Journal of Hazardous Materials A109 (2004) 1–11

Journal of Hazardous Materials

www.elsevier.com/locate/jhazmat

Planning for protective action decision making: evacuate or shelter-in-place

John H. Sorensen, Barry L. Shumpert*, Barbara M. Vogt

Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

Received 6 November 2003; received in revised form 12 March 2004; accepted 13 March 2004

Abstract

Protecting the public from an airborne hazardous chemical release requires that appropriate protective actions be selected quickly. When deciding whether to recommend evacuation or shelter-in-place, decision makers must weigh the interaction of numerous factors that characterize the release, the meteorological conditions, and the populations that may be affected. This article examines the components of the protective action decision process and describes steps that should be taken in a planning context to prepare for efficient decision making during an emergency. Methods of organizing information to facilitate decision making are identified, and a model useful for detailed analysis of specific emergency scenarios is described.

Keywords: Protective action decision making; Evacuation; Shelter-in-place; Emergency planning; Hazardous chemical response

1. Introduction

The need for protective actions in response to chemical hazards has long been recognized by experts, but became of serious national concern only following the 1984 accidental release of methyl isocyananate in Bhopal, India [1]. Protective action decision making is an important emergency planning issue for nuclear power generators as well [2–4].

Deciding whether to recommend evacuation or shelter-in-place is one of the most important questions facing local emergency managers as they respond to a toxic chemical release. That such a complex decision with such important potential consequences must be made with such urgency places tremendous responsibility on the managers and officials involved. The factors that influence the protective action decision are complex but fairly well documented. Among other things, these factors include population distribution, projected or actual exposure to a chemical substance, availability of adequate shelters, and evacuation time estimates. Officials should recommend shelter-in-place only when there is reasonable assurance that moving people beyond their residence, workplace, or school will endanger their health and safety more so than allowing them to remain in place. A decision to evacuate the public, on the other hand, should be based on the reasonable assurance that removing people from the affected area is in the best interest of their health and safety and exposes them to minimal risk.

In reality, the protective action decision is also a resource-dependent decision. The availability of transportation and other resources, including shelters, factors heavily in the decision making process. Each institutional facility (e.g., hospitals, schools, day care centers, correctional facilities, assisted living facilities, and nursing homes) in the community should be considered individually to determine the specific measures that will provide maximum protection for its residents.

Researchers have devoted considerable attention to the evacuation/shelter-in-place protection decision. While several decision aids have been developed, no single approach has achieved widespread acceptance based on validity, utility, and effectiveness [5,6]. This article summarizes what is currently known about the evacuation/shelter-in-place protection decision and points to available literature that more thoroughly explores the individual components of the decision. The next section summarizes the major issues in protective action decision process. This is followed by a discus-

---

* Corresponding author. Tel.: +1-865-576-8100;
fax: +1-865-574-5938.
E-mail address: shumpertbl@ornl.gov (B.L. Shumpert).

0304-3894/$ – see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhazmat.2004.03.004

sion of all the factors that may bear on the protective action decision process. The final section addresses how to make a protective action decision.

2. Critical components of the protective action decision process

Conceptually, the evacuation/in-place protection decision is simple and revolves around two questions [7]:

(1) Will shelter-in-place provide adequate protection?
(2) Is there enough time to evacuate?

The answers to these questions indicate the appropriate response. Obviously, if the answer to one, but not both, is ‘yes,’ the appropriate response has been determined. If the answers to both are ‘yes,’ then either option is satisfactory, and the issue should be decided on the basis of other considerations (e.g., community disruption or cost). If, however, both questions are answered ‘no,’ emergency planners and officials face a serious problem and must consider exceptional alternatives (e.g., expedited evacuation, enhanced sheltering, or evacuation of only those persons with access to private vehicles).

In many cases a combined response may be called for, with in-place sheltering recommended for some areas close to the release and in the possible path of contamination, and evacuation recommended for other areas which have more time before possible exposure to the chemical. Effective communication with the public, however, often turns out to be a problem for such combined response strategies [8]. Poor communication may lead people to ignore official recommendations and take the action they perceive to be in their best interest. Furthermore, if the recommended protective action is not perceived to be an effective means of protection, people will likely do what they judge to be effective. For example, in the World Trade Center attacks of September 11, 2001, people in the second tower were told to stay in their offices after the first plane hit the other tower; however, many reportedly chose to evacuate because they perceived staying in the building was risky [9].

Some researchers suggest that the public be educated to consider shelter-in-place protection as the first and immediate response on being alerted that a chemical emergency has occurred [10,5]. Contra Costa County in California is currently utilizing this approach. They promote a three-stage response–shelter, shut, and listen. The rationale for this approach is that, in addition to providing some protection while authorities assess the situation and develop a response strategy, this approach facilitates communication by getting people inside and tuned to the emergency alert system (EAS). If an evacuation is then necessary, authorities can issue detailed instructions via the EAS with some confidence that a large portion of the affected population will quickly hear and understand them.

While the two questions pertinent to the evacuation versus shelter-in-place protection decision are simple, the process involved in answering the questions is much more complicated. The answer to each depends on the interaction of various pieces of information regarding the hazardous chemical and the nature of its release, the affected community, and meteorological conditions. Some of the necessary information can be gathered by the emergency planning agency before an emergency occurs; other data, for example the current meteorological conditions, must be collected during the decision process following notification that a toxic chemical has been (or is likely to be) released. In many cases, there will be uncertainty regarding the interaction of the various types of information, and answers to the two pertinent questions will not be clear-cut. Emergency planners and officials will best be able to deal with this uncertainty if they have a thorough understanding of the mechanical, technical, and behavioral aspects of the evacuation and sheltering in-place options.

In addition to deciding what protective action to implement, another important decision is when to terminate a protective action. In particular for shelter-in-place, it may be critical to remove people or ventilate a shelter to prevent exposure after the plume has passed. The worst-case shelter situation is when the toxic material enters the shelter before it is closed up and then people remain in the shelter for a long time after the plume has passed. In this situation the exposure to the chemical can be greater than for an outdoor unprotected dosage.

3. Factors determining the level of protection offered by protective actions

The ability of a protective action to adequately protect people in an affected area throughout the duration of the emergency depends on the characteristics of the toxic chemical(s) involved, the size and nature of the release, meteorological conditions, the characteristics of the population affected, and the ability of available structures in the area to provide protection from outdoor chemical concentrations. To assess the effectiveness of shelter-in-place, the emergency planner must be able to predict the outdoor plume concentration of the toxic chemical(s) that will occur in the risk area, estimate the resulting concentration that will occur inside the buildings in which people seek shelter, and calculate the indoor estimated level of exposure. For evacuation, the planner should be able to predict the outdoor concentration of the toxic chemical(s) that will occur in the risk area, estimate when people will leave and when they will reach a safe distance, estimate the concentration that will occur while people are still evacuating, and calculate exposures to those who evacuate in the plume and those who have not left when the plume arrives.

3.1. *Characteristics of the released chemical*

The form (liquid, aerosol, or vapor), the density, and the vapor pressure of the chemical influence the speed and concentration with which it will be released into the atmosphere and how far the plume or cloud will travel before dissipating. These are important factors in determining the area that will be affected by a dangerous chemical concentration.

The nature of the hazard posed by the chemical is a factor in assessing the effectiveness of shelter-in-place protection. Considerations include the degree of health hazard (level of toxicity), the dangerous dosage or concentration, and the nature of the toxic load (peak concentration or time-integrated dosage). In-place sheltering is effective at reducing peak concentrations for a limited time, but may be less effective at reducing the cumulative dose over a longer period [11].

In-place sheltering is usually not suitable in response to releases of chemicals that are dangerously flammable or explosive in the atmosphere. However, some researchers point out that sheltering could still be preferable in areas where evacuation cannot be carried out quickly. “Do first responders really want people running around outdoors when the flammable/explosive material is also outdoors?” they ask [12].

The amount of chemical released (or expected to be released) into the environment, the rate of release and expected changes in the rate, and the expected duration of the release are important factors in evaluating the effectiveness of shelter-in-place protection. The amount of chemical released and the rate of release are among the determinants of the outdoor concentration that, in turn, is a major determinant of the indoor concentration. The expected duration of the release is significant because shelter-in-place protection is most effective at reducing indoor concentrations associated with a short-term release. For a longer-term release, more of the chemical will seep into the sheltering structures, thus resulting in higher indoor concentrations and longer exposures for people sheltering.

3.2. *Potential meteorological conditions at the site*

Critical meteorological conditions include wind speed, wind direction, temperature, and atmospheric stability. Wind speed and direction are important in determining which areas will be affected and how long it will take the chemical to reach them. In addition, wind speed influences the ability of a structure to provide protection from contamination. The higher the wind speed, the more quickly a chemical vapor will infiltrate a structure and raise concentrations to dangerous levels [12,13]. Temperature is also a consideration; the greater the difference between inside and outside temperatures, the more quickly the chemical will infiltrate the structures providing protection [12]. Inversion conditions may also be important, causing a chemical plume to travel closer to the ground and dissipate less rapidly if not impeded by vegetation or other structures.

Planners should analyze historical weather records to develop planning scenarios of potential meteorological conditions during an accident. It is important and helpful to identify the historically worst-case meteorological conditions to use in planning protective actions. Worst case is usually defined as light winds under stable atmospheric conditions. By asking such questions as—what is the longest period of time that the combination of very stable atmosphere (class E/F) and low wind speeds ($<3\,\mathrm{m/s}$) have occurred?—planners can base their decisions on credible events and not on assumptions that may be embedded in dispersion models. This is particularly important when using a Guassian dispersion model that assumes constant meteorology. Unreasonable assumptions can create unrealistic plume length estimates.

3.3. *Characteristics of structures surrounding the facility*

Data gathered during the planning process can be used to assess the protective effectiveness of structures in the area surrounding the chemical facility. Are there mostly older wooden frame buildings or newer more energy efficient (airtight) houses in the area at risk? If the structures surrounding the chemical facility are old and in poor condition, and have not been weatherized, it is likely that they will have high air exchange rates and provide little protection from a chemical vapor release. It may be feasible, however, to recommend evacuation for residents in zones where housing is leaky and in-place sheltering for zones where houses are more airtight. In such situations it is extremely important to convey to the public why two different actions are being recommended.

Air infiltration will be determined not only by the leakiness of the building but by other factors such as wind speed, indoor–outdoor temperature differences, and vegetative cover around the structure.

3.3.1. *Why building age is important*

A building’s age is a good predictor of its air infiltration rate. Prior to 1965, US building codes did not include energy conservation standards. As in other areas of housing standards, local governments set the requirements for the construction of buildings in the interest of public health, safety, and general welfare. However, in the late 1960s and early 1970s energy conservation became an issue of national concern. Federal and state governments began working together to develop building standards that incorporated energy efficiency. The result was the “Energy Conservation in New Building Design” [14]. One of the performance standards established was for the exterior envelope of the building. The need to reduce energy consumption in buildings resulted in more stringent weatherization requirements for new construction.

Concern for reducing air infiltration rates has also played a significant role in the US Department of Energy’s (DOE) research initiatives. Grot and Clar [15] examined over 200 dwellings occupied by low-income households in 14 cities across the US, representing all major climatic zones. Two types of measures were used: a tracer-gas decay which uses air sample bags to measure natural air infiltration and a fan depressurization test that measures induced air exchange rates (as a measure of the tightness of a building’s envelope).

The latter method was used as a diagnostic tool to assist weatherization crews in analyzing the leakiness of buildings. The results of the study demonstrated that building weatherization techniques can reduce air infiltration rates significantly.

Gettings et al. [16] reported on the results of a study on low-income, single-family buildings. The study identified a wide range of air leakage rates and found that, in addition to leakage around doors and windows, other characteristics of a house add significantly to its infiltration rate. These characteristics include the types of walls and ceilings, number of attic accesses, presence of fireplaces, and insulation of electrical outlets. The study concludes that a 16% reduction in air leakage rates can be achieved by standard infiltration retrofit procedures.

3.3.2. Air exchange in residential buildings

Based on the history of building codes and overall construction practices, homes constructed since the early- to mid-1970s are likely to have significantly lower infiltration rates than homes constructed earlier. Housing built before 1950 will likely be unsuitable for sheltering without weatherization [17]. Other recent studies have found that the trend toward tighter homes has continued. Thatcher et al. [18] cite data showing that homes constructed after 1980 are approximately 50% more airtight than houses constructed before that time. Sherman and Matson [19] conducted a meta-data analysis of houses across the US, which indicates that the trend toward tighter houses peaked about 1997 then leveled off.

A well-constructed energy efficient house may have an air exchange rate of 0.1 acph (air changes per hour) under ideal conditions. This may go as high as 0.8 acph in strong winds and/or a high air temperature differential. An average house may have a minimum rate of 0.3 acph and range as high as 2.4 acph under worst-case conditions (high wind speeds and high temperature differential). This is consistent with observations on a house in Canada where the exchange rate varied between 0.1 and 0.5 acph during a 1-month period [20]. An older house will have more variability with a rate range between 0.5 and 5 acph being the norm. Overall, the average air exchange rate for single-family housing in the US is around 0.7–0.8 acph. Apartment buildings will likely have similar air exchange rates [21,22].

Home air exchange rates may also vary by geographic region. While one study [23] found no correlation between geographic region and air exchange rate for residential structures, another study [19] found that the variation in tightness among new conventionally constructed homes is explained by the region in which the home is located. New conventional homes in cold regions (Wisconsin and Alaska are given as examples) are found to be significantly less leaky than those built in warmer regions. In addition, houses constructed as part of an energy efficiency program were generally tighter than those built using conventional methods.

3.3.3. Air exchange in office buildings

A limited number of studies have been conducted on the suitability of office buildings and high-rise buildings as shelters. The overall evidence suggests that this category of buildings has lower air exchange rates than single story residential structures [21,22]. The lower exchange rates may be due to the fact that windows in such buildings are often permanently sealed and these buildings usually have a smaller ratio of exterior surface area to interior volume than residential buildings [18]. An average air exchange rate for office buildings is estimated to be 0.66 acph and an industrial building to be 0.31 acph with the HVAC system(s) off and doors and windows closed [21,22].

3.3.4. Wind speed and temperature differentials

Air infiltration into a building is also influenced by the wind speed. The higher the wind speed, the higher the infiltration rate. The relationship is fairly linear. A house with an air exchange rate of 0.5 acph when winds are calm will have an estimated air exchange of rate of 1 acph at 4 mph, 2 acph at 8 mph and 4 acph at 16 mph.

Temperature differences between outside and inside will also affect infiltration rates. The greater the temperature differential, the greater the infiltration. The relative importance of temperature differential is minor in comparison to other factors affecting infiltration [21,22]. Limited data suggest that temperature differential of 20 degrees F will double the infiltration rate, and a differential of 60° may triple or quadruple the infiltration rate.

3.3.5. Air exchange in vehicles

Several studies have been conducted on air exchange in both stationary and moving vehicles. Fletcher and Saunders [24] found that the air exchange in a stationary vehicle with vents closed ranged from 0.5 acph with light wind conditions (1 mps) to around 9 acph at high wind speeds (10 mps). This is in accordance with an earlier study that showed an average exchange rate in a stationary vehicle of 0.5 acph [25]. Moving vehicles offer little protection. Fletcher and Saunders [24] found that air exchange ranged from about 15 acph at 35 mph to over 40 acph at 70 mph. Earlier, Peterson and Sabersky [26] documented air exchange rates between 18 and 38 acph at speeds between 0 and 55 mph.

3.3.6. Air replacement time

The time required to replace air inside a structure (or vehicle) is not a linear function of air exchange. A house with an air exchange rate of 1 acph will not have 100% replacement of air in 1 h. This is due to interior mixing of the air. Another way to say this is a house with an air exchange of 1 acph that is exposed to a toxic plume for 1 h will not have the same toxic concentration inside as the outside. Some of the toxic materials that enter the house will also exit the house. Some basic rules of thumb on replacement relation-

Table 1
Air replacement times

Percent of air replaced	Air changes per hour (acph)			
	0.25	0.5	1.0	2.0
63	4 h	2 h	1 h	0.5 h
95	12 h	6 h	3 h	1.5 h

Source: Fletcher and Saunders [24].

ships are shown in Table 1, which is based on calculations made by Fletcher and Saunders [24]. The table shows the length of time required to replace 63 and 95% of the air in structures at different air exchange rates. A house with 0.5 acph will take about 6 h to exchange 95% of the inside air with outside air. At 32 acph, 95% of the air inside a moving automobile would be replaced in 8 min.

3.4. Time available before the public is exposed

The characteristics of the chemical release and weather conditions largely determine the amount of time available before the people in an area are exposed to the chemical. The timing of the release—when it occurs or is expected to occur—and the distance of the release from the inhabited area are the principal release characteristics affecting the time available before a toxic concentration reaches the area. These factors, along with wind direction and wind speed, indicate which areas are likely to be contaminated by a release and how long the chemical will take to reach a specific area. In addition, the emergency planner should consider the amount of chemical released and the rate of release to estimate the expected variation in concentration over time. A number of public domain and commercial models are available that forecast plume dispersion and calculate plume arrival times.

3.5. Time required to implement protective actions: evacuation versus shelter-in-place

3.5.1. Evacuation

Evacuation is the most common response to chemical releases. In the early 1980s nearly 60 evacuations occurred yearly due to hazardous chemical releases [27]. Cutter [28] estimates that, worldwide, technological disasters led to 25 evacuations involving 5000 or more people over a 15-year-period.

Evacuation is a complex undertaking requiring the coordination of a wide variety of factors. In a case study of emergency planning issues at a waste incinerator, Lindell [29] notes that hazardous plumes could arrive in populated areas before people could evacuate or while they were evacuating. Estimating the time that would be required to evacuate an area affected by a release of toxic chemical makes use of various types of information, many of which can be collected beforehand. Adequate time must be allowed for all phases of the evacuation, including: (1) reaching an official decision to evacuate, (2) mobilizing community evacuation resources, (3) communicating appropriate protective action instructions to the public, (4) individual mobilization of resources to leave the area at risk, and (5) completing the physical evacuation of people occupying the affected area.

The time required to reach a decision and to mobilize resources depends, to a large extent, on the quality of emergency response pre-planning, although planners and decision makers will certainly have to deal with unique aspects of the situation at-hand. Some research indicates that, once a decision is made to protect the public, a considerable amount of time (up to one to two hours using conventional warning practices) may elapse before most people in the affected area hear, absorb, and decide to respond to the instructions [30,31]. Innovative design of the alert/warning system along with an effective public education program will minimize, but not eliminate, the delay.

The time required to accomplish the evacuation once the physical movement of people is underway depends on the characteristics of the area and on the available evacuation resources. Pertinent characteristics of the area include the size and density of the population to be evacuated, the presence of people requiring special attention (e.g., hospitals, nursing homes, prisons, handicapped, elderly, children, and transients), and the geometry and capacity of the transportation network, current weather conditions, and time of day. Quantitative evacuation studies can aid in estimating the time required to evacuate an area [32]. Research indicates that, contrary to popular belief, warning and evacuation times do not necessarily increase with population size and density, because, as these factors increase, so does the capacity of the infrastructure (e.g., street system, public transportation resources) necessary for moving people out of the area [33].

Transportation network geometry, however, may be of great significance. A community with an open network characterized by a grid of streets and roads will be easier to evacuate than a community with a closed network where there are a limited number of egress paths. Suburban areas with subdivisions and gated communities may be particularly difficult to evacuate. This was experienced in the Oakland wildfires when the rapid spread of the fire blocked egress on the single road out of the area. In addition, although rural areas may not experience traffic congestion, limited roads may constrain egress by requiring movement toward the source of the hazard.

Crucial evacuation resources include appropriate modes of transport for evacuees, personnel to guide the evacuees and facilitate the flow of traffic, and safe destinations for the evacuees. Private automobiles will be the prevalent mode of transportation in most situations, but buses, taxis, and ambulances may also often be required. It should be recognized that 100% of the people told to evacuate will not do so. Evacuation compliance rates in hazardous material accidents, however, will likely be high, probably as high as 98% [34].

3.5.2. Shelter-in-place

One of the major problems with the analyses and frameworks that have been used to evaluate shelter-in-place for protection against chemical releases is that they ignore the fact that time is required to implement sheltering as well as evacuation. Sheltering does not occur without a warning. Warnings require time. People may not respond instantly to a warning. Rather people tend to seek additional information from multiple sources including friends, relatives, and the media. Furthermore, sheltering from a chemical release takes time to implement, as people may need to go inside, close windows and doors and shut off HVAC systems. Additional time is required if expedient measures, such as taping around doors and windows, are taken to seal a room. Thus a real potential exists for exposure to an outdoor concentration prior to reaching a shelter environment or for an outdoor concentration of chemical to enter a structure before it is closed up. Several analyses suggest that it will take 5–10 min on average to implement shelter-in-place, once a sheltering decision is made by a household. Expedient shelter will take a longer time. Data from a limited set of trials indicate that the time it takes to tape and seal a room is likely to average 17 min, with a minimum of 3 min and a maximum of 39 min [35].

Compliance rates for sheltering have not been extensively documented. In situations where both shelter and evacuation have been advised, compliance with the sheltering recommendation has not been very high [8].

4. Protective action decision making

As discussed earlier, the decision to recommend evacuation or sheltering depends on whether (a) the affected people will have time to evacuate before the chemical plume arrives and (b) whether available shelters will prevent people from receiving a harmful exposure to the chemical.

A successful evacuation removes people from the affected area and avoids exposing them to a harmful concentration of the toxic chemical. An inappropriate decision to evacuate, on the other hand, can have negative consequences if it results in the population of the affected area being caught outdoors or in their vehicles when contamination enters the area. Sheltering can be worse than evacuation if shelters are leaky, people are not told when to come out of the shelter, or the release continues for a long time.

The planning process can help identify situations for which either evacuation or sheltering is clearly preferred. Several approaches for accomplishing this have been developed with the aid of computer models [35–37]. If such an exercise results in ambiguous cases, then a procedure is needed to make a final choice of actions based on the conditions at the time of the emergency.

In addition to technical considerations pertaining to the evacuation/shelter-in-place protection decision, local emergency planners and officials must also consider behavioral aspects: How will the public react to the officials' recommended action? In particular, research indicates that a recommendation to seek shelter-in-place protection may be met with skepticism by the public and may lead them to take actions that are counter to their safety [7]. Limited empirical evidence supports this hypothesis. In a study in West Helena, Arkansas, where part of a community was told to evacuate and another part to shelter in response to an organophosphate pesticide accident, most of those told to shelter evacuated instead [8]. There was no evidence, however, of prior public information explaining the reasons for sheltering. Several explanations have been offered for this potential problem with sheltering. The option of shelter-in-place protection is much less familiar than evacuation, and people are thus reluctant to believe that it will be effective. The public may lack faith in the official making the recommendation. In addition, people may perceive that sheltering is not an effective strategy for protection. More fundamentally, they may be obeying a basic psychological force that tells them to take action by fleeing from an environmental hazard over which they have no control rather than passively seeking protection [11].

4.1. Decision making aids

Several methods to help make protective action decisions include checklists, decision matrices, decision trees or decision tables. Checklists present various attributes of a decision problem and allow for systematic consideration of each attribute. Decision matrices frame decision outcomes by 2 or 3 key attributes of the decision. Decision trees and tables pose a series of yes/no questions or sets of criteria which lead decision makers down branches of the tree or cells of the table to a desired outcome. In this section, we will apply both a checklist and a decision tree approach to further explore decision making options.

4.2. Checklists

Table 2 illustrates a checklist approach to the evacuation/sheltering decision. The first column lists various decision attributes. The second and third columns list the attribute values that favor either shelter or evacuation.

Table 2
Protective action checklist

Attribute	Shelter	Evacuation
Infiltration	Tight housing	Leaky housing
Plume duration	Short	Long
Time of day	Night	Day
Population density	High	Low
Road geometry	Closed	Open
Road conditions	Poor	Good
Population mobility	Immobile	Mobile
Traffic flow	Constrained	Unconstrained
Public perception of shelter effectiveness	High	Low
Toxic load	High	Low

For some of the attributes more quantitative values could be assigned. For example, one might shelter with an expected plume duration of less than 30 min and evacuate with an expected plume duration of over 120 min. The middle ground of 30 to 120 min is a "gray area" where the decision outcome is unclear.

The advantage of this approach is that it is relatively easy to do. Among the disadvantages are that it will not lead to a clear-cut decision in every planning case, it may not optimize the safety of the public, and the relative influence of each checklist item is not accounted for.

4.3. Decision trees

Two sample decision trees for deciding between shelter-in-place and evacuation are found in Fig. 1. Decision trees pose a series of yes/no questions to the user. Answers to these questions lead to a path through the tree to an ending outcome. The protective action decision trees discussed here have three outcomes:

- evacuate,
- shelter,
- conduct a detailed analysis.

The last of these outcomes is necessary because, under certain conditions, yes/no questions cannot lead to the identification of a preferable option.

Decision trees may differ depending on the goals and objectives of protective action planning. Examples of different, but not necessarily mutually exclusive, goals are

- avoid fatalities,
- minimize total population exposure,
- minimize number of people exposed,
- minimize fatalities,
- minimize expected population risk,
- reduce exposure below a threshold level (i.e. no deaths exposure),
- reduce exposure to "As Low As Reasonably Achievable" (ALARA).

Example decision trees for the first two goals are provided in Fig. 1. The choice of goals is essentially a public policy decision involving difficult tradeoffs. For example, policy makers must decide whether it is better to (1) minimize fatalities by having a large percent of the population exposed to a sublethal, but harmful, level of chemical or (2) minimize the number of people exposed by choosing to avoid exposure for most people, while allowing a few to be exposed to a potentially fatal level of the chemical.

In examining the decision trees we find that only in a few instances is there a clear-cut decision to evacuate or shelter. This could mean that much more complex decision criteria are needed in the tree. This is problematic, as our current theoretical understanding of the decision does not allow more complex decision trees. In addition, even with more complex trees we lack the empirical foundation to apply the decision logic.

4.4. Detailed analysis

A detailed analysis will likely require the use of one or more computer models and a structured approach to the analysis. One such model is the protective action dosage reduction estimator (PADRE). The following discussion of PADRE is intended to illustrate the logic behind conducting a detailed analysis and is not an endorsement of the particular model. PADRE is an emergency-planning tool that allows planners to assess the expected dosage reduction from implementing alternative protective actions under different scenarios. PADRE evaluates three protective actions: evacuation, sheltering, and respiratory protection. (Respiratory protection is the use of masks or hoods to filter air that is breathed in.) Scenarios can be specified with respect to the accident size, meteorological conditions, and emergency response system.

PADRE allows the user to generate an emergency response scenario. With PADRE the user can incrementally change a single attribute value in the scenario and almost instantaneously see the effect on the expected dose given that scenario. For example, one can compare the effectiveness of evacuating in a given accident scenario if the wind speed is 1, 2, 3, or 4 mps. Likewise one can compare the effectiveness of sheltering given a 10 lb release versus an 800 lb release.

An overview of PADRE is presented in Fig. 2. PADRE 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 of PADRE characterizes another step in the emergency response process. The warning-diffusion module characterizes warning system effectiveness in terms of the probability of receiving warning at various times in the warning process. The response-decision module characterizes the public's decision to respond to the warning message in terms of public 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 at risk implementing the protective measure. Such a joint probability must account for the period of time at which each previous step is achieved. For example, if warning is not received until minute three, the probability of response before minute three is essentially zero. On the first iteration, the probability of the decision to warn and warning receipt are multiplied to form

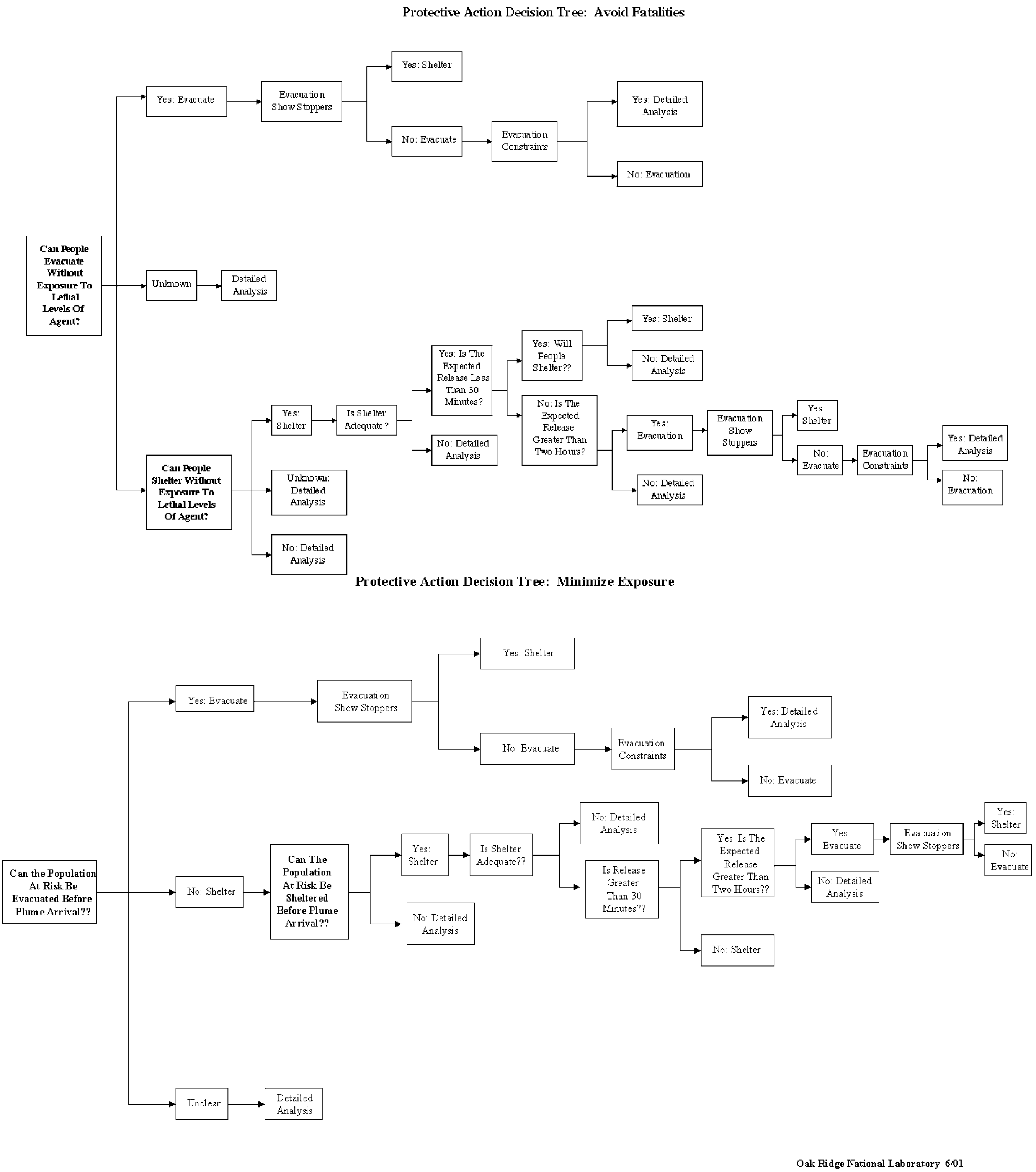

Fig. 1. Protective action decision tree: avoid fatalities.

a joint probability of a decision to warn and warning receipt. On the second iteration, this joint probability and the probability of response produce the joint probability of reaching a decision to warn, receiving it, and responding to the warning message. Finally, combining that joint probability with the probability of completing implementation of the protective action produces an estimate of the final joint probability of achieving the protection action for each time period, "*t*".

Accident characterization, particularly the type and amount of chemical agent released, together with the me-

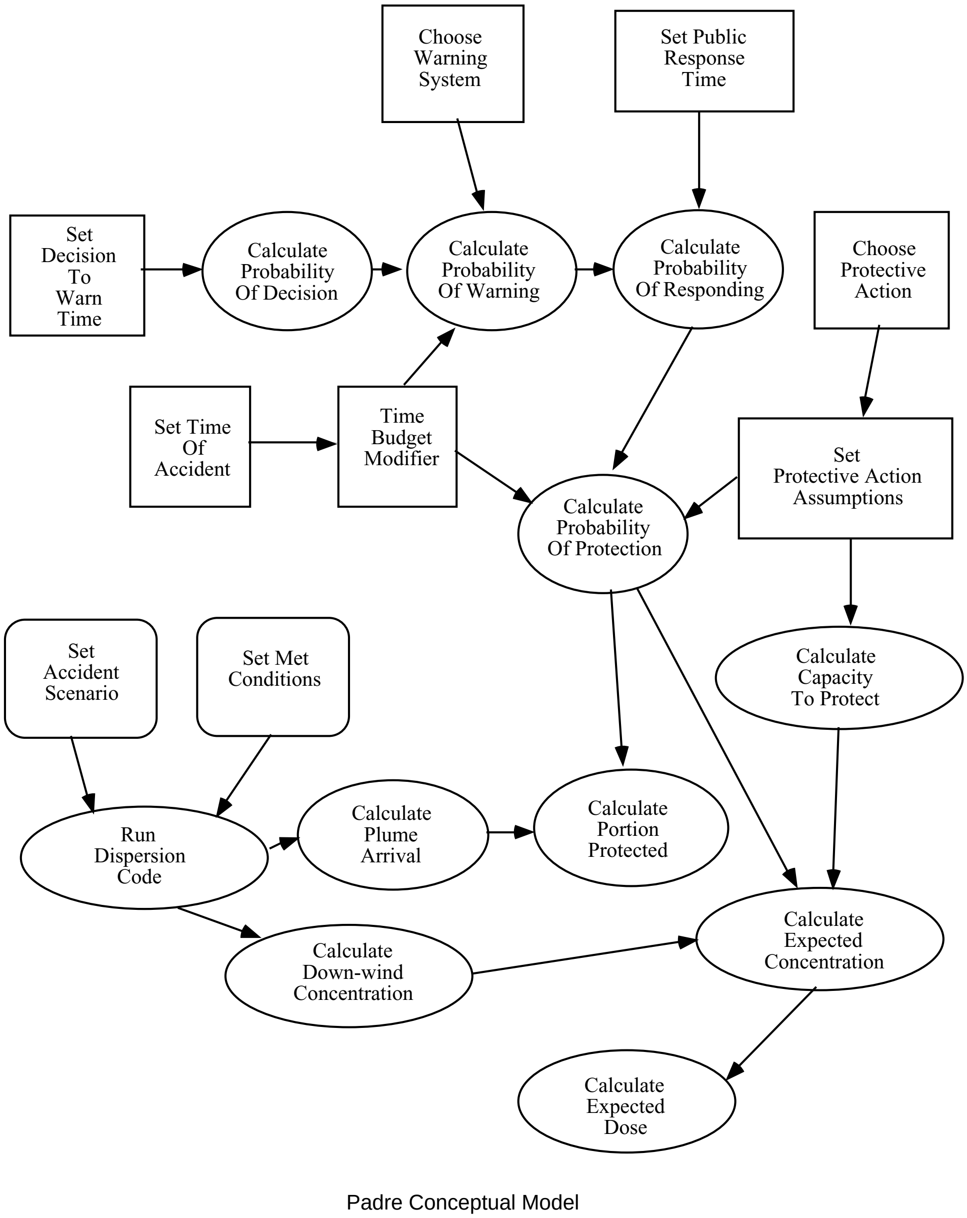

Fig. 2. Flow diagram of PADRE.

teorological characterization, allows estimation of plume dispersion for given downwind distances. These data alone determine concentrations of agent in the unprotected environment. In addition, the type of chemical agent allows the modeler to select the appropriate anticipated human health impacts for comparing the estimated unprotected and protected exposures.

Finally by integrating the probability of protection, with the dosage reduction from the selected protective action, one can calculate the expected dosage for that scenario-specific application of the protective action. The expected dosages and health consequences resulting from evacuation and sheltering can then be compared to the indicated appropriate protective action recommendation.

5. Conclusions

In making decisions to protect people's lives, we look for simple yet robust solutions with a high degree of certainty. Unfortunately, a simple technical decision making method for choosing protective actions does not exist. Simple rules do not work under all circumstances, or even for a large set of circumstances. A checklist approach is useful but likely will not result in an optimal decision. Furthermore the decision cannot be a seat-of-the-pants effort or based on intuition or hunches without preplanning.

The decision trees in Fig. 1 illustrate that this type of decision aid can help in some cases, but not all, and perhaps not in many. In addition, using a decision tree will involve a great amount of analysis, which needs to occur during a planning and not in a response mode.

There are a few clear case situations in which either evacuation or sheltering is clearly preferred. These include the following cases:

- when no fatalities are expected, either protective action is feasible,
- when people can be evacuated before plume arrival, evacuation is preferable,
- when conditions make evacuation impossible, shelter is preferable,
- when releases are extremely short, sheltering is preferable,
- when releases are extremely long, evacuation is preferable,
- when major portions of the public are unlikely to take a particular action, the choice may be limited to one alternative.

In most cases, detailed analysis may be required to determine if one action is more effective in protecting the public than another. Computer simulation models will be necessary to support these detailed analyses because the problem is too complex or has too many dimensions to analyze on paper. If models are utilized, it is important that the analyst and people using the results of the analysis are familiar with the assumptions of the model(s), understand the general nature of how the model works, and understand the limits and uncertainty of the model and its results. This includes the person(s) legally responsible for making the protective action recommendation and decision (often an elected official). If this decision maker(s) does not understand or trust the analyses that were performed during planning, an inappropriate recommendation could result.

Finally, decision models per-se are useful to the technical analyst, but will be of little use to decision makers unless they are coupled with decision support tools. Such tools could involve expert systems utilizing case-based logic that contain extensive libraries of accident scenarios coupled with protective action look-up tables to choose the best protective scheme for a given scenario. Alternatively, decision rules could be incorporated into the simulation models that would estimate the optimum decision given a specified decision objective. Either approach could be incorporated into a GIS database enabling spatial display of the model results. When decision makers are presented with complex decisions that require rapid decision, it will be decision support tools that can make a difference in reducing human exposure to toxic chemical.

References

[1] S.L. Cutter, Airborne toxic releases: are communities prepared? Environment 29 (6) (1987) 12–17.

[2] M. Lindell, An overview of protective action decision-making for a nuclear power plant emergency, J. Hazard. Mater. 75 (2–3) (2000) 113–129.

[3] C. Conklin, J. Edwards, Selection of protective guides for nuclear incidents, J. Hazard. Mater. 75 (2–3) (2000) 131–144.

[4] T. McKenna, Protective action recommendations based upon plant conditions, J. Hazard. Mater. 75 (2–3) (2000) 145–164.

[5] A.M. Ujihara, Responding to Chemical Accidents by Sheltering in Place, Resources, No. 94, Winter, 1989.

[6] M.S. Mannan, D.L. Kilpatick, The pros and cons of shelter-in-place, Process Safety Progr. 19 (4) (2000) 210–218.

[7] T.S. Glickman, A.M. Ujihara (Eds.), Proceedings of the Conference on In-place Protection During Chemical Emergencies, 30 November–1 December 1988, Resources for the Future, Center for Risk Management, 1989.

[8] B.M.Vogt, J.H. Sorensen, Description of Survey Data Regarding the Chemical Repackaging Plant Accident, West Helena, Arkansas, ORNL/TM-13722, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1999.

[9] M.T. Moore, D. Cauchon, Delay Meant Death on 9/11, USA Today, 3 September 2002.

[10] P.R. Jann, Evaluation of Temporary Safe Havens, Prepared for the 81st Annual Air Pollution Control Association Meeting, Dallas, Texas, 1988.

[11] D.J. Wilson, Stay Indoors or Evacuate to Avoid Exposure to Toxic Gas? Emergency Preparedness Digest, January–March 1987, pp. 19–24.

[12] D.J. Wilson, B. Morrison, Ordering Shelter or Evacuation During an Outdoor Toxic Gas Release Incident: The C.A.F.C. Decision Flow Chart, Presented at Fire-Rescue Canada 2000, Montreal, 13–18 August 2000.

[13] D.J. Wilson, Variation of Indoor Shelter Effectiveness Caused by Air Leakage Variability of Houses in Canada and the USA, USEPA/FEMA Conference on Sheltering in Place During Chemical Emergencies, 30 November–1 December 1988.

[14] ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers), ASHRAE Standard 90-75: Energy Conservation in New Building Design, ASHRAE, New York, New York, 1975.

[15] R.A. Grot, R.E. Clar, Air leakage characteristics and weatherization techniques for low-income housing, in: Proceedings of the American Society of Heating, Refrigeration, and Air-Conditioning Engineers Conference, Thermal Performance of the Exterior Envelopes of Buildings, ASHRAE SP28, Atlanta, Georgia, 1981, pp. 178–194.

[16] M.B. Gettings, L.N. McCold, J.A. Schlegel, Field Test Evaluation of Conservation Retrofits of Low-Income, Single-Family Buildings in Wisconsin: Blower-Door-Directed Infiltration Reduction Procedure, Field Test Implementation and Results, ORNL/CON 228/P5, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1988.

[17] B.M. Vogt, H.K. Hardee, J.H. Sorensen, B.L. Shumpert, Assessment of Housing Stock Age in the Vicinity of Chemical Stockpile Sites, ORNL/TM-13742, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1999.

[18] T.L. Thatcher, T.E. McKone, W.J. Fisk, M.D. Sohn, W.W. Delp, W.J. Riley, R.G. Sextro, Factors Affecting the Concentration of Outdoor Particles Indoors (COPI): Identification of Data Needs and Existing Data, LBNL-49321, Lawrence Berkeley National Laboratory, Berkeley, California, 2001.

[19] M.H. Sherman, N.E. Matson, Air Tightness of New U.S. Houses: A Preliminary Report, LBNL-48671, Lawrence Berkeley National Laboratory, Berkeley, California, 2002.

[20] D.J. Wilson, J.D. Dale, Measurement of Wind Shelter Effects on Air Infiltration, Conference on Thermal Performance of Exterior Envelopes of Buildings, Clearwater Beach, Florida, 2–5 December 1985.

[21] R.J. Engelmann, Effectiveness of Sheltering in Buildings and Vehicles for Plutonium, Department of Energy Report DOE/EH-0159T, U.S. Department of Energy, Washington, DC, 1990.

[22] R.J. Engelmann, Sheltering effectiveness against plutonium provided by buildings, Atmos. Environ. 26a (11) (1992).

[23] D.J. Wilson, Do Leaky Buildings Provide Effective Shelter? in: Proceedings of the 10th Annual Conference, Major Industrial Accidents Council of Canada, Edmonton Alberta, 4–7 November 1996.

[24] B. Fletcher, C.J. Saunders, Air change rates in stationary and moving vehicles, J. Hazard. Mater. 38 (1994) 243–246.

[25] R.J. Engelmann, W.R. Pendergast, J.R. White, M.E. Hall, The effectiveness of stationary automobiles as shelters in accidental releases of toxic materials, Atmos. Environ. 26a (17) (1992) 3119–3125.

[26] G.A. Peterson, R.H. Sabersky, Measurement of pollutants inside an automobile, J. Air Pollut. Contr. Assoc. 25 (1975) 1028–1032.

[27] J. Sorensen, Evacuations due to chemical accidents, J. Hazard. Mater. 14 (1987) 247–257.

[28] S.L. Cutter, Fleeing from harm: international trends in evacuations from chemical accidents, Int. J. Mass Emergencies Diasters 9 (2) (1991) 267–285.

[29] M. Lindell, Assessing emergency preparedness in support of hazardous facility risk analyses—application to siting a US hazardous-waste incinerator, J. Hazard. Mater. 40 (3) (1995) 297–319.

[30] J.H. Sorensen, B.M. Vogt, D.S. Mileti, Evacuation: An Assessment of Planning and Research, Report prepared for U.S. Federal Emergency Management Agency, RR-9, 1987.

[31] J.H. Sorensen, Evaluation of Warning and Protective Action Implementation Times for Chemical Weapons Accidents, Report prepared for the Office of Program Executive Officer, Aberdeen Proving Ground, Maryland, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1988.

[32] F. Southworth, Regional Evacuation Modeling: A State-of-the-Art Review, ORNL/TM-11740, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1990.

[33] B.M. Vogt, J.H. Sorensen, Evacuation Research: A Reassessment, ORNL/TM-11908, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1992.

[34] J.H. Sorensen, D.S. Mileti, Warning and evacuation: answering some basic questions, Ind. Crisis Quart. 2 (1988) 195–209.

[35] G. Rogers, et al., Evaluating Protective Actions for Chemical Agent Emergencies, ORNL-6615, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1990.

[36] Alberta Public Safety Services, A Technical Study of Shelter Versus Evacuation When Faced with a Release of Hydrogen Sulphide, Alberta Public Safety Services, 1992.

[37] SSI, Development of a Default Protective Action Decision Strategy for the Kentucky Chemical Stockpile Emergency Preparedness Program, Report Prepared for the Kentucky Disaster and Emergency Services Department of Military Affairs, Frankfort, Kentucky, Harrisburg, Pennsylvania, 1998.