
A Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy

by

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Abstract

We develop and apply an integrated modeling system to estimate fatalities from intentional release of 17 tons of chlorine from a tank truck in a generic urban area. A public response model specifies locations and actions of the populace. A chemical source term model predicts initial characteristics of the chlorine vapor and aerosol cloud. An atmospheric dispersion model predicts cloud spreading and movement. A building air exchange model simulates movement of chlorine from outdoors into buildings at each location. A dose-response model translates chlorine exposures into predicted fatalities. Important parameters outside defender control include wind speed, atmospheric stability class, amount of chlorine released, and dose-response model parameters. Without fast and effective defense response, with 2.5 m/s wind and stability class F, we estimate approximately 4000 (half within ~10 minutes) to 30,000 fatalities (half within ~20 minutes), depending on dose-response model. Although we assume 7% of the population was outdoors, they represent 60% to 90% of fatalities. Changing weather conditions result in approximately 50%- to 90%-lower total fatalities. Measures such as sheltering-in-place, evacuation, and use of security barriers and cryogenic storage, can reduce fatalities, sometimes by 50% or more, depending on response speed and other factors.

After an intentional release of chlorine in an office district, public responses such as sheltering-in-place could save many lives if rapid enough. However, previous work does not estimate how fast and effective such responses would be for several possible investments in attack detection, public alert, and building ventilation, nor whether such measures would be cost effective. We estimate public response times with investment
options in place, and resulting changes in fatalities. For each option, we also estimate system costs, and cost effectiveness in terms of cost per net death avoided. The results indicate that with the systems in place, responses are still likely to be too slow to save a significant number of people, and instead, most options would probably increase total fatalities. Median estimated cost per net death averted depends strongly on dose-response model and other factors, but is not low enough for any of the options considered to pass a cost-effectiveness test requiring $\leq 10M per statistical life saved across all of the chlorine exposure dose-response and ingress-delay models used. At this point, it seems inappropriate to invest in these options as a cost-effective way to reduce fatalities from chlorine attack in an office district.

A chlorine attack on an area with large numbers of people outdoors may result in very high fatalities. We apply an integrated modeling system to estimate fatalities from intentional release of 17 tons of chlorine from a tank truck at the National Mall in Washington, DC, under the most common weather conditions of the evening of July 4th, 2008. Without evacuation or a substantial buffer zone between the release and the crowd downwind, such an attack results in 30k-40k estimated fatalities. Evacuation with too small a buffer zone may not significantly reduce fatalities. Evacuation crosswind at 50 m/min after 1 minute, with 100 m buffer zone, reduces fatalities by 14-15% using estimated movement speed reduction from chlorine exposure, and 40-41% without estimated speed reduction. Potential difficulties in effective evacuation may instead suggest reliance on security measures to keep possible chlorine releases some distance away from the crowd. That can reduce fatalities without evacuation if a release is kept 600 m to 4 km away from the crowd, depending on dose-response model. However,
releases from a shorter distance upwind from the crowd can cause fatalities 22-47% higher than a release in the middle of the crowd.

A chlorine tank truck attack may cause thousands of fatalities, and public responses rapid enough to save many lives may often be infeasible. As a means of preventing chlorine truck attack, we consider the onsite generation of chlorine or hypochlorite at all US facilities currently receiving chlorine by truck. We estimate amounts of chlorine shipped by truck in the US, as well as the cost of generating chlorine at each facility. We then calculate system costs, and cost effectiveness in terms of cost per net death avoided. Median estimated amount of chlorine trucked in the US is 500k tons/year, with 80% going to water and wastewater treatment. The median increase in annualized costs across the US to generate chlorine or hypochlorite solution instead of shipping chlorine by truck is $800 million/year. Median estimated cost per death averted is $10M or less for US annual chlorine truck attack probability above 0.02, depending on dose-response model and other factors.
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Chapter 1: Introduction

1.1 Problem Statement

Many consider toxic-by-inhalation industrial chemicals such as chlorine as attractive weapons of mass effect for terrorists [1, 2]. The chemical industry has undertaken both voluntary and government-mandated efforts to assess and address chemical facility and transport security risks [3-7]. However, some argue these initiatives do not adequately protect the public and that more governmental regulation of chemical industry security and operation is required, especially to encourage chemical and process changes that directly reduce hazard [8-10].

There is a significant literature on the risk of accidental chemical release, allowing estimation of both accident consequence and probability [11-13], but there is little publicly available work that quantitatively evaluates risks and mitigation measures for a terrorist-caused release of an acutely toxic industrial chemical as a weapon of mass effect. Houghton [1] considers small releases of chlorine and other chemicals, and considers decontamination and medical treatment. However, those measures may have limited value, especially for larger releases. Chang et al. and Powell et al. have modeled chlorine attacks based on 100-ton releases from stationary chemical facilities [14, 15]. They consider options including enhanced detection, evacuation, shelter-in-place, decontamination and medical response capabilities. They conclude that none of these are likely to have significant effect in reducing fatalities, and estimate that their monetized benefits would be less than their costs. However, it is not clear that the options they consider represent the best available. For example, their improved-response options
assume the use of emergency broadcast and reverse-911 notification (resulting in mean
notification time of 15 minutes from a baseline of one hour) but do not discuss other
alternatives or more systematic changes that might further reduce response times.
Finally, although estimates have been made of the costs of reducing or modifying the use
and shipment of chlorine, these either do not aggregate estimated costs across the US [10,
16, 17] or they assume the imposition of unnecessarily drastic and expensive measures
such as the elimination of the use of all chlorine in pharmaceuticals [18].

This dissertation addresses the following questions:

- If terrorists released chlorine in a typical downtown area or at an outdoor
event, how many people would likely die, and how quickly, if protective actions
were not possible?

- How much could we reduce fatalities by preparing countermeasures, such
as installing sensors and warning systems, and training the public in order to
improve the speed and effectiveness of evacuation and sheltering-in-place?

- How much might risks be reduced if we were to use cryogenic storage of
chlorine instead of pressurized storage, or if we avoid transporting liquid chlorine
entirely by generating chlorine at end-user facilities?

- How effective are countermeasures if used in combination, and would any
of them depend on others being employed simultaneously?

- For each countermeasure or combination, what would be required to
implement it, and how much would that cost?
1.2 Scope

Many measures could reduce the risk of terrorist attack using chlorine. Table 1-1 lists and categorizes some of these.

<table>
<thead>
<tr>
<th>Table 1-1: Possible Countermeasures Against Chlorine Attack</th>
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<tbody>
<tr>
<td><strong>Security</strong></td>
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<tr>
<td><strong>Reducing probability of successful chlorine-release attack</strong></td>
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<tr>
<td><strong>Reducing public exposure to chlorine after release</strong></td>
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<tr>
<td><strong>Reducing harm after chlorine release</strong></td>
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</table>
Table 1 includes a number of possible countermeasures which are not modeled in this dissertation work. This dissertation does not evaluate any options which would primarily reduce the probability of a successful attack but not necessarily its consequences, which includes many security measures undertaken by both industry and government. While attack probability estimation would be difficult at best, there are fairly well-established models in the literature for estimation of acute health effects of a release. Options based on rerouting rail or road shipments of chlorine or relocating stationary facilities using chlorine could have value in addressing those sources of chlorine but may have little relevance to averting chlorine tanker-truck attacks, since tanker trucks or functional equivalents could be driven to targets far from areas where chlorine is usually found. The equipment and training of hazardous materials (hazmat) responders can mitigate vapor clouds from continuous chlorine releases, but may not be able to substantially affect the vapor cloud produced by the total instantaneous release of the contents of a container of pressurized chlorine. For protection of the general public, filters and absorbents, including improvised respiratory protection [19, 20] and water sprays [21] seem likely to be less protective and/or less cost effective than other measures considered in this dissertation. Finally, although rapid medical treatment might have significant value in reducing fatalities from acute chlorine inhalation [1], the number of victims in a large attack might overwhelm treatment facilities, preventing many from receiving care quickly enough.

Measures considered in this dissertation are extensions of existing practices, though their usefulness and cost effectiveness specifically as chlorine truck attack countermeasures is not clear from available literature. Sheltering and evacuation are both
standard practice and generally recommended [22] though the choice of which is best depends on circumstances [23]. Inherently safer technologies (IST) that reduce chlorine release hazards are routinely considered by the chemical industry, and their increased use is advocated by some public interest groups and as well as by the National Academies [24], though several industry groups oppose IST mandates. Security barriers to provide a buffer zone between a chlorine release and targets downwind could be similar to measures already taken to protect against vehicle-borne bombs at high-value targets and special events, though the cloud from a chlorine truck attack may be fatal at distances greater than the standoff distances commonly used for blast protection.

Some terrorism risk and decision analyses have framed the impact of terrorist attacks primarily in normative, benefit-cost terms, using nominal dollar values for the value of a statistical life and other possible impacts of a terrorist attack in order to compare the estimated societal benefits of defense options against their costs [15, 25]. Such benefit-cost analysis could be performed for chlorine attack defense strategies if we estimate numbers of less-than-fatal injuries, the costs of treating injuries, and indirect economic impacts of chlorine attacks. However, risk reduction measures may be justified on the basis of life-saving cost effectiveness without full benefit-cost assessments, if estimated baseline attack risk is high enough and countermeasure cost per fatality averted is low enough. US Office of Management and Budget guidance suggests that agencies’ regulations pass benefit-cost or cost-effectiveness tests using a value per statistical life in the range of $1-10 million [26-28].

One issue in decision analysis for defense against an adaptive adversary is how to account for reduction in benefits from mitigation measures if attackers respond to
defensive measures by changing targets, attack modes or methods [29, 30]. Attempting to anticipate changes in attacker strategy within the context of a particular attack scenario is a first step, but credibly anticipating changes to choice of target or attack mode is a problem on a larger scale, with compounded complexity and uncertainty. A particular attack scenario’s probability could be estimated while accounting for attacker choice between attack scenarios, using probabilistic terror attack risk models such as those of Risk Management Solutions [31]. However, benefit-cost analyses can also be performed while treating attack scenario probability as an exogenous parameter, such as in the analyses of von Winterfeldt and O’Sullivan [25] and Powell et al. [15]. This dissertation takes such a parametric approach in assessing attack countermeasure cost effectiveness. Uncertainties about attack scenario probability may then be addressed separately from uncertainties about the value of countermeasures within the context of a particular attack scenario.

1.3 Research Objectives and Structure of Dissertation

This dissertation addresses the following research objectives:

- Estimate the number of fatal exposures if terrorists released chlorine in a typical urban core or at an outdoor event, first if no protective action were possible and second if various mitigation measures were used either singly or in combination.
- Estimate implementation costs for each countermeasure or combination.
- Assess life-saving cost effectiveness of each countermeasure or combination.

In Chapter 2, we develop and employ an integrated modeling system to estimate the number of fatal exposures if terrorists released chlorine in a typical urban core, both with
and without various mitigation measures. The modeling system combines public response, chemical source term, atmospheric dispersion, building air exchange, and dose-response sub-models. The public response model specifies the locations and actions of people in the area. The chemical source term model predicts mass, phase and other characteristics of the cloud of chlorine vapor and aerosol immediately following a chlorine release. The atmospheric dispersion model then predicts how a chlorine cloud spreads and moves outdoors over time. The building air exchange model simulates the movement of chlorine from outdoors into buildings at each location. The resulting chlorine-exposure profiles are translated by the dose-response model into predicted fatalities. We use the modeling system to investigate the effects of parameters reflecting mitigation measures, such as public response times for evacuation or sheltering-in-place. We also investigate sensitivity parameters that may be predicted or influenced by attackers, such as weather conditions or volume of chlorine released, as well as parameters not predicted or influenced by either attackers or defenders, such as dose-response relationships. Mitigation measures considered include sheltering-in-place, evacuation, security barriers, and cryogenic storage instead of pressurized storage.

In Chapter 3, we assess costs, life-saving effectiveness, and cost effectiveness of several investment options for sheltering-in-place capability enhancement for an office district. To do that, we estimate what new systems would be required, how effective they would be in reducing fatalities, and how much they would cost. We consider potential improvements in chlorine attack detection, public alerting, and building ventilation control. For each sheltering response option, we estimate sheltering response times and alert compliance rates, which, along with weather conditions, choice of dose-response
model and other factors, allow us to estimate net fatalities avoided. For each option, we estimate up-front costs of necessary equipment, costs of false alarms, and other factors, and use these to estimate annualized costs. With net fatalities avoided and annualized costs, we estimate cost per net death avoided, as a function of attack scenario probability.

The integrated models of Chapter 2 are too computationally intensive to run large numbers of simulations quickly, so we use the integrated models to generate response surfaces that approximate the input-output relationships of the integrated models over required parameter ranges but require much less computation time. Input parameter value distributions are estimated using available information in emergency response literature and similar sources. Probability distributions of outputs are estimated using Latin hypercube sampling.

In Chapter 4, we examine another chlorine truck attack scenario, in which the target is a special event with large numbers of people outdoors. We estimate fatalities both with and without mitigation measures, including evacuation and buffer zones from security barriers, using the integrated modeling system developed in Chapter 2.

In Chapter 5, we assess the cost and cost effectiveness of a chlorine control measure, i.e. the onsite generation of chlorine (or equivalent amounts of hypochlorite solution, where appropriate) at end-user locations instead of delivering it by truck. We first estimate the amounts of chlorine being delivered by truck in the United States. We then estimate up-front costs of necessary equipment, as well as electricity and other costs, and use these to estimate annualized costs. Estimates of attack fatalities possible without onsite generation are based on the modeling work in Chapter 2. Finally we estimate cost
per net death avoided, as a function of attack scenario probability. We estimate probability distributions of inputs and outputs using Latin hypercube sampling.

In the conclusion in Chapter 6, we summarize the implications and caveats of the previous four chapters, and make further recommendations for public policy and future research.
Chapter 2: Chlorine Truck Attack Consequences and Mitigation

2.1 Introduction

While terrorists have not yet used toxic-by-inhalation industrial chemicals such as chlorine as a weapon of mass effect in the West, many consider them attractive to terrorists [1, 2], and in 2006-2007 there were several small attacks with vehicle-borne explosives and containers of chlorine in Iraq. The chemical industry has undertaken both voluntary and government-mandated efforts to assess and address chemical facility and transport security risks [3-7]. However, some argue these initiatives do not adequately protect the public and that more governmental regulation of chemical industry security and operation is required, especially to encourage chemical and process changes that directly reduce hazard [8-10].

Literature on accidental release consequence and probability is extensive [11-13], but a terrorist may be able to cause a chemical release scenario that would be unlikely or even impossible as an accidental release. Rapid decontamination and medical treatment may reduce probability of fatality from chlorine exposure [1], but large attacks could produce a number of victims high enough to overwhelm treatment capacities and reduce its value as a response option. Powell et al. [15] model 100-ton chlorine releases, with base-case fatality estimates ranging from 0 to 1563, and a mean of 78. They estimate that evacuation and shelter-in-place orders delivered by first responders driving through neighborhoods or by reverse-911 calls, which they estimate would take a total of 90 to 135 minutes to deliver, would not significantly reduce fatalities in a large chlorine attack.
However, faster sheltering or evacuation responses may be possible with other technologies or techniques.

In this chapter, we develop an integrated modeling system and apply it to a set of attack scenarios involving the release of the contents of a tanker truck of chlorine. We choose chlorine because of its volatility, toxicity and ubiquity as an industrial chemical [1, 2, 12, 13] and we choose a tanker truck because one might be driven to any accessible location. We estimate the effects of simple strategies that attackers might use to increase fatalities, such as timing an attack to coincide with particular weather conditions. We also estimate the effects of measures that defenders might use to decrease fatalities, such as rapid sheltering-in-place actions. We address the following questions: If terrorists released chlorine in a typical urban core, how many people might die, and how quickly, if protective actions were not taken? What factors are most important for determining the number of fatalities? How much could we reduce fatalities by preparing mitigation measures, and how quickly would these need to be used to be effective? Would cryogenic storage of chlorine (as opposed to pressurized storage) reduce fatalities by slowing chlorine release?

2.2 Model Description

In order to estimate the fatalities that might result from a chemical release scenario, we develop a modeling system that combines public response, chemical source term, atmospheric dispersion, building air exchange, and dose-response sub-models (see Figure 2-1). The public response model specifies the locations and actions of people in the area. The chemical source term model predicts mass, phase and other characteristics of the
cloud of chlorine vapor and aerosol immediately following a chlorine release. The atmospheric dispersion model then predicts how a chlorine cloud spreads and moves outdoors over time. The building air exchange model simulates the movement of chlorine from outdoors into buildings at each location. The resulting chlorine-exposure profiles are translated by the dose-response model into predicted fatalities.

Weather Conditions, Public Response Rules, and Other Inputs

- Chemical Source Term
- Atmospheric Dispersion
- Building Air Exchange
  - Indoor Exposures
  - Outdoor Exposures
- Dose-Response
  - Estimated Fatalities

**Figure 2-1: Overview of Modeling System Developed to Estimate Fatalities from a Chlorine Attack**

The atmospheric dispersion model outputs allow chlorine concentration calculation at any point in the area of the chlorine release, at each of sixty output timesteps. The first sixty timesteps are determined by the atmospheric dispersion model, depending primarily on specified weather conditions, and generally run between fifteen seconds and several minutes each. We then continue indoor-outdoor building air exchange calculations with timesteps of one minute each until a total of 180 minutes of simulated time has passed, which is generally long enough to capture essentially all fatal exposures for these scenarios. We impose a grid on the area, and calculate chlorine concentrations at each gridpoint. Horizontally, the grid has square cells that are 25 m on a side, beginning 350
m upwind and extending 5250 m downwind of the release, and approximately 500 m in both crosswind directions. Vertically, gridpoints begin at 2 m height above ground, approximately the height of a standing person, and go up by 4 m per gridpoint (approximately the distance between floors of a building) to a maximum of 38 m above ground (the tenth-floor level). We assume people and buildings are distributed uniformly across the area affected by the chemical cloud, and a specified ratio of people initially indoors to people initially outdoors. We treat people in vehicles as either outdoors (if their windows are open, or they leave their vehicles) or indoors (if their windows and air vents are shut, or they move into buildings nearby).

### 2.2.1 Public Response Model

First we consider the case where no defensive response is made to a chlorine attack. In a no-defense-response case, we assume all people in the area stay where they are (i.e. neither people outdoors nor indoors try to change positions) and take no other protective action (e.g. building ventilation systems are not shut down). We then consider cases where the public responds to an alert provided by authorities soon after an attack occurs (potentially based on detection and warning systems not yet in place), as well as cases where no external alert is provided but people take protective action after detecting (via odor or otherwise) dangerous chlorine concentrations in their area. For mitigation, we consider evacuation, sheltering in place, and use of security barriers.

For evacuation, we assume systems have been installed to rapidly detect and alert all people outdoors in the area. Given an alert, people outdoors are assumed to begin walking at a specified time and speed, and continue walking until they either leave the area.
toxic-cloud area or die. We assume people have enough training and/or information so they walk crosswind, not downwind, away from the chlorine release, as is generally recommended [22]. We simulate evacuation only of people who are already outdoors at the time of a chlorine release, and assume any people who are indoors at the time of a chlorine release stay indoors, either because of training or direction by authorities.

We also consider the use of a security perimeter around people outdoors, to ensure distance between people the release and people outdoors. In these cases, we assume attackers approach people outdoors from upwind and release chlorine at the edge of the security perimeter.

For sheltering-in-place, we consider people outdoors moving indoors, as well as shutdown of building ventilation systems. For people outdoors, we consider cases where people receive, or do not receive, external alert of attack. For people receiving an alert, we assume that all alive at that time go into a nearby building at a specified time after the attack. Where people outdoors do not receive an attack alert, we assume that people have training (e.g. per Davis et al. [19]) such that they start walking towards a nearby building once they reach an irritant level of chlorine exposure (e.g. above 5 ppm chlorine), and then take a specified amount of time to get indoors if not delayed by further chlorine exposure. We assume that people indoors stay indoors, and that attack alerts are sent to shut down building ventilation systems at a specified time. The goals of simultaneously moving people indoors and effectively sealing buildings against chlorine intrusion might be difficult to reconcile. Potential building ventilation system solutions include positive-pressure air supply, adsorption filters, and air intakes well above street level.
Exposure to chlorine may reduce the effectiveness of evacuation and sheltering, as people suffer health effects. Various sources estimate the chlorine odor perception threshold at 0.02-0.05 ppm [32] to 3.5 ppm [33], and ~100 ppm is reported to incapacitate after a few seconds [34]. Based on these values and other evidence [12, 22, 32-37], we have created rules for chlorine-exposure delays during both evacuation and sheltering. For evacuation by people outdoors, we assume that at 30-60 ppm chlorine, walking speed is 50% of original speed, and above 60 ppm, walking speed is 25% of original speed. For sheltering by people outdoors, we assume that at 30-60 ppm chlorine, ingress is delayed by two minutes, and above 60 ppm, ingress is delayed by an additional 5 minutes. For cases where people begin sheltering movement after chlorine concentration reaches an irritant threshold, we assume they begin movement at 5 ppm; subsequent delay rules are then as previously described. These rules are implemented at every time interval. For example, if chlorine concentration goes from 10 ppm in timestep A to 100 ppm in timestep B, sheltering time is delayed by five minutes, not by seven. These rules assume that chlorine exposure slows people but does not actually stop their movement until they receive a fatal exposure according to the dose-response model used in a given simulation run, which may overestimate sheltering and evacuation effectiveness.

One major limitation of our behavioral model is that we assume people take no actions besides those we specify, or in the no-defense-response case we assume they effectively take no action at all, which may not be realistic [12, 22, 35, 38-43]. However, it is a necessary simplifying assumption for the purposes of this chapter.
2.2.2 Chlorine Source Term Models

At atmospheric pressure, chlorine’s boiling point is -34°C, and at 27°C, chlorine’s vapor pressure is 8.1 atmospheres. Chlorine is generally stored and transported as a liquid, and there are two methods of keeping it in the liquid phase: high pressure or low temperature. Pressurized storage is more common. If a vessel containing a superheated liquid develops a large rupture, a portion of the liquid undergoes flash vaporization. The flashed fraction is determined by simple heat balance, with the latent heat of vaporization supplied by the non-flashing liquid dropping from its initial temperature to its boiling point [12, 44]. Much or all of the non-flashed liquid becomes entrained with the exiting vapor stream and breaks into droplets, forming an aerosol, and then either evaporates and adds to the vapor cloud mass or falls to the ground as “rainout”. Experiments indicate that the fraction of non-flashed liquid chlorine that becomes entrained would be ≥98% at ≥0°C ambient [45], and droplet rainout is 30-40% at 0°C ambient and ≤4% at ≥20°C ambient, with rainout pools often evaporating very quickly [46-48]. For the ambient temperatures and attack scenario we consider, we assume total entrainment and zero rainout, which is simple and fairly realistic, though these assumptions may result in an upward bias in fatality estimates, especially for low ambient temperatures (e.g., 0°C).

We also consider cryogenic storage of chlorine below its boiling point as a possibly lower-risk alternative to high-pressure storage. If such a vessel is ruptured, the contents will not undergo flash vaporization but instead will form a spreading and boiling liquid pool, creating chlorine vapor but no significant amounts of chlorine aerosol. For pool spreading, we use the equations given by Webber [49] for a spreading, boiling pool on a smooth, horizontal, solid surface, in which expansion is driven by gravity and resisted by
viscous friction. For an instantaneous release of volume $V$ at time $t$ whose only reduction in volume is due to evaporation, $dV/dt = WA$, where $W(t)$ is the vaporization rate and $A(t)$ is the pool area. For a circular pool of radius $R(t)$ and radial flow velocity $dR/dt = U(t)$,

$$\frac{dU}{dt} = \frac{4gH(1-s)}{R} - F$$

(Eq. 2-1)

where $g$ is the gravitational acceleration constant, $H = V/A$ is the mean pool depth, and $F$ is a frictional resistance term corresponding to either laminar or turbulent resistance, depending on the Reynolds number at the time. The pool shape factor $s$ is given by $s = b/H$, where $b$ is the minimum depth of the pool, which depends on the liquid and the surface but is of the same order of the capillary depth $(\sigma/g\rho)^{1/2}$, where $\sigma$ is the liquid surface tension. For the pool vaporization rate $W(t)$ we use a one-dimensional heat conduction equation [44] given by

$$W(t) = \frac{k_s(T_s - T)}{(\pi \alpha t)^{1/2}}$$

(Eq. 2-2)

where $k_s$ is the thermal conductivity of the surface, $T_s$ is the temperature of the surface, $T$ is the temperature of the liquid pool, and $\alpha$ is the thermal diffusivity of the surface. We assume the ground surface begins at the same temperature as the ambient air. We couple and evaluate the equations numerically with a timestep of 0.01 seconds. We stop pool spreading when the pool reaches depth $b$, but assume vaporization and heat conduction continues until the liquid pool is fully vaporized. We then calculate mean pool area, evaporation rate, and duration for input to the atmospheric dispersion model.
2.2.3 Atmospheric Dispersion Model

Because of its initially high density, a chlorine cloud’s dispersion is first dominated by gravity-driven slumping. However, once enough mixing and warming have occurred, the density difference will be low enough that normal turbulence-driven passive dispersion dominates [50]. In order to model both regimes of chlorine dispersion, we use the SLAB atmospheric dispersion model [51]. SLAB is a Lagrangian model based on equations for conservation of species, cloud mass, energy, and momentum in three dimensions, with cloud properties averaged over its volume. Ambient velocity is a function of height, but cloud velocity is averaged over its height. SLAB accounts for turbulent mixing with vertical and horizontal entrainment velocities, which depend on meteorological parameters (wind speed at 10 m height, Pasquill stability class, and surface roughness). SLAB assumes no dry or wet deposition. It accounts for evaporation of entrained aerosol and condensation of water vapor, assuming thermodynamic equilibrium. The transition from density-driven to passive dispersion is modeled using a shape parameter, which gradually changes the cloud’s concentration profile from a sharply defined box to a Gaussian distribution in three dimensions. Hanna et al. [52] compared SLAB-predicted ground-level maximum plume centerline concentrations with field test observations for continuous and instantaneous releases in open fields, and found agreement within a factor of two for both geometric mean bias and scatter, similar to other available models tested.

Because SLAB assumes a flat surface free of obstructions taller than the chlorine vapor cloud, such as buildings, using SLAB to model dispersion in an urban environment probably biases fatality estimates upwards. From overhead images, we estimate areal
densities of buildings in business districts of New York and Washington DC at around 70%. Field tests show that cubical obstacle areal densities of ~10% cause little effect on the lateral characteristics of passive gas dispersion [53], but 44% density caused initial increases in lateral or crosswind dispersion consistent with a one-unit shift toward lower stability class (e.g. from C to B), and slight initial reductions in ground-level centerline concentrations, though these effects disappeared after approximately six cubes downwind [54]. Presence of cubical obstacles also increased passive gas cloud height by ~40%, though taller obstacles would probably have less effect on vertical dispersion [53]. Decreasing atmospheric stability generally increases dispersion, which typically reduces predicted fatalities (see Section 5), though increased dispersion could also increase fatalities in some situations. If field-test cubes correspond to real-world city blocks, their dispersion effects may be important, since typically half or more of our models’ predicted fatal exposures occur in the first six city blocks (600-1200 m) downwind of the release.

We use output from SLAB to calculate outdoor chlorine concentration as a function of time, at specified points in space. These are used directly in calculating chlorine exposures for people outdoors. To calculate chlorine exposures for people indoors, outdoor chlorine concentrations are passed to the building air exchange model.

### 2.2.4 Indoor-Outdoor Building Air Exchange Model

In the area of a chlorine vapor cloud, chlorine vapor may infiltrate buildings or enter their ventilation system air intakes. If the air in a building space is well mixed, then the rate of change of chlorine concentration indoors is given by
where \( C \) is the chemical concentration, \( t \) is the time, \( \lambda \) is the indoor-outdoor air exchange rate, and subscripts \( i \) and \( o \) refer to indoor and outdoor, respectively [12]. \( C_i(t) \) is then evaluated numerically, where \( C_o(t) \) at a given location comes from the dispersion model output, and \( C_i(t=0)=0 \). We treat each floor in a building as its own space to reflect changes in chemical concentration of a dense gas cloud with height above ground. Assuming well-mixed indoor spaces may result in somewhat upward-biased fatality estimates, without several minutes of normal ventilation system operation after contaminant introduction [55-57].

The dispersion and building air exchange models are used to produce concentrations as a function of location and time for both outdoor and indoor spaces. These are fed to the dose-response model to determine the probability of fatality for people across locations.

2.2.5 Dose-Response Model

We use a number of dose-response models for estimation of fatality probability from chlorine inhalation exposure, all with probit (probability unit) equation form [39, 40, 58-63]. By definition, the probit variable is normally distributed and has a mean value of five and a standard deviation of one. We use a convenient form of the conversion from probit variable \( Y \) to probability \( P \), where

\[
P = 0.5 \left[ 1 + \frac{Y - 5}{|Y - 5|} \text{erf} \left( \frac{|Y - 5|}{\sqrt{2}} \right) \right]
\]  

(Eq. 2-4)
and where “erf” is the error function [18]. The probit equations used in this chapter are of the form,

\[ Y = k_1 + k_2 \ln \left( \sum_i C_i^n T_i \right) \]  

(Eq. 2-5)

where vapor concentration \( C(t) \) is evaluated for each time-step \( i \) of duration \( T_i \) [44], and \( k_1, k_2 \) and \( n \) are constants determined largely by animal experiments. Where not otherwise specified, we use the constants developed by Withers and Lees [35, 59, 64] for estimating probability of fatality from acute inhalation exposure to chlorine, assuming an inhalation rate of 12 L/min for “standard” physical activity, “applicable to most daytime activity”. Withers and Lees [59] derive separate values for a regular population of healthy adults, and a more vulnerable population of sensitive individuals, the latter comprised principally of “children, old people, and people with respiratory or heart disorders”. Withers and Lees estimate that 25% of the population is in the vulnerable category, 75% is in the regular category, and when using the Withers and Lees dose-response model parameter values, we run each simulation once with each dose-response model and then weight-sum the two results. By default, the Withers and Lees model assumes no medical treatment.

There are several limitations of available dose-response models for acute fatality from chlorine exposure, probably the greatest of which are their uncertainties. Dose-response models resulting in lower fatality estimates (e.g. RPA) seem more likely to be accurate than models resulting in higher fatality estimates (e.g. Eisenberg et al.), since they were typically developed later, with more data available from animal experiments. We address sensitivity to choice of dose-response model in Section 5.
2.3 Scenario Description and Parameter Values

The basic scenario we consider is an instantaneous release of the 17-ton cargo of a chlorine tanker truck, in an office or downtown area of a major city, during normal business or commuting hours. An outdoor release of chlorine in a downtown or office area might see higher fatalities than most other areas because of high population density, high rates of ventilation with outdoor air, and high numbers of people outdoors.

We divide parameters into three categories, according to who may influence them: attackers, defenders, or neither attackers nor defenders.

2.3.1 Parameters Influenced By Attackers

We assume that attackers would time their attacks to coincide with weather conditions that would produce higher fatalities. Weather conditions varied here include temperature (summer: 27°C, fall/spring: 20°C, winter: 0°C), time of day (day/night), wind speed (at 10 m above ground), and Pasquill stability class (A-F). Pasquill classification defines night as the period from one hour before sunset to one hour after dawn [65-67], which by our estimation can overlap with normal business and commuting hours much of the year, but not in summer. We explore sensitivity of results to weather conditions in Section 5.

2.3.2 Parameters Influenced by Defenders

Measures such as chemical sensors, public training programs and automatic response systems might enable much faster and better-informed public responses to a chlorine
attack. We examine the effects of mitigation measures implemented at 1, 2, 5, 10, 15 and 30 minutes after chlorine release, or at 1, 3, and 5 minutes after local chlorine concentrations reach irritant levels, depending on the measures considered.

For normal ventilation system operation, we consider indoor-outdoor air exchange rates of 3 and 1 ACH (air changes per hour). Where not otherwise specified, we use 3 ACH, which may give upward bias to those fatality estimates [13, 68, 69]. For ventilation shutdown, we consider 1 and 0 ACH [69-71], though in some cases 0 ACH may require the use of positive-pressure systems and other measures.

For evacuation, we use two walking speeds, 25 and 50 m/min, generally within the abilities of adults [72, 73]. On most city streets, we estimate people could walk 20-30 m or less to get to the nearest doorway, which would take about half a minute or less at normal walking speeds, though chlorine exposure could impede movement. Congestion may also slow movement in places with crowd densities above 1-2 people/m² [74], but our assumptions result in mean outdoor population density of 0.01 people / m².

For security barriers, we consider the following distances between a chlorine release and the edge of a crowd outdoors: 0, 100, 200, 500, 1000, and 2000 m. We explore the effects of mitigation measures in Section 7.

2.3.3 Parameters Not Influenced by Attackers or Defenders

For some parameters, we generally assume base-case values. Some of these parameters are ones that would not be influenced by either attackers or defenders, such as dose-response model constants. Other parameters might be affected by attackers or defenders, but changes in their values would generally have simple linear effects on
fatality estimates. Changes in indoor and outdoor population densities would produce proportional changes in fatalities until ingress or egress bottlenecks were reached, i.e. if people cannot get through streets or doorways quickly enough because too many others are trying to do the same. Table 2-1 lists parameters and their base-case and sensitivity-analysis values. The fraction of people outdoors is for daytime [75], and the daytime population density, number of floors per building, and fraction of buildings with air intakes at each floor are based on the Washington, DC office district [76]. Buildings without air intakes at each floor are assumed to have air intakes at the 10th floor level. Chlorine container sizes are based on several that are commonly used in chlorine transport by road and rail [12, 77, 78]. Surface roughness height is estimated as ~10% of height of nearby objects [51], e.g. automobiles. Minimum downwind distance for completion of SLAB dispersion calculation was adjusted to provide adequate spatial and temporal coverage of the dispersion domain. The initial height of a vapor cloud from pressurized storage is estimated as either approximately the height of a tank truck (3 m), or with initial cloud height approximately equal to initial cloud radius (6 m). The initial height of cryogenic liquid pool is based on the approximate height of a tank truck’s underside. Base-case thermal characteristics of the surface under a cryogenic pool are for asphalt, the sensitivity analysis values are for concrete [79]. Minimum cryogenic liquid pool depth is estimated per Webber [49]. We analyze sensitivity to changes in these parameters in Section 5.
<table>
<thead>
<tr>
<th>Parameter and Source for Values</th>
<th>Base-Case Value</th>
<th>Sensitivity Analysis Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population density</td>
<td>158,000 capita/mi$^2$</td>
<td>NA</td>
</tr>
<tr>
<td>Number of floors of buildings</td>
<td>10</td>
<td>NA</td>
</tr>
<tr>
<td>Fraction of people outdoors</td>
<td>7%</td>
<td>NA</td>
</tr>
<tr>
<td>Fraction of buildings with air intakes at each floor</td>
<td>20%</td>
<td>NA</td>
</tr>
<tr>
<td>Mass in chlorine container</td>
<td>17 tons</td>
<td>1, 90 tons</td>
</tr>
<tr>
<td>Surface roughness height</td>
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<td>0.075 m</td>
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<tr>
<td>Relative humidity</td>
<td>50%</td>
<td>1, 99%</td>
</tr>
<tr>
<td>Minimum downwind distance for completion of SLAB dispersion calculation</td>
<td>4000 m</td>
<td>8000 m</td>
</tr>
<tr>
<td>Initial height of cloud for pressurized storage</td>
<td>3 m</td>
<td>6 m</td>
</tr>
<tr>
<td>Fraction of non-flashed liquid chlorine entrained for pressurized storage</td>
<td>100%</td>
<td>0, 22, 43, 65, 86%</td>
</tr>
<tr>
<td>Thermal conductivity of surface under cryogenic pool</td>
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<td>1.28 W/m-K</td>
</tr>
<tr>
<td>Thermal diffusivity of surface under cryogenic pool</td>
<td>0.0036 cm$^2$/s</td>
<td>0.0066 cm$^2$/s</td>
</tr>
<tr>
<td>Initial height of cryogenic liquid pool</td>
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<td>0.5 m</td>
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<tr>
<td>Minimum cryogenic liquid pool depth</td>
<td>1.3 mm</td>
<td>2.6 mm</td>
</tr>
</tbody>
</table>

### 2.4 Example Simulation Run Results

To illustrate the use of the modeling system, we give the results of an example simulation run assuming a summer day (27°C ambient), 7 m/s wind speed, and Pasquill stability class D, with no defense response. After rupture of the pressure vessel of chlorine, 20% of the contents undergo flash vaporization and the other 80% is entrained as aerosol droplets. SLAB output indicates that the aerosol portion of the cloud vaporizes within fifteen seconds. High density drives the cloud’s spread for about a minute, after which passive turbulence dominates dispersion. To illustrate spatial extent, Figure 2-2 shows ground-level chlorine concentration contours, one minute after chlorine release.
After completing the simulation run, calculating exposures, and using the Withers and Lees dose-response model for all locations in the area affected by the chlorine cloud, Figure 2-3 shows fatalities for the example conditions as a function of time. Fatal exposures from an outdoor chlorine release occur more quickly for people outdoors than indoors; in this example, over 60% of outdoor fatalities occur within the first two minutes. Although only 7% of people in the area are assumed to be outdoors, they represent 91% of predicted fatalities after 60 minutes, and a higher proportion before that. These results suggest that seeking shelter in buildings might be a promising defense strategy, and that events with large crowds outdoors could be especially vulnerable and
may benefit from security barriers and other measures (see Section 6 for more analysis of such measures). Most fatalities indoors are people on the first floor or two, in buildings with air intakes on each floor, not in buildings with ventilation system air intakes at roof level.

![Figure 2-3: Fatalities as Function of Time in Example Simulation Run](image)

### 2.5 Sensitivity Analysis for Base Case

To gauge the importance of selected parameters not directly affected by mitigation measures, we estimate fatalities when varying the values of those parameters, assuming no defense response.

Figure 2-4 gives the result of simultaneously varying wind speed and stability class for pressurized storage. (NAs are “not applicable” combinations.) Results for cryogenic storage were roughly similar. When varied simultaneously over the ranges considered, wind speed and Pasquill stability class are important parameters, causing variation of fatalities from approximately 300 to 8000 when using the Withers and Lees dose-
response model constants. Variation in ambient temperature from 0 to 27°C has relatively little effect, causing ~10% difference in fatalities, with higher temperatures causing higher fatalities. Of the conditions considered, the highest no-defense-response fatalities (both indoors and outdoors) are produced by releases with stability class F and wind speed 2.5 m/s.

Predicted fatalities are highly sensitive to choice of dose-response parameter (probit equation) values. There are essentially three groups of dose-response model parameter sources: the high-range fatality estimate models, Eisenberg et al. [61] and Perry and Articola ([58]); the mid-range fatality estimate Withers and Lees model ([59]); and the low-range fatality estimate models, RPA [63] and Harris and Moses [39], ten Berge and van Heemst [40], TNO [62], and World Bank [60]. Differences in predicted fatalities roughly correspond to model estimates of the chlorine concentration causing fatality in
50% of people exposed for 30 minutes, or the 30-minute LC50, which is 34 ppm for Eisenberg et al. [61] and 418 ppm for RPA [39]. Where not otherwise specified, we use the Withers and Lees model. Compared to the no-defense-response, highest-fatality-weather estimate of 8000 fatalities for the Withers and Lees dose-response model, the low-range estimates are about a factor of two lower (e.g. 3700 for RPA), and the high-range estimates are about a factor of four higher (e.g. 33,000 for Eisenberg et al.). The fraction of people outdoors among estimated fatalities in the no-defensive-response case, under highest-fatality weather conditions, is 60% for Eisenberg et al., 80% for Withers and Lees, and 90% for RPA dose-response constants.

The speed with which estimated fatalities occur is also sensitive to both weather conditions and dose-response model. Figure 2-5 shows total fatalities as a function of time for several dose-response models, for both highest-fatality and median-fatality weather conditions at each point in time. The highest-fatality values represent the maximum that terrorists could cause if they time attacks with weather conditions producing high fatalities. The median values serve as a rough indicator of the central tendency of fatalities across the full set of weather conditions considered. Which weather conditions cause highest fatalities at each moment in time depends on several factors, including the time after chlorine release. There is more time for response, or response at a particular time averts a greater proportion of no-defense-response fatalities, if higher-fatality-estimate (low LC-50) dose-response models are correct. Under highest-fatality weather conditions, the time until 50% of eventual fatalities are reached is approximately 22 minutes with Eisenberg et al., 15 minutes with Withers and Lees, and 8 minutes with RPA dose-response models. Total fatalities under median-fatality weather conditions are
approximately 20% of total fatalities under highest-fatality weather conditions for Eisenberg et al., 10% for Withers and Lees, and 20% for RPA dose-response. Under many weather conditions, there will be less time to save lives than under highest-fatality weather conditions. Under median-fatality weather conditions, the time until 50% of eventual fatalities are reached is 4 minutes for Eisenberg et al., 2 minutes for Withers and Lees, and 2 minutes for RPA dose-response.

For the remaining parameters in the sensitivity analysis, we vary parameters one at a time. Unless otherwise specified, for the following analyses in this section we assume a total instantaneous release from pressurized storage, with 2.5 m/s wind, stability class F, 20°C ambient temperature, and no defense response.
Some sensitivity analysis results are too simple to warrant figures or tables in this chapter. Estimated fatalities are approximately proportional released chlorine mass, which depends on chlorine container size and entrainment of liquid chlorine (where un-entrained liquid remains in the container and does not contribute to the vapor cloud). More specifically, increases in outdoor fatalities are fairly proportional to increases in released mass, but increases in indoor fatalities are disproportionately high. That is probably because larger-mass releases lead to larger and longer-lasting clouds. For people outdoors, fatal exposures typically occur quickly, so cloud size is more important than cloud duration. For people indoors, exposures are strongly dependent not just on cloud size but also on cloud duration. The result indicates rail transport, with tank cars each carrying 90 tons of chlorine, may be a very significant hazard if its route goes through a densely populated area.

Specified changes in other selected parameters affected total fatalities for a no-defense-response case by less than 15% (and less than 1% for most parameters). These parameters include surface roughness, relative humidity, initial height of cloud (for pressurized storage), surface material (for cryogenic storage), initial height of cryogenic pool, and minimum depth of cryogenic pool.

### 2.6 Mitigation Measure Analysis

To assess ways in which defenders might reduce fatalities, we estimate fatalities when employing each of several different measures, including sheltering-in-place, evacuation, security barriers, and cryogenic storage instead of pressurized storage.
Where not otherwise specified, we use highest-fatality weather conditions, Withers and Lees dose-response, and air exchange rate of 3 ACH for all buildings in the area.

### 2.6.1 Seeking Shelter: Sheltering-In-Place for People Outdoors at Time of Attack

For sheltering-in-place, first we consider the case where people outdoors at the time of attack receive an alert of attack, then move indoors. (Note that if people outdoors move indoors, we still refer to them as outdoor fatalities.) We calculate outdoor fatalities as a function of how soon after a chlorine release people outdoors get indoors, before delays from chlorine exposure. We also compare cases where chlorine exposure causes no delay, to cases with our estimated rules for such delays. Figure 2-6 shows the results. For 50% reduction of outdoor fatalities, people would need to move indoors after approximately ten minutes if chlorine exposure does not delay movement. However, estimated delays from chlorine exposure effectively add four to seven minutes to ingress time, increasing fatalities by ~1000. Sensitivities to weather and dose-response model are similar to those for fatalities as a function of time without defense response. For 50% outdoor fatality reduction, people would need to move indoors after approximately 20 minutes with the Eisenberg et al. dose-response model, vs. 7 minutes with RPA dose-response. Under median-weather conditions, if people get indoors after five minutes, reduction in outdoor fatalities range from 24% with Eisenberg et al. to 0% with RPA dose-response.
Next we consider the case where no rapid alert system is in place, but instead people have enough training to independently recognize chlorine exposure (e.g. by smelling it, instead of hearing an alarm) and rapidly take shelter. We calculate outdoor fatalities as a function of time between when people decide to seek shelter and when they arrive indoors, if not delayed by chlorine exposure. Figure 2-7 shows the results. For 50% reduction of outdoor fatalities, people would need to move indoors approximately four minutes after exposure to ≥5 ppm chlorine, if chlorine exposure does not delay movement. However, estimated delays from chlorine exposure effectively add four minutes to ingress time, increasing fatalities by ~2000. Sensitivities to dose-response model and weather conditions are similar to those for sheltering with external warning.
2.6.2 Improving Shelter: Sheltering-In-Place for People Indoors at Time of Attack

Next, we consider sheltering for people indoors at the time of the chlorine attack, i.e. shutting down ventilation systems to reduce indoor air contamination. Figure 2-8 shows indoor fatalities as a function of time when ventilation is shut down, for several building air exchange rates before and after ventilation shutdown. To achieve a 50% reduction in fatalities for people indoors at the time of the attack, building air intakes would need to shut down within approximately two to six minutes, depending on starting and ending ACH. A lower starting or normal-operation ACH allows more shutdown time, and also reduces fatalities without ventilation shutdown. In some cases, it would be better not to shut down ventilation, since doing so can trap enough chlorine inside to cause a net
increase of indoor fatalities if shutdown takes more than approximately five minutes, depending on starting and ending ACH. Similar trends and critical times are seen if using other dose-response models under highest-fatality weather conditions. Under median-weather conditions, ventilation shutdown must occur in less than one minute to avoid fatality increases.

![Diagram](image)

**Figure 2-8: Effects of Reducing Building Ventilation Rate (Air Changes per Hour or ACH)**

### 2.6.3 Evacuation and Security Perimeters

For people outdoors in areas without accessible buildings nearby that can be used for shelter, evacuation may be an appropriate response to a chlorine attack. Authorities may also implement security barriers to ensure distance between a chlorine release and people outdoors in particular areas. In some cases, these measures may be combined.
For evacuation, we consider the case where all people outdoors receive an attack alert and begin walking crosswind away from the chlorine cloud, and continue walking until they either leave the toxic-cloud area or die. Figure 2-9 shows outdoor fatality estimates as a function of the time after chlorine release when people begin walking, with and without chlorine-exposure delay rules, assuming 50 m/minute walking speed. To achieve a 50% reduction in estimated outdoor fatalities, evacuation crosswind at 50 m/min would need to begin after approximately 12 minutes if chlorine exposure does not cause movement delays. However, estimated delays from chlorine exposure effectively halve fatality reductions. Walking speed is also important. To achieve a 50% reduction in estimated outdoor fatalities, evacuation crosswind at 25 m/min would need to begin after approximately four minutes if chlorine exposure does not cause movement delays, and in less than one minute with delay rules. Sensitivity to dose-response model is similar. To achieve a 50% reduction in estimated outdoor fatalities with movement delay rules, evacuation crosswind at 50 m/min would need to begin after approximately three minutes with Eisenberg et al. dose-response, and in less than one minute (or cannot be achieved) with RPA dose-response. Sensitivity to weather is similar to that seen for sheltering for people outdoors. Under median-fatality weather, to achieve a 50% reduction in estimated outdoor fatalities with delay rules, evacuation crosswind at 50 m/min would need to begin after approximately one minute with Eisenberg et al. dose-response, and in less than one minute (or cannot be achieved) with RPA dose-response.
Next we consider the use of a security perimeter around people outdoors, both with and without evacuation. Figure 2-10 shows estimated outdoor fatalities as a function of the downwind distance between a chlorine release and the edge of a crowd outdoors, with and without evacuation at 50 m/minute walking crosswind starting after five minutes, for several chlorine exposure delay rules. (In Figure 2-10, there is a difference in predicted fatalities between the two no-evacuation lines, even for a security perimeter of 0 m distance from the edge of the crowd. That is because normally we assume there are people uniformly distributed across the area upwind of a chlorine release, as well as downwind. In case of a security perimeter of any distance, even at 0 m from the edge of the crowd, we assume there is nobody upwind of a chlorine release.) Without evacuation, achieving 50% reduction in outdoor fatalities requires a buffer zone of approximately 700 m (with RPA dose-response) to over 2000 m (for Eisenberg et al. dose-response). With evacuation at 50 m/minute walking crosswind starting after five
minutes, assuming estimated chlorine exposure movement delay rules, achieving 50% reduction in outdoor fatalities requires a buffer zone of approximately 300 m. Buffer zones can be shorter under other weather conditions (i.e. for very high wind speeds or very low-stability Pasquill classes).

![Figure 2-10: Outdoor Fatalities with Security Perimeter and Evacuation Crosswind](image)

### 2.6.4 Cryogenic vs. Pressurized Storage

To compare cryogenic to pressurized storage, we consider again the case where no further action is taken by defenders. For the cryogenic source term, in a typical run at 27°C, spread of the cryogenic pool was virtually complete after about 90 seconds (to a radius of about 24 m) and took seven minutes to evaporate. Figure 2-11 shows fatalities as a function of time for both cryogenic and pressurized storage, if defenders take no action. The fatality-time curve for cryogenic storage is generally about 20% lower than,
or about five minutes behind, the curve for pressurized storage (e.g. the time until 50% of eventual no-defense-response fatalities are reached is approximately 15 minutes for pressurized storage, and 20 minutes for cryogenic storage). However, fatalities for the two are virtually the same after 30 minutes. (Though it appears that after 60 minutes, cryogenic storage can actually result in a 4% increase in total fatalities over pressurized storage, examination of model outputs indicates that this may be primarily due to differences in dispersion speed and duration between the two release types; increasing the pressurized-storage release duration to a similar amount of time increases estimated fatalities by 3.3% under the same conditions.) These trends are relatively insensitive to dose-response model. Cryogenic storage could have more value if terrorists do not time attacks to coincide with highest-fatality weather conditions, especially if very rapid public responses are not possible. After 30 minutes, median-fatality weather conditions for cryogenic storage are 26% of predicted fatalities for median-fatality weather conditions for pressurized storage. That may be because relative to pressurized storage, cryogenic storage takes more time between vessel rupture and completion of vapor cloud formation. That reduces fatalities by decreasing peak vapor concentrations, under weather conditions with higher wind speed, lower Pasquill stability, and lower ambient temperatures. Median-fatality weather estimates are somewhat sensitive to dose-response model. After 30 minutes, with Eisenberg et al. dose-response, median-fatality weather conditions for cryogenic storage are 67% of predicted fatalities for median-fatality weather conditions for pressurized storage, and 14% for RPA dose-response. Fatality-time trends for combined use of cryogenic storage and responses such as evacuation and sheltering are generally very similar to those for pressurized storage, apart from the
downward/rightward shift previously discussed (generally equivalent to approximately five extra minutes in response time).

Figure 2-11: Fatalities vs. Time for Cryogenic and Pressurized Storage

2.7 Discussion

We estimate that the lower limit on response times, assuming the use of rapid attack detection, alert and response systems, would be one minute after a chlorine release, though higher response times may be more likely in many cases. Electrochemical and other types of sensors for continuous air sampling are commercially available, with detection times of several seconds for chlorine and other chemicals, and dispersion model outputs indicate that the vapor cloud from a release of 17 tons of chlorine would spread to 60-100 m diameter after about 15-30 seconds, depending on weather conditions and chlorine storage method. Calls to the emergency-reporting number 911 were placed
within one minute of the 2005 rail accident and chlorine spill in Graniteville, SC, and first responders were on route to the scene about one minute later [67]. For buildings with ventilation systems, existing or additional controls could enable either air intakes to be shut or the power to ventilation fans to be cut within a few seconds of activation.

Some buildings, such as those with high occupant densities, may normally operate with high indoor-outdoor air exchange rates to ensure adequate ventilation. Otherwise, building operators in areas at high risk of outdoor chlorine attack may want to consider reducing indoor-outdoor air exchange rates during normal operation. People in vehicles may be as well off staying where they are, turning off the air-supply fan and sealing the vents, as heading into a nearby building. It may also be dangerous for them to try to drive away, since they may unintentionally drive into higher-concentration areas.

Public response measures would have limitations and drawbacks, in addition to tradeoffs between factors such as speeds of responses, costs, and false alarm rates. Many people may not hear or understand instructions for self-protection, some may ignore them, and others may simply be unlucky enough to be too close to a chlorine release for any response. Movement delays caused by chlorine exposure may be worse than under our estimated rules. Amending our evacuation delay rules to stop movement at 100 ppm reduces outdoor fatalities averted under highest-fatality weather conditions by between ~10% and 100%, depending on the dose-response model and when evacuation begins. Attackers may try to take advantage of public responses, such as in a two-stage attack where people fleeing a chlorine release at event outdoors move into a booby-trapped area, though it may be possible to anticipate and address many of the ways that attackers might attempt to increase fatalities.
This chapter has focused on ruptures causing instantaneous total release of the contents of chlorine tanks, but attackers may often find it easier to cause smaller ruptures, resulting in slower releases. Adapting our modeling system to ruptures emptying a tank via flashing two-phase flow through an orifice [80], forming horizontal jets, indicates that such releases could result in approximately the same number of fatalities as an instantaneous release, if such a release takes 10 minutes or less. That may be a greater concern for 90-ton chlorine rail cars and larger stationary storage than for 17-ton tank trucks, and therefore is not a focus of this chapter. However, it does indicate again that the location and security of chlorine rail cars and stationary storage should be taken seriously.

Some information on the 2006-2007 chlorine truck attacks in Iraq has been publicly accessible through press releases, the media and other open sources [81-100]. Available attack data are too limited for evaluation or calibration of our models and assumptions, but we can make some comparisons. Most Iraq chlorine attacks apparently involved a total of approximately one ton of chlorine in one or more containers, whereas our base case scenario assumed total release of 17 tons of chlorine. There may also be differences between our scenario and the Iraq attack conditions with respect to other important factors for which less information is publicly available, such as amount of chlorine consumed in the explosions that ruptured the containers, amount of liquid chlorine left in containers after rupture, weather conditions, outdoor and indoor population densities, distances between the release and the victims, and protective actions taken by people in the area. Based in part on discussions with experts, we believe it is possible for terrorists to use explosives to release the contents of a container of chlorine with virtually total
entrainment and negligible chlorine consumption. However, the results of Fletcher [45] suggest that under some conditions, a small enough rupture could result in very low entrainment of non-flashed liquid chlorine, and thus ~80-90% reduction in the amount of chlorine released. It has also been stated that in at least some of the Iraq attacks, "the explosions burned most of the chlorine gas" [100], which further reduces predicted fatalities by an amount roughly proportional to the fraction of chlorine vapor consumed in the explosion (i.e., a 50% reduction in released chlorine vapor results in ~50% reduction in predicted fatalities). If we start from our base-case scenario and parameter values as defined in Section 2.3, then make chlorine container size 1 ton, released with negligible entrainment of liquid chlorine and 50% consumption of vaporized chlorine (i.e., a release of 90 kg chlorine vapor), for 2.5 and 4 m/s wind speeds and Pasquill stabilities ranging from A to F, the results are fatality predictions ranging from approximately 0 to 10, 1 to 20, and 30 to 300 fatalities for the RPA, Withers and Lees, and Eisenberg et al. dose-response models, respectively. While some of those fatality predictions are as low as the numbers seen in the Iraq attacks, some are significantly higher. Iraq attack fatalities ranged from 0 to approximately 20-40 fatalities, depending on the attack and the report. (Most fatalities were actually caused by explosion damage instead of by chlorine inhalation [81, 82, 100], though some victims might have died from chlorine exposure if the blast had not killed them first. One attack was reported to involve 100 lbs of high explosives [81], for which calculations with open-air blast and blast-effects models [101, 102] indicate people standing within 5 m would have ≤1% survival rates.) As discussed in Section 2 and elsewhere in this chapter, we expect that our modeling choices and assumptions give upward bias to our fatality predictions.
2.8 Conclusion

Chlorine may be an attractive weapon of mass effect for terrorists, but there is little publicly available work that estimates the range of potential fatalities from a chlorine attack, and the extent to which fatality reductions might be achieved with mitigation measures. We have used public response, chemical source term, atmospheric dispersion, building air exchange, and dose-response models to estimate fatalities from intentional release of 17 tons of chlorine from a tank truck in a generic urban area. We assumed that attackers can use weather predictions or other means to time their attacks to coincide with weather conditions producing higher fatalities, and can cause tank ruptures leading to effectively instantaneous release of tank contents. Rapid release of the entire cargo of 17 tons of chlorine from one tank truck could result in the formation of a toxic cloud stretching over tens of city blocks within a few minutes.

Predicted fatalities are strongly sensitive to wind speed, atmospheric stability class, amount of chlorine released, and dose-response model parameters. Without defensive response, under highest-fatality weather conditions, using the Withers and Lees dose-response model, we estimate approximately 8000 fatal exposures, with 50% occurring within 15 minutes. With other dose-response models, under the same weather conditions, no-defense-response fatality estimates range from approximately 4000 to approximately 30,000 fatalities. Total fatalities under median-fatality weather conditions are approximately 10-20% of total fatalities under highest-fatality weather conditions, depending on dose-response model.
If chlorine is released outdoors, exposure risk is much higher for people outdoors than indoors. We assumed that people in the area were 7% outdoors and 93% indoors, but the fraction of estimated fatalities that are people outdoors in the no-response case, under highest-fatality weather conditions, ranges from 60-90%. Most fatalities indoors are people on the first few floors, so it greatly can reduce hazard for those indoors if air intakes are at roof level instead of on each floor. Changes in mass of chlorine released result in roughly proportional increases in outdoor fatalities, though disproportionately high increases in indoor fatalities, probably because larger-mass releases lead to larger and longer-lasting clouds. Changes in some parameters, such as indoor and outdoor population densities, would produce proportional changes in fatality estimates in the no-defense-response case.

If implemented quickly and widely enough, rapid public responses such as sheltering-in-place and evacuation could significantly reduce fatalities from a chlorine attack. However, practical response times may be significantly longer, with the result that the reduction in mortality would be small.

Under highest-fatality weather conditions, with the Withers and Lees dose-response model, to achieve a 50% reduction in fatalities for people outdoors at the time of attack by taking shelter in nearby buildings, people would need to move indoors approximately ten minutes after a chlorine release. However, estimated delays from chlorine exposure effectively add four to seven minutes to ingress time, increasing fatalities by ~1000. To achieve a 50% reduction in fatalities for people indoors at the time of the attack, building air intakes would need to be shut approximately two to six minutes after the attack depending on building air exchange rates before and after shutdown, though later
shutdowns can increase fatalities by trapping poison inside. To achieve a 50% reduction in estimated outdoor fatalities, evacuation crosswind at 50 m/min would need to begin after approximately 12 minutes if chlorine exposure does not cause movement delays. Achieving a 50% reduction in estimated outdoor fatalities with only a security perimeter would require a distance between the chlorine release and people outdoors of approximately 1200 m. For mitigation measure cases, trends in sensitivities to weather conditions and dose-response model are generally similar to those for no-defense-response cases.

Fatality estimates for the models and scenario we consider in this chapter are much higher than the numbers of fatalities in the 2006-2007 chlorine attacks in Iraq. When our estimates are adjusted to correspond to the conditions in those attacks, as estimated from publicly available information, we obtain fatality predictions roughly similar to, but often higher than, the numbers actually seen in Iraq. We expect that our models and assumptions are biased towards overestimating fatalities. We suggest readers use caution in applying our results, and place less importance on specific values of our model predictions than on trends in those predictions.
3.1 Introduction

Falkenrath [2] has stated that “of all the various remaining civilian vulnerabilities in America today, one stands alone as uniquely deadly, pervasive, and susceptible to terrorist attack: toxic-inhalation-hazard industrial chemicals, such as chlorine, ammonia, phosgene, methyl bromide, hydrochloric and various other acids”. Houghton [1] states that “while using toxic industrial chemicals might not kill as many as would chemical warfare agents, the likelihood of terrorists acquiring TICs [toxic industrial chemicals] is higher and the fear generated by their use might be just as great during and after such a terrorist incident as it would be during or after an attack involving military grade chemicals.”

In this chapter, we estimate costs and live-saving effectiveness of several mitigation options for an attack scenario involving the release of the contents of a tanker truck of chlorine. Chlorine is volatile, toxic, and ubiquitous as an industrial chemical. A tanker truck might be driven to any accessible location. An estimated 1.6 million tons of chlorine were transported by truck in 1993 [13]. It would take one 17-ton truckload to cause the scenario we consider in this chapter.

Chapter 2 indicated that an intentional release of the 17-ton cargo of a chlorine tank truck in an office district of a major US city could result in thousands of fatalities, especially if protective measures are not implemented within a few minutes and with a high degree of public compliance. With 2.5 m/s wind and stability class F, and without
fast and effective defense response, Chapter 2 indicated approximately 4000 (half within ~10 minutes) to 30,000 fatalities (half within ~20 minutes), depending on dose-response model. Although they assumed 7% of the population was outdoors, they represented 60% to 90% of fatalities. To achieve a 50% reduction in fatalities for people outdoors at the time of attack by taking shelter in nearby buildings, people in the area would need to have moved indoors approximately 7 to 20 minutes after a chlorine release, depending on dose-response model. To achieve a 50% reduction in fatalities for people indoors at the time of the attack, building air intakes would need to be shut approximately two to six minutes after the attack, depending on initial air exchange rates and dose-response model. However, in some cases, sheltering-in-place can result in net increase in fatalities. For example, if performed at the wrong time, ventilation shutdown can increase net deaths by trapping chlorine vapor inside.

Work is being done to evaluate and improve capabilities for responding to chemical attack. Houghton [1] considered small releases of chlorine and other chemicals, as well as decontamination and medical treatment. Emergency management and medical professionals interviewed by Houghton indicate that rapid decontamination and medical treatment may significantly reduce probability of fatality from chlorine exposure. However, large attacks could produce numbers of victims that overwhelm treatment capacities, thereby reducing its value as a response option. The US Department of Homeland Security has been funding research and development for advanced chemical sensors and alert dissemination systems that could help warn the public of a terrorist attack, potentially reducing response times and increasing effectiveness of actions such as sheltering-in-place. Some researchers recommend the use of sheltering-in-place in
response to large, malevolent releases of toxic chemicals [103]. Other work suggests that status-quo responses may take too long to be effective. Researchers at US National Laboratories have modeled chlorine attacks based on releases from stationary chemical facilities [15]. They consider a variety of measures, including chemical detectors, public training for improved sheltering-in-place compliance, and reverse-911 phone alerts. The authors state that these measures would have “an insignificant effect on mitigating the consequences of a large-scale chlorine release”, and thus that for a risk-neutral decision maker, the expected value of monetized societal benefits of these measures would be less than their costs. They conclude that those options would not reduce fatalities significantly in a large chlorine attack. In the status-quo scenario, they estimate that after the chlorine release event at a chemical plant, it takes 15 minutes for release detection at the plant, 15 minutes for government notification by the plant, 60 minutes for authorities to initiate mitigation measures such as sheltering in place or evacuation, 60 minutes for first responders to drive through the area making announcements with megaphones, and 15 minutes for members of the public to shelter in place by taking steps such as turning off ventilation systems. In light of the results of Chapter 2, these assumptions lead to high public exposure. However, with extensive preparations, in the event of a chlorine release in an office district, it could be possible to more quickly alert people in the area, have them move into buildings nearby, and automatically shut down building air intakes.

Following recent precedent, this chapter will frame the impact of terrorist attacks, and the value of countermeasures, in normative, societal benefit-cost terms, using nominal dollar amounts for the value of a statistical life and other impacts, in order to compare the estimated societal benefits of defense options against their costs [15, 25]. US Office of
Management and Budget guidance suggests that agencies’ regulations pass benefit-cost or cost-effectiveness tests using a value per statistical life in the range of $1-10 million [26-28]. In this chapter, we will assess cost effectiveness of chlorine attack risk reduction measures in terms of cost per net death avoided.

The risk of an event can be separated into the consequence and the probability of an event, and this chapter is primarily concerned with estimating the consequences of an attack rather than its probability. A particular attack scenario’s probability could be estimated while accounting for attacker choice between attack scenarios, using probabilistic terror attack risk models such as those of Risk Management Solutions [31]. However, there are large and irreducible uncertainties associated with attack scenario probability estimation [25]. In the Lugar [104] survey of national security experts, estimates of the probability of a major terrorist attack causing numerous fatalities with chemical weapons somewhere in the world over the next 10 years ranged from 0 to 100%, with a median of 15%. Benefit-cost and cost-effectiveness analyses can be performed while treating attack scenario probability as an exogenous parameter, without explicitly modeling attack scenario substitution, as in the analyses of von Winterfeldt and O’Sullivan [25] and Powell et al. [15]. Uncertainties about attack scenario probability may then be addressed separately from uncertainties about the value of defense measures within the context of a particular attack scenario.

This chapter evaluates, for several sheltering-in-place capability enhancement strategies, what new systems would be required, their cost, and their effectiveness. In the next section, we provide an overview of the attack scenario and options we consider. In section three we describe the models we use, and present parameter values and sources.
In section four, we present and analyze model outputs. We provide further discussion in section five, and conclude in section six.

### 3.2 Attack Scenario and Mitigation Options

The basic scenario is a release of the 17-ton cargo of a chlorine tanker truck in an office or downtown area of a major city during normal business or commuting hours. A tanker truck can be driven to any accessible location. An outdoor release of chlorine in an office district would result in higher fatalities than many other areas because of population density, rates of indoor ventilation with outdoor air, and the number of people outdoors. We assume that attackers time their attacks to coincide with weather conditions producing higher fatalities. We use the weather conditions that Chapter 2 indicated would produce the highest fatalities if no defensive response were taken, i.e. 2.5 m/s wind, Pasquill stability class F, and 20°C ambient. In that case, Chapter 2 indicates that near 100% of fatal exposures occur by 60 minutes after the chlorine release. In light of the response times presented by Powell et al. [15], who estimate that status-quo, first-responder-based chlorine attack detection and public alert responses may take one hour or more to initiate and disseminate a sheltering-in-place order, the base case is a reasonable description of the current status quo.

We consider potential improvements in each of three categories: chlorine attack detection, public alerting, and building ventilation control. In each category, we consider an option with potential to improve capabilities for sheltering-in-place public response performance. Each of these would require installation of equipment and other preparations undertaken before a chlorine release. The options are listed in Table 3-1.
The systems and alerts we consider are based on covering the office district of Washington, DC, an area of approximately 1.3 mi\(^2\) with approximately 200k people during the workday.

<table>
<thead>
<tr>
<th>Component</th>
<th>Option to Consider</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection system</td>
<td>First responders report probable chlorine release after arriving on scene (status quo, no investment)</td>
</tr>
<tr>
<td>Primary public alert systems in area of release</td>
<td>Network of chlorine sensors and cameras, installed before attack</td>
</tr>
<tr>
<td>Building response systems</td>
<td>Network of public alert units, comprised of weather radios and loudspeakers, installed before attack</td>
</tr>
<tr>
<td></td>
<td>Ventilation-shutdown units in buildings, installed before attack</td>
</tr>
<tr>
<td></td>
<td>No ventilation-shutdown units in buildings (status quo)</td>
</tr>
</tbody>
</table>

For detection of chlorine release by first responders, we assume no change from the status quo is necessary. First responders may be able to quickly identify a release of chlorine by smell [1] as well as by visual indicators of chemical release. For dedicated chemical sensors, we assume the use of electrochemical sensors, which are in common use for leak detection in facilities storing chlorine. We assume placement of one sensor per block or per street intersection with nominal block sizes of 50m by 100m, or equivalent coverage density in areas with blocks of other sizes. One arrangement would be to install the detectors on traffic signal or street light posts, to give easier access to existing power and communication lines. Exposure to acidic chemicals can trigger false alarms for electrochemical sensors. Smoke products can contain acidic species such as HCl, so some events such as automobile accidents may produce false positives. Dirt and soot can also block sensor pores, leading to false negatives. Heat and humidity extremes may also affect electrochemical sensor performance. One way to reduce false alarm rates could be to install cameras along with the electrochemical sensors, allowing emergency management personnel in a remote location to view camera feeds and visually check the scene before sounding a shelter-in-place alert.
The alert methods we consider are based on audio alerts and voice instructions. These can quickly and effectively communicate necessary instructions without providing prior training, with relatively high compliance rates [105]. We assume public alert units consist of weather radios with loudspeakers, with one public alert unit installed outdoors per city block. We assume that emergency managers have the capacity to quickly send alerts to the Emergency Alert System, either via HazCollect units currently under development [106] or via communication channels that exist now. We do not include costs for responders to acquire HazCollect systems, nor for their dispatchers to use the equivalent, nor other infrastructure or societal costs for rapid alerts using the Emergency Alert System. We assume that a shelter-in-place alert would be given to the entire downtown area, partly to account for uncertainties in area attacked and where cloud will go, the possibility of another attack simultaneously or soon following, and partly because the weather radio system itself allows alert-location specification only down to the level of a county or 1/9th of a county.

For ventilation shutdown units, weather radios would be linked to control units or even to simple relays. For buildings with ventilation systems, existing or additional controls could enable either air intakes to be shut or the power to ventilation fans to be cut within a few seconds of activation. Manual building-air shutdowns would be slower, and dependent on the actions of building operators or occupants. We assume that the shutdown units reduce ventilation rates long enough for chlorine to disperse e.g. several hours, either by default or according to the weather-radio alert duration specified by authorities.
3.3 Cost Effectiveness Model Description

A simplified influence diagram of the cost effectiveness model is shown in Figure 3-1. Arrows indicate the direction of influence, e.g. attack detection time affects calculated response times.

![Figure 3-1: Simplified Influence Diagram of Models](image)

For each sheltering response option, we estimate sheltering response times and alert compliance rates, which, along with weather conditions, choice of dose-response model...
and other factors, allow us to estimate net fatalities avoided. For each option, we estimate up-front costs of necessary equipment, costs of false alarms, and other factors, and use these to estimate annualized costs. With net fatalities avoided and annualized costs, we estimate cost per net death avoided, as a function of attack scenario probability.

The models in this chapter are primarily implemented in Analytica, with some calculations performed using Matlab and Excel. To estimate probability distributions of outputs, Latin hypercube sampling is performed in Analytica, with sample size of 1000. Continuous-valued inputs are varied according to the probability distributions given in Table 3-2, the Appendix, and as discussed in the following sections.

### 3.3.1 Fatality Estimation Model

First, we estimate the numbers of fatalities averted by use of the candidate investment options. The integrated fatality estimation models of Chapter 2 are too computationally intensive to run large numbers of simulations quickly, so we used the integrated models to generate response surfaces that approximate the input-output relationships of the integrated models over required parameter ranges but require much less computation time [15]. Using the integrated models of Chapter 2, we estimate fatalities for a set of simulation runs with inputs generated using full-factorial combinations of building indoor-outdoor air exchange rate before ventilation shutdown (0, 0.5, 1, 2.6, and 15 air changes per hour or ACH), air exchange rate after shutdown, if applicable (0.2, 0.4, and 0.7 ACH), dose-response model (Eisenberg et al. and RPA), ventilation shutdown time and ingress time (1, 5, 10, 15, 20, 30, 40, 50 and 60 minutes for each), and rules for ingress delay caused by chlorine exposure (with and without delay, see Chapter 2), all
with weather conditions of 2.5 m/s wind and stability class F, and the other parameter values used in the Chapter 2 base-case analysis. For each combination, we estimate fatalities averted for cases of sheltering with and without ventilation shutdown, for both 100% and 0% sheltering compliance. We then feed the data points to the program, Matlab, to generate response surfaces or regressions for each combination, as functions of ingress and ventilation shutdown times and building air exchange rates \((x_1, ..., x_4)\), as well as second and third-power transformations \((x_1^2, x_1^3, ...)\) and first and second-order interaction terms \((x_1 \cdot x_2, x_1^2 \cdot x_2, ...)\) for those variables. To generate each response surface, we perform a stepwise multiple linear regression, which adds coefficients/variables to the model one at a time in increasing order of p-value, up to p-value of 0.05. The resulting regressions had F-statistic values \(\geq 100\) (p-value = 0); see Table A-1 in the Appendix for more details on goodness-of-fit. Response surface errors are in addition to any resulting from the modeling system developed in Chapter 2.

Fatality calculations incorporate weighted sums for the fractions of buildings with air intakes at the roof level vs. at each floor, chlorine-exposure ingress delay rule, and the fraction of people complying with a sheltering order vs. those taking no action. Ingress time is the sum of time to detect attack, time for authorities to decide to issue an alert, time for an alert to be disseminated once initiated, time for members of the public to decide to comply with sheltering warning, and the time to get indoors once moving. Time to get indoors can also include movement delays from chlorine exposure; the rules we use for estimating movement delays from exposure to chlorine are described and discussed in Chapter 2. For strategies with ventilation shutdown units, building ventilation shutdown time is the sum of time to detect attack, time for authorities to
decide to issue an alert, and time for an alert to be disseminated once initiated. We treat
the time for building ventilation system shutdown once alert is issued as negligible, since
it is likely to be well under a minute if using automatic shutdown units.

If faced with a toxic chemical release, authorities’ decision process for whether to
issue a shelter-in-place warning, and the amount of time to make that decision, may be
affected by a number of factors, such as information about the release itself,
meteorological conditions, and expected public response. Analysts have suggested that
sheltering-in-place be implemented if it provides adequate protection, especially for
short-duration releases of high-toxic-load chemicals such as chlorine, and if there is not
enough time to evacuate [23]. Officials surveyed by Sorensen, Rogers et al. [107] stated
that for urgent or fast-moving events, on average two people would be involved in
emergency decision making, and frequently only one person would be required. Because
of the dependence of the decision-making process on local conditions, resources and
procedures, we do not model this process in detail. Instead, as given in Table 3-2, we use
a distribution of decision times reflecting possible conditions ranging from the best
demonstrated in historical incidents, i.e. one minute [108], to the average performance
expected in a normal chemical emergency, i.e. 30 minutes [107]. Alerting decisions in
many chemical emergencies have taken much longer than 30 minutes [108] and there is
no guarantee that official decisions will be made quickly, or at all [109, 110]. However,
in the context of this chlorine tank truck attack scenario, if an alert decision takes longer
than 30 minutes then the result would not be much different from a no-alert case.

Speed of public response and rates of compliance with warnings to take actions –
such as sheltering-in-place or evacuating – are likely to depend on many factors. These
include the warning content, clarity, detail, frequency and consistency, perceived urgency of hazard, relative proximity to the source of disaster, prior disaster experience and false alarm rates, level of familiarity with and confidence in the effectiveness of recommended protective actions, visibility and familiarity with available or recommended routes or destinations, level of trust in authorities giving messages, interpretation of the warning, discussion of the warning with others, actions taken by others nearby, whether people are present in groups such as families or are a collection of unaffiliated individuals, ability to hear or otherwise receive and understand alert and instructions, sensory cues of hazard such as visible cloud or odor, location and activities of individuals at the time when alarm is received, and tasks performed before beginning movement, such as gathering valuables or family [23, 105, 109, 111-121]. The fraction of people outdoors and in vehicles, who would be alerted by a siren, has been judged at 90% [110, 122]. However, spoken instructions may not be directly understood, especially by non-English speakers. We assume no significant movement impediments from congestion effects, but they are possible in areas with crowd densities above approximately 1-2 people/m² [74]. We do not model those factors here, partly because of their complexities and interdependencies and the high uncertainty of predicted sheltering-order compliance rates even for essentially status-quo alert dissemination methods [42]. Instead, we simply treat compliance rate as an input whose value is varied parametrically.

The modeling system developed in Chapter 2 is more likely to result in over-estimates than under-estimates of fatality predictions, which suggests that less importance be placed on specific values of their model predictions than on general trends of relative
changes in predictions caused by changes of inputs. As those results are the foundation for this chapter’s analysis, those caveats also apply to this chapter.

3.3.2 Cost Estimation Model

Next, we estimate costs for each investment option, which include both equipment costs and the opportunity costs of the public when sheltering alerts disrupt their day. We assume placement of one sensor per block or per street intersection with nominal block sizes of 50m by 100m. Material and installation costs of equipment are assumed to be paid now and every $x$ years, where $x$ is the equipment lifetime, up to a total project lifetime of 30 years. These capital and replacement costs are first discounted to the present, then annualized using a standard mortgage calculation with a period of 30 years. Total annual system costs also include annual maintenance costs where applicable (i.e. sensors) and false alarm costs. The cost per false alarm is the opportunity cost of members of the public in the area covered by the alert, whose activities are disrupted for the duration of the alert. The systems and alerts we consider are based on covering the office district of Washington, DC. The cost of covering a larger area, or more cities, would be approximately proportional to the area covered. All costs are in 2008 dollars, and all discount rates are in real or inflation-adjusted terms.

3.3.3 Calculating Cost Effectiveness

Finally, for each investment option considered, we combine estimated fatality changes with estimated costs to calculate expected cost per death averted,
$C_a = \frac{C_s}{P \cdot \text{Max}[0.1, (F_o - F_w)]}$ (Eq. 3-1)

where $C_a$ is the cost per net death averted by use of a system ($/statistical life saved), $C_s$ is the annualized system cost ($/year), $P$ is the annual probability of a single chlorine tank truck attack or the expected number of attacks per year in the area covered by the system (attacks/year), and $F_o$ and $F_w$ are the number of estimated fatalities with and without the system in place, respectively (lives/attack). We treat attack scenario probability as an exogenous variable. Equation 3-1 is formulated to address the possibility that the systems result in net increase in fatalities. In those cases, the formula results in a very high cost per death averted (and a failure to pass a given cost-effectiveness test), instead of the nonsensical result of negative cost per death averted.

### 3.3.4 Parameter Values

To reflect uncertainties of input parameter values, and to assess consequent uncertainties in our model outputs, we estimate and propagate parameter uncertainties using Latin hypercube sampling. For each of 1000 sample iterations, a value of each probabilistic input variable is sampled from the probability distributions specified in Table 3-2 and the Appendix, and is applied to the entire population (of people, or of buildings, etc.) in the area. For some parameters, such as distance to nearby door, applying a single value to the entire population in the area is a simplifying approximation, since in reality each person in the area might have a different distance to a nearby door. For these parameters, the values should be understood as representative of the actual distribution for the population in the area, e.g. a mean value. This
approximation could skew the distribution of output parameters, and may increase weight at the tails of output distributions. We assume parameters are uncorrelated.

<table>
<thead>
<tr>
<th>Parameter (units)</th>
<th>Values, and Probability Distributions Where Applicable</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attack detection time (minutes) First responders</td>
<td>Triangular(3,7,15) Chemical detectors and cameras</td>
<td>Houghton [1], NTSB [123], USFA [124] NCASI [125]</td>
</tr>
<tr>
<td>Authorities' sheltering alert decision time (minutes)</td>
<td>Triangular (1, 10, 30)</td>
<td>Sorensen, Rogers et al. [107], Lindell and Perry [109], Rogers and Sorensen [126], Rogers [108]</td>
</tr>
<tr>
<td>Authorities' alert message creation and dissemination time (minutes)</td>
<td>Triangular(2,4, 9)</td>
<td>Moore [127], Paese [106]</td>
</tr>
<tr>
<td>Public's sheltering decision time (minutes)</td>
<td>Triangular (0.25, 1, 5)</td>
<td>Geyer, Bellamy et al. [105], Sime and Kimura [117], Proulx [118], Sime [119], Proulx [120]</td>
</tr>
<tr>
<td>Distance to nearby door (m)</td>
<td>Triangular (1, 50, 200)</td>
<td>-</td>
</tr>
<tr>
<td>Walking speed (m/min)</td>
<td>Uniform (40, 60)</td>
<td>Pauls [72], Nelson and Mowrer [74]</td>
</tr>
<tr>
<td>Time to pass through door once reached (minutes)</td>
<td>Uniform (0, 1)</td>
<td>Pauls [72], Nelson and Mowrer [74]</td>
</tr>
<tr>
<td>Sheltering compliance rate (fraction)</td>
<td>Uniform (0,1)</td>
<td>Dombroski [42], Powell et al. [15]</td>
</tr>
<tr>
<td>Chlorine inhalation dose-response model</td>
<td>(as per each source)</td>
<td>Eisenberg et al [61], RPA [63]</td>
</tr>
<tr>
<td>Chemical attack false alarm rate (alerts/year)</td>
<td>Uniform(0,6)</td>
<td>Proulx [120]</td>
</tr>
<tr>
<td>Hours of disruption per person per alarm</td>
<td>Triangular (0, 1, 8)</td>
<td>Hakim et al. [128]</td>
</tr>
<tr>
<td>Fraction of people in area with opportunity cost imposed by false alarm</td>
<td>Uniform(Fraction of people outdoors, 1)</td>
<td></td>
</tr>
<tr>
<td>Annual income of people in area affected by alarms ($/yr)</td>
<td>50k</td>
<td>Bishaw [129]</td>
</tr>
<tr>
<td>Area needing alert system coverage (mi²)</td>
<td>1.3</td>
<td>-</td>
</tr>
<tr>
<td>Annual probability of chlorine truck attack in area covered by detector and alert systems</td>
<td>0.001, 0.01, 0.1, 1</td>
<td>-</td>
</tr>
<tr>
<td>Weather conditions</td>
<td>2.5 m/s wind, Pasquill stability class F, 20˚ C ambient</td>
<td>Chapter 2</td>
</tr>
</tbody>
</table>
3.4 Results

Figure 3-2 shows net deaths averted for the four investment options, for both the RPA and Eisenberg et al. dose-response models, if chlorine exposure does not cause movement delays. With no movement delays from chlorine exposure, most options have either positive or negative median values of net fatalities averted (i.e. are likely to either reduce or increase total fatalities), depending on dose-response model. However, with estimated movement delays from chlorine exposure, all options have negative median fatalities averted for both dose-response models, except for the option of chemical sensors and ventilation shutdown when using the Eisenberg et al. dose-response model.

Figures 3-2a and 3-2b: Net Deaths Averted for Selected Dose-Response Models
If false alarms are not rare, annualized system costs may be dominated by false alarm costs. Median estimated capital costs (labor + materials) are $400k for the outdoor alert system, $2M for the chemical detector system, and $20M for the ventilation shutdown system. Median estimated cost per false alarm is $6M. With no false alarms per year, median estimated annualized system costs are $3M/year for the most-expensive option of chemical sensors plus ventilation shutdown units, and $50k/year for the least expensive option of no dedicated chemical sensors or ventilation-shutdown units (i.e., only installing outdoor alert units), but going from zero to one false alarm per year increases median estimated annualized costs of each option by approximately $6M/year. Figure 3-3 shows annualized costs of each option, assuming one false alarm per year.

![Figure 3-3: Annualized Costs with One False Alarm per Year](image)

The investment option with lowest median estimated cost per death averted depends primarily on median fatalities averted, which (as previously discussed) depends in turn on dose-response model and whether chlorine exposure causes movement delays. Figure 3-4 shows cost per net death averted as a function of attack scenario probability, for the investment option of chemical sensors and no ventilation shutdown units, for both the...
RPA and Eisenberg et al. dose-response models, assuming no movement delays from chlorine exposure. If chlorine exposure does not cause movement delays, the option has median estimated cost per net death averted of $10M or less for annual attack probability of 0.001 with the Eisenberg et al. dose-response model, and 0.4 with the RPA dose-response model. However, with movement delays, neither this nor the other investment options have median estimated cost per net death averted under $10M with both dose-response models, not even with an annual attack probability of 1.

![Figure 3-4: Cost per Net Death Averted with Chemical Sensors and No Ventilation Shutdown Units](image)

### 3.5 Discussion

To identify the probabilistic input variables whose uncertainties most affect output predictions, we use the importance analysis function in Analytica. The function uses the absolute rank-order correlation between each input sample and the output sample as an indicator of the strength of monotonic relations between each uncertain input and a selected output, both linear and otherwise [130, 131]. The most important parameters for
cost per net death avoided are attack probability and the choice of dose-response model. The next most important parameters, depending on option and dose-response model, are either alert decision time or the parameters affecting annual false alarm costs (false alarm rate and factors related to cost per false alarm, such as the fraction of people in area affected by a false alarm, and the hours of disruption per person per alarm). After dose response model, the most important parameter for prediction of net deaths averted, for many options and dose-response models, is alert decision time. Starting air exchange rate and sheltering compliance fraction are next-most important, or as important as alert decision time, depending on option and dose-response model. Fatalities as functions of sheltering times, air exchange rates, and dose response models are presented and discussed in Chapter 2. Sheltering compliance rate has a linear effect on fatalities averted. The most important parameters for prediction of annualized system costs are annual false alarm cost factors.

Although Chapter 2 indicated that rapid sheltering-in-place measures could significantly reduce fatalities, the results of this chapter indicate that such measures are likely to take too long to save many lives, and in some cases could actually increase total fatalities. For example, sealing buildings too late, after chlorine vapor has already entered, can increase occupants’ chlorine exposure. With chemical sensors, median ventilation-shutdown time is 19 minutes, and median ingress time (if not delayed by chlorine exposure) is 23 minutes. Based on median time for each component of sheltering time, authorities’ alert decision time is the longest step, with a median of 13 minutes. The second longest, if using first responders to detect a chlorine release, is attack detection time, with a median of eight minutes (for electrochemical sensors, it is
less than a minute). Median times for sheltering decision and ingress movement times for people outdoors sum to four minutes if chlorine exposure does not cause movement delays. Median alert dissemination time with public address system is five minutes. If the assumptions in this chapter are accurate, then the decision-making step may have higher potential to be a bottleneck than other stages. If authorities’ alert time is one minute (the lower limit of the range we have assumed in this chapter) and chemical detectors are used, then public sheltering decision time and movement time become the limiting factors. If all response times are at their lower limits as estimated in this chapter, the resulting ingress time and ventilation shutdown time (if applicable) are both approximately 10 minutes, for all options considered. In that case, with estimated movement delays from chlorine exposure, median net fatalities averted are 200 to 10k with ventilation shutdown, and 300 to 5k without ventilation shutdown, depending on dose-response model. Then all options considered have cost per net death averted at or below $10M with attack probability of <0.001 for Eisenberg et al., and 0.02 for RPA dose-response.

This chapter has assumed an attack during weather conditions with high atmospheric stability and slow dispersion, which leads to high fatalities without defense response. Chapter 2 indicates that attacks under other weather conditions would result in fewer fatalities without defense response, and less time for sheltering to work, and thus lower likelihood of fatalities averted by a sheltering response system. Chapter 2 also indicates that dose-response models with low concentration thresholds for chlorine toxicity (e.g. Eisenberg et al.) generally result in higher estimated fatalities, and a longer time until enough dispersion has occurred to end exposure hazard, than dose-response models with
high chlorine toxicity concentration thresholds (e.g. RPA). Correspondingly, response at a particular time averts a greater proportion of no-defense-response fatalities if higher-fatality-estimate dose-response models are correct. However, dose-response models resulting in lower fatality estimates (e.g. RPA) seem more likely to be accurate than models resulting in higher fatality estimates (e.g. Eisenberg et al.), since they were typically developed later, with more data available from animal experiments.

A number of logistical and behavioral issues may need to be addressed for sheltering strategies to work. There may be value in installing public alert units indoors as well as outdoors, to help prevent people indoors from going outdoors. In a short-duration outdoor release of chlorine, the hazard to people outdoors is much greater than to those outdoors. We have assumed that 93% of the people in the area are indoors and 7% outdoors at the time of the chlorine release, and that people indoors would stay indoors for the duration of the release. All else equal, if 10% of the people indoors at the time of the chlorine release moved outdoors immediately after the release, the modeling system of Chapter 2 predicts total fatalities would increase by approximately a factor of two. Management or occupants in some buildings may be reluctant to let strangers into their buildings. In some buildings, high infiltration rates may require people on the ground floor to quickly move to higher floors to escape chlorine cloud, which may cause delays or worse.

Public response actions would have a better chance of saving people farther away from a release than people close to a release. Chapter 2 indicates that the initial spread of chlorine cloud occurs very quickly, so people very near to the release may not be able to escape high concentrations. The target in the scenario we have analyzed in this chapter is
a fairly homogenous area, large enough that the end to chlorine fatality hazard occurs either because people in the area have taken protective action, or because the cloud has dispersed and diluted to a concentration below fatality hazard. If applying a chlorine attack detection and alert system to protect only a smaller area (e.g., only on one specific city block), and if an attacker could release chlorine in or very near to that area, then rapid and effective attack detection and alert system becomes more difficult. In that case, measures such as security barriers may help maintain distance from potential attackers.

Chapter 2 indicates that walking crosswind away from the path of a chlorine cloud could reduce fatalities by amounts that could be comparable to sheltering-in-place, depending on walking speeds and other factors. Some people may be more inclined to comply with instructions to evacuate than to shelter-in-place, because of factors such as the intuitive appeal of evacuation as a response to toxic chemical release, and relative unfamiliarity with (and possible skepticism of the effectiveness of) sheltering in place [23]. One requirement for effective evacuation from chemical release is for the public to know in which direction to go. Real-time information from chemical sensors and weather data, as well as computer simulations to predict which way a puff or plume is likely to be moving, could help inform alerts. Systems based on weather radio-linked public address units may be able to help alert and guide people outdoors to evacuate the area, but communication of critical information to people in each location may happen more quickly, and produce higher compliance rates, if each alert unit received or generated directions specific to its location. It may be useful to incorporate systems using traffic lights and other means to quickly direct large numbers of vehicles out of a city, as have been tested in Washington, DC recently.
Sabotage and distractions might prevent rapid public response in the case of an attack, even if drills or other events provide empirical evidence of the short response times and high public compliance rates that would be necessary to save lives. Attackers may also take advantage of response procedures, e.g. setting up a hoax chlorine attack and using a sheltering alert to help them gain access to a building. Such issues can and should be anticipated by system designers and authorities, but just as it may be impossible to prevent a chlorine attack, it may be impossible to ensure effective public response after an attack or to prevent attackers from seeking to exploit emergency response procedures.

### 3.6 Conclusion

Chapter 2 indicated that if the cargo of a chlorine tank truck were released in an attack on a typical office district, sheltering-in-place could significantly reduce fatalities if performed quickly enough. However, the results of this chapter indicate that even with electrochemical sensors, public address units, and automatic building ventilation systems, responses are likely to take too long to save many lives, and may instead be more likely to increase total fatalities (e.g. by sealing buildings too late, after chlorine vapor has already entered). With no false alarms per year, median estimated annualized costs are $3M/year for the most-expensive investment option of chemical sensors plus ventilation shutdown units, and $50k/year for the least expensive investment option of no dedicated chemical sensors or ventilation-shutdown units (i.e., only installing outdoor alert units), but going from zero false alarms to one false alarm per year increases median estimated annualized costs of each option by approximately $6M/year. None of the investment options pass a cost-effectiveness test requiring estimated cost per net death averted of

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≤$10M across all combinations of dose-response and ingress-delay models. At this point, it seems inappropriate to invest in these options as a cost-effective way to cost-effectively reduce fatalities from chlorine attack in an office district.
Chapter 4: Consequences and Mitigation of Chlorine Attack on Outdoor Special Event

4.1 Introduction

While terrorists have not yet used toxic-by-inhalation industrial chemicals such as chlorine as a weapon of mass effect in the West, in 2006-2007 there were several small attacks with vehicle-borne explosives and containers of chlorine in Iraq, and many consider them attractive to terrorists targeting the United States. Falkenrath [2] has stated that “of all the various remaining civilian vulnerabilities in America today, one stands alone as uniquely deadly, pervasive, and susceptible to terrorist attack: toxic-inhalation-hazard industrial chemicals, such as chlorine, ammonia, phosgene, methyl bromide, hydrochloric and various other acids”. Houghton [1] states that “while using toxic industrial chemicals might not kill as many as would chemical warfare agents, the likelihood of terrorists acquiring TICs [toxic industrial chemicals] is higher and the fear generated by their use might be just as great during and after such a terrorist incident as it would be during or after an attack involving military grade chemicals.” The chemical industry has undertaken both voluntary and government-mandated efforts to assess and address chemical facility and transport security risks [3-7]. However, some argue these initiatives do not adequately protect the public and that more governmental regulation of chemical industry security and operation is required, especially to encourage chemical and process changes that directly reduce hazard [8-10].

In this chapter, we estimate fatalities for an attack scenario involving the release of the contents of a tanker truck of chlorine at a special event outdoors, both with and
without mitigation measures. Chlorine is volatile, toxic, and ubiquitous as an industrial chemical. A tanker truck might be driven to any accessible location. An estimated 1.6 million tons of chlorine were transported by truck in 1993 [13]. It would take one truckload to cause the scenario we consider in this chapter. Chapter 2 estimated that an intentional release of the 17-ton cargo of a chlorine tank truck in an office district of a major US city could result in thousands of fatalities, especially if protective measures are not implemented quickly enough to be effective. With 2.5 m/s wind and stability class F, and without fast and effective defense response, Chapter 2 estimated approximately 4000 (half within ~10 minutes) to 30,000 fatalities (half within ~20 minutes), depending on dose-response model. Although they assumed only 7% of the population was outdoors, they represented 60% to 90% of fatalities. Chapter 2 indicated that an attack on a special event outdoors might result higher fatalities than an attack on a downtown/office area because of higher densities of people outdoors. Testimony to the Washington, DC city council by Boris [132] reportedly estimated 100k fatalities from July 4th attack involving chlorine railcar on rail line near the National Mall. For an office-district attack scenario, Chapter 2 indicates that evacuation and security barriers can significantly reduce fatalities, if responses are quick enough, or with a security barrier creating enough buffer-zone distance between the chlorine release and people downwind. To achieve a 50% reduction in outdoor fatalities for that scenario, under the weather conditions causing highest fatalities without defense response, requires either a buffer zone of approximately 700 to 2000+ m, or evacuation movement crosswind at 50 m/min would need to begin in 3 minutes or less (and may not be possible at all), depending on dose-response model assumed. Chapter 3 indicates that even with enhanced response system for rapid
sheltering in place, responses to an attack in an office district would likely be too slow to save a significant number of lives. However, responses may be faster for a special event such as a July 4th celebration on the National Mall than for an attack in an office district, if emergency personnel are already in the immediate area. Many special events already use one or several forms of security perimeter, as well as evacuation procedures for response to fires or other emergencies.

This chapter addresses the following questions: For this location and attack scenario, how many fatalities would result without effective defense response? Would evacuation and buffer zones save lives? How many? Under what conditions? In the next section, we provide an overview of the chlorine truck attack scenario and mitigation options we consider in this chapter, as well as the models and parameter values we use. We present and analyze model outputs in section three, provide further discussion in section four, and conclude in section five.

### 4.2 Attack Scenario, Mitigation Options, and Fatality Estimation Model

The basic scenario is a release of the 17-ton cargo of a chlorine tanker truck at the National Mall in Washington, DC, on July 4th. We assume terrorists cause a tank rupture leading to effectively instantaneous release of the tank’s contents. Chapter 2 indicates that such a release could result in the formation of a toxic cloud with immediately hazardous ground-level concentrations covering tens of city blocks within one minute. Figure 4-1 is an overhead diagram of the attack scenario. The wind is blowing across the field, and the attacker approaches from the upwind direction before releasing the
chemical, so that the chemical blows across the field. We consider two mitigation measures that could reduce fatalities: evacuation, and a buffer zone achieved with a security barrier. For evacuation, we assume systems have been implemented to rapidly detect and alert all people outdoors in the area, after which all people outdoors begin walking at a specified time and speed, and continue walking until they either leave the toxic-cloud area or die. We assume people evacuating are given directions to walk crosswind (not downwind) away from the chlorine release, as is generally recommended [22]. In the case of a security perimeter around people outdoors, which can create a buffer zone of distance between the chlorine release and people outdoors, we assume attackers approach people outdoors from upwind and release chlorine at the edge of the security perimeter. We assume security barriers have gaps narrow enough to prevent cars and trucks from passing, but wide enough not to impede normal walking at the crowd densities assumed here. We assume the attack takes place on the east half of the National Mall, a field 200 m wide and 1400 m long, running from east to west. (The west half is approximately 400 m wide and 1700 m long, but part of its area is taken up by pools and other features.) We assume a total of 400,000 people [133] are uniformly distributed across the Mall, resulting in a density of 0.4 people/m², and we treat the number of people outside the field as negligible. The cloud from an instantaneous release is an oval-shaped puff, not a continuous plume, but as it spreads and moves downwind, it makes a cigar-shaped footprint that is typically hundreds of meters wide and thousands of meters long, depending on weather conditions.
Attackers may be able to time their attacks to coincide with weather conditions causing high fatalities. However, an attack during an annual event may have less flexibility in timing for weather conditions than an attack on a target such as an office district. According to publicly available weather data from two weather stations within two blocks of the east half of the National Mall wind in that area blew 1-4 m/s from the north or northeast for 60-80% of the time between 7 and 10 PM on July 4, 2008 [134]. Similar patterns were seen in the area on other days in early July, though available data for these stations only go back to early 2008. For the purposes of this chapter, we treat the direction of the wind as being directly from the north, i.e. perpendicular to the length of the field. Where not otherwise stated, we assume wind speed of 2.5 m/s, and Pasquill stability class E (moderately slow dispersion).

We estimate fatalities for a set of simulation runs with specified inputs using the integrated modeling system developed in Chapter 2, which combines sub-models for...
public response, chemical source term, atmospheric dispersion, and dose-response. A public response model specifies the locations and actions of people in the area. The chemical source term model predicts mass, phase and other characteristics of the cloud of chlorine vapor and aerosol immediately following a chlorine release. The atmospheric dispersion model then predicts how a chlorine cloud spreads and moves outdoors over time. The resulting chlorine-exposure profiles are translated by the dose-response model into predicted fatalities. Fatalities are affected strongly by wind speed and Pasquill stability class (which depend on time of day, wind speed, and cloud cover). The modeling system is more likely to result in over-estimates than under-estimates of fatality predictions, and its caveats also apply to this chapter since it is the foundation for this chapter’s analysis. We suggest that less importance be placed on specific values of the model predictions than on trends in predictions.

We generate a set of simulation run inputs using full-factorial combinations of the following variables: evacuation starting times (1, 5, 10, and 15 minutes after chlorine release, and no evacuation); evacuation walking speeds (25 and 50 m/min) generally within the abilities of adults in low-density crowds moving through level passageways [72, 73]; buffer zone distances (from -100 m to 2100 m, at 200 m intervals); three dose-response models that Chapter 2 indicates are representative of the range of models available in literature, i.e. Eisenberg et al. [61], Withers and Lees [59], and RPA [63]; and weather conditions (the same set of wind speed and stability class combinations considered in Chapter 2, except all at 20°C for this chapter). In evacuation cases, we assume 100% compliance. Where not otherwise stated, we assume that walking speeds are reduced by chlorine exposure according to the rules of Chapter 2, i.e. at 30-60 ppm
chlorine, walking speed is 50% of original speed, and above 60 ppm, walking speed is 25% of original speed. For parameter values not specified in this section, we use the base-case values of Chapter 2.

4.3 Results

For an attack with no security barrier (-100 m upwind distance) and with no defense response, under 2.5 m/s wind and Pasquill stability E conditions, estimated fatalities are 30k-40k, depending on the dose-response model that is assumed. Without a substantial security barrier in place, even very rapid evacuation does not significantly reduce fatalities. Evacuation crosswind at 50 m/min after 1 minute, with 100 m upwind distance, reduces fatalities by 14-15% using rules for estimated movement speed reduction from chlorine exposure, and 40-41% without speed reduction rules. To reduce fatalities using a security barrier without evacuation requires keeping the chlorine release from 600 m to 4 km upwind of the crowd, depending on dose-response model. Releases from a shorter distance upwind from the crowd can cause fatalities 22-47% higher than a release in the middle of the crowd. These trends are illustrated in Figure 4-2, which presents results with the Withers and Lees dose-response model and with estimated movement speed reduction from chlorine exposure. (The horizontal axis, evacuation start time, is not to scale.) If evacuation is not possible, achieving 50% reduction in fatalities requires 1500 m buffer zone. Equivalent fatality reduction is also achieved with a 900 m buffer zone and evacuation after 1 minute.
4.4 Discussion

The finding that small buffer zones without evacuation could actually increase fatalities results from the small width of the National Mall, and the long downwind distance over which a spreading cloud of chlorine vapor crossing the Mall is likely to remain fatally toxic: moving from one part of the danger zone to another is not much help. The model-predicted increase in fatalities with increase in downwind distance is due to spreading of the cloud’s footprint; after enough additional downwind distance,
enough dilution has occurred that increased buffer zone distance reduces fatalities. That contrasts with the scenario considered in Chapter 2 where chlorine is released in an area that is both longer and wider than the that the chlorine cloud’s footprint. There, evacuation and security barriers often reduced fatalities, but did not increase fatalities for any response time or buffer zone distance considered. (When starting with vulnerable people under every part of the danger zone, it is an improvement to get any people out.) Before implementing buffer zones in other contexts, readers should consider whether one or both of those cases are similar to their own, and whether buffer zone measures are likely to decrease or increase fatalities.

As in Chapter 1, one limitation of the behavioral model used in this chapter is that we assume people take no actions besides those we specify, and in the no-defense-response case we assume they effectively take no action at all, which may not be realistic. People may independently decide to leave locations with high concentrations of chlorine [22, 35, 38-40], and some may be successful. However, others may do things that could greatly increase their risk instead. In the catastrophic release of methyl isocyanate in Bhopal, India in 1984, some people indoors rushed outdoors to try to flee, and some people outdoors headed towards the cloud’s source instead of out of its path [12]. In an emergency, people might take risk-increasing actions because of ignorance or confusion about the best action to take, because of altruism, or to reach family [41-43]. People in emergencies and evacuations for many kinds of incidents, including catastrophic fires and the 1993 World Trade Center bombing, have generally exhibited adaptive, orderly, and mutually supportive behavior [41, 135, 136]. However, counterproductive panic behavior is more likely with large numbers of strangers in a confined space, a strong
collective need to move out of that space, and limited or blocked points of departure [42, 135]. As remarked in Chapter 2, public response speeds and compliance rates after warnings to take actions such as evacuation may also depend on other factors [23, 105, 109, 111-121], and predicted evacuation compliance rates may have large uncertainties [42].

Congestion effects and egress bottlenecks may further limit evacuation effectiveness. We assume evacuations occur at walking speeds typical for adults in low-density crowds through level passageways, and our crowd density assumptions for this National Mall attack scenario result in an estimate of 0.4 people/m$^2$. Movement speeds can be significantly reduced at crowd densities above approximately 1-2 people/m$^2$, approaching zero at crowd densities above 4 to 6 people/m$^2$ [74, 137]. People can lose voluntary movement control, and suffer shockwaves, trampling and compressive asphyxia at densities above ~7 people/m$^2$ [136]. If people at the ends of the field are not able or willing to move promptly after an evacuation alert is issued, that could slow or even prevent movement of those in the middle. These issues present potential hazards, even (or especially) if event security planners do not intend to rely on rapid evacuation, if many people in the crowd believe a toxic chemical release has occurred nearby and decide to leave the area but cannot do so safely. A hoax attack may also present similar dangers.

Changes in wind speed and Pasquill stability class can significantly increase or decrease estimated fatalities, depending on mitigation measures and other factors. Changes in wind direction may also increase fatalities by blowing down the length of the field, or decrease fatalities by blowing the cloud away from the field. This chapter
assumes attack on the 200 m wide east half of the National Mall. An attack on the 400 m wide west half would have higher fatalities, in many cases approximately twice as high, depending on buffer zone distance, weather conditions, and other factors. Changes in population density would produce proportional changes in fatalities, except in cases where densities became high enough to reduce walking speeds.

First responders may be able to quickly identify a release of chlorine by smell [1] as well as by visual indicators of chemical release, though some training may be necessary. Electrochemical and other types of sensors for continuous air sampling are commercially available, with detection times of several seconds for chlorine and other chemicals. Exposure to acidic chemicals can trigger false alarms for electrochemical sensors. Smoke products can contain acidic species such as HCl, so some events such as automobile accidents may produce false positives. Dirt and soot can also block sensor pores, leading to false negatives. Heat and humidity extremes may also affect electrochemical sensor performance. One way to reduce false alarm rates could be to install cameras along with electrochemical sensors, allowing emergency management personnel in a remote location to view camera feeds to visually check the scene before sounding an evacuation alert. Real-time information from chemical sensors and weather data, as well as computer simulations to predict a chlorine cloud’s movement, may be helpful. People can respond quickly to emergencies if appropriately trained, either to report an event or to take other action. For example, calls to the emergency-reporting number 911 were placed within one minute of the 2005 rail accident and chlorine spill in Graniteville, SC, and first responders were en route to the scene about one minute later [67]. Fire alarms, public address, reverse-911 and other systems demonstrate that it is
possible to quickly provide information to people outdoors or indoors. We estimate that the lower limit on response times, assuming the use of rapid attack detection, alert and response systems, would be one minute after a chlorine release, though higher response times may be more likely in many cases. Audio alerts and voice instructions can quickly and effectively communicate necessary instructions without the need for prior public training, with relatively high public compliance rates [105], and may be delivered via systems such as loudspeakers mounted on emergency vehicles.

Even if drills or other events provide empirical evidence of the short response times and high public compliance rates that would be necessary to save lives, sabotage and distractions might prevent rapid public response in the case of an attack. Attackers may also seek to exploit evacuation procedures, e.g. to set up a hoax chlorine attack (or even a real chlorine attack) in order to funnel evacuees into a nearby area for more devastating attacks. An attacker may seek to increase fatalities by releasing chlorine a short distance upwind from a crowd instead of in the middle of the crowd, even if security measures do not establish a buffer zone. Many such issues can and should be anticipated by system designers and authorities, but just as it may be impossible to prevent a chlorine attack, it may be impossible to ensure effective public response after an attack or to prevent attackers from seeking to exploit countermeasures and responses.

4.5 Conclusion

Without evacuation, or a buffer zone created by a security barrier, release of 17 tons of chlorine at National Mall under the most common weather conditions of the evening of July 4th, 2008 results in 30k-40k estimated fatalities. Evacuation with too small a buffer
zone may not significantly reduce fatalities. Evacuation crosswind at 50 m/min after 1 minute, with 100 m buffer zone, reduces fatalities by 14-15% using estimated movement speed reduction from chlorine exposure, and 40-41% without estimated speed reduction. Potential difficulties in effective evacuation may instead suggest reliance on a buffer zone, but a release a short distance away can cause higher fatalities than a release in the middle of the crowd. Without evacuation, releases from a short distance upwind from the crowd can cause fatalities 22-47% higher than a release in the middle of the crowd, and to begin to reduce fatalities requires keeping the release from 600 m to 4 km upwind from the crowd, depending on dose-response model. These patterns are likely due to the small width of the National Mall, relative to the distance over which a spreading cloud of chlorine vapor crossing the Mall is likely to remain fatally toxic.

The models and assumptions developed in Chapter 2, upon which this chapter is based, are probably biased towards overestimating fatalities. We suggest readers use caution in applying the results of this chapter, and place less importance on specific values of estimates in this chapter than on trends in predictions.
Chapter 5: Cost Effectiveness of Onsite Chlorine Generation as Chlorine Truck Attack Prevention

5.1 Introduction

Falkenrath [2] has stated that “of all the various remaining civilian vulnerabilities in America today, one stands alone as uniquely deadly, pervasive, and susceptible to terrorist attack: toxic-inhalation-hazard industrial chemicals, such as chlorine, ammonia, phosgene, methyl bromide, hydrochloric and various other acids”. Houghton [1] states that “while using toxic industrial chemicals might not kill as many as would chemical warfare agents, the likelihood of terrorists acquiring TICs [toxic industrial chemicals] is higher and the fear generated by their use might be just as great during and after such a terrorist incident as it would be during or after an attack involving military grade chemicals.” An estimated 1.6 million tons of chlorine were transported by truck in 1993 [13]. A tanker truck might be driven to any accessible location. Chapter 2 estimated that an intentional release of the 17-ton cargo of a chlorine tank truck in an office district of a major US city could result in thousands of fatalities, especially if protective measures are not implemented quickly enough to be effective. In the event of such an attack, Chapter 3 indicated that it may be quite difficult to implement responses fast and effective enough to save a significant number of lives.

The chemical industry has undertaken both voluntary and government-mandated efforts to assess and address chemical facility and transport security risks [3-7]. The US Transportation Security Administration has mandated rerouting of railcars carrying chlorine and other poison inhalation hazard chemicals around densely populated areas,
where cost effective [138]. However, that may not reduce the risk of chlorine truck attack, since trucks could be driven to targets no matter what their normal route or origin. Security measures can reduce the probability of successful theft or hijacking of tank trucks, but such measures might be overcome by well-prepared adversaries. Hijacking chlorine tank trucks is not the only way attackers might obtain chlorine: in a 2007 sting, New York City police successfully purchased 100-pound capacity chlorine cylinders using bogus identification, though subterfuge may have been unnecessary since reportedly vendors are not required to verify their customers’ identification or report transactions [139, 140]. Some argue existing practices do not adequately protect the public and that more governmental regulation of chemical industry security and operation is required, especially to encourage chemical and process changes that directly reduce hazards [8-10]. Some had previously considered a large-scale shift away from chlorine to reduce environmental and public health impacts associated with chlorine-based product life cycles [141, 142]. However, such an extensive change would not be necessary to mitigate the risk of chlorine truck attack. Much of the chlorine shipped by truck is used in water and wastewater treatment [10]. A number of water and wastewater facilities have recently switched from gaseous chlorine to hypochlorite solution or other alternative disinfectants, due in part to security concerns [17, 143]. For many facilities, capital and operating costs of disinfection alternatives may be prohibitively high if funding assistance is not provided. In a survey of 50 wastewater experts identifying key actions for security-enhancing activities most deserving of federal support, the highest number of respondents, 29 of 50, gave high priority to the replacement of gaseous chlorine and other disinfection chemicals with less hazardous alternatives [144]. However, to the best of
our knowledge, no publicly available analyses have estimated either the cost or the cost-
effectiveness of measures allowing the total elimination of shipping chlorine by truck to
prevent a chlorine truck attack in the US.

Following recent precedent, this chapter will frame the impact of terrorist attacks, and
the value of countermeasures, in normative, societal benefit-cost terms, using nominal
dollar amounts for the value of a statistical life and other impacts, in order to compare the
estimated societal benefits of defense options against their costs [15, 25]. US Office of
Management and Budget guidance suggests that agencies’ regulations pass benefit-cost
or cost-effectiveness tests using a value per statistical life in the range of $1-10 million
[26-28]. In this chapter, we will assess cost effectiveness of chlorine attack risk reduction
measures in terms of cost per net death avoided.

The risk of an event can be separated into the consequence and the probability of an
event. A particular attack scenario’s probability could be estimated while accounting for
attacker choice between attack scenarios, using probabilistic terror attack risk models
such as those of Risk Management Solutions [31]. However, there are large and
irreducible uncertainties associated with attack scenario probability estimation [25]. In
the Lugar [104] survey of national security experts, estimates of the probability of a
major terrorist attack causing numerous fatalities with chemical weapons somewhere in
the world over the next 10 years ranged from 0 to 100%, with a median of 15%. Benefit-
cost and cost-effectiveness analyses can be performed while treating attack scenario
probability as an exogenous parameter, without explicitly modeling attack scenario
substitution, as in the analyses of von Winterfeldt and O’Sullivan [25] and Powell et al.
[15]. Uncertainties about attack scenario probability may then be addressed separately
from uncertainties about the value of mitigation and prevention measures within the context of a particular attack scenario.

In this chapter, we address the following questions: How much chlorine is shipped by truck in the United States? How much would it cost to generate that chlorine, or hypochlorite if appropriate, onsite? How cost effective would those measures be for preventing a chlorine truck attack? In the next section, we provide an overview of the chlorine truck attack scenario and prevention option we consider. In section three we describe the models we use, and present values and sources we use for parameters. We present and analyze results in section four, provide further discussion in section five, and conclude in section six.

5.2 Attack Scenario and Prevention

The base-case attack scenario is a release of the 17-ton cargo of a chlorine tanker truck in an office or downtown area of a major city during normal business or commuting hours. A tanker truck can be driven to any accessible location. An outdoor release of chlorine in an office district would result in higher fatalities than many other areas because of population density, rates of indoor ventilation with outdoor air, and the number of people outdoors. We assume that attackers time their attacks to coincide with weather conditions producing higher fatalities. We use the weather conditions that Chapter 2 indicated would produce the highest fatalities if no defensive response were taken, i.e. 2.5 m/s wind, Pasquill stability class F (relatively slow dispersion), and 20°C ambient. In that case, Chapter 2 estimate near 100% of fatal exposures occur by 60 minutes after the chlorine release. In light of the response times presented by Powell et
al. [15], who estimate that status-quo, first-responder-based chlorine attack detection and public alert responses may take one hour or more to initiate and disseminate a sheltering-in-place order, the base case is a reasonable description of the status quo result of a chlorine truck attack.

In this chapter, we consider only one investment strategy as a change from the status quo: the onsite generation of either sodium hypochlorite solution, where appropriate for user needs (e.g. for water and wastewater treatment), or gaseous chlorine where needed. We do not consider the shipment of hypochlorite. Using shipped hypochlorite does generally have lower end-user costs than onsite generation, e.g. an estimated $533k capital cost for a wastewater facility using delivered hypochlorite vs. $1.2 million for onsite generation [143]. However, hypochlorite solution tends to degrade relatively quickly at the high concentrations commonly used for commercial delivery (e.g. 12% solutions), and can react to produce significant amounts of chlorine vapor, especially if mixed with acids [78]. Furthermore, hypochlorite solution is generally made at facilities with significant amounts of chlorine and sodium hydroxide onsite (e.g. with chlorine shipped to them in 90-ton railcars), often with populated areas nearby. Purchasing hypochlorite from such facilities may shift risk from one populated area to another, rather than reducing risks overall. We also do not consider UV or ozone as treatment options for either water or wastewater treatment. For wastewater utilities, estimated capital cost of UV is approximately 23% higher than hypochlorite generation system of comparable capacity, and ozone is generally more expensive overall than other options [143]. Finally, maintaining similar levels of free chlorine in treated water, with either gaseous chlorine or hypochlorite solution as sources of free chlorine, may help minimize the kinds
of water treatment system changes that can cause unintended consequences in water quality. A switch from chlorine to chloramines has been linked to the leaching of lead from pipe scale in Washington, DC [145]. However, hypochlorite may not be more appropriate than gaseous chlorine for all water treatment systems, or may require additional engineering in some cases, since switching from gaseous chlorine to hypochlorite can increase pH of treated water.

There are a number of onsite chlorine and hypochlorite generation systems available, with different capacities, configurations and other characteristics. The most essential part is the electrolysis cell. Using inputs of salt, water and electricity, these produce either chlorine gas and NaOH solution, or hypochlorite solution, depending on the design. Hydrogen gas is a byproduct. Systems directly producing chlorine and NaOH can subsequently produce hypochlorite by mixing the chlorine and NaOH, but other systems directly produce hypochlorite in the electrolysis cell. The equipment generally takes an amount of room roughly equivalent to, or somewhat larger than, the delivered-chlorine storage and distribution equipment it replaces. Systems not capturing byproduct hydrogen gas are designed to vent it safely to the atmosphere, and we assume hydrogen venting (though captured hydrogen might be used as a fuel, perhaps offsetting some costs).

Onsite generation of chlorine at end-user facilities currently receiving it by truck would reduce risks of transportation accidents involving chlorine, but these statistical risks may already be relatively low, on average. Brown et al. [13] estimate the number of public exposures exceeding fatal thresholds resulting from accident-related highway releases of chlorine over a period of ten years as having a mean of 13 and a median of 89.
zero. We do not estimate increases in risks of accidental NaOH release from creating and storing byproduct NaOH, and subsequently transporting the NaOH through areas that may not have had them before. Himes [146] indicates that the major acute health risk from a release of 50% NaOH solution is inhalation of aerosol formed by a crack in steel pipe, which can be effectively mitigated by use of polyethylene sleeving, though the possibility of spills and leaks with lower consequences would remain. We do not estimate changes in risks of chlorine release at end-user facilities. However, facilities could at least reduce the amount of chlorine onsite by generating it as needed instead of storing larger quantities, and generation of sodium hypochlorite solution, especially <1% concentration, could further lower release hazards. Finally, while some have argued that security costs at many facilities go down if they do not need to guard bulk chlorine, we do not estimate such changes here.

5.3 Cost Effectiveness Model

To assess cost effectiveness of onsite chlorine generation to prevent chlorine truck attacks, we first estimate the amounts of chlorine being delivered by truck in the United States. We estimate up-front costs of necessary equipment, as well as electricity and other costs, and use these to estimate annualized costs. Estimates of attack fatalities possible without onsite generation are based on the modeling work in Chapter 2. Then we estimate cost per net death avoided, as a function of attack scenario probability. To estimate probability distributions of outputs, Latin hypercube sampling is performed in Analytica, with model sample size of 1000 iterations. Continuous-valued inputs are varied according to the probability distributions given in Table 5-1 and the following.
All prices are adjusted for inflation to dollars in 2008. A simplified influence diagram of the cost effectiveness model is shown in Figure 5-1. Arrows indicate the direction of influence, e.g. electricity prices affect variable costs of onsite chlorine generation.

![Figure 5-1: Simplified Influence Diagram of Models](image)

To estimate attack fatalities possible without onsite generation while incorporating uncertainty about dose-response and building air exchange rates, we use response surfaces, with probability distributions for uncertain variables. To generate response surfaces of fatalities, we use the integrated models of Chapter 2, with full-factorial combinations of building indoor-outdoor air exchange rate (0, 0.5, 1, 2.6, and 15 air
changes per hour or ACH) and dose-response model (Eisenberg et al. and RPA), all with weather conditions of 2.5 m/s wind and stability class F, and other parameters at Chapter 2 base-case values. We perform stepwise regression with inputs of $x$, $x^2$, and $x^3$, where $x$ is building air exchange rate. The resulting regressions have $F$ statistic values $\geq 200$ ($p$ value $< 0.01$). Fatality estimates then use a probability distribution for building air exchange rates, as given in Table 5-1. These fatality estimates are the values for $F_o$ in Equation 5-1, described later in this section. Response surface fatality estimation errors and biases are addition to those of the modeling system of Chapter 2, which are more likely to result in over-estimates than under-estimates of fatality predictions.

To identify end-user facilities receiving chlorine by truck and to estimate their usage of chlorine, we start with data on all US facilities with $\geq 2500$ lbs typical maximum chlorine inventory, as listed in a May 2008 version of the US Environmental Protection Agency’s Risk Management Program database, RMP*Info [147]. RMP data includes facilities in all 50 states, as well as territories such as Guam and Puerto Rico, and we exclude data on the latter. We exclude facilities that have been deregistered. We exclude chlorine producers, packagers and distributors using the Chlorine Institute pamphlet lists of chlorine producers and packagers, NAICS codes, and facility names. To identify most current information on each facility, we use only the maximum chlorine inventories on the latest submissions for each facility. We categorize facilities as not receiving chlorine by truck if they have substantially over 180klbs inventory, or if were on Orum’s list of water facilities receiving chlorine by rail [17]. We automatically categorize facilities as getting chlorine trucked to them if they have substantially less than 100k lbs inventory. For remaining facilities with approximately 100k-180k lbs inventory, we look at the
executive summaries in their RMP submissions, or reason from similar facilities with more substantive information. After identifying facilities receiving chlorine by truck, we identify facilities using chlorine for water and wastewater treatment, using NAICS codes, facility names, and information from their executive summaries. Using the assumption that, on average, facilities use chlorine at rates proportional to their maximum inventories (or conversely, that average chlorine inventory turnover period is constant across all facilities), we calculate the fractions of chlorine used in water treatment vs. other uses, and the fraction of chlorine trucked vs. not trucked. Using those numbers, as well as available estimates of the total amounts of overall US chlorine usage, and usage in water treatment, we can calculate the total amount of chlorine trucked in the US.

There are several ways in which our chlorine use model may introduce error and bias. First, the RMP database does not have accurate information on all users of chlorine [148, 149]. The RMP rules do not require facilities with less than 2500 lbs. maximum chlorine inventory to submit reports. Some facilities that are supposed to submit reports do not comply, and facilities using small amounts of chlorine seem less likely to file RMP reports than large chlorine users. As a result, we probably underestimate the amount of chlorine currently shipped by truck, and thus also the cost per death averted by onsite generation. Second, some facilities may have longer average inventory turnover periods than others. In particular, it seems likely that water and wastewater facilities may keep relatively larger reserves than some industrial users. However, our analyses indicate water and wastewater facilities have approximately 80% of the chlorine inventory for facilities receiving chlorine by truck, and Orum [10] provides a similar estimate. Third, we have assumed that literature estimates of chlorine used for water treatment refer to
municipal drinking water treatment and wastewater or sewage treatment, but not to quasi-
similar uses such as treating the water used in cooling towers. Facilities in the latter
category account for 8% of inventory for facilities receiving chlorine by truck. Including
those facilities in the water treatment category would reduce estimated chlorine trucked,
and cost per death averted, by 14%.

Next, we estimate the difference between the cost of purchasing chlorine and the
annualized total cost of generating either chlorine or sodium hypochlorite onsite at all US
end-user facilities currently receiving chlorine by truck. Where necessary, we adjust
historical prices for inflation using the Consumer Price Index [150] and then make all
subsequent cost calculations in 2008 dollars. We use RMP*Info data to identify in which
state each facility is located. For electricity prices in each state, we use estimates of
average retail electricity prices for the industrial sector [151]. To represent uncertainty
about electricity prices, we use inflation-adjusted prices over several recent years in each
state. We use a similar approach in estimating the probability distribution of prices for
bulk refined salt, purchased chlorine, capital costs, and maintenance costs, except that for
those variables we treat differences in costs between states as negligible. The lower
bound of electricity needed for electrolysis of chlorine is the amount used in large,
modern, commercial membrane facilities, and the upper bound is the amount needed by
early, somewhat small membrane systems. Based in part on reported capital and
maintenance costs for water and wastewater facilities that have recently switched or are
considering switching from delivered chlorine to onsite chlorine or hypochlorite
generation, we assume capital and maintenance costs are proportional to maximum
chlorine inventory at a facility. Given other uncertainties, we assume negligible
differences between costs of shipping chlorine and salt, between costs of labor for
operation of gaseous chlorine and onsite generation of chlorine, and between capital and
other costs of generation of gaseous chlorine and hypochlorite. We assume that non-
water treatment facilities generating chlorine generating excess caustic are able to sell or
give away their byproduct caustic solution at negligible cost to the generating facilities,
e.g. to other industrial facilities whose effluent requires pH adjustment before discharge.
To annualize capital costs of equipment, we use a standard mortgage calculation with a
period of 30 years. Discount rates are in real terms, i.e. after adjustment for inflation.
We assume that onsite chlorine generation for the facilities considered would not affect
market prices for chlorine, electricity, or other cost inputs.

The cost model has a number of possible sources of error and bias, the most important
of which is its treatment of capital and maintenance costs. That is based upon a small
number of cases: six facilities for capital costs, and two years of data at one facility for
maintenance costs. The inventory distribution is both lumpy and long-tailed (five
facilities had listed chlorine inventories between 4 and 30 tons, and one had listed
inventory of 102 tons). If including the largest facility, linear regression of capital costs
vs. facility chlorine inventory in the RMP database indicates statistical significance for
proportionality of capital cost to chlorine inventory (p=0.001). However, the intercept
has a negative estimated value, which is nonsensical, though that regression parameter
estimate has less statistical significance (p=0.10) and the upper end of the 95%
confidence interval for that parameter is above zero. If not including the largest facility,
the value of the intercept becomes positive (again at p=0.10), but proportionality of
capital cost to chlorine inventory has much lower statistical significance (p=0.21). The
result is a wide range across the six facilities for calculated ratios of capital cost to chlorine inventory, which is reflected in the estimated probability distribution for the corresponding cost model variable.

Finally, using estimated base-case chlorine truck attack fatalities, and costs for attack prevention via onsite generation of chlorine, we calculate expected cost per death averted, $C_a$ ($/\text{statistical life saved}$), as

$$C_a = \frac{C_s}{P \cdot (F_o - F_w)} \quad \text{(Eq. 5-1)}$$

where $C_s$ is the annualized system cost ($/\text{year}$), $P$ is the annual probability of a single chlorine tank truck attack or the expected number of attacks per year in the United States (attacks/year), and $F_w$ and $F_o$ are the number of estimated fatalities with and without the system in place, respectively (lives/attack). We assume $F_w$ is zero. We treat attack scenario probability as an exogenous variable.

To reflect uncertainties of input parameter values, and to assess consequent uncertainties in our model outputs, we estimate and propagate parameter uncertainties using Latin hypercube sampling. For each of 1000 Latin hypercube sample iterations, a value of each input parameter is sampled from the probability distributions specified in Table 5-1, as well in Chapters 2 and 3, and is applied to all facilities or to the US overall. For some parameters, such as input prices, applying a single value to all facilities is a simplifying approximation, since in reality each facility in the area might face different local prices. For these parameters, the values should be understood as representative of the actual distribution across facilities, e.g. mean values. This approximation could skew the distribution of output parameters, and may increase weight at the tails of output distributions. We assume parameters are uncorrelated.
Table 5-1: Selected Parameters and Values

<table>
<thead>
<tr>
<th>Parameter (units)</th>
<th>Assumed Probability Distribution of Values</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total amount of chlorine generated and used in US (tons/year)</td>
<td>Uniform(11M,15M)</td>
<td>[152-154]</td>
</tr>
<tr>
<td>Fraction of US chlorine use for water treatment</td>
<td>Uniform(0.03, 0.07)</td>
<td>[78, 152, 153, 155]</td>
</tr>
<tr>
<td>Salt prices ($/ton NaCl)</td>
<td>Uniform(60, 110)</td>
<td>[156-162]</td>
</tr>
<tr>
<td>Salt needed per ton chlorine generated (ton NaCl / ton Cl)</td>
<td>Uniform(1.75, 3.5)</td>
<td>[78, 161]</td>
</tr>
<tr>
<td>Electricity needed per ton chlorine generated (kWh / ton Cl)</td>
<td>Uniform(2000, 4000)</td>
<td>[78, 163, 164]</td>
</tr>
<tr>
<td>Capital costs per lb chlorine inventory in RMP database ($ / lb)</td>
<td>Triangular (50, 130, 310)</td>
<td>[143, 165-167]</td>
</tr>
<tr>
<td>Annual maintenance costs per lb chlorine inventory in RMP database ($ / year - lb)</td>
<td>Uniform(4, 5)</td>
<td>[165]</td>
</tr>
<tr>
<td>Market price of chlorine delivered by truck ($/ton)</td>
<td>Uniform(40,420)</td>
<td>[152, 153, 168]</td>
</tr>
<tr>
<td>Discount rate</td>
<td>0.03, 0.04, 0.06 (use 0.04 if not otherwise stated)</td>
<td>[169]</td>
</tr>
<tr>
<td>Chlorine inhalation dose-response model</td>
<td>(as per each source)</td>
<td>Eisenberg et al [61], RPA [63]</td>
</tr>
<tr>
<td>Annual probability of chlorine truck attack</td>
<td>0.001, 0.01, 0.1, 1</td>
<td>-</td>
</tr>
<tr>
<td>Building air exchange rates (air changes per hour or ACH)</td>
<td>Lognormal(Median: 1, Std. Dev.: 3.5), truncated at 15</td>
<td>[68]</td>
</tr>
</tbody>
</table>

5.4 Results

The median estimated amount of chlorine moved by truck in the US is 500k tons/year, 80% of which goes to water and wastewater treatment. Median chlorine inventory turnover period is 19 days. Median delivered cost for trucked chlorine in the US totals $100 million/year, and the median increase in costs to generate chlorine or hypochlorite solution instead of shipping chlorine by truck is $800 million/year. Figure 5-2 shows cost per death averted vs. annual chlorine truck attack probability, for the highest-fatality and lowest-fatality dose-response models considered. Median cost per
death averted is $10M or less for annual probability of chlorine truck attack in the US above 0.02 if using the RPA dose-response model, and for attack probability above 0.003 if using the Eisenberg et al. dose-response model.

![Figure 5-2: Cost per Death Averted by Onsite Chlorine Generation](image)

### 5.5 Discussion

Biases in the modeling system developed in Chapter 2 are likely to result in overestimates of fatalities averted in the base case chlorine truck attack scenario. Dose-response models resulting in lower fatality estimates (e.g. RPA) seem more likely to be accurate than models resulting in higher fatality estimates (e.g. Eisenberg et al.), since they were typically developed later, with more data available from animal experiments. In addition, this chapter has assumed an attack during weather conditions with high atmospheric stability and slow dispersion, which leads to high fatalities without defense response. If instead, potential attacks are more likely under other weather conditions that
would result in fewer fatalities, it would significantly reduce the value of attack prevention measures.

To identify the input parameters whose uncertainties most affect predictions of outputs, we perform importance analysis using Analytica. It uses the absolute rank-order correlation between each input sample and the output sample as an indicator of the strength of monotonic relations between each uncertain input and a selected output, both linear and otherwise [130]. For cost per death averted, the most important parameters are attack probability and the choice of dose-response model, followed by capital costs, ventilation rates of buildings in the area of a chlorine release, and market prices for chlorine. The most important parameter affecting estimated amount of chlorine trucked is the fraction of US chlorine use going into water treatment. The most important parameter for cost of chlorine generation is capital costs.

Based on median values of annualized costs totaled across the US, capital costs are the largest cost component, with a median of $500M/year. Median cost is $200M/year for maintenance, $100M/year for electricity, and $100M/year for salt. The $400M/year annualized capital cost estimate assumes 4% real discount rate. Median annualized capital cost is $400M/year with 3% discount rate, and $600M/year with 6% discount rate.

Using the mean estimate of fatal exposures resulting from accident-related highway releases of chlorine from Brown et al. [13], 1.3 fatalities per year, and a value per statistical life saved of $10 million, the expected value of transportation accident reduction would be $13 million per year. That is two orders of magnitude too low for onsite chlorine generation to pass a cost-effectiveness test if its only benefit is the avoidance of fatalities from truck accidents causing chlorine releases.
Ceasing shipment of chlorine by truck could prevent chlorine truck attacks if the only way to obtain chlorine for a truck attack is to steal, hijack, or otherwise obtain chlorine from a truck shipment. However, it may be possible for potential attackers to obtain chlorine for truck attacks by other means, such as the acquisition of chlorine generation and packaging equipment. It may be appropriate to take steps to identify legitimate users of chlorine and chlorine generation equipment, though it may be difficult to make such measures both meaningful and cost-effective. Even if new policies towards chlorine trucking and onsite generation do not eliminate chlorine truck shipments, reducing the amount of chlorine being shipped may make it easier to improve security on remaining chlorine shipments. However, a too-simple attempt to reduce chlorine truck attack risks, such as just banning chlorine trucks, may result in other shifts of risk burden rather than overall risk reduction. Many water and wastewater facilities use commercial bleach instead of gaseous chlorine, which is often made nearby at plants receiving rail shipments of chlorine. Merely banning chlorine trucking might thus increase accidental and intentional release risks for chlorine rail cars in transit or in storage in high population areas. Similar shifts of risk may occur if regulations mandate substitution of bleach for chlorine at water treatment facilities [170, 171]. Avoiding such unintended consequences may require careful consideration of regulations and incentives.

Some facilities, especially water and wastewater treatment facilities, may want to store some chlorine or hypochlorite in case the generation equipment or the electric grid goes down. However, storing large amounts of chlorine may increase attack risk. Storing large amounts of hypochlorite solution may not be viable either, since high-concentration solutions degrade relatively quickly, and storage can take a large amount of
space, especially for low-concentration solutions. It may be better to have input materials and electrical generators in reserve. The median chlorine inventory for facilities currently receiving chlorine by truck is 10 tons. To be able to generate an equivalent amount of chlorine onsite would require approximately 3000 gallons of diesel fuel (many gasoline tanker trucks are larger), 4000 gallons salt, and a 7000W diesel generator (which would cost ~$7000 and be approximately one cubic meter in size).

## 5.6 Conclusion

Onsite generation of chlorine and hypochlorite at facilities currently receiving chlorine by truck may cost effectively prevent chlorine truck attack fatality estimates if the attack scenario probability is above particular thresholds. Median estimated cost per death averted is $10M or less for US annual chlorine truck attack probability above 0.02 if using the RPA dose-response model, and for attack probability above 0.003 if using the Eisenberg et al. dose-response model. However, likely modeling errors and biases probably underestimate cost per death averted, and therefore also underestimate threshold attack probabilities where prevention becomes cost effective.

If the estimated probability of chlorine truck attack in the US is sufficiently high, it could be cost-effective to invest in onsite chlorine generation at end-user facilities as one means of preventing chlorine truck attack. However, merely banning chlorine trucking might increase attack risks on chlorine rail cars in transit or in storage in high population areas. Additional regulation and incentives may be necessary to prevent such unintended consequences.
Chapter 6: Conclusion

6.1 Research Questions and Results

The research questions addressed in this dissertation, and associated results, are:

1) Estimate the number of fatal exposures if terrorists released chlorine in a typical urban core or at an outdoor event, first if no protective action were possible and second if various mitigation measures were used either singly or in combination.

Without fast and effective defense response, intentional release of 17 tons of chlorine from a tank truck in a generic urban area with 2.5 m/s wind and Pasquill stability class F, could result in approximately 4000 (half within ~10 minutes) to 30,000 fatalities (half within ~20 minutes), depending on dose-response model. Changing weather conditions result in approximately 50%- to 90%-lower total fatalities. Measures such as sheltering-in-place, evacuation, and use of security barriers and cryogenic storage, can reduce fatalities, sometimes by 50% or more, depending on response speed and other factors. However, median estimated total response times for four candidate investment options that could improve sheltering response time were still too long to substantially reduce fatalities, and in many cases the options were more likely to increase total fatalities than reduce them.

A chlorine truck attack at an event with larger numbers of people outdoors, i.e. the National Mall in Washington, DC, under the most common weather conditions of the evening of July 4th, 2008 results in 30k-40k estimated fatalities. Evacuation alone may not significantly reduce fatalities, which may instead suggest reliance on security
measures to keep possible chlorine releases some distance away from the crowd. That can reduce fatalities without evacuation if a release is kept 600 m to 4 km away from the crowd, depending on dose-response model. However, releases from a short distance (a few hundred meters) upwind from the crowd can cause fatalities 22-47% higher than a release in the middle of the crowd.

2) **Estimate implementation costs for each countermeasure or combination.**

With no false alarms per year, median estimated annualized costs are $3M/year for the most expensive investment option of chemical sensors plus ventilation shutdown units, and $50k/year for the least expensive investment option of no dedicated chemical sensors or ventilation-shutdown units (i.e., only installing outdoor alert units), but going from zero to one false alarm per year increases median estimated annualized costs of each option by approximately $6M/year.

The median increase in annualized costs across the US to generate chlorine or hypochlorite solution instead of shipping chlorine by truck is $800 million/year.

3) **Assess life-saving cost effectiveness of each countermeasure or combination.**

For the sheltering enhancement system investment options, median estimated cost per net death averted depends strongly on dose-response model and other factors, but is not low enough for any of the options considered to pass a cost-effectiveness test requiring \( \leq $10M \) per statistical life saved across all of the chlorine exposure dose-response and ingress-delay models used.
For onsite chlorine generation, median estimated cost per death averted is $10M or less if annual probability of office-area chlorine truck attack in the US is above 0.02, depending on dose-response model and other factors.

6.2 Discussion and Policy Implications

If terrorists have the desire and capability to carry out a chlorine truck attack, they may be able to cause thousands of fatalities. In some cases, very rapid public responses such as sheltering-in-place or evacuation could save a significant number of lives. However, practical limitations to response strategies, including false alarm costs, may prevent them from being fast enough to have much value. Furthermore, in some cases, such responses may be more likely to increase total fatalities than decrease them. These problems suggest that chlorine attack prevention may be a more effective life-saving strategy than response.

Onsite chlorine generation to replace chlorine trucking may be a cost effective chlorine attack scenario prevention measure, if baseline attack probability is high enough. However, a simple ban of chlorine trucking may result in changes that shift risk burdens without substantially reducing overall risks. Many water and wastewater facilities use commercial bleach instead of gaseous chlorine, which is often made nearby at plants receiving rail shipments of chlorine. Merely banning chlorine trucking might increase attack risks on chlorine rail cars in transit or in storage in high population areas. Careful consideration of regulations and incentives may be necessary to prevent such unintended consequences.
Probable inherent biases and errors in our fatality estimation modeling system likely result in overestimation of fatalities and underestimation of cost per death averted, and thus also underestimation of threshold attack probabilities required for prevention to be cost effective. In addition, the cost-effectiveness calculations have assumed attacks during weather conditions with high atmospheric stability and slow dispersion, which leads to high fatalities without defense response. Attacks under other weather conditions would generally result in fewer fatalities without defense response, reducing the number of lives saved by mitigation or prevention measures, and reducing their cost effectiveness.

6.3 Intended Research Contributions

In this dissertation, we have applied methods and concepts in quantitative risk, decision, and policy analysis to specific issues (toxic chemical release risks) in a new area (terrorism risk and homeland security) in which little such work is publicly available. This research fills critical gaps in the literature by estimating consequences of terrorist attack using chlorine, and quantifying fatality-reduction and cost-effectiveness decision spaces for mitigation and prevention measures. This dissertation focuses solely on impacts of fatalities from chlorine attack and excludes other attack consequence types and other attack modes from analysis. However, methods used in this work could be applied to any attack mode causing fatalities, such as other toxic chemicals or certain bio-weapons, and could also be extended to assess other attack consequences, such as non-lethal injuries.
This dissertation is divided into four main chapters, each written as a stand-alone research paper. The findings of this research will be communicated via peer-reviewed archival journals, issue briefs to stakeholders, and professional conferences. In an earlier form, some of this dissertation work has already been presented at professional conferences, and also served as basis for a draft briefing document for DHS and discussions with New York City police after chlorine attacks in Iraq in early 2007.

The models, assumptions, and parameters we used were based mostly on publicly available literature, and partly on discussions with subject matter experts. We investigated actions attackers and defenders could take to increase or decrease fatalities, which can be important because of the strategic nature of terrorism in facing an intelligent adversary. We obtain lessons that could be useful to defenders. Most things we have identified that attackers could do to increase fatalities are fairly obvious, or could be deduced from publicly available literature. We have not described more sensitive details, to avoid giving potential attackers information that may not otherwise be available to them.

### 6.4 Future Work

Research building directly on this dissertation work, with possible applicability to other areas of terrorist attack risk, could include:

- Assessing a fuller range of costs of chlorine attack, such as for non-lethal injuries. While risk reduction measures may be justified merely on the basis of life-saving cost effectiveness, their attractiveness may be increased by including other benefits.
• Estimation of costs of onsite chlorine generation or other chlorine-shipment alternatives for facilities currently receiving chlorine by rail. Computable general equilibrium models or related methods may be appropriate, due to potentially large and complex impacts of the volumes of chlorine involved.

• Development of mental-models based risk communications for terrorist attack using chlorine. These may help save lives in the event of an attack, e.g. by reducing the number of people unintentionally moving into a chlorine vapor cloud.

• Using strategic and probabilistic models of attacker group formation, attack scenario selection and execution to estimate probabilities of chlorine truck attack and other attack scenarios, both with and without various defense measures. Such work could incorporate results from this dissertation on effects of attacker and defender actions on chlorine attack fatalities.
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Appendices

Appendix A: Response Surface Fit Statistics for Chapter 3

Table A-1 presents goodness-of-fit measures for multiple regressions of averted fatalities used in Chapter 3. Regressions for 0% compliance without ventilation shutdown are not included, since the number of averted fatalities is zero in those cases.

<table>
<thead>
<tr>
<th>Dose-response model</th>
<th>Ingress delay from Cl exposure</th>
<th>Sheltering compliance rate</th>
<th>Ventilation shutdown</th>
<th>Degrees of Freedom</th>
<th>F statistic</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>df₀</td>
<td>dfₑ</td>
<td></td>
</tr>
<tr>
<td>Eisenberg et al.</td>
<td>Estimated delay</td>
<td>100%</td>
<td>Without</td>
<td>6</td>
<td>38</td>
<td>1050</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100%</td>
<td>With</td>
<td>14</td>
<td>498</td>
<td>1623</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0%</td>
<td>With</td>
<td>12</td>
<td>500</td>
<td>943</td>
</tr>
<tr>
<td></td>
<td>No delay</td>
<td>100%</td>
<td>Without</td>
<td>7</td>
<td>37</td>
<td>1201</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100%</td>
<td>With</td>
<td>15</td>
<td>497</td>
<td>1734</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0%</td>
<td>With</td>
<td>12</td>
<td>500</td>
<td>943</td>
</tr>
<tr>
<td>RPA</td>
<td>Estimated delay</td>
<td>100%</td>
<td>Without</td>
<td>3</td>
<td>41</td>
<td>217</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100%</td>
<td>With</td>
<td>14</td>
<td>498</td>
<td>285</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0%</td>
<td>With</td>
<td>11</td>
<td>501</td>
<td>213</td>
</tr>
<tr>
<td></td>
<td>No delay</td>
<td>100%</td>
<td>Without</td>
<td>6</td>
<td>38</td>
<td>1292</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100%</td>
<td>With</td>
<td>14</td>
<td>498</td>
<td>107</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0%</td>
<td>With</td>
<td>12</td>
<td>500</td>
<td>124</td>
</tr>
</tbody>
</table>

Appendix B: Parameter Values for Chapter 3

Table B-1 lists values, sources and reasoning for parameters in Chapter 3. For parameters not listed below (e.g. population density), see Chapter 2.
Table B-1: Parameter Values for Chapter 3

<table>
<thead>
<tr>
<th>Parameter (units)</th>
<th>Values and Probability Distributions</th>
<th>Sources and Reasoning</th>
</tr>
</thead>
<tbody>
<tr>
<td>First responders</td>
<td>Triangular(3,7,15)</td>
<td>Based on timelines of Houghton [1] and NTSB [123], assume two minutes after chlorine release for first call to emergency reporting number 911 and dispatch of first responders. Number of minutes for first responder arrival time in NFIRS data on 74 hazmat incidents in Washington, DC in 2005 [124] resembles Triangular(1.5, 13). First responders such as firefighters would recognize smell and other indicators of likely chlorine release very quickly after arriving on scene [1], assume this takes negligible amount of time.</td>
</tr>
<tr>
<td>Chemical detectors and cameras</td>
<td>Uniform(0.2, 1)</td>
<td>Based on tests of electrochemical sensors [125] assume detection times of approximately 10 seconds or less once cloud reaches sensor. SLAB outputs indicate the vapor cloud from instantaneous total release of 17 tons of pressurized chlorine would spread to 100m diameter in approximately 30 seconds, depending on weather conditions. Assume information immediately fed to emergency management personnel and that recognition of likely chlorine attack indicators takes negligible amount of time.</td>
</tr>
<tr>
<td>Authorities’ sheltering alert decision time (minutes)</td>
<td>Triangular (1, 10, 30)</td>
<td>Minimum: Based on minimum time for official alert decisions in study of historical hazmat incidents [108]. Mode: Lindell and Perry [109] say alert decision time could be very short, “a few minutes” if officials are trained and authority provided, especially if only one official is needed. Rogers and Sorensen [126], without citing specific data or assumptions, estimate the hazardous chemical release warning decision process takes an average of 10 minutes. Maximum: Assume performance equivalent to the average of a normal chemical emergency: In a survey of officials by Sorensen, Rogers et al. [107], the mean of estimated most-likely times to mobilize the necessary people and make a decision to notify the public minutes was 30 minutes.</td>
</tr>
<tr>
<td>Authorities’ alert message creation and dissemination time (minutes)</td>
<td>Triangular(2, 4, 9)</td>
<td>Minimum: Negligible time for message entry if computer automatically collects information, plus two minutes for message to play, per Moore [127]. Mode: Two minutes to enter message with HazCollect or equivalent, per Paese [106], plus two minutes for message to play, per Moore [127]. Maximum: The seven minutes Paese [106] says it now takes to enter needed information, plus two minutes to play message.</td>
</tr>
<tr>
<td>Public’s sheltering decision time (minutes)</td>
<td>Triangular (0.25, 1, 5)</td>
<td>Based on experiments measuring time until egress begun or decided after fire alarms and verbal instructions, in a school, apartment buildings, a laboratory and a subway station [105, 117-120].</td>
</tr>
<tr>
<td>Distance to nearby door (m)</td>
<td>Triangular (1, 50, 200)</td>
<td>Minimum: If already next to door. Mode: door probably accessible in building on block. Maximum: if have to go to next block.</td>
</tr>
<tr>
<td>Walking speed (m/min)</td>
<td>Uniform (40, 60)</td>
<td>Crowd conditions, level passageways [72, 74].</td>
</tr>
<tr>
<td>Time to pass through door once reached (minutes)</td>
<td>Uniform (0, 1)</td>
<td>With no impediment other than queuing, estimate approximately 40-60 people per minute through door [72, 74].</td>
</tr>
<tr>
<td>Sheltering compliance rate (fraction)</td>
<td>Uniform (0, 1)</td>
<td>Based partly on ranges for analogous scenarios [15, 42].</td>
</tr>
<tr>
<td>Dose-response model</td>
<td>Eisenberg et al [61], RPA [63]</td>
<td>Representative of groups of models in the literature. See Chapter 2 for values and discussion.</td>
</tr>
<tr>
<td>Chemical attack false alarm rate (alerts/year)</td>
<td>Uniform(0,6)</td>
<td>Maximum: Proulx [120] suggests one false alarm every two months is high for fire alarms. Assume that above 6 false alarms per year would either prompt methods to reduce costs per false alarm, or would end project.</td>
</tr>
<tr>
<td>Hours of disruption per person per alarm</td>
<td>Triangular (0, 1, 8)</td>
<td>Minimum: 0 (might only be plausible if people ignore alarm). Mode: Average amount of time police officer spends for false burglar alarm in residential area [128]. Maximum: Whole work day.</td>
</tr>
<tr>
<td>Description</td>
<td>Distribution</td>
<td>Notes</td>
</tr>
<tr>
<td>----------------------------------------------------------------------------</td>
<td>--------------------------------------------------</td>
<td>----------------------------------------------------------------------</td>
</tr>
<tr>
<td>Fraction of people in area with opportunity cost imposed by false alarm</td>
<td>Uniform(Fraction of people outdoors, 1)</td>
<td>Alarm will disrupt activities of some fraction of people in the area. Minimum: only people outdoors at time of release Maximum: all people in area including those indoors Bishaw [129]</td>
</tr>
<tr>
<td>Annual income of people in area affected by alarms ($/yr)</td>
<td>50k</td>
<td>Based on aerial photography of office district of Washington, DC Similar to range of estimates in Lugar [104]</td>
</tr>
<tr>
<td>Area needing alert system coverage (mi²)</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>Annual probability of attack in area covered by detector and alert systems</td>
<td>0.001, 0.01, 0.1, 1</td>
<td></td>
</tr>
<tr>
<td>Weather conditions</td>
<td>Nighttime, 2.5 m/s wind, Pasquill stability class F, 20˚C ambient</td>
<td>Highest-fatality weather conditions if no effective defense response (Chapter 2)</td>
</tr>
<tr>
<td>Outdoor alert units per block</td>
<td>1</td>
<td>Assume one sensor unit and one alert unit per block/intersection in area covered</td>
</tr>
<tr>
<td>Cost per outdoor public alert unit ($/unit)</td>
<td>Uniform (450, 620)</td>
<td>Materials for public address system: $230 [172]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Materials for weather radio: $50-100 [172]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Installation: 2-3 hours of one electrician’s time: $100-150 [172]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Overhead and profit: ~20-30% of materials + labor [172]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Materials for camera: $300-700 [172]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Installation: 4-8 hours of one electrician’s time: $200-400 [172]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Overhead and profit: ~20-30% of materials + labor [172]</td>
</tr>
<tr>
<td>Maintenance cost per chemical sensor ($/sensor-year)</td>
<td>Uniform(900,1100)</td>
<td>Materials: $600/year for materials for quarterly calibration, which takes five minutes and not much training [173]. Sensors need replacement every 3 years [173] so assume 1/3 need replacement each year, sensor itself is $350 [174] Labor: 0.5-3 hours of one electrician’s time: $25-150 [172] Overhead and profit: ~20-30% of materials + labor [172]</td>
</tr>
<tr>
<td>Buildings per block</td>
<td>Triangular (1, 5, 10)</td>
<td>Aerial photos of Washington, DC</td>
</tr>
<tr>
<td>Fraction of buildings with air intakes at roof / 10th floor level</td>
<td>Triangular (0.75, 0.8, 0.85)</td>
<td>Personal observation in Washington, DC</td>
</tr>
<tr>
<td>Fraction of buildings with multiple HVAC units on floor</td>
<td>Estimate half of buildings without HVAC intakes on roof have window-mounted HVAC units, the rest have a central unit on each floor</td>
<td>Estimate based on personal observation in Washington, DC</td>
</tr>
<tr>
<td>Number of floors for which to shut down ventilation</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Window-mounted HVAC units per floor needing them</td>
<td>Uniform (10, 50)</td>
<td>Aerial photos of Washington, DC</td>
</tr>
<tr>
<td>Cost of shutdown units for central HVAC ($/unit)</td>
<td>Uniform (240, 1000)</td>
<td>Materials equivalent to weather radio + HVAC control or circuit breaker: $150 – 600 [172]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Labor: 1-3 hour of one electrician’s time: $50-150 [172]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Overhead and profit: ~20-30% of materials + labor [172]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Materials equivalent to weather radio + surge protector: $75-150 [172]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Labor: 0.25 hour of one electrician’s time: $25 [172]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Overhead and profit: ~20-30% of materials + labor [172]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Based on range of inflation-adjusted US government interest rates in past several decades [169]</td>
</tr>
<tr>
<td>Cost per plug-through shutdown unit for window-mounted HVAC ($/unit)</td>
<td>Uniform (120, 230)</td>
<td></td>
</tr>
<tr>
<td>Discount rate</td>
<td>0.03, 0.04, 0.06 (use 0.04 if not otherwise stated)</td>
<td></td>
</tr>
<tr>
<td>Equipment lifetime (years)</td>
<td>10, 15, 30; equal probabilities</td>
<td>-</td>
</tr>
<tr>
<td>Initial building air exchange rates (air changes per hour or ACH)</td>
<td>Lognormal(Median: 1, Std. Dev.: 3.5), truncated at 15</td>
<td>[68]</td>
</tr>
<tr>
<td>Building air exchange rates after shutdown, if applicable (ACH)</td>
<td>Triangular (0.2, 0.36, 0.7) unless sampled rate &lt; initial rate, then use initial rate</td>
<td>[70, 71]</td>
</tr>
</tbody>
</table>
Appendix C: Derivation of Cost Effectiveness Formulae

To calculate annualized material and installation costs of equipment in Chapter 5, we use a standard mortgage calculation with a period of 30 years: the Analytica formula is 
\[ \text{Pmt}(r, t, C_p) \] where \( r \) is the discount rate, \( t \) is the project lifetime (years), and \( C_p \) is the capital cost. Adding annual costs \( C_e, C_r, C_m \) for electricity, materials and maintenance, respectively, gives

\[ C_s = \text{Pmt}(r, t, C_p) + C_e + C_r + C_m \]  
(Eq. C-1)

In each year \( i \), the annualized costs \( C_{si} \) are the same, i.e. \( C_{s1} = C_{s2} = C_{s3} \), etc.

For each system option considered, we calculate values of expected cost per death averted,

\[ C_a = \frac{C_s}{P \cdot (F_o - F_w)} \]  
(Eq. C-2)

where \( C_a \) is the cost per net death averted by use of a system ($/statistical life saved), \( C_s \) is the annualized system cost ($/year), \( P \) is the annual probability of a single chlorine tank truck attack or the expected number of attacks per year in the area covered by the system (attacks/year), and \( F_w \) and \( F_o \) are the number of estimated fatalities with and without the system in place, respectively (lives/attack).

If the annual probability of attack \( P \) is the same in each year of the project, the expected number of fatalities averted in year \( i \) is \( (P \cdot (F_o - F_w))_i \) and the future value of the expected cost per death averted in year \( i \) is

\[ C_{ai} = \frac{C_{si}}{(P \cdot (F_o - F_w))_i} \]  
(Eq. C-3)

The present value of expected cost per death averted in year \( i \) is
\[
PV(C_{ai}) = \frac{C_{si} \left( \frac{1}{1+r} \right)^i}{(P \cdot (F_o - F_w))_i \cdot \left( \frac{1}{1+r} \right)^i}
\]  
(Eq. C-4)

where \( r \) is the discount rate. Summing across years \( i \), the net present value of expected cost per death averted is

\[
NPV(C_a) = \sum_i \left( \frac{C_{si} \left( \frac{1}{1+r} \right)^i}{(P \cdot (F_o - F_w))_i \cdot \left( \frac{1}{1+r} \right)^i} \right)
\]  
(Eq. C-5)

Pulling out constants, and canceling terms,

\[
NPV(C_a) = \frac{C_{si}}{(P \cdot (F_o - F_w))_i} \sum_i \left( \frac{1}{1+r} \right)^i = \frac{C_{si}}{(P \cdot (F_o - F_w))_i}
\]  
(Eq. C-6)

Since each input variable is the same in every year \( i \),

\[
NPV(C_a) = \frac{C_s}{P \cdot (F_o - F_w)} = C_a
\]  
(Eq. C-7)

which is equivalent to Equation 5-1, the cost effectiveness equation we use in Chapter 5.

Equation 3-1, the cost effectiveness formula we use in Chapter 3,

\[
C_a = \frac{C_s}{P \cdot Max[0.1, (F_o - F_w)]}
\]

is a modification of Equation 5-1, formulated to address the possibility that the systems result in net increase in fatalities. In those cases, the equation results in a very high cost per death averted (and a failure to pass a given cost-effectiveness test), instead of the nonsensical result of negative cost per death averted.