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Protecting Civilian Populations during Chemical Agent Emergencies

George O. Rogers, John H. Sorensen, and Anneta P. Watson

I. Summary

This research summarizes a model developed to examine the effect various protective actions have on expected exposure under a variety of release and meteorological conditions. The model compares the expected exposure without protection, with the expected given a specified emergency response system, and the capacity of the selected action to protect (assuming that all

people to be protected have implemented the protective measure). These exposure estimates are graphically displayed over time from the beginning of the event in the context of their anticipated acute human health effects.

Preliminary analyses of accident scenarios indicate that whenever there is enough time to complete an evacuation before a plume's impact, evacuation is the preferred alternative for most people in areas likely to be affected by potential accidents. In-place shelters are most appropriate in circumstances where time to respond is severely limited, with pressurized shelters providing the maximal protection. Respiratory protection measures may be used to significantly reduce exposure in any accident; however, leakage around respiratory devices remains the dominant technical factor in the use of respiratory devices to protect civilians. Hence, respiratory protection is most appropriately used in conjunction with either evacuation or reduced-infiltration, in-place shelters.

A terrorist event scenario involving the introduction of a limited amount of agent, in a relatively dense population area, under stable meteorological conditions that would disperse agent in maximal concentrations, is also considered. Such terrorist events may be characterized by either an unannounced and sudden release of agent, or an extortion involving a threat to release agent. Unfortunately, evacuation is not always a feasible response to terrorist acts, because in sudden releases, people in close proximity to the release point would be unable to evacuate without exposure; in extortion events, the terrorist response to an evacuation, if detected, is unknown. Moreover, because the target and impact area are unknown, potentially affected portions of cities cannot be evacuated before the terrorist event. In-place shelters can provide a measure of protection for civilian populations from terrorist acts resulting in agent release, because they can be implemented almost immediately, and they provide excellent protection from percutaneous exposure to droplets and aerosals. Complete protection for people within 1 km of a release cannot be fully achieved with in-place protection without extremely rapid implementation and very low exchange rates. Respiratory protection is particularly well suited for protection from exposure stemming from acts of purposive harm. Using respiratory devices has the advantages of rapid implementation, and effective exposure reduction, but has the disadvantage of requiring extensive maintenance and training to be effective, and safe. No protective action can be completely effective for terrorist acts of the sudden release variety, owing to the potential for exposure before implementation of protection.

II. Introduction

Emergency preparedness measures can reduce the risks of adverse health effects of accidents involving chemical agents. This article describes the protective action evaluator for chemic
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2. human behavior in emergencies;
3. human health effects.

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s. This article describes the protective action evaluator for chemical emergencies (PAECE) developed for the U.S. Army and the Federal Emergency Management Agency's Chemical Stockpile Emergency Planning Program to evaluate the extent to which alternative protective measures are likely to reduce exposure (Rogers *et al.*, 1990; Chester, 1988; Sorensen, 1988). Which protective actions are best suited for response to hazard(s) presented by chemical agents? And which populations are most appropriately protected by what measure? Historically, the selection of protective actions has been based on experience with previous disasters, and the experience of others. Modeling has been used to systematically examine protective actions (Drabek, 1986; Pate-Cornell, 1986; Glickman and Ujihara, 1988, 1990; Lindell and Barnes, 1985, 1986). Research regarding chemical hazards has focused on

1. the physical ability to protect affected groups;
2. human behavior in emergencies; and
3. human health effects.

Analyzing the physical aspects of protection has focused on characterizing the nature of the hazard as well as the design and development of equipment and actions to physically reduce exposure. Evaluating behavioral response to disasters has focused on various aspects of individual and social organizational response to disaster. Analyzing potential human health effects composes by far the most extensive body of research and has concentrated on both acute and delayed effects. The current analysis attempts to integrate these three perspectives as they apply to the selection of protective actions for the public in the event of chemical agent release.

This chapter summarizes a conceptual model for evaluating protective action strategies and presents a selected analysis of some planning accidents/events to determine the effectiveness of alternative measures of protection for chemical agents. The model includes hazard identification and assessment, airborne dispersion, organizational and community decisions, emergency warning, public response, implementation, and immediate recovery. The model was developed to examine the extent of protection against accidental releases of chemical agents at storage facilities in the continental United States; it will also be used to examine a terrorism or wartime event aimed at civilian populations.

The model was developed to assist emergency managers in selecting the best combination of protective actions to afford optimal protection for the people at risk. It can randomly simulate realistic accident conditions, emergency exercise scenarios, the responses taken, and their associated consequences. Eventually the model may be adapted to use real-time data (in the event of an accident) to assist emergency managers in making decisions regarding appropriate protective actions during chemical agent emergencies. The availability of such a system that can evaluate the effectiveness of various protective-action strategies in the context of the complete emergency response, also makes more general inquiries possible, such as evaluating the relative importance of each emergency response function (e.g., accident assessment. decision making, warning), and provides insight into emergency preparedness efforts (Rogers *et al.*, 1989).

III. An Approach for Evaluating Protective Actions

Conceptually, the effectiveness of any particular protective action taken in the event of a chemical accident depends on the ability of those actions to reduce chemical exposure to tolerable levels and the probability that the people to be protected will take the action in a timely manner. Figure 1

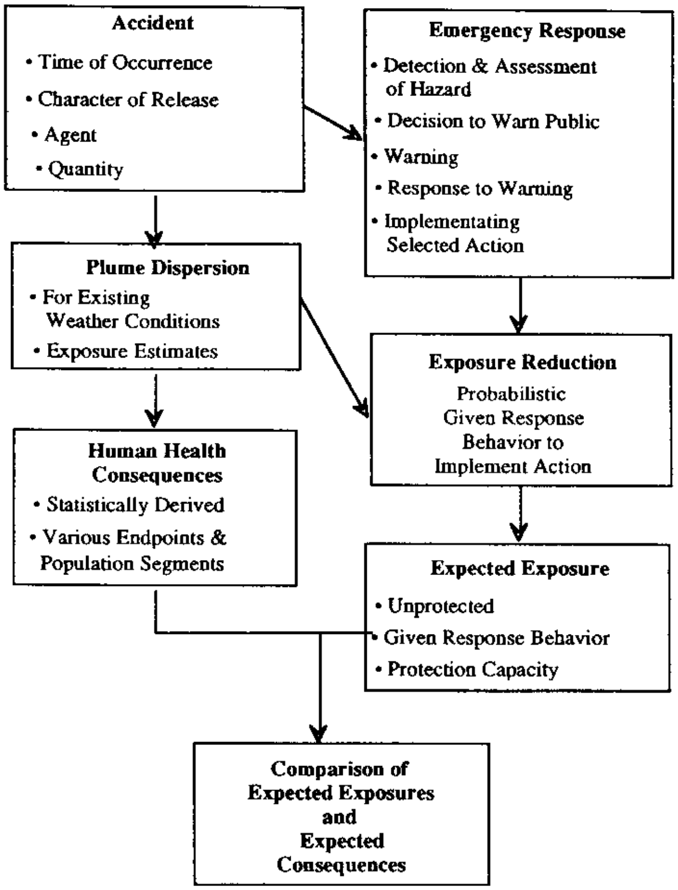

Figure 1 Conceptual framework for evaluating protective action effectiveness.

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A. Chemical Agent Releases

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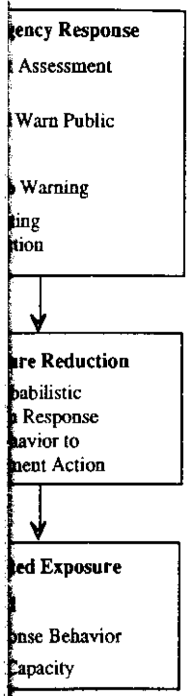
ticular protective action taken in on the ability of those actions to els and the probability that the on in a timely manner. Figure 1



protective action effectiveness.

presents an overview of the model. Two factors that determine an action's ability to reduce exposure to tolerable levels are (1) the degree of hazard or amount of toxic agent present in the unprotected environment, and (2) the protective action's ability to either reduce or avoid that exposure. The timeliness may be thought of as a function of the amount of time it takes for a toxic plume to travel to a given distance, compared with the time it takes the emergency response system to get people at that distance to protect themselves from, or avoid, harm.

Examining protective actions in the context of potential accidents, the complete emergency response system and the associated environment provide a comprehensive evaluation of the effectiveness of protection. The PAECE model summarizes protection effectiveness in terms of (1) the potential accidents likely to occur, (2) the complete emergency response system leading to the implementation of the protective action, and (3) those parts of the environment significantly affecting either the character of the accident, or the nature of the response, or both.

Given the presence of equivalent hazards, two considerations underlie the effectiveness of each protective action. The first is the inherent ability of each measure to avoid or reduce exposure. Hence, capacity to protect or avoid includes only the action's physical capability to protect or avoid. For example, the ability of a respiratory device to protect is dependent on (1) the efficiency of the charcoal filter in removing airborne chemicals, and (2) the degree to which leakage around the filters can be prevented. This physical capacity of protection determines the maximal exposure reduction people using a given device or measure can achieve.

The second consideration is the amount of time required to complete a given action, because a protective measure can reduce exposure only when it is implemented. The completion of a protective action involves the time it takes (1) to detect the hazard, assess the situation, and decide a warning is appropriate; (2) to disseminate the warning message that both alerts people to the potential for harm and notifies them concerning appropriate responses; (3) for the public to decide on an appropriate course of action; and (4) for people to implement the selected action. The time needed to complete this chain of events determines the extent of exposure before the implementation of a protective action. Acts of purposive harm (e.g., terrorism and war) are likely to elicit rapid response chains, because the intent for harm rips away the mask of fate; the detection of an event (e.g., the launch of a missile) has understood outcomes and responses.

A. Chemical Agent Releases

Potential accidents involving the unitary chemical stockpile were studied in the course of the preparation of the programmatic environmental impact statement (U.S. Army, 1988; Fraize *et al.*, 1989). The results of that analysis played a critical role in the decision for on-site disposal (Ambrose, 1988). Although it is impossible to identify all possible accident sequences and events in advance, the distribution of accidents is represented by the data base developed for the program (Fraize *et al.*, 1987). The accidents have a probability of occurrence of 1×10^{-8} or greater (at least 1 chance in 100 million disposal programs). The quantity of specific agent released, estimated duration of release, and expected downwind distance of the releases are used to summarize the distribution. Terrorist acts were considered separately. Should either existing munitions or terrorist-manufactured armaments be introduced into populated areas (e.g., London, New York, Los Angeles, Tel Aviv), particularly those with recognized air-inversion problems, the current risk analysis is unlikely to represent the full range of associated consequences (i.e., the consequences could be more serious).

B. Plume Dispersion

Assessment of the onset, duration, and magnitude of the hazard is also a prerequisite for evaluating protective actions. The dispersion of agent can be determined over time at a given downwind distance from the source of the release. The total exposure is estimated using an air-dispersion model developed by Whitacre *et al.* (1987) specifically for the determination of inhalation exposure to chemical agents. The model assumes a Gaussian distribution of agent in the vertical and cross-wind directions as the agent disperses downwind. The development of Gaussian models has been documented extensively in the literature (Sutton, 1932; Gifford, 1968; Pasquill, 1974), and many existing dispersion models use Gaussian distributions.

Another air-dispersion model estimates partial exposure for a particular distance over time (Seigh, 1988). Concentrations over 1-min intervals are summed to estimate the inhalation exposure for unprotected people at a given distance. This partial-exposure model assumes the same Gaussian distribution of agent, but does not include some of the more sophisticated techniques in the total inhalation-exposure model, such as vapor depletion. Therefore, the results of the partial-exposure model are normalized by the total inhalation-exposure results so that the shape of the curve representing exposure accumulated with time is the same, and the total inhalation exposures from both models match. This method of evaluation allows the user to specify meteorological conditions in terms of wind speed, stability class, and mixing height.

C. Human Health Effects

Data quantifying known acute an
agents have been summarized (U.S.
et al. 1989a,b). These values are l
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personnel under battlefield conditi
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tive to nerve or vesicant agent exp
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tory passages, and underdeveloped
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This approach was then used
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C. Human Health Effects

Data quantifying known acute and delayed effects of nerve and vesicant agents have been summarized (U.S. Department of the Army, 1988; Watson *et al.* 1989a,b). These values are largely extrapolated from the results of laboratory animal exposure as a means of estimating the response of military personnel under battlefield conditions (i.e., young adult, male, combat personnel). Standard anatomical assumptions regarding body weight, respiratory volume, and inspiration rates are made to calculate the body burden resulting from inhalation exposure to a given Ct (i.e., atmospheric concentration, C, multiplied by time, t, in mg·min/m^3). By further assuming that the body burden derived from the Ct values associated with a specific toxic endpoint will generate the same toxic endpoint in individuals with characteristically different anatomical parameters (e.g., adult females, children, and newborns), a new but biologically equivalent Ct can be calculated. This logic assumes that other gender and/or age classes are not inherently more sensitive to nerve or vesicant agent exposure than young adult males. This latter assumption is probably untrue, owing to the thin epidermis, small respiratory passages, and underdeveloped detoxification systems of young children. However, in the absence of age-specific exposure–response data to support scaling on the basis of epidermal thickness, airway diameter, or metabolism, a body burden estimated from standard anatomical data is a reasonable approach.

This approach was then used to convert available inhalation data for nerve and vesicant agents. The resulting age/gender analysis of acute exposure effects result in inhalation exposure estimates for observable (threshold) effects and 50% lethal concentration fatalities (LCt_{50}) in adult males and newborns at various levels of exertion. (The LCt_{50} is the statistically derived lethal concentration multiplied by time that would kill 50% of the exposed population). These estimates are matched on the basis of the extent of activity required to implement the protective action, and subsequently compared to the estimated exposure resulting from the selected accident under various circumstances (Table I). Adult males and newborn infants are selected to represent the extremes of population sensitivity to agent exposure. Where observable effects were characterized by a range of values, the minimum was used for comparing scenario results.

This analysis emphasized inhalation exposures rather than dermal or percutaneous exposures, owing to the differential toxicity displayed by these two routes of entry. Inhalation exposures for a given biological endpoint, such as LCt_{50}, are usually much less than the percutaneous exposure. For example, compare the inhalation and percutaneous LCt_{50} values for GB, a highly volatile organophosphate nerve agent. The inhalation LCt_{50} is 70 mg·min/m^3,

Table I
Estimated Inhalation Exposure Levels for Acute Agent Health Effects

Agent	Age/gender	Activity[a] level	Observed effects[b] (mg·min/m^3)	LCt$_{50}$ (mg·min/m^3)[c]
GB	Adult male	Light	1–2	70
	Adult male	Resting	2–4[d]	100
	Newborn	Light	0.2–0.5	33
	Newborn	Resting	0.7–1.4[d]	47
VX	Adult male	Light	0.05–0.8[e]	30
	Adult male	Resting	0.09–1.6	36
	Newborn	Light	0.02–0.4[e]	14
	Newborn	Resting	0.07–1.2	17
H/HD	Adult male	Unreported	—	1500
	Newborn	Unreported	—	702

[a] Mild activity inhalation rates assumed for most of the day; resting activity inhalation levels are used when the population at risk is usually asleep (midnight to 5 AM).

[b] The observed-effects range includes the estimated ECt$_{50}$ for miosis as well as the estimated population threshold for no neuromuscular effects (tremors).

[c] Fatal exposures are rounded to the nearest whole number. From data summarized in App. B of Chemical Stockpile Disposal Program Programmatic EIS (U.S. Department of the Army, 1988) and assumptions of Table 3.2 in Rogers *et al.* (1990). GB LCt$_{50}$ of 70 mg·min/m^3 based on value cited in U.S. Department of the Army (1974), *Chemical Agent Data Sheets*, Vol. 1, EO-SR-74001, Edgewood Arsenal Special Report, Defense Technical Information Center, Alexandria, Virginia. The D2PC code considers the LCt$_{50}$ value for GB to be 50 mg·min/m^3.

[d] Calculated for resting inhalation rates. From (Table 3.2 in Rogers *et al.* (1990).

[e] Calculated for light activity inhalation rates. From Table 3.2 in Rogers *et al.* (1990).

whereas the percutaneous GB exposure is 15,000 mg·min/m^3 (U.S. Department of the Army, 1974). Thus 50% mortality in an adult population with respiratory protection but no skin protection in a GB atmosphere would be attained at more than 200 times the GB air concentration necessary to induce 50% mortality in an adult population with no respiratory protection (for the same period of exposure). The inhalation route of exposure is clearly much more sensitive than the dermal.

Because agent GB is the most volatile agent in the unitary stockpile, it presents the largest potential for agent transport to off-post locations. VX is the most potent of the agents being considered, and it is persistent; however, it is much less volatile than GB and does not readily disperse. Equal quantities of GB and VX would affect different downwind areas. Mustard agents are considered the least potent of these agents, because the LCt$_{50}$ inhalation exposure is so high (1500 mg·min/m^3) in comparison with the LCt$_{50}$ inhalation exposures for VX (30 mg·min/m^3) and GB (70 mg·min/m^3).

However, mustard agents are knov
latent effects that will require cons
and decision making.

D. Decision to Warn

The decision to warn involves the
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Behavioral data from 13 comm
emergencies document the length of

ute Agent Health Effects

Observed effects[b] (mg·min/m^3)	LCt$_{50}$ (mg·min/m^3)[c]
1–2	70
2–4[d]	100
0.2–0.5	33
0.7–1.4[d]	47
0.05–0.8[e]	30
0.09–1.6	36
0.02–0.4[e]	14
0.07–1.2	17
—	1500
—	702

of the day; resting activity inhalation
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downwind areas. Mustard agents
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/m^3) and GB (70 mg·min/m^3).

However, mustard agents are known carcinogens; any exposure may have latent effects that will require consideration in protective action planning and decision making.

D. Decision to Warn

The decision to warn involves the detection and assessment of hazard, as well as the mobilization of decision makers and completion of the decision process. People and organizations differ in ability to conduct and accomplish the activities that are crucial to initiation of the emergency response process. Hence the initiation of emergency response with the decision to warn is distributed over time into the accident, depending on a variety of factors. Once the hazard has been detected, the extent of the hazard will have to be assessed to determine the nature of appropriate response. In the meantime, the timing of the decision to warn depends on the mobilization process, the number of people required to reach a decision, and the perception of the urgency required by the situation. The perception of urgency determines whether emergency decisions are accelerated to meet requirements of severe crises, or extended over longer periods.

Sorensen *et al.* (1988) asked emergency managers from communities around the country to characterize the number of people that would need to be involved in emergency decisions. In emergencies described as urgent, "fast-moving" events, emergency managers indicated that one person was frequently all that was needed, but on average, two people were involved in emergency decision making. Emergency decision making expanded to an average of five people in more slowly developing events.

Urgency reduces the estimates of the amount of time required to assemble the necessary people and make the decision. These data indicate that community officials would take 15 to 20 min under ideal conditions to decide to warn the public. Rogers and Sorensen (1988) examine relative effectiveness of emergency warning systems. They find that even with better than ideal decision times (e.g., 10 min) many people in close proximity can be exposed before being warned in fast-moving events. Most likely estimates of the amount of time required to make decisions to warn the public in an emergency averaged about 30 min in rapidly progressing events. Many factors can interfere with mobilizing decision makers, and the uncertainty in making the decision. Sorensen *et al.* (1988) conclude that whereas communities are capable of making timely decisions in emergencies, there are no guarantees that timely decisions will be reached even when the situation warrants.

Behavioral data from 13 community emergency responses to chemical emergencies document the length of time required to make a decision to warn the public (Rogers *et al.*, 1990). These limited data indicate that a decision to warn the public was made in about half of these cases in 15 to 20 min, with about two thirds reaching a decision to warn in about 30 min, and in one case, the public was not officially warned.

These data seem to indicate that emergency decision making can be compressed to meet urgency, but the decision to warn the public is not simultaneous with the occurrence of the event. Advance planning can reduce the amount of time required to make decisions by reducing the number of people required to make emergency decisions, identifying critical factors in the decision, accelerating mobilization of required people and resources, and outlining the framework for decisions in emergencies. The decision to warn represents the time between a release and initiation of the public warning process.

E. Emergency Warning

Warning people of impending danger involves two conceptually distinct processes—alerting and notification. Alerting makes people aware of an imminent hazard. Alerting deals with the ability of emergency officials to make people aware of the threat. Alerting frequently involves the technical ability to break routine acoustic environments to cue people to seek additional information. In contrast, notification focuses on how people interpret the warning message. The way people interpret the warning message is critically important in their selection of appropriate behavior in response to emergency warnings. Emergency warning messages are received through a series of pathways that change their meaning. This results from an interplay of cognitive processes and existing social structures (Rogers, 1989). People have existing estimates of the threats presented by their environments. Furthermore, these estimates, together with personal experience, provide the basis for selecting behavior, that is, whether to accept, ignore, disseminate, challenge, or confirm the warning message (Rogers, 1989; Baker, 1979; Williams, 1964).

The emergency warning process resembles the diffusion of other types of information or communications, except that it usually occurs over a shorter period. The basic mathematical form is a logistic function. The cumulative proportion of people receiving the warning forms an S-curve, which is determined by the exponential form of the initial alerting process and the logistic form of the subsequent passage of the warning and message through the social network (Rogers and Nehnevajsa, 1987).

The alerting is characterized as a "broadcast process" that disseminates the emergency warning, which is centralized in the sense that many are alerted from a single source simultaneously. In contrast, the social network process

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is characterized as a "birth process
and subsequently tell others (Lave
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$$dn/dt = k[a_1(N - n$$

where k is the portion of the popu
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cess. N is the proportion of the po
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Sorensen (1988) characterize various
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Rogers and Sorensen (1989) show t
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F. Public Response to Emerge

Emergency warnings that result in
logical discomfort and uncertaint
resolved through response. Respo
both the characteristic message an
message evaluates the anticipated s
the context of certainty and ambig
of relevance; for example, "Is the
relevance of the warning message
saster experience, relative proximi
interpretation, and discussion with

Janis (1958) describes effective
balance between fear-arousing and
the impending danger in sufficient d
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ed data indicate that a decision to
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is characterized as a "birth process" whereby people first hear of the event and subsequently tell others (Lave and March, 1975). The general mathematical specification of the diffusion curve, including both broadcast and birth processes, is

$$dn/dt = k[a_1(N - n)] + (1 - k)[a_2 n(N - n)],$$

where k is the portion of the population alerted via the broadcast process, that is, the proportion of people who are alerted to the potential for harm who immediately recognize the meaning of the alert signal. The quantity $(1 - k)$ represents the proportion of people left to be warned. The broadcast parameter, a_1, summarizes the efficiency of the alerting process, and the birth parameter, a_2, summarizes the effectiveness of the social network process. N is the proportion of the population to be warned, and n is the proportion warned at the beginning of each period $(t_0, t_1, \ldots, t_i, \ldots)$. Rogers and Sorensen (1988) characterize various warning systems by specifying the broadcast and birth parameters, representing the dependence of each system on alerting and social network processes, respectively. For example, the social network parameter for a siren system will be relatively high because it depends on recipients to take an active role in their own warning (i.e., they must do something). Usually this entails seeking further information via another (secondary) source. Comparing these warning system characterizations with available data regarding public receipt of warning in two train derailments, Rogers and Sorensen (1989) show that these representations of warning diffusion closely resemble the empirically observed receipt of warning.

F. Public Response to Emergency Warning

Emergency warnings that result in the recognition of threat, create psychological discomfort and uncertainty about the impending event, which is resolved through response. Response to the emergency warning involves both the characteristic message and the receiver. The person receiving the message evaluates the anticipated severity, timing, and location of impact, in the context of certainty and ambiguity. The message is personalized in terms of relevance; for example, "Is the threat likely to affect me?" The resulting relevance of the warning message is determined in the context of prior disaster experience, relative proximity, credibility of the source of warning, interpretation, and discussion with others.

Janis (1958) describes effective warning messages as requiring a delicate balance between fear-arousing and fear-reducing statements. By describing the impending danger in sufficient detail, a vivid mental image of the impending crisis is evoked. The fear-arousing part of the warning message reduces the possibility of surprise, and invokes response. The realistic presentation of the mitigating activities provides information regarding both the actions of authorities and those of individuals. This fear-reducing component of the warning message provides the foundation for adaptive response. The fear-arousing content alerts the public to the potential for harm, whereas the fear-reducing statements notify the public (Rogers and Nehnevajsa, 1987).

One aspect of response is the passage of time between when people receive the warning message and when they take action to avoid harm. The timing of public response (principally evacuation) to emergency warnings has been studied in conjunction with three train derailments involving chemical releases, in Mississauga, Ontario, Pittsburgh and Confluence, Pennsylvania, and a chemical plant fire in Nanticoke, Pennsylvania (Fig. 2).

The public's response to emergencies often begins spontaneously before receiving an official warning. The response functions associated with the four cases of public response to chemical releases are similar, in that each approaches complete response, generally characterized by a logistic function or S-shaped curve. More people responded more quickly to the Confluence accident than to the other accidents, summarized by the response curves in Figure 2. The Nanticoke curve is nearly as high as the Confluence curve, but takes slightly longer to reach its maximum. The Pittsburgh and Mississauga response curves are similar; however, the Mississauga curve is smoother, owing to the estimation procedures used by Burton *et al.* (1981). The Pittsburgh, Confluence, and Nanticoke curves represent raw empirical distributions.

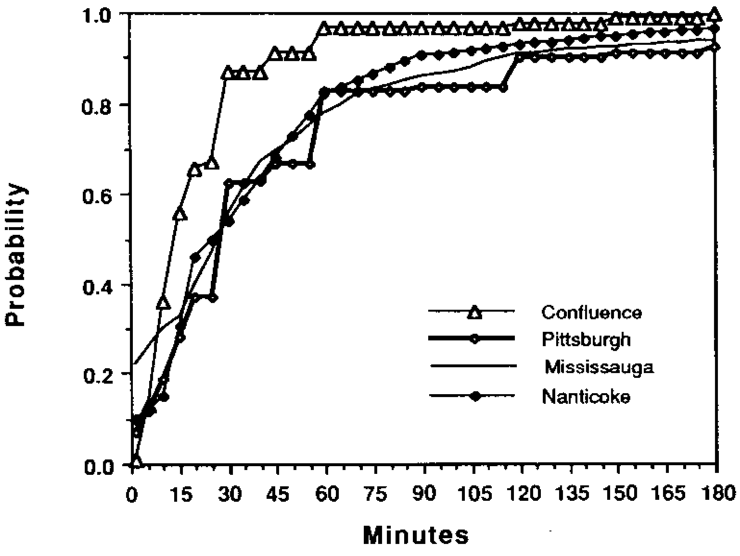

Figure 2 Public response to emergency warning.

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G. Implementation of Protecti

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IV. Estimating Protective-Actio

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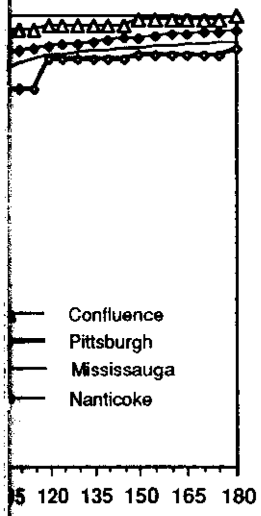

ing.

For the purposes of evaluating protective actions for chemical emergencies, public response may be characterized in terms of these limited data regarding the timing of public response. The model allows the response functions to be scaled to reflect specific preparedness scenarios. For example, scaling responses up might be associated with effective public information programs; scaling them down might represent complacency associated with a relatively incident-free history.

G. *Implementation of Protective Action*

Under every emergency response scenario, the implementation of the selected protective action is distributed over time, beginning at the time of the decision to respond. Each protective measure requires different sets of actions; thus, implementation depends on the actions taken. Evacuation may be characterized in terms of a detailed evacuation time estimate (ETE) (Urbanik, 1981; Urbanik *et al.*, 1980; Aldrich *et al.*, 1978; Aldrich *et al.*, 1979; Tweedie *et al.*, 1986; Walsh *et al.*, 1983). The ETEs are estimated clearance times for various populations at risk. The user evaluates evacuation scenarios by specifying the clearance time, as the minutes between the decision to respond and the completion of the evacuation.

All in-place shelters are implemented by closing exterior doors and windows, and turning off heating, cooling, and circulation systems; expedient shelters also require people to tape and seal an interior room; hence, they require more time to implement. PAECE allows the evaluator to select empirically based curves that reflect these sets of actions or simply select a time at which the implementation will be completed.

Personal protection via a respiratory device involves first locating that device and then fitting it properly in place. Trained military personnel are expected to be capable of implementing these procedures in very rapid order (< 10 sec). PAECE allows the implementation of respiratory protection to be specified at 1-min intervals, as selected by the evaluator.

IV. Estimating Protective-Action Effectiveness

The effectiveness of protection involves the physical ability of various protective actions to reduce exposure to chemical agents. Exposure reduction capacity assumes all behavioral or response functions are adequately performed to assure design criteria performance of protection measures. Exposure reduction capacity, therefore, does not take into consideration the proportion of the population or number of people implementing the specified respiratory device. The exposure-reduction capacity is the sum of the reduced concentrations over time.

A. Protection Capacity

For a respiratory device, the ability to reduce exposure is a simple function of leakage around the device and penetration through the filter, known as breakthrough. For a respiratory device characterized by leakage, L, and breakthrough, B, the protection capacity is calculated as a direct function of L and B, and the concentration of agent in the unprotected environment. For any moment, t, the protective capacity of a respiratory device is expressed as the expected concentration while using a given respiratory device,

$$C_p = (1 - b)C_u L + bC_u,$$

where C_u is the concentration of chemical in the unprotected environment at t, L is leakage, and b is equal to 1 if the sum of C_u exceeds the breakthrough standard B at time t; otherwise, b is 0. The first part of the binomial represents the leakage before reaching the breakthrough standard, and the second part of the binomial accumulates the entire unprotected concentration once the breakthrough standard is reached.

For in-place shelters, the ability to reduce exposure depends on the amount of infiltration from the unprotected environment to the protected environment and the difference in agent concentration between the protected and unprotected environments. For any moment, t, the protection capacity of an in-place shelter is expressed as the expected concentration in the protected environment,

$$C_{pt} = C_{pt-1} + I(C_{ut-1} - C_{pt-1}),$$

where C_p and C_u are as previously defined, I is the infiltration rate in period t, and C_p is the amount of agent in the protected environment at the beginning of the period. This formulation allows for the mixing of fresh (noncontaminated) air into the protected environment as the plume passes by; C_u becomes smaller than C_p at the same rate, I, at which it became contaminated as the plume arrived.

For evacuation, the reduced concentrations are a simple function of the proportion of the population completing evacuation and the concentration of agent in the unprotected environment. The protection capacity associated with evacuation for any moment t is expressed as the expected concentration given the probability of completing the evacuation at time t,

$$C_p = [1 - P(\mathrm{e})]C_u,$$

where C_u is the unprotected concentration and $P(\mathrm{e})$ is the probability of completing evacuation. Unfortunately, the completion of evacuation cannot be neatly partitioned into the physical aspects and the behavioral elements, because evacuation time is a function of driving behavior and physical structure (e.g., carrying capacity of roads, maximal attainable speeds of vehicles).

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C. Model Overview

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In theory, if all road networks were large enough to accommodate all evacuation traffic, then exposure-reduction capacity for evacuation would be complete (i.e., no exposure would be received); however, because the times at which evacuations can be completed are both structural and behavioral, the exposure-reduction capacity for evacuation can exceed zero. The protection capacity may also be expressed in terms of exposure at time t as

$$Ct_p = \sum C_{pt}.$$

B. Response-Adjusted Exposure

To accurately reflect the effectiveness of a protective action, the measure must reflect the probability of implementing the action. Expected exposure for a given population at time t is calculated as

$$E(C_p) = (P(\mathrm{i})C_p) + (1 - P(\mathrm{i}))C_u,$$

where $P(\mathrm{i})$ is the joint probability of having reached a decision to warn, receiving warning, deciding to respond, and implementing that response at time t, and C_p and C_u are the protected and unprotected inhalation exposures, respectively. The expected concentration-time integral accumulates the expected concentration $E(C_p)$, from time zero to t, to represent the cumulative exposure, Ct, anticipated for a population protected by protective active i. This expected exposure in the protected environment is a probabilistic measure of population exposure for the given protective action.

C. Model Overview

The PAECE model is conceptually composed of a number of modules that address specific aspects of protective action decision making. Conceptually the model consists of those modules characterizing the nature of the hazard and its consequences and the modules characterizing emergency response (Fig. 3). PAECE begins with the specification of the initiating events in terms of the time and nature of the accident resulting in a release. The time of the release determines (1) the time at which the emergency response begins, (2) the distribution of people in various locations, and (3) the likelihood of the occurrence of various meteorological conditions.

Each module in the emergency response process characterizes another step toward attaining public response. The warning diffusion module characterizes warning system effectiveness in terms of the probability of receiving warning at various times in the process. The response decision module characterizes the public's decision to respond to the warning message in terms of public

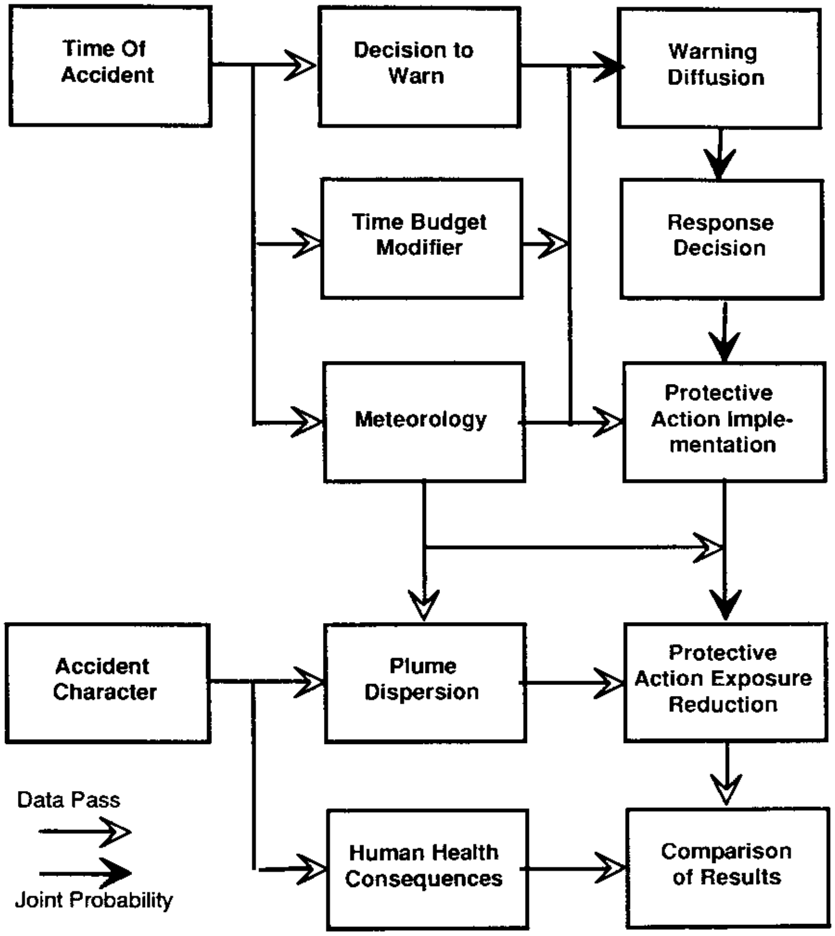

Figure 3 Conceptual model of protective action evaluation for chemical accidents.

response to previous chemical emergencies. The protective action implementation module characterizes the implementation of various protective actions in terms of probability of completion once the decision to respond is made. The probability of a completed protective action is the joint probability of (1) public officials deciding to warn, (2) the public receiving the warning, (3) the population at risk deciding to respond, and (4) the population implementing of the protective measure. Such a joint probability accounts for the time each emergency response step takes.

Accident characterization in terms of the type and amount of agent released, together with the meteorological characterization, allows the estimation of plume dispersion for given downwind distances. These data alone

determine atmospheric concentrat
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V. Application of the Model

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A. Evacuation

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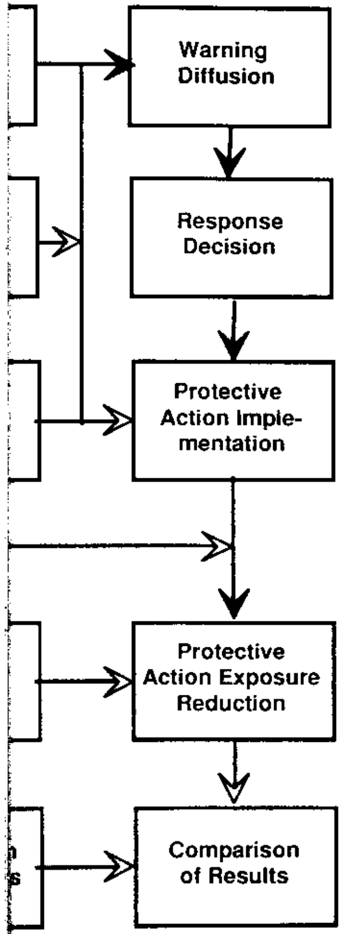

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determine atmospheric concentrations of agent in the unprotected environment. In addition, the type of agent allows selection of the appropriate anticipated human health effects for comparison with the estimated unprotected and protected exposures.

V. Application of the Model

In addition to summarizing the results of the analysis done to support the Chemical Stockpile Emergency Preparedness Program (Rogers *et al.*, 1990), this chapter examines a terrorist event scenario. This scenario posits the production of chemical agent and weapons by terrorists, rather than the theft of weapons from one of the existing stockpile locations or the on-site detonation/release of agent. The latter events are deemed to be within the bounds of the distribution of events considered in the risk analysis prepared in conjunction with the programmatic EIS (Fraize *et al.*, 1989). Terrorist production of agent *in situ*, or the production of agent and subsequent transportation to a given location, implies that the size of release is probably limited (e.g., likely to be less than 500 pounds), but that a release could occur in an area (e.g., within 1 km) characterized by relatively dense populations. It can be assumed only that terrorist would attempt to maximize impact by releasing agent under stable conditions that would disperse agent in maximal concentrations. For these reasons the scenario examined assumes a stable meteorological condition and light winds (i.e., 1 m/sec winds and E stability).

Because of the nature of a purposive act of terrorism, it is likely that public officials will be able to reach a decision to act quite quickly (e.g., less than 2 min); even for sudden "out-of-the-blue" events public officials require minimal time to recognize the occurrence of an event, coordinate decision makers and communicate the result to those that must implement the decision. In periods of heightened tensions (e.g., such as the Iraqi missile attacks), people are likely to be vigilant to the potential for harm, which will tend to make warning systems very effective, and make rapid public response likely. Hence, the scenarios examined herein assume a very effective warning system comprising both sirens and telephone system for outdoor and indoor alerting and notification, respectively, and a very rapid decision by the public to respond to those warnings (e.g., 2 min).

A. Evacuation

Evacuations involve a series of organizational and individual or family decisions. At the individual or family level the decisions include (1) whether to evacuate, (2) when to evacuate, (3) what to take, (4) how to travel, (5) route of travel, (6) where to go, and (7) when to return. The nature of these decisions helps to illustrate that evacuation is a complex social process and not a stimulus–response event. While these decisions are being made, considerable communication and social interactions occur.

Evacuation is summarized in terms of a time associated with clearing an area at risk. One way to conceptualize this is in terms of the time it takes to arrive at a safe distance. A range of clearance-time assumptions can be used to evaluate the effectiveness of protection achieved with evacuation. Hence, 5- and 10-min clearance times represent rapid clearance of an area. A 1-min clearance time represents being able to outrun the leading edge of the plume.

Evacuation is not always a feasible response to terrorist acts. Terrorist events are likely to be either an unannounced and a sudden release of agent, or an extortion involving a threat to release agent. In the former, those close to the release point would be unable to evacuate without exposure. In the latter, if the terrorists detected an evacuation, the possibility exists that they would immediately release agent. Its feasibility would depend on the specifics of the situation. Evacuation would be ineffective for people within some minimal distance (e.g., 1 km) of a release. In most terrorist scenarios, the evacuation of urban areas could be considered a victory for the terrorist; in wartime events, evacuation might even lead to retargeting weapons carrying chemical agent. Moreover, because the target and impact area are unknown, potentially affected portions of cities cannot be evacuated before the terrorist event.

Evacuation of people within 1 km in response to sudden purposive acts is probably not feasible (Fig. 4); and within 2 km, evacuation is not likely to be effective except in the extortion scenario, in which people might be able to vacate before the release of agent. For people located at or beyond 2 km, evacuation can be an appropriate response because of the limitations on the size of release (e.g., < 500 lbs). This means that with rapid onset, characterized by faster wind speeds and less stable conditions, the lack of time to response is compensated for by the greater mixing and lower concentrations; under slower onset conditions, the increased concentrations are compensated for by the increased response time. Because people are likely to take less time to respond to terrorist events, evacuation can be effective beyond 2 km for a release stemming from a terrorist event.

B. In-Place Shelter

In-place protection involves the reduction of air exchange between the exterior toxic environment and the interior sheltered environment. The degree to which the flow of potentially contaminated air flows into the shelter can be used to generally characterize the type of in-place protection.

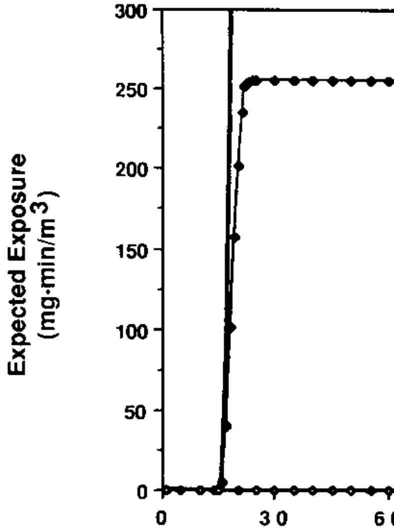

Figure 4 Expected exposure at 1 k
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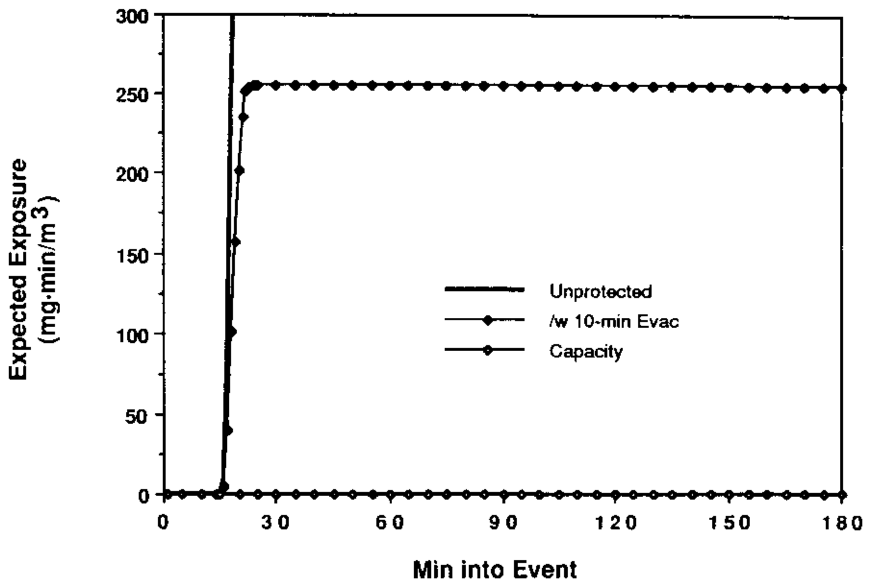


Figure 4 Expected exposure at 1 km downwind of terrorist event for 10-min evacuation.

Extensive energy-conservation research has shown that air exchange in most U.S. dwellings are distributed from fairly leaky units at about 1.5 air changes per hour (ACH) to the more tightly sealed units at 0.5 ACH (EPRI, 1983; Bonneville Power Administration, 1983; National Research Council, 1981 as summarized in Mueller Associates *et al.*, 1985; Kolb and Baylon, 1989). These rates have been shown to be related to wind speed (Grimsrud *et al.*, 1984a,b; Strandon and Berteig, 1980), orientation to the wind (Mattingly and Peters, 1977), structural characteristics (EPRI, 1988; Reinhold and Sonderegger, 1983; Sherman *et al.*, 1984; Lawrence Berkeley Laboratory, 1984; Saudia National Laboratories and AnaChem, Inc., 1981), and temperature difference between the indoor and outdoor environments (Lawrence Berkeley Laboratory, 1984; Stranden and Berteig, 1980; Grimsrud *et al.*, 1982, 1984a,b).

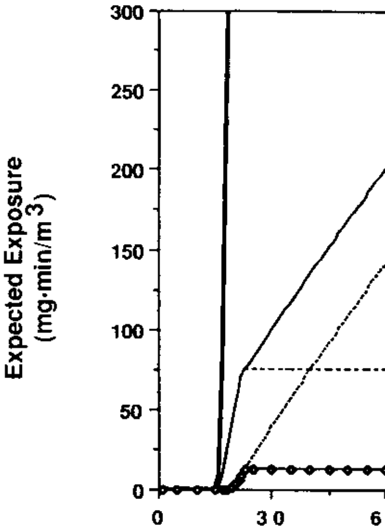
The amount of protection afforded by shelters is determined by exchange rates. Three basic shelter alternatives are pressurized, enhanced, and expedient. Pressurized shelters are characterized as a special case where there is no exchange of air from the unprotected to the protected environment (0.0 ACH). Enhanced shelters are weatherized structures where the exchange of air between interior and exterior environments is reduced. Because these structures are weatherized in advance, they can be assumed to have low exchange rates (0.5 ACH) and require only that doors and windows be closed to achieve the associated level of protection. Expedient shelters can achieve further reductions in air exchange (represented here as 0.2 ACH), but require either more time to implement at the time of the release or prerelease treatment of a room within the dwelling to achieve maximal protection.

Normal sheltering in leaky dwelling units (1.5 ACH) was not considered in this analysis because, (1) it is inconsistent with the sheltering approach taken here, and (2) in cases where normal sheltering will be effective, enhanced will also be effective. Hence, normal sheltering can be examined further in those instances in which enhanced shelters are effective to determine the impact of such a planning decision. Implementation of pressurized and enhanced shelters, prepared in advance, involves closing doors and windows.

For situations characterized by adverse health effects on the public, evacuation of an area is preferable to in-place shelter, if it can be completed before the public can obtain an effective dose. The preference for evacuation is based on two fundamental contrasts between in-place sheltering and evacuation; first, whereas a portion of the exposure continues after implementation of in-place shelters, exposure is avoided completely when evacuated; and second, shelters that reduce but do not eliminate infiltration of toxic agents will have to be vacated once the plume has passed to afford maximal protection, whereas no structural second step is required of evacuation. Slow implementation and improper ventilation of the shelter after the passage of the plume can augment exposure beyond what would otherwise be expected at that distance.

In-place protection characterized by reduced infiltration provides limited protection in long-duration events, because the character of the exchange rate allows a portion of what is in the unprotected environment to enter the sheltered environment. Hence, over long-duration releases, in-place shelters downwind will continue to accumulate agent concentrations in shelter air under certain conditions. Even small concentrations of agent can be incapacitating or lethal (Watson *et al.*, 1989a). Hence, in-place shelters characterized by .5 ACH exchanged rate can be recommended in response to small continuous releases, but only for relatively short durations. Populations potentially exposed to larger releases (exceeding 5 mg·min/m^3) or those with unknown or long durations should avoid exposure via evacuation if possible.

Considering the terrorist scenarios discussed earlier, in-place sheltering can provide protection for people in close proximity to the release point (Fig. 5). In-place shelters can provide a measure of protection for civilian populations from terrorist acts resulting in agent release, because they can be implemented almost immediately, and they provide excellent protection from percutaneous exposure to droplets and aerosals. Like other protective actions, in-place shelters are likely to protect better when there is less to protect against; faster winds with less stability mix better and yield lower exposures; as a result, more



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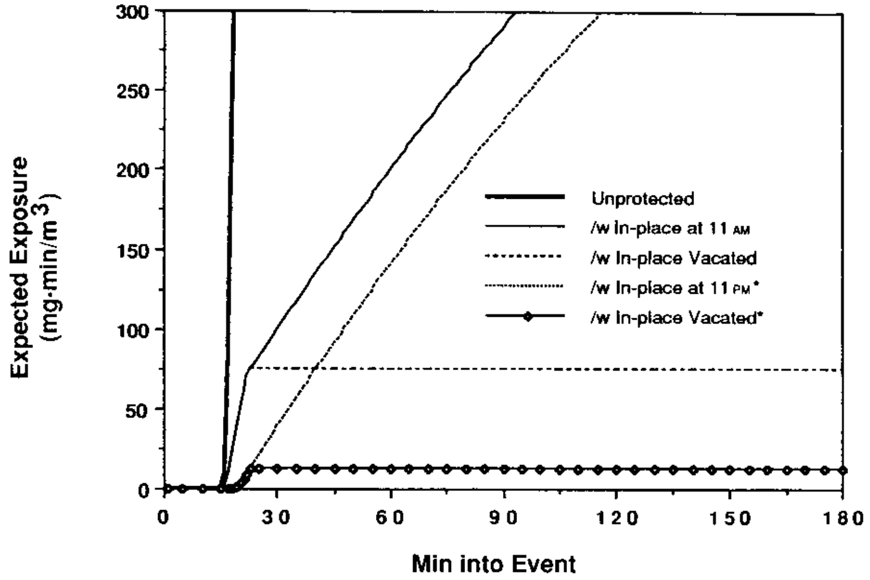

Figure 5 Expected exposure at 1 km downwind of a terrorist event with in-place sheltering. *Capacity of in-place shelter reached.

remote distances are subjected to smaller air concentrations. Even though in-place shelters can achieve protection in relatively close proximity, complete protection for people within 1 km of a release cannot be fully achieved without extremely rapid implementation and very low (or zero) exchange rates.

Enhanced shelters are likely to be implemented in conjunction with expedient measures within. This approach to in-place protection affords a moderate degree of protection quickly, with greater protection after completion of the taping and sealing of the interior room. Hence by curtailing exposure early in the period through rapid implementation, and limiting continued exposure later in the emergency owing to the reduced infiltration associated with taping and sealing an interior room, a combined method provides optimal protection among the nonpressurized, in-place shelters.

C. Respiratory Protection

Individual respiratory protection involves the removal of agent before inhalation through the use of specialized filtration devices. Efficacy of any respiratory device designed for use in chemical environs is generally characterized by the degree of leakage around the device (e.g., at the seal between the face and device) (leakage) and the amount of agent that can be absorbed before the filter capacity is exceeded (breakthrough). Breakthrough values are further defined as the Ct (mg·min/m^3) at which the filter capacity is exceeded and the wearer begins to inhale air containing ambient concentrations of agent.

Respirators are capable of providing excellent protection from inhalation exposure to aerosols *and* vapor. Respirators include a facepiece assembly fitted with filters to remove airborne toxic compounds. They do not supply air and are not intended for use in an oxygen-deficient atmosphere. Available facepiece designs provide varying degrees of protection to the eyes, face, and respiratory organ/tissues. Only a full-face respiratory design is evaluated in this analysis; no expedient devices were assessed. Other forms of respiratory protection are more fully decribed in Rogers *et al.*, (1990).

Filter elements are packed with activated charcoal impregnated with salts of copper, silver, and/or chromium to augment the capacity of the filter to absorb or denature chemical agents. Filter capacity at any given time is largely a function of storage conditions and regular maintenance and replacement of filter elements.

A preliminary analysis examined the sources of poor fit that would compromise the integrity of a good mask-to-face seal among the U.S. public. Frequency of facial hair among males, eyeglass wear patterns, the proportion of undersized adults (who would be expected to have small faces and thus, be more difficult to fit within the range of standard facepiece assemblies), and the percentage of denture wearers were all considered (Rogers *et al.*, 1990). The current analysis assumes that 15% of the general public using respiratory devices will experience poor fit conditions from all causes. Thus, the assumed respiratory device leakage rate was 0.15 for all scenarios examined herein. The 15% leakage rate may be greater than expected during public implementation; however, this assumption underscores the need for careful fitting, maintenance, and consideration of supplemental protection to reduce infiltration (such as the use of hoods in combination with a respirator). Rogers *et al.* (1990) suggest that relatively small leakage rates allow effective concentrations to accumulate inside the respiratory device, particularly when agent concentrations are high or the plume is of long duration. Mitigation of the respirator seal problem significantly reduces the potential for fatalities. To the extent that respiratory protection is considered a viable option, other respiratory alternatives for toddlers and/or infants will be required. Several hood-jacket and infant-carrier designs equipped with battery-driven or passive filters are commercially available (Rogers *et al.*, 1990; Appendix C).

Breakthrough of the filter canister was determined to be a problem mostly for mus scenarios that included use of NATO civilian-standard filters. The NATO civilian standards that a respirator protect the wearer from the toxic effects of two exposures of nonpersist nerve agents (i.e., GA or GB) for a total Ct of 1500 mg·min/m^3 each, or from vapor exposure persistent agent (i.e., VX) at a Ct of 1000 mg·min/m^3 (NATO, 1983). In all other agent scenarios,

fatal exposures for protected popula
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Respirators made available for civi
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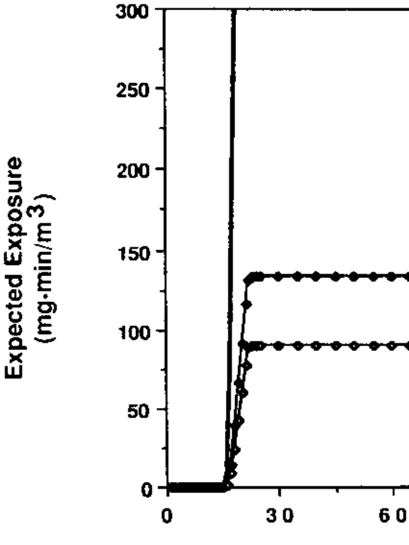

Figure 6 Expected exposure at 1 km
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fatal exposures for protected populations were the result of exposure via leaky respirator seals and the timing of warning, response, and implementation. Respirators made available for civilian use should incorporate filter design specifications at least as stringent as the U.S. military-issue standard (i.e., Ct = 159,000 mg·min/m^3).

Based on a preliminary analysis of PAECE results, respiratory protection is an important alternative for people in areas near the point of agent release. The farther people are from the release point, the less likely respiratory protection will be needed to assure their safety. Respiratory protection for individuals at 3 and 10 km lends itself well to combined approaches, where sheltering of various types or evacuation can be performed in conjunction with respirator use. The maintenance and fitting requirements necessary for effective respirator use would be best served by institutional management and device ownership at the local level. Community health departments or the like could handle the responsibility of training and fitting the protected population, distributing respiratory devices, and running periodic maintenance checks and drills.

Respiratory protection is particularly well suited for protection from exposure stemming from acts of purposive harm (Fig. 6). Using respiratory devices has the advantages of rapid implementation, and effective exposure

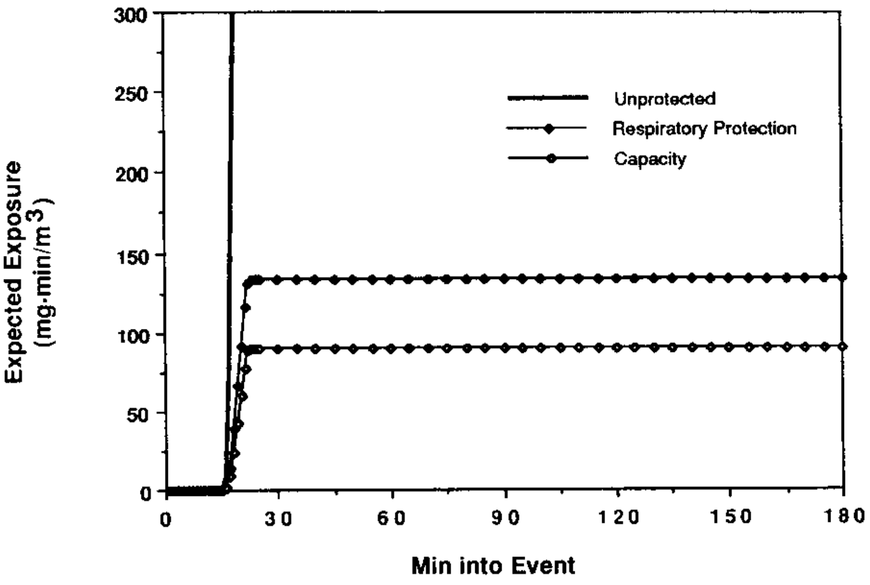

Figure 6 Expected exposure at 1 km downwind of terrorist event with respiratory protection.

reduction, but has the disadvantage of the extensive maintenance and training involved to be effective and safe. For example, some of the unfortunate deaths associated with using respiratory devices among civilians (e.g., in Tel Aviv) could be avoided with more extensive training. Whereas respiratory protection can be completely effective at avoiding exposures within 1 km, respiratory devices need to be deployed before exposure to a plume. Terrorist acts, of the sudden-release variety, can still result in inhalation exposures before deployment of respiratory protection, as well as result in percutaneous exposures.

VI. Discussion

The combination of using respiratory protection with in-place shelters is particularly effective against releases resulting from acts of purposive harm (Fig. 7). Once again, however, no protective action will be completely effective for terrorist acts of the sudden-release variety, owing to the potential for exposure before implementation of protection. The international experience in Tel Aviv and Riyadh seems to suggest that people in a state of vigilence will monitor a situation and be ready to implement protective actions involving both in-place sheltering and respiratory protection.

Table II summarizes some of the general conclusions from an analysis using the PAECE model (Rogers *et al.*, 1990). This research suggests that the

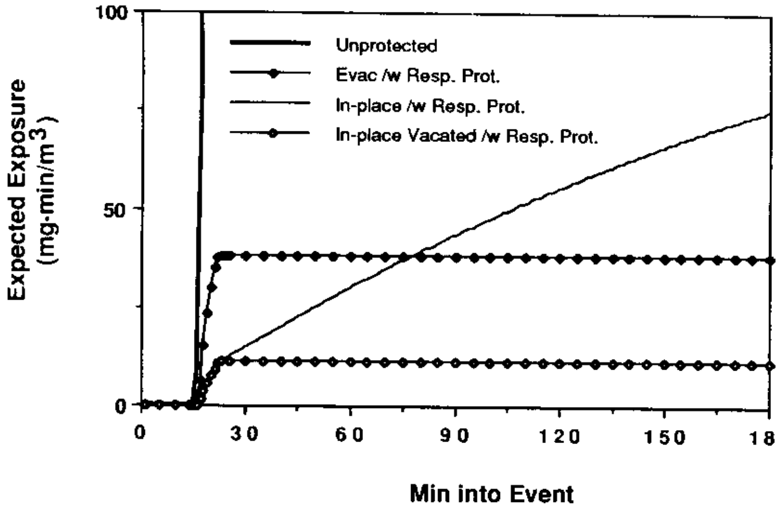

Figure 7 Expected exposure at 1 km downwind of terrorist event for evacuation and in-place shelter with respiratory protection.

Table II
Summary of Protective Action Recomm

Quantity released	1
Less than 5-km distance	
Small	Shelter/ev
Medium	Evacuatic
Large	Evacuatic shelters
5- to 10-km distance	
Small	Evacuatic
Medium	Evacuatic
Large	Evacuatic
More than 10-km distance	
Small	NA[a]
Medium	Evacuatic
Large	Evacuatic

[a] Not applicable because these releases of G
distance under these winds with exposures e

preferred protective action is very
evacuation scenarios for goal-orien
that evacuation is a viable option
source of agent release. This conclu
time it takes for a release to traverse
winds, or approximately 50 min wit
winds, and the tendency to disperse
amount of time available at this dis
an evacuation.

When situations are characteri
effects, and an evacuation of the ar
effective agent concentrations on ar
shelter alternatives. This finding ar
particularly critical for infants, wit
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When either long-duration even
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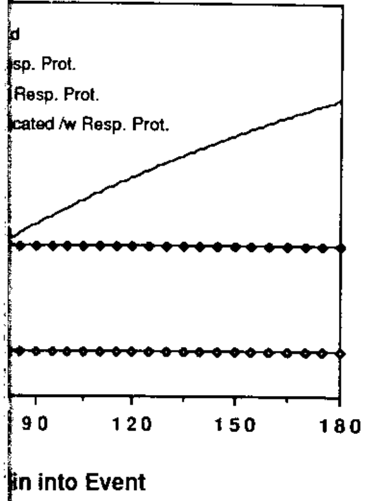

nd of terrorist event for evacuation and

Table II
Summary of Protective Action Recommendations

Quantity released	Winds 1 m/sec	 3 m/sec
Less than 5-km distance		
Small	Shelter/evacuation	NA[a]
Medium	Evacuation	Evacuation/pressurized shelters
Large	Evacuation/pressurized shelters	Pressurized shelters
5- to 10-km distance		
Small	Evacuation	NA[a]
Medium	Evacuation	Evacuation/respiratory protection
Large	Evacuation	Evacuation/pressurized shelters
More than 10-km distance		
Small	NA[a]	NA[a]
Medium	Evacuation	NA[a]
Large	Evacuation	Evacuation

[a] Not applicable because these releases of GB, VX, and H/HD are unlikely to traverse this distance under these winds with exposures exceeding the LCt_{50}.

preferred protective action is very likely to be evacuation. The analysis of evacuation scenarios for goal-oriented emergency response systems indicates that evacuation is a viable option for people located over 10 km from the source of agent release. This conclusion is generally driven by the amount of time it takes for a release to traverse 10 km (i.e., more than 2.5 hr with 1 m/sec winds, or approximately 50 min with 3 m/sec winds) with moderate and light winds, and the tendency to disperse significantly with winds of 6 m/sec. The amount of time available at this distance generally allows implementation of an evacuation.

When situations are characterized by the potential for adverse health effects, and an evacuation of the area can be completed before the advent of effective agent concentrations on an area, evacuation is preferable to in-place shelter alternatives. This finding arises because exposure continues, which is particularly critical for infants, within reduced-infiltration shelters after the in-place shelters are fully implemented. Because of this continued exposure, reduced-infiltration shelters will have to be ventilated or vacated once the plume has passed.

When either long-duration events, or very high concentrations are likely, reduced-infiltration, in-place shelters provide only limited protection. Hence, to the extent possible, evacuation should be used whenever it can be completed before plume arrival, or when avenues of egress are clearly not being besieged by the plume. In-place sheltering is most appropriate when time to respond is severely limited. In these cases, pressurized shelters provide the maximal protection for those people within. Enhanced shelters could also be used to afford significant protection to people in close proximity; however, in situations characterized by the potential for toxic air concentrations, it would be inappropriate to recommend enhanced shelters alone; because of the additional protection afforded by implementing expedient measures within enhanced shelters, the pro-active expedient activities (e.g., taping and sealing) should be undertaken as well.

Moreover, under conditions of relatively minor release (e.g., expected to result in reversible health effects, such as eye pinpointing), reduced-infiltration, in-place sheltering can provide significant protection at minimal cost. These benefits are significantly increased when implementation is augmented by the current location of people in indoor locations (e.g., in the dead of night). But emergency planners will have to exercise considerable care in recommending such actions, so that people can ventilate or vacate in-place shelters once the plume has passed. Further, such measures are probably inappropriate in scenarios in which the current "minor" release may become a long-duration or more extreme release situation. Hence, emergency managers would be ill advised to recommend reduced-infiltration, in-place shelter when releases are not yet controlled (e.g., where the fire is still burning), or where the plume may become a long-duration event because of meteorological conditions (e.g., during early evening hours, when winds may shift or become calm).

To the extent that respiratory protection devices are used, emergency planners will have to expand considerable effort to limit exposure associated with leakage around the device. This analysis clearly points out the need to carefully fit people expected to use these devices, undertake considerable maintenance programs to assure continued filter and seal effectiveness, and consider the use of respiratory devices that will accommodate a variety of fit/seal problems associated with the general public. It also points out that respiratory protection must be implemented very quickly for it to be considered a viable option.

Emergency managers could even augment each structure's ability to limit infiltration passively, by having electrical power turned off in the area(s) likely to be affected, which would automatically shut down whole-house circulating systems and reduce the amount of infiltration. One consequence of this action, however, would be that warning via electrical devices (e.g., radios and TVs) could be eliminated. Hospitals and other facilities where electricity is critical would have to use auxiliary generators. In areas where telephone ring-down systems were being used to alert and notify the public, that system could go ahead and give advance notice of the need to vacate or ventilate the in-place shelter.

VII. Conclusions

In order to provide acceptable
agent, emergency response has to b
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VII. Conclusions

In order to provide acceptable protection from catastrophic releases of agent, emergency response has to be rapid enough to get people to implement the action. One way to achieve more rapid response to public warnings is to provide the public with enough information to allow them to confirm the conclusion reached by the officials making the recommendation.

An evacuation of the area is an effective response to situations likely to result in adverse health effects, when they can be completed before the arrival of effective agent concentrations. Generally, evacuation is preferable to in-place shelter alternatives, because it avoids the potential for continued exposure. However, these conditions are not always possible to meet. In relatively minor releases (e.g., expected to result in reversible health effects, such as eye pinpointing), significant protection can be provided at minimal cost with reduced-infiltration, in-place sheltering strategies. Recommending reduced-infiltration, in-place sheltering is a risky strategy when releases are not yet controlled, or any time the duration of the event is unknown and a long-duration event is possible. With the possible exception of worst-case events, characterized by very large releases under slow onset (1 m/sec winds), the marginal benefit of using respiratory devices in conjunction with evacuation means that emergency managers may find it more useful to enhance their ability to detect, assess and make decisions, and communicate them to the public so that rapid implementation of evacuation can be achieved, than to supply respirators to the public and maintain them once they are issued. Moreover, because pressurized shelters eliminate exposure, it is unnecessary to consider the use of respiratory devices in addition to pressurized in-place protection.

The common behavioral underpinnings for the exposure associated with both respiratory protection and reduced-infiltration shelters, particularly enhanced sheltering, means that adding respiratory protection to in-place sheltering does not necessarily reduced exposure. Hence, for large releases under rapid onset, pressurized shelters are more likely to provide acceptable protection than combining respiratory protection with reduced-infiltration shelters. Moreover, when considered in conjunction with the supply, maintenance, and potential liability issues raised by the use of respiratory devices, pressurized shelters are likely to be considered preferable.

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