6.0	297.0	53.0	3	4.827E+02	7.830E+01	1.836E+02	3.285E+01	1.639E+02	2.982E+01
1.5	292.0	63.0	4	1.484E+03	2.641E+02	4.767E+02	1.277E+02	4.143E+02	1.176E+02
3.0	292.0	63.0	4	1.067E+03	1.590E+02	3.823E+02	7.320E+01	3.384E+02	6.715E+01
6.0	292.0	63.0	4	7.410E+02	1.009E+02	2.749E+02	4.225E+01	2.446E+02	3.842E+01
1.5	286.0	74.0	5	2.170E+03	3.563E+02	5.989E+02	1.595E+02	5.096E+02	1.456E+02
3.0	286.0	74.0	5	1.666E+03	2.157E+02	5.600E+02	9.843E+01	4.914E+02	9.001E+01
Composite Maximum				2.170E+03	3.563E+02	5.989E+02	1.595E+02	5.096E+02	1.456E+02

(1) Maximum extent that 3 ppm was exceeded.

(2) Maximum extent that 20 ppm was exceeded.

(3) Maximum extent that 25 ppm was exceeded.

Chlorine Hazard Footprints
Continuous Release, 1" Line Rupture
1800.(sec) Averaging Time

Met Scenario				ERPG-2(1)		ERPG-3(2)		IDLH(3)	
u (m/s)	temp (K)	rh (%)	ipas	x (m)	wid (m)	x (m)	wid (m)	x (m)	wid (m)
1.5	297.0	53.0	2	1.119E+03	3.292E+02	4.059E+02	1.598E+02	3.603E+02	1.483E+02
1.5	297.0	53.0	3	2.360E+03	4.393E+02	8.459E+02	2.338E+02	7.512E+02	2.186E+02
3.0	297.0	53.0	3	1.549E+03	2.656E+02	5.540E+02	1.243E+02	4.909E+02	1.147E+02
6.0	297.0	53.0	3	1.065E+03	1.725E+02	3.928E+02	7.369E+01	3.496E+02	6.723E+01
1.5	292.0	63.0	4	3.756E+03	6.090E+02	1.226E+03	3.097E+02	1.075E+03	2.871E+02
3.0	292.0	63.0	4	2.461E+03	3.490E+02	8.385E+02	1.618E+02	7.390E+02	1.486E+02
6.0	292.0	63.0	4	1.670E+03	2.216E+02	5.957E+02	9.395E+01	5.282E+02	8.562E+01
1.5	286.0	74.0	5	5.893E+03	8.716E+02	1.723E+03	4.240E+02	1.491E+03	3.899E+02
3.0	286.0	74.0	5	4.038E+03	4.850E+02	1.292E+03	2.224E+02	1.131E+03	2.042E+02
Composite Maximum				5.893E+03	8.716E+02	1.723E+03	4.240E+02	1.491E+03	3.899E+02

(1) Maximum extent that 3 ppm was exceeded.

(2) Maximum extent that 20 ppm was exceeded.

(3) Maximum extent that 25 ppm was exceeded.

Chlorine Hazard Footprints
Continuous Release, 2" Line Rupture
1800.(sec) Averaging Time

Met Scenario				ERPG-2(1)		ERPG-3(2)		IDLH(3)	
u (m/s)	temp (K)	rh (%)	ipas	x (m)	wid (m)	x (m)	wid (m)	x (m)	wid (m)
1.5	297.0	53.0	2	2.662E+03	7.232E+02	9.467E+02	3.587E+02	8.416E+02	3.341E+02
1.5	297.0	53.0	3	6.146E+03	1.012E+03	2.122E+03	5.466E+02	1.880E+03	5.075E+02
3.0	297.0	53.0	3	3.760E+03	5.787E+02	1.303E+03	2.761E+02	1.155E+03	2.557E+02
6.0	297.0	53.0	3	2.477E+03	3.739E+02	8.817E+02	1.606E+02	7.832E+02	1.463E+02
1.5	292.0	63.0	4	1.000E+04	1.408E+03	2.910E+03	7.124E+02	2.523E+03	6.572E+02
3.0	292.0	63.0	4	6.276E+03	7.948E+02	1.993E+03	3.802E+02	1.750E+03	3.506E+02
6.0	292.0	63.0	4	4.055E+03	4.921E+02	1.366E+03	2.150E+02	1.206E+03	1.965E+02
1.5	286.0	74.0	5	1.500E+04	2.127E+03	3.712E+03	9.719E+02	3.144E+03	8.834E+02
3.0	286.0	74.0	5	1.077E+04	1.137E+03	3.043E+03	5.279E+02	2.643E+03	4.859E+02
Composite Maximum				1.500E+04	2.127E+03	3.712E+03	9.719E+02	3.144E+03	8.834E+02

(1) Maximum extent that 3 ppm was exceeded.

(2) Maximum extent that 20 ppm was exceeded.

(3) Maximum extent that 25 ppm was exceeded.

Chlorine Hazard Footprints
Continuous Release, 3" Line Rupture
1800.(sec) Averaging Time

Met Scenario				ERPG-2(1)		ERPG-3(2)		IDLH(3)	
u (m/s)	temp (K)	rh (%)	ipas	x (m)	wid (m)	x (m)	wid (m)	x (m)	wid (m)
1.5	297.0	53.0	2	4.582E+03	1.143E+03	1.588E+03	5.887E+02	1.411E+03	5.499E+02
1.5	297.0	53.0	3	1.147E+04	1.656E+03	3.734E+03	8.714E+02	3.266E+03	8.053E+02
3.0	297.0	53.0	3	6.603E+03	9.189E+02	2.203E+03	4.585E+02	1.950E+03	4.262E+02
6.0	297.0	53.0	3	4.183E+03	5.882E+02	1.433E+03	2.574E+02	1.270E+03	2.360E+02
1.5	292.0	63.0	4	1.891E+04	2.370E+03	4.831E+03	1.178E+03	4.130E+03	1.085E+03
3.0	292.0	63.0	4	1.152E+04	1.278E+03	3.387E+03	6.240E+02	2.960E+03	5.772E+02
6.0	292.0	63.0	4	7.129E+03	7.811E+02	2.260E+03	3.489E+02	1.989E+03	3.183E+02
1.5	286.0	74.0	5	2.803E+04	3.766E+03	6.016E+03	1.646E+03	5.030E+03	1.489E+03
3.0	286.0	74.0	5	2.045E+04	1.904E+03	5.071E+03	8.725E+02	4.364E+03	7.984E+02
Composite Maximum				2.803E+04	3.766E+03	6.016E+03	1.646E+03	5.030E+03	1.489E+03

(1) Maximum extent that 3 ppm was exceeded.

(2) Maximum extent that 20 ppm was exceeded.

(3) Maximum extent that 25 ppm was exceeded.

Ammonia Hazard Footprints
5 Minute Release, 1/2" Line Rupture
300.(sec) Averaging Time

Met Scenario				ERPG-2(1)		IDLH(2)		ERPG-3(3)	
u (m/s)	temp (K)	rh (%)	ipas	x (m)	wid (m)	x (m)	wid (m)	x (m)	wid (m)
1.5	297.0	53.0	2	7.129E+01	2.003E+01	4.396E+01	1.769E+01	2.918E+01	1.568E+01
1.5	297.0	53.0	3	1.211E+02	2.726E+01	7.025E+01	2.359E+01	4.365E+01	2.041E+01
3.0	297.0	53.0	3	9.187E+01	1.507E+01	5.535E+01	1.277E+01	3.570E+01	1.139E+01
6.0	297.0	53.0	3	6.786E+01	1.044E+01	4.183E+01	8.775E+00	2.770E+01	7.986E+00
1.5	292.0	63.0	4	1.640E+02	3.370E+01	9.026E+01	2.849E+01	5.304E+01	2.409E+01
3.0	292.0	63.0	4	1.345E+02	1.566E+01	8.017E+01	1.366E+01	5.106E+01	1.233E+01
6.0	292.0	63.0	4	9.629E+01	1.279E+01	5.757E+01	9.898E+00	3.685E+01	8.971E+00
1.5	286.0	74.0	5	2.107E+02	4.378E+01	1.114E+02	3.577E+01	6.133E+01	2.935E+01
3.0	286.0	74.0	5	1.987E+02	2.079E+01	1.139E+02	1.792E+01	6.946E+01	1.592E+01
Composite Maximum				2.107E+02	4.378E+01	1.139E+02	3.577E+01	6.946E+01	2.935E+01

(1) Maximum extent that 490 ppm (criteria adjusted to 5 minutes) was exceeded.

(2) Maximum extent that 1200 ppm (criteria adjusted to 5 minutes) was exceeded.

(3) Maximum extent that 2500 ppm (criteria adjusted to 5 minutes) was exceeded.

Ammonia Hazard Footprints
5 Minute Release, 1" Line Rupture
300.(sec) Averaging Time

Met Scenario				ERPG-2(1)		IDLH(2)		ERPG-3(3)	
u (m/s)	temp (K)	rh (%)	ipas	x (m)	wid (m)	x (m)	wid (m)	x (m)	wid (m)
1.5	297.0	53.0	2	1.443E+02	5.195E+01	8.676E+01	4.276E+01	5.644E+01	3.587E+01
1.5	297.0	53.0	3	2.449E+02	5.971E+01	1.392E+02	4.793E+01	8.377E+01	3.954E+01
3.0	297.0	53.0	3	1.965E+02	3.834E+01	1.176E+02	3.129E+01	7.580E+01	2.651E+01
6.0	297.0	53.0	3	1.461E+02	2.333E+01	9.013E+01	1.798E+01	5.992E+01	1.598E+01
1.5	292.0	63.0	4	3.034E+02	7.494E+01	1.611E+02	5.791E+01	8.929E+01	4.617E+01
3.0	292.0	63.0	4	2.813E+02	4.479E+01	1.628E+02	3.514E+01	1.009E+02	2.921E+01
6.0	292.0	63.0	4	2.146E+02	2.760E+01	1.298E+02	2.062E+01	8.444E+01	1.729E+01
1.5	286.0	74.0	5	3.354E+02	9.150E+01	1.620E+02	6.617E+01	8.353E+01	4.967E+01
3.0	286.0	74.0	5	3.932E+02	5.659E+01	2.156E+02	4.293E+01	1.267E+02	3.445E+01
Composite Maximum				3.932E+02	9.150E+01	2.156E+02	6.617E+01	1.267E+02	4.967E+01

(1) Maximum extent that 490 ppm (criteria adjusted to 5 minutes) was exceeded.

(2) Maximum extent that 1200 ppm (criteria adjusted to 5 minutes) was exceeded.

(3) Maximum extent that 2500 ppm (criteria adjusted to 5 minutes) was exceeded.

Ammonia Hazard Footprints
5 Minute Release, 2" Line Rupture
300.(sec) Averaging Time

Met Scenario				ERPG-2(1)		IDLH(2)		ERPG-3(3)	
u (m/s)	temp (K)	rh (%)	ipas	x (m)	wid (m)	x (m)	wid (m)	x (m)	wid (m)
1.5	297.0	53.0	2	3.016E+02	1.168E+02	1.759E+02	9.004E+01	1.105E+02	7.129E+01
1.5	297.0	53.0	3	4.678E+02	1.481E+02	2.413E+02	1.096E+02	1.294E+02	8.425E+01
3.0	297.0	53.0	3	4.273E+02	9.896E+01	2.513E+02	7.640E+01	1.582E+02	6.138E+01
6.0	297.0	53.0	3	3.198E+02	5.468E+01	1.966E+02	4.257E+01	1.310E+02	3.577E+01
1.5	292.0	63.0	4	5.044E+02	1.850E+02	2.421E+02	1.316E+02	1.244E+02	9.615E+01
3.0	292.0	63.0	4	5.541E+02	1.134E+02	3.062E+02	8.390E+01	1.784E+02	6.520E+01
6.0	292.0	63.0	4	4.696E+02	6.320E+01	2.811E+02	4.655E+01	1.817E+02	3.712E+01
1.5	286.0	74.0	5	5.120E+02	2.370E+02	2.339E+02	1.574E+02	1.170E+02	1.087E+02
3.0	286.0	74.0	5	6.711E+02	1.323E+02	3.442E+02	9.223E+01	1.858E+02	6.782E+01
Composite Maximum				6.711E+02	2.370E+02	3.442E+02	1.574E+02	1.858E+02	1.087E+02

(1) Maximum extent that 490 ppm (criteria adjusted to 5 minutes) was exceeded.

(2) Maximum extent that 1200 ppm (criteria adjusted to 5 minutes) was exceeded.

(3) Maximum extent that 2500 ppm (criteria adjusted to 5 minutes) was exceeded.

Ammonia Hazard Footprints
5 Minute Release, 3" Line Rupture
300.(sec) Averaging Time

Met Scenario				ERPG-2(1)		IDLH(2)		ERPG-3(3)	
u (m/s)	temp (K)	rh (%)	ipas	x (m)	wid (m)	x (m)	wid (m)	x (m)	wid (m)
1.5	297.0	53.0	2	4.357E+02	1.637E+02	2.486E+02	1.210E+02	1.486E+02	9.383E+01
1.5	297.0	53.0	3	6.494E+02	1.986E+02	3.190E+02	1.444E+02	1.665E+02	1.097E+02
3.0	297.0	53.0	3	6.274E+02	1.290E+02	3.580E+02	9.487E+01	2.153E+02	7.374E+01
6.0	297.0	53.0	3	4.997E+02	7.897E+01	3.045E+02	5.856E+01	2.006E+02	4.698E+01
1.5	292.0	63.0	4	6.801E+02	2.574E+02	3.143E+02	1.772E+02	1.586E+02	1.269E+02
3.0	292.0	63.0	4	7.798E+02	1.616E+02	4.124E+02	1.144E+02	2.289E+02	8.623E+01
6.0	292.0	63.0	4	7.180E+02	1.016E+02	4.181E+02	7.343E+01	2.628E+02	5.671E+01
1.5	286.0	74.0	5	6.979E+02	3.048E+02	3.122E+02	1.956E+02	1.557E+02	1.326E+02
3.0	286.0	74.0	5	9.181E+02	2.080E+02	4.431E+02	1.393E+02	2.299E+02	9.881E+01
Composite Maximum				9.181E+02	3.048E+02	4.431E+02	1.956E+02	2.628E+02	1.326E+02

(1) Maximum extent that 490 ppm (criteria adjusted to 5 minutes) was exceeded.

(2) Maximum extent that 1200 ppm (criteria adjusted to 5 minutes) was exceeded.

(3) Maximum extent that 2500 ppm (criteria adjusted to 5 minutes) was exceeded.

Ammonia Hazard Footprints
5 Minute Release, 6" Line Rupture
300.(sec) Averaging Time

Met Scenario				ERPG-2(1)		IDLH(2)		ERPG-3(3)	
u (m/s)	temp (K)	rh (%)	ipas	x (m)	wid (m)	x (m)	wid (m)	x (m)	wid (m)
1.5	297.0	53.0	2	9.381E+02	4.010E+02	4.951E+02	2.837E+02	2.755E+02	2.103E+02
1.5	297.0	53.0	3	1.261E+03	4.963E+02	5.740E+02	3.471E+02	2.915E+02	2.495E+02
3.0	297.0	53.0	3	1.313E+03	3.060E+02	6.854E+02	2.193E+02	3.784E+02	1.655E+02
6.0	297.0	53.0	3	1.041E+03	1.714E+02	6.056E+02	1.237E+02	3.802E+02	9.425E+01
1.5	292.0	63.0	4	1.298E+03	7.577E+02	5.898E+02	5.007E+02	3.070E+02	3.335E+02
3.0	292.0	63.0	4	1.674E+03	4.541E+02	7.997E+02	3.165E+02	4.234E+02	2.297E+02
6.0	292.0	63.0	4	1.417E+03	2.234E+02	7.714E+02	1.556E+02	4.505E+02	1.151E+02
1.5	286.0	74.0	5	1.217E+03	7.090E+02	5.340E+02	4.403E+02	2.743E+02	2.848E+02
3.0	286.0	74.0	5	1.716E+03	4.468E+02	7.367E+02	2.822E+02	3.687E+02	1.915E+02
Composite Maximum				1.716E+03	7.577E+02	7.997E+02	5.007E+02	4.505E+02	3.335E+02

(1) Maximum extent that 490 ppm (criteria adjusted to 5 minutes) was exceeded.

(2) Maximum extent that 1200 ppm (criteria adjusted to 5 minutes) was exceeded.

(3) Maximum extent that 2500 ppm (criteria adjusted to 5 minutes) was exceeded.

Chlorine Hazard Footprints
5 Minute Release, 1/2" Line Rupture
300.(sec) Averaging Time

Met Scenario				ERPG-2(1)		ERPG-3(2)		IDLH(3)	
u (m/s)	temp (K)	rh (%)	ipas	x (m)	wid (m)	x (m)	wid (m)	x (m)	wid (m)
1.5	297.0	53.0	2	3.705E+02	8.324E+01	1.408E+02	4.208E+01	1.279E+02	3.988E+01
1.5	297.0	53.0	3	6.988E+02	1.167E+02	2.520E+02	6.072E+01	2.295E+02	5.757E+01
3.0	297.0	53.0	3	5.162E+02	6.598E+01	1.913E+02	3.162E+01	1.737E+02	2.976E+01
6.0	297.0	53.0	3	3.627E+02	4.213E+01	1.382E+02	1.813E+01	1.259E+02	1.682E+01
1.5	292.0	63.0	4	9.758E+02	1.563E+02	3.243E+02	7.473E+01	2.893E+02	7.004E+01
3.0	292.0	63.0	4	7.526E+02	8.780E+01	2.810E+02	4.189E+01	2.540E+02	3.933E+01
6.0	292.0	63.0	4	5.523E+02	5.417E+01	2.049E+02	2.340E+01	1.862E+02	2.175E+01
1.5	286.0	74.0	5	1.209E+03	1.911E+02	3.729E+02	8.887E+01	3.286E+02	8.236E+01
3.0	286.0	74.0	5	1.135E+03	1.201E+02	3.952E+02	5.571E+01	3.593E+02	5.197E+01
Composite Maximum				1.209E+03	1.911E+02	3.952E+02	8.887E+01	3.593E+02	8.236E+01

(1) Maximum extent that 7.5 ppm (criteria adjusted to 5 minutes) was exceeded.

(2) Maximum extent that 50 ppm (criteria adjusted to 5 minutes) was exceeded.

(3) Maximum extent that 60 ppm (criteria adjusted to 5 minutes) was exceeded.

Chlorine Hazard Footprints
5 Minute Release, 1" Line Rupture
300.(sec) Averaging Time

Met Scenario				ERPG-2(1)		ERPG-3(2)		IDLH(3)	
u (m/s)	temp (K)	rh (%)	ipas	x (m)	wid (m)	x (m)	wid (m)	x (m)	wid (m)
1.5	297.0	53.0	2	8.067E+02	1.901E+02	2.972E+02	9.287E+01	2.713E+02	8.786E+01
1.5	297.0	53.0	3	1.592E+03	2.666E+02	5.956E+02	1.393E+02	5.411E+02	1.312E+02
3.0	297.0	53.0	3	1.099E+03	1.475E+02	4.092E+02	7.141E+01	3.704E+02	6.719E+01
6.0	297.0	53.0	3	7.920E+02	9.301E+01	2.935E+02	4.091E+01	2.667E+02	3.802E+01
1.5	292.0	63.0	4	2.170E+03	3.416E+02	7.859E+02	1.817E+02	7.110E+02	1.704E+02
3.0	292.0	63.0	4	1.699E+03	1.979E+02	5.950E+02	9.191E+01	5.406E+02	8.573E+01
6.0	292.0	63.0	4	1.224E+03	1.196E+02	4.409E+02	5.198E+01	3.995E+02	4.827E+01
1.5	286.0	74.0	5	2.754E+03	4.198E+02	9.252E+02	2.292E+02	8.307E+02	2.158E+02
3.0	286.0	74.0	5	2.704E+03	2.770E+02	8.651E+02	1.255E+02	7.763E+02	1.169E+02
Composite Maximum				2.754E+03	4.198E+02	9.252E+02	2.292E+02	8.307E+02	2.158E+02

(1) Maximum extent that 7.5 ppm (criteria adjusted to 5 minutes) was exceeded.

(2) Maximum extent that 50 ppm (criteria adjusted to 5 minutes) was exceeded.

(3) Maximum extent that 60 ppm (criteria adjusted to 5 minutes) was exceeded.

Chlorine Hazard Footprints
5 Minute Release, 2" Line Rupture
300.(sec) Averaging Time

Met Scenario				ERPG-2(1)		ERPG-3(2)		IDLH(3)	
u (m/s)	temp (K)	rh (%)	ipas	x (m)	wid (m)	x (m)	wid (m)	x (m)	wid (m)
1.5	297.0	53.0	2	1.819E+03	4.345E+02	6.793E+02	2.139E+02	6.172E+02	2.018E+02
1.5	297.0	53.0	3	3.528E+03	5.800E+02	1.367E+03	3.218E+02	1.245E+03	3.025E+02
3.0	297.0	53.0	3	2.625E+03	3.346E+02	9.191E+02	1.598E+02	8.363E+02	1.507E+02
6.0	297.0	53.0	3	1.771E+03	2.022E+02	6.561E+02	8.925E+01	5.959E+02	8.263E+01
1.5	292.0	63.0	4	4.658E+03	7.104E+02	1.608E+03	3.928E+02	1.447E+03	3.705E+02
3.0	292.0	63.0	4	4.262E+03	4.650E+02	1.356E+03	2.208E+02	1.218E+03	2.056E+02
6.0	292.0	63.0	4	2.766E+03	2.696E+02	1.002E+03	1.196E+02	9.066E+02	1.117E+02
1.5	286.0	74.0	5	5.582E+03	8.891E+02	1.735E+03	4.840E+02	1.542E+03	4.554E+02
3.0	286.0	74.0	5	6.602E+03	6.460E+02	2.028E+03	3.023E+02	1.809E+03	2.815E+02
Composite Maximum				6.602E+03	8.891E+02	2.028E+03	4.840E+02	1.809E+03	4.554E+02

(1) Maximum extent that 7.5 ppm (criteria adjusted to 5 minutes) was exceeded.

(2) Maximum extent that 50 ppm (criteria adjusted to 5 minutes) was exceeded.

(3) Maximum extent that 60 ppm (criteria adjusted to 5 minutes) was exceeded.

Chlorine Hazard Footprints
5 Minute Release, 3" Line Rupture
300.(sec) Averaging Time

Met Scenario				ERPG-2(1)		ERPG-3(2)		IDLH(3)	
u (m/s)	temp (K)	rh (%)	ipas	x (m)	wid (m)	x (m)	wid (m)	x (m)	wid (m)
1.5	297.0	53.0	2	2.891E+03	6.852E+02	1.135E+03	3.607E+02	1.036E+03	3.418E+02
1.5	297.0	53.0	3	5.644E+03	8.751E+02	2.124E+03	4.916E+02	1.921E+03	4.616E+02
3.0	297.0	53.0	3	4.589E+03	5.503E+02	1.542E+03	2.746E+02	1.397E+03	2.588E+02
6.0	297.0	53.0	3	2.898E+03	3.227E+02	1.061E+03	1.445E+02	9.622E+02	1.338E+02
1.5	292.0	63.0	4	7.149E+03	1.099E+03	2.346E+03	6.206E+02	2.097E+03	5.831E+02
3.0	292.0	63.0	4	7.483E+03	7.570E+02	2.311E+03	3.662E+02	2.068E+03	3.414E+02
6.0	292.0	63.0	4	4.737E+03	4.328E+02	1.579E+03	1.952E+02	1.432E+03	1.815E+02
1.5	286.0	74.0	5	8.267E+03	1.380E+03	2.446E+03	7.600E+02	2.160E+03	7.125E+02
3.0	286.0	74.0	5	1.085E+04	1.043E+03	3.286E+03	4.964E+02	2.920E+03	4.634E+02
Composite Maximum				1.085E+04	1.380E+03	3.286E+03	7.600E+02	2.920E+03	7.125E+02

(1) Maximum extent that 7.5 ppm (criteria adjusted to 5 minutes) was exceeded.

(2) Maximum extent that 50 ppm (criteria adjusted to 5 minutes) was exceeded.

(3) Maximum extent that 60 ppm (criteria adjusted to 5 minutes) was exceeded.

Ammonia Hazard Footprints
Catastrophic Failure of 1 T Vessel
300.(sec) Averaging Time

Met Scenario				ERPG-2(1)		IDLH(2)		ERPG-3(3)	
u (m/s)	temp (K)	rh (%)	ipas	x (m)	wid (m)	x (m)	wid (m)	x (m)	wid (m)
1.5	297.0	53.0	2	1.662E+02	1.182E+02	1.071E+02	9.799E+01	7.704E+01	8.255E+01
1.5	297.0	53.0	3	3.020E+02	1.202E+02	1.829E+02	9.884E+01	1.182E+02	8.402E+01
3.0	297.0	53.0	3	2.260E+02	9.488E+01	1.380E+02	7.484E+01	8.942E+01	6.348E+01
6.0	297.0	53.0	3	1.683E+02	7.420E+01	1.016E+02	5.886E+01	6.513E+01	4.688E+01
1.5	292.0	63.0	4	4.018E+02	1.242E+02	2.278E+02	1.009E+02	1.406E+02	8.542E+01
3.0	292.0	63.0	4	2.969E+02	1.019E+02	1.711E+02	7.927E+01	1.067E+02	6.725E+01
6.0	292.0	63.0	4	2.152E+02	7.850E+01	1.237E+02	6.240E+01	7.660E+01	5.030E+01
1.5	286.0	74.0	5	5.467E+02	1.338E+02	3.012E+02	1.072E+02	1.806E+02	9.030E+01
3.0	286.0	74.0	5	4.156E+02	1.103E+02	2.309E+02	8.466E+01	1.401E+02	7.166E+01
Composite Maximum				5.467E+02	1.338E+02	3.012E+02	1.072E+02	1.806E+02	9.030E+01

(1) Maximum extent that 490 ppm (criteria adjusted to 5 minutes) was exceeded.

(2) Maximum extent that 1200 ppm (criteria adjusted to 5 minutes) was exceeded.

(3) Maximum extent that 2500 ppm (criteria adjusted to 5 minutes) was exceeded.

Ammonia Hazard Footprints
Catastrophic Failure of 20 T Vessel
300.(sec) Averaging Time

Met Scenario				ERPG-2(1)		IDLH(2)		ERPG-3(3)	
u (m/s)	temp (K)	rh (%)	ipas	x (m)	wid (m)	x (m)	wid (m)	x (m)	wid (m)
1.5	297.0	53.0	2	9.189E+02	4.719E+02	6.147E+02	3.975E+02	4.583E+02	3.402E+02
1.5	297.0	53.0	3	1.637E+03	4.784E+02	1.038E+03	4.002E+02	7.050E+02	3.457E+02
3.0	297.0	53.0	3	1.380E+03	4.054E+02	8.770E+02	3.276E+02	5.984E+02	2.718E+02
6.0	297.0	53.0	3	1.011E+03	3.037E+02	6.500E+02	2.395E+02	4.421E+02	1.975E+02
1.5	292.0	63.0	4	2.032E+03	4.944E+02	1.207E+03	4.096E+02	7.855E+02	3.516E+02
3.0	292.0	63.0	4	1.798E+03	4.423E+02	1.073E+03	3.519E+02	7.043E+02	2.892E+02
6.0	292.0	63.0	4	1.298E+03	3.318E+02	7.905E+02	2.568E+02	5.190E+02	2.131E+02
1.5	286.0	74.0	5	2.535E+03	5.350E+02	1.459E+03	4.374E+02	9.245E+02	3.720E+02
3.0	286.0	74.0	5	2.556E+03	5.033E+02	1.457E+03	3.924E+02	9.282E+02	3.174E+02
Composite Maximum				2.556E+03	5.350E+02	1.459E+03	4.374E+02	9.282E+02	3.720E+02

(1) Maximum extent that 490 ppm (criteria adjusted to 5 minutes) was exceeded.

(2) Maximum extent that 1200 ppm (criteria adjusted to 5 minutes) was exceeded.

(3) Maximum extent that 2500 ppm (criteria adjusted to 5 minutes) was exceeded.

Ammonia Hazard Footprints
Catastrophic Failure of 50 T Vessel
300.(sec) Averaging Time

Met Scenario				ERPG-2(1)		IDLH(2)		ERPG-3(3)	
u (m/s)	temp (K)	rh (%)	ipas	x (m)	wid (m)	x (m)	wid (m)	x (m)	wid (m)
1.5	297.0	53.0	2	1.493E+03	6.775E+02	9.937E+02	5.747E+02	7.402E+02	4.948E+02
1.5	297.0	53.0	3	2.566E+03	6.715E+02	1.629E+03	5.676E+02	1.122E+03	4.941E+02
3.0	297.0	53.0	3	2.370E+03	6.041E+02	1.515E+03	4.922E+02	1.044E+03	4.108E+02
6.0	297.0	53.0	3	1.789E+03	4.792E+02	1.159E+03	3.755E+02	8.004E+02	3.115E+02
1.5	292.0	63.0	4	3.204E+03	7.145E+02	1.908E+03	6.002E+02	1.255E+03	5.197E+02
3.0	292.0	63.0	4	3.053E+03	6.285E+02	1.807E+03	5.048E+02	1.190E+03	4.165E+02
6.0	292.0	63.0	4	2.243E+03	5.022E+02	1.366E+03	3.839E+02	9.086E+02	3.185E+02
1.5	286.0	74.0	5	4.080E+03	7.456E+02	2.290E+03	6.176E+02	1.455E+03	5.284E+02
3.0	286.0	74.0	5	4.423E+03	7.338E+02	2.487E+03	5.752E+02	1.581E+03	4.673E+02
Composite Maximum				4.423E+03	7.456E+02	2.487E+03	6.176E+02	1.581E+03	5.284E+02

(1) Maximum extent that 490 ppm (criteria adjusted to 5 minutes) was exceeded.

(2) Maximum extent that 1200 ppm (criteria adjusted to 5 minutes) was exceeded.

(3) Maximum extent that 2500 ppm (criteria adjusted to 5 minutes) was exceeded.

Ammonia Hazard Footprints
Catastrophic Failure of 100 T Vessel
300.(sec) Averaging Time

Met Scenario				ERPG-2(1)		IDLH(2)		ERPG-3(3)	
u (m/s)	temp (K)	rh (%)	ipas	x (m)	wid (m)	x (m)	wid (m)	x (m)	wid (m)
1.5	297.0	53.0	2	2.131E+03	8.826E+02	1.419E+03	7.516E+02	1.056E+03	6.487E+02
1.5	297.0	53.0	3	3.588E+03	8.650E+02	2.269E+03	7.372E+02	1.578E+03	6.452E+02
3.0	297.0	53.0	3	3.536E+03	7.990E+02	2.260E+03	6.548E+02	1.564E+03	5.499E+02
6.0	297.0	53.0	3	2.555E+03	6.036E+02	1.658E+03	4.704E+02	1.151E+03	3.886E+02
1.5	292.0	63.0	4	4.482E+03	9.164E+02	2.651E+03	7.779E+02	1.747E+03	6.777E+02
3.0	292.0	63.0	4	4.657E+03	8.486E+02	2.730E+03	6.867E+02	1.797E+03	5.719E+02
6.0	292.0	63.0	4	3.435E+03	6.926E+02	2.083E+03	5.320E+02	1.392E+03	4.382E+02
1.5	286.0	74.0	5	5.989E+03	9.707E+02	3.183E+03	8.120E+02	2.018E+03	6.980E+02
3.0	286.0	74.0	5	6.701E+03	9.895E+02	3.724E+03	7.814E+02	2.363E+03	6.394E+02
Composite Maximum				6.701E+03	9.895E+02	3.724E+03	8.120E+02	2.363E+03	6.980E+02

(1) Maximum extent that 490 ppm (criteria adjusted to 5 minutes) was exceeded.

(2) Maximum extent that 1200 ppm (criteria adjusted to 5 minutes) was exceeded.

(3) Maximum extent that 2500 ppm (criteria adjusted to 5 minutes) was exceeded.

Ammonia Hazard Footprints
Catastrophic Failure of 200 T Vessel
300.(sec) Averaging Time

Met Scenario				ERPG-2(1)		IDLH(2)		ERPG-3(3)	
u (m/s)	temp (K)	rh (%)	ipas	x (m)	wid (m)	x (m)	wid (m)	x (m)	wid (m)
1.5	297.0	53.0	2	3.036E+03	1.174E+03	2.031E+03	1.001E+03	1.517E+03	8.685E+02
1.5	297.0	53.0	3	5.022E+03	1.121E+03	3.157E+03	9.645E+02	2.207E+03	8.490E+02
3.0	297.0	53.0	3	5.346E+03	1.067E+03	3.407E+03	8.813E+02	2.361E+03	7.466E+02
6.0	297.0	53.0	3	3.972E+03	8.397E+02	2.571E+03	6.627E+02	1.792E+03	5.442E+02
1.5	292.0	63.0	4	6.321E+03	1.185E+03	3.658E+03	1.016E+03	2.413E+03	8.914E+02
3.0	292.0	63.0	4	7.198E+03	1.180E+03	4.196E+03	9.643E+02	2.764E+03	8.110E+02
6.0	292.0	63.0	4	5.295E+03	9.433E+02	3.175E+03	7.336E+02	2.120E+03	5.973E+02
1.5	286.0	74.0	5	8.248E+03	1.317E+03	4.349E+03	1.112E+03	2.766E+03	9.611E+02
3.0	286.0	74.0	5	1.003E+04	1.344E+03	5.518E+03	1.070E+03	3.503E+03	8.848E+02
Composite Maximum				1.003E+04	1.344E+03	5.518E+03	1.112E+03	3.503E+03	9.611E+02

(1) Maximum extent that 490 ppm (criteria adjusted to 5 minutes) was exceeded.

(2) Maximum extent that 1200 ppm (criteria adjusted to 5 minutes) was exceeded.

(3) Maximum extent that 2500 ppm (criteria adjusted to 5 minutes) was exceeded.

Chlorine Hazard Footprints
Catastrophic Failure of 1 T Vessel
300.(sec) Averaging Time

Met Scenario				ERPG-2(1)		ERPG-3(2)		IDLH(3)	
u (m/s)	temp (K)	rh (%)	ipas	x (m)	wid (m)	x (m)	wid (m)	x (m)	wid (m)
1.5	297.0	53.0	2	7.502E+02	2.110E+02	2.690E+02	1.131E+02	2.441E+02	1.079E+02
1.5	297.0	53.0	3	1.522E+03	2.700E+02	5.719E+02	1.517E+02	5.221E+02	1.441E+02
3.0	297.0	53.0	3	1.048E+03	1.929E+02	3.822E+02	1.080E+02	3.479E+02	1.026E+02
6.0	297.0	53.0	3	7.011E+02	1.344E+02	2.498E+02	7.469E+01	2.264E+02	7.091E+01
1.5	292.0	63.0	4	2.149E+03	3.217E+02	7.758E+02	1.694E+02	7.029E+02	1.596E+02
3.0	292.0	63.0	4	1.613E+03	2.502E+02	5.456E+02	1.310E+02	4.915E+02	1.237E+02
6.0	292.0	63.0	4	1.079E+03	1.786E+02	3.639E+02	9.429E+01	3.273E+02	8.928E+01
1.5	286.0	74.0	5	2.792E+03	3.741E+02	9.801E+02	1.944E+02	8.849E+02	1.830E+02
3.0	286.0	74.0	5	2.531E+03	3.046E+02	8.077E+02	1.511E+02	7.247E+02	1.416E+02
Composite Maximum				2.792E+03	3.741E+02	9.801E+02	1.944E+02	8.849E+02	1.830E+02

(1) Maximum extent that 7.5 ppm (criteria adjusted to 5 minutes) was exceeded.

(2) Maximum extent that 50 ppm (criteria adjusted to 5 minutes) was exceeded.

(3) Maximum extent that 60 ppm (criteria adjusted to 5 minutes) was exceeded.

Chlorine Hazard Footprints
Catastrophic Failure of 2 T Vessel
300.(sec) Averaging Time

Met Scenario				ERPG-2(1)		ERPG-3(2)		IDLH(3)	
u (m/s)	temp (K)	rh (%)	ipas	x (m)	wid (m)	x (m)	wid (m)	x (m)	wid (m)
1.5	297.0	53.0	2	1.102E+03	2.960E+02	3.983E+02	1.610E+02	3.622E+02	1.536E+02
1.5	297.0	53.0	3	2.223E+03	3.766E+02	8.542E+02	2.149E+02	7.818E+02	2.039E+02
3.0	297.0	53.0	3	1.568E+03	2.726E+02	5.778E+02	1.543E+02	5.272E+02	1.466E+02
6.0	297.0	53.0	3	1.046E+03	2.066E+02	3.832E+02	1.198E+02	3.490E+02	1.133E+02
1.5	292.0	63.0	4	3.115E+03	4.553E+02	1.139E+03	2.478E+02	1.034E+03	2.339E+02
3.0	292.0	63.0	4	2.453E+03	3.475E+02	8.310E+02	1.827E+02	7.501E+02	1.727E+02
6.0	292.0	63.0	4	1.622E+03	2.451E+02	5.498E+02	1.292E+02	4.955E+02	1.216E+02
1.5	286.0	74.0	5	3.926E+03	5.109E+02	1.391E+03	2.688E+02	1.259E+03	2.530E+02
3.0	286.0	74.0	5	3.886E+03	4.370E+02	1.220E+03	2.169E+02	1.096E+03	2.037E+02
Composite Maximum				3.926E+03	5.109E+02	1.391E+03	2.688E+02	1.259E+03	2.530E+02

(1) Maximum extent that 7.5 ppm (criteria adjusted to 5 minutes) was exceeded.

(2) Maximum extent that 50 ppm (criteria adjusted to 5 minutes) was exceeded.

(3) Maximum extent that 60 ppm (criteria adjusted to 5 minutes) was exceeded.

Chlorine Hazard Footprints
Catastrophic Failure of 20 T Vessel
300.(sec) Averaging Time

Met Scenario				ERPG-2(1)		ERPG-3(2)		IDLH(3)	
u (m/s)	temp (K)	rh (%)	ipas	x (m)	wid (m)	x (m)	wid (m)	x (m)	wid (m)
1.5	297.0	53.0	2	3.864E+03	8.940E+02	1.496E+03	5.424E+02	1.372E+03	5.256E+02
1.5	297.0	53.0	3	7.660E+03	1.077E+03	3.145E+03	6.529E+02	2.892E+03	6.231E+02
3.0	297.0	53.0	3	6.561E+03	8.527E+02	2.386E+03	5.006E+02	2.184E+03	4.766E+02
6.0	297.0	53.0	3	4.108E+03	5.932E+02	1.488E+03	3.465E+02	1.360E+03	3.302E+02
1.5	292.0	63.0	4	1.003E+04	1.220E+03	3.756E+03	7.075E+02	3.427E+03	6.710E+02
3.0	292.0	63.0	4	1.078E+04	1.074E+03	3.422E+03	5.817E+02	3.088E+03	5.503E+02
6.0	292.0	63.0	4	6.868E+03	7.487E+02	2.202E+03	4.022E+02	1.987E+03	3.808E+02
1.5	286.0	74.0	5	1.204E+04	1.379E+03	4.307E+03	7.543E+02	3.915E+03	7.116E+02
3.0	286.0	74.0	5	1.617E+04	1.384E+03	4.931E+03	7.060E+02	4.425E+03	6.648E+02
Composite Maximum				1.617E+04	1.384E+03	4.931E+03	7.543E+02	4.425E+03	7.116E+02

(1) Maximum extent that 7.5 ppm (criteria adjusted to 5 minutes) was exceeded.

(2) Maximum extent that 50 ppm (criteria adjusted to 5 minutes) was exceeded.

(3) Maximum extent that 60 ppm (criteria adjusted to 5 minutes) was exceeded.

Chlorine Hazard Footprints
Catastrophic Failure of 90 T Vessel
300.(sec) Averaging Time

Met Scenario				ERPG-2(1)		ERPG-3(2)		IDLH(3)	
u (m/s)	temp (K)	rh (%)	ipas	x (m)	wid (m)	x (m)	wid (m)	x (m)	wid (m)
1.5	297.0	53.0	2	8.474E+03	1.684E+03	3.394E+03	1.123E+03	3.133E+03	1.086E+03
1.5	297.0	53.0	3	1.712E+04	1.947E+03	7.021E+03	1.226E+03	6.465E+03	1.174E+03
3.0	297.0	53.0	3	1.812E+04	1.720E+03	6.315E+03	1.029E+03	5.779E+03	9.821E+02
6.0	297.0	53.0	3	1.128E+04	1.202E+03	3.823E+03	7.145E+02	3.492E+03	6.821E+02
1.5	292.0	63.0	4	2.176E+04	2.211E+03	7.996E+03	1.323E+03	7.310E+03	1.262E+03
3.0	292.0	63.0	4	2.882E+04	2.152E+03	8.774E+03	1.199E+03	7.914E+03	1.136E+03
6.0	292.0	63.0	4	2.127E+04	1.554E+03	5.751E+03	8.416E+02	5.163E+03	7.972E+02
1.5	286.0	74.0	5	2.503E+04	2.601E+03	8.843E+03	1.432E+03	8.057E+03	1.359E+03
3.0	286.0	74.0	5	3.808E+04	2.766E+03	1.144E+04	1.458E+03	1.030E+04	1.371E+03
Composite Maximum				3.808E+04	2.766E+03	1.144E+04	1.458E+03	1.030E+04	1.371E+03

(1) Maximum extent that 7.5 ppm (criteria adjusted to 5 minutes) was exceeded.

(2) Maximum extent that 50 ppm (criteria adjusted to 5 minutes) was exceeded.

(3) Maximum extent that 60 ppm (criteria adjusted to 5 minutes) was exceeded.

Ammonia Hazard Footprints
Continuous Release, 1/2" Line Rupture
1800.(sec) Averaging Time

Met Scenario				ERPG-2(1)		IDLH(2)		ERPG-3(3)	
u (m/s)	temp (K)	rh (%)	ipas	x (m)	wid (m)	x (m)	wid (m)	x (m)	wid (m)
1.5	297.0	53.0	2	8.708E+01	4.926E+01	5.157E+01	4.031E+01	3.429E+01	3.381E+01
1.5	297.0	53.0	3	1.635E+02	4.432E+01	9.496E+01	3.831E+01	6.138E+01	3.377E+01
3.0	297.0	53.0	3	1.156E+02	3.776E+01	6.719E+01	3.062E+01	4.363E+01	2.581E+01
6.0	297.0	53.0	3	8.840E+01	2.142E+01	5.363E+01	1.753E+01	3.628E+01	1.593E+01
1.5	292.0	63.0	4	1.868E+02	7.816E+01	9.451E+01	5.942E+01	5.436E+01	4.711E+01
3.0	292.0	63.0	4	1.597E+02	4.551E+01	8.829E+01	3.537E+01	5.451E+01	2.914E+01
6.0	292.0	63.0	4	1.264E+02	2.639E+01	7.440E+01	2.030E+01	4.875E+01	1.780E+01
1.5	286.0	74.0	5	2.921E+02	8.295E+01	1.481E+02	6.494E+01	8.486E+01	5.334E+01
3.0	286.0	74.0	5	2.180E+02	5.884E+01	1.141E+02	4.454E+01	6.720E+01	3.576E+01
Composite Maximum				2.921E+02	8.295E+01	1.481E+02	6.494E+01	8.486E+01	5.334E+01

(1) Maximum extent that 200 ppm was exceeded.

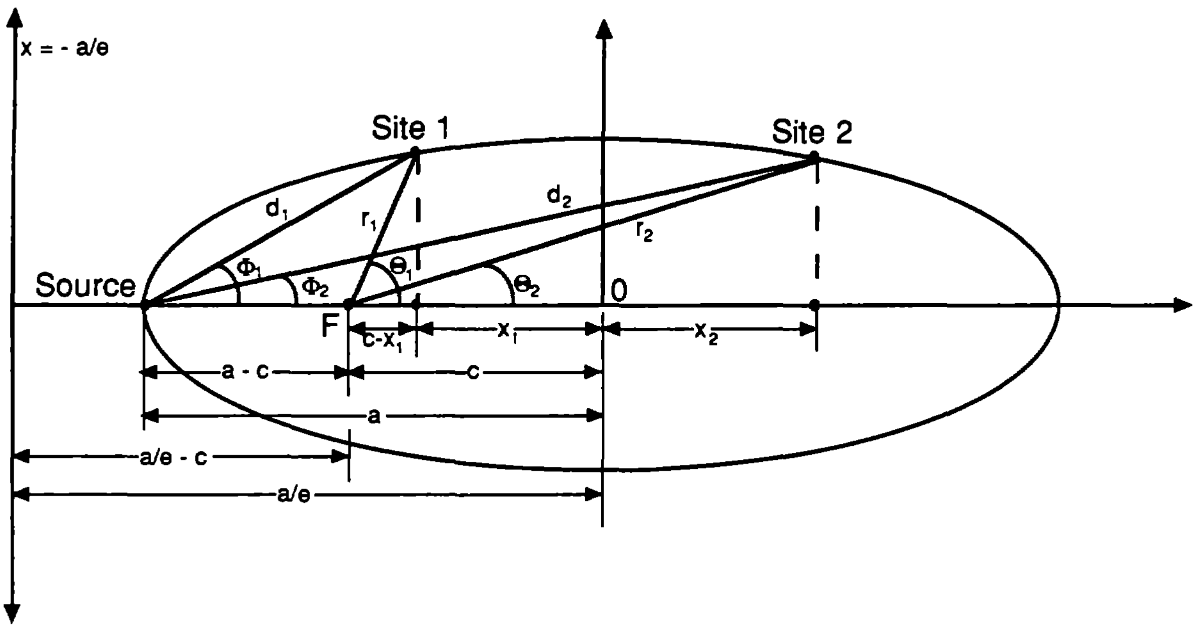
(2) Maximum extent that 500 ppm was exceeded.

(3) Maximum extent that 1000 ppm was exceeded.

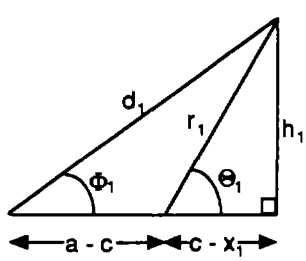
APPENDIX C

DERIVATION OF X AS A FUNCTION OF a, b, AND d

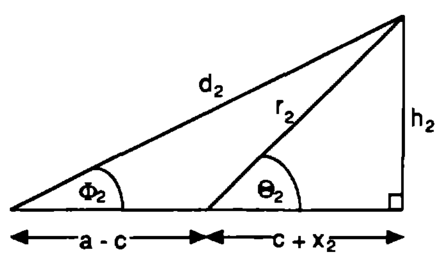
Derivation of X as a Function of a, b, and d



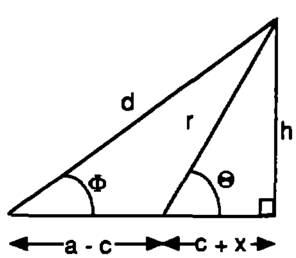
Case 1: d < square root of ($a^2 + b^2$)



Case 2: d > square root of ($a^2 + b^2$)



General Case



Given: a and b are the semiaxes of the ellipse, c is the distance from the center of the ellipse to the focus, e is the eccentricity of the ellipse, and $x = \pm a/e$ are the equations of the directrices. And

$$a^2 - c^2 = b^2 \qquad e = c/a$$

And k is defined as follows: $$k = \frac{(a^2 - b^2)^{\frac{1}{2}}}{a}$$

Assume: d is the distance from the endpoint of the major axis (the source) to some point on the edge of the ellipse (the site), and r is the distance from the focus to that same point.

Case 1

From the definition of a right triangle:

1) the triangle with angle θ_1:

$$(c - x_1)^2 + h_1^2 = r_1^2$$

2) the triangle with angle Φ_1:

$$[(a-c)+(c-x_1)]^2 + h_1^2 = d_1^2$$

$$(a - x_1)^2 + h_1^2 = d_1^2$$

Solving both equations for h_1^2:

$$h_1^2 = (c - x_1)^2 - r_1^2 = (a - x_1)^2 - d_1^2$$

$$r_1^2 = (c - x_1)^2 - (a - x_1)^2 + d_1^2$$

Case 2

From the definition of a right triangle:

1) the triangle with angle θ_2:

$$(c + x_2)^2 + h_2^2 = r_2^2$$

2) the triangle with angle Φ_2:

$$[(a-c)+(c+x_2)]^2 + h_2^2 = d_2^2$$

$$(a + x_2)^2 + h_2^2 = d_2^2$$

Solving both equations for h_2^2:

$$h_2^2 = (c + x_2)^2 - r_2^2 = (a + x_2)^2 - d_2^2$$

$$r_2^2 = (c + x_2)^2 - (a + x_2)^2 + d_2^2$$

--> X may be measured from the center of the ellipse:
X will be negative to the left of the center, positive to the right
x_1 will be negative, x_2 will be positive

--> we can use the following equation for any ellipse, and any site:

(1) $$r^2 = (c + x)^2 - (a + x)^2 + d^2$$

However, we know from the definition of an ellipse:

$$r = \frac{ke}{1 - e\cos\theta}$$

where θ is the angle formed by a line connecting the focus and the point on the edege of the ellipse, and the major axis [$\cos\theta = (c + x)/r$]. k and e are as defined above.

Substituting, we get,

$$r = \frac{ke}{1 - e(c+x)/r}$$

$$r(1 - e(c+x)/r) = ke$$

$$r - e(c+x) = ke$$

and,

$$r = ke + e(c+x) = e(k + c + x)$$

squaring both sides, and using equation 1, we get

$$r^2 = e^2 (k + c + x)^2 = (c + x)^2 - (a + x)^2 + d^2$$

$$e^2 (k^2 + 2ck + 2cx + 2kx + c^2 + x^2) = c^2 + 2cx - a^2 - 2ax + d^2$$

$$x[e^2(2c + 2k + x)] + e^2(k^2 + 2ck + c^2) = x(2c - 2a) + (c^2 - a^2 + d^2)$$

$$x[2(c - a) - e^2(2c + 2k + x)] = e^2 (k^2 + 2ck + c^2) - c^2 + a^2 - d^2$$

but $c^2 = a^2 - b^2$; $e^2 = (c/a)^2 = (a^2 - b^2)/a^2$; and

$$k = a/e - c = \frac{b^2(a^2 - b^2)^{\frac{1}{2}}}{a^2 - b^2}$$

Substituting yields:

$$x\left[2[(a^2-b^2)^{\frac{1}{2}} - a] - \frac{(a^2-b^2)}{a^2}\left[2(a^2-b^2)^{\frac{1}{2}} + 2b^2\frac{(a^2-b^2)^{\frac{1}{2}}}{a^2-b^2} + x\right]\right] =$$

$$\frac{a^2-b^2}{a^2}\left[\frac{b^4 (a^2-b^2)}{(a^2-b^2)^2} + \frac{2(a^2-b^2)^{\frac{1}{2}}(b^2(a^2-b^2)^{\frac{1}{2}})}{(a^2-b^2)} + a^2-b^2\right] - (a^2-b^2) + a^2 - d^2$$

Simplifying yields:

$$x^2(a^2 - b^2)/a^2 + x(2a) + (a^2 + b^2 - d^2) = 0$$

Solving by the quadratic equation, we get:

$$x = \frac{-a^3 \pm a(b^4 - b^2d^2 + a^2d^2)^{\frac{1}{2}}}{a^2 - b^2}$$

NATIONAL CENTER FOR EARTHQUAKE ENGINEERING RESEARCH
LIST OF TECHNICAL REPORTS

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NCEER-87-0001 "First-Year Program in Research, Education and Technology Transfer," 3/5/87, (PB88-134275, A04, MF-A01).

NCEER-87-0002 "Experimental Evaluation of Instantaneous Optimal Algorithms for Structural Control," by R.C. Lin, T.T. Soong and A.M. Reinhorn, 4/20/87, (PB88-134341, A04, MF-A01).

NCEER-87-0003 "Experimentation Using the Earthquake Simulation Facilities at University at Buffalo," by A.M. Reinhorn and R.L. Ketter, to be published.

NCEER-87-0004 "The System Characteristics and Performance of a Shaking Table," by J.S. Hwang, K.C. Chang and G.C. Lee, 6/1/87, (PB88-134259, A03, MF-A01). This report is available only through NTIS (see address given above).

NCEER-87-0005 "A Finite Element Formulation for Nonlinear Viscoplastic Material Using a Q Model," by O. Gyebi and G. Dasgupta, 11/2/87, (PB88-213764, A08, MF-A01).

NCEER-87-0006 "Symbolic Manipulation Program (SMP) - Algebraic Codes for Two and Three Dimensional Finite Element Formulations," by X. Lee and G. Dasgupta, 11/9/87, (PB88-218522, A05, MF-A01).

NCEER-87-0007 "Instantaneous Optimal Control Laws for Tall Buildings Under Seismic Excitations," by J.N. Yang, A. Akbarpour and P. Ghaemmaghami, 6/10/87, (PB88-134333, A06, MF-A01). This report is only available through NTIS (see address given above).

NCEER-87-0008 "IDARC: Inelastic Damage Analysis of Reinforced Concrete Frame - Shear-Wall Structures," by Y.J. Park, A.M. Reinhorn and S.K. Kunnath, 7/20/87, (PB88-134325, A09, MF-A01). This report is only available through NTIS (see address given above).

NCEER-87-0009 "Liquefaction Potential for New York State: A Preliminary Report on Sites in Manhattan and Buffalo," by M. Budhu, V. Vijayakumar, R.F. Giese and L. Baumgras, 8/31/87, (PB88-163704, A03, MF-A01). This report is available only through NTIS (see address given above).

NCEER-87-0010 "Vertical and Torsional Vibration of Foundations in Inhomogeneous Media," by A.S. Veletsos and K.W. Dotson, 6/1/87, (PB88-134291, A03, MF-A01). This report is only available through NTIS (see address given above).

NCEER-87-0011 "Seismic Probabilistic Risk Assessment and Seismic Margins Studies for Nuclear Power Plants," by Howard H.M. Hwang, 6/15/87, (PB88-134267, A03, MF-A01). This report is only available through NTIS (see address given above).

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NCEER-87-0013 "Frequency Response of Secondary Systems Under Seismic Excitation," by J.A. HoLung, J. Cai and Y.K. Lin, 7/31/87, (PB88-134317, A05, MF-A01). This report is only available through NTIS (see address given above).

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NCEER-87-0015 "Detection and Assessment of Seismic Structural Damage," by E. DiPasquale and A.S. Cakmak, 8/25/87, (PB88-163712, A05, MF-A01). This report is only available through NTIS (see address given above).

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NCEER-87-0018 "Practical Considerations for Structural Control: System Uncertainty, System Time Delay and Truncation of Small Control Forces," J.N. Yang and A. Akbarpour, 8/10/87, (PB88-163738, A08, MF-A01). This report is only available through NTIS (see address given above).

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NCEER-87-0023 "Active Structural Control in Civil Engineering," by T.T. Soong, 11/11/87, (PB88-187778, A03, MF-A01).

NCEER-87-0024 "Vertical and Torsional Impedances for Radially Inhomogeneous Viscoelastic Soil Layers," by K.W. Dotson and A.S. Veletsos, 12/87, (PB88-187786, A03, MF-A01).

NCEER-87-0025 "Proceedings from the Symposium on Seismic Hazards, Ground Motions, Soil-Liquefaction and Engineering Practice in Eastern North America," October 20-22, 1987, edited by K.H. Jacob, 12/87, (PB88-188115, A23, MF-A01).

NCEER-87-0026 "Report on the Whittier-Narrows, California, Earthquake of October 1, 1987," by J. Pantelic and A. Reinhorn, 11/87, (PB88-187752, A03, MF-A01). This report is available only through NTIS (see address given above).

NCEER-87-0027 "Design of a Modular Program for Transient Nonlinear Analysis of Large 3-D Building Structures," by S. Srivastav and J.F. Abel, 12/30/87, (PB88-187950, A05, MF-A01). This report is only available through NTIS (see address given above).

NCEER-87-0028 "Second-Year Program in Research, Education and Technology Transfer," 3/8/88, (PB88-219480, A04, MF-A01).

NCEER-88-0001 "Workshop on Seismic Computer Analysis and Design of Buildings With Interactive Graphics," by W. McGuire, J.F. Abel and C.H. Conley, 1/18/88, (PB88-187760, A03, MF-A01). This report is only available through NTIS (see address given above).

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NCEER-88-0003 "Substructuring Techniques in the Time Domain for Primary-Secondary Structural Systems," by G.D. Manolis and G. Juhn, 2/10/88, (PB88-213780, A04, MF-A01).

NCEER-88-0004 "Iterative Seismic Analysis of Primary-Secondary Systems," by A. Singhal, L.D. Lutes and P.D. Spanos, 2/23/88, (PB88-213798, A04, MF-A01).

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