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DECIDING BETWEEN IN-PLACE PROTECTION AND EVACUATION IN TOXIC VAPOR CLOUD EMERGENCIES

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Summary

During toxic vapor cloud emergencies, responders faced with the need to take a protective action have the option of calling for in-place protection (also known as sheltering in-place) or ordering an evacuation. In-place protection may be preferable if the vapor cloud threatens to spread rapidly, but due to infiltration, staying indoors may not provide adequate protection. This paper views the research on comparing these two protective action options, and describes a decision aid for choosing between in-place protection and evacuation.

Introduction

When an accident involving hazardous materials occurs at a fixed facility (a chemical plant or a storage location) or during transportation, there is often a threat that the surrounding area will be exposed to a toxic vapor cloud. Under these circumstances there will generally be two options for protective action available to the emergency response decision-maker: keep the public sheltered in their homes or other buildings, or begin to evacuate the public from the area.

It has become standard operating procedure in most parts of Europe to emphasize in-place protection in response to chemical release emergencies. For instance, a local Swedish public information folder entitled *If The Alarm Goes* instructs the public to go indoors when they hear repeated short blasts of an alarm, and to close windows and doors, turn off the ventilation system, and tune to a designated radio station. The folder also recommends breathing through a temporary filter of wet cloth "if the gas becomes uncomfortable."

By contrast, in the United States, emergency responders have traditionally emphasized the use of evacuation as a protective action, perhaps because of the infrequent occurrence of toxic vapor cloud emergencies. One exception is in the area surrounding the Bridesburg chemical complex in Philadelphia, where an information sheet prepared by Rohm & Haas and Allied Chemical instructs local residents to seek shelter when they hear a long rotation tone from sirens

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that have been installed in the area, and then to close their windows and doors, turn off their ventilation systems, and tune their radios to certain stations for emergency broadcast information. A map that shows evacuation zones and relocation centers is included with this information. Another exception is the Kanawha Valley in West Virgina, which is home to a number of chemical manufacturing facilities. The community interest pages of the local phone book contain the statement that in-place protection "is a proven, effective emergency protective action which is used when there is insufficient time to evacuate in the event of an airborne hazardous material release." The accompanying instructions are essentially the same as Bridesburg's, along with additional directions to cover cracks with tape or wet rags and go to rooms with few or no windows and, if told to do so, to cover one's nose and mouth with a wet cloth. Also included are an example of an emergency announcement and advice on preparing for an evacuation.

Emergency preparedness under SARA Title III

Recognizing the need for local communities to be better prepared for chemical release emergencies, Congress enacted the Emergency Planning and Community Right-To-Know Act of 1986, also known as Title III of the Superfund Amendments and Reauthorization Act (SARA). The law requires that states establish emergency planning districts and that communities develop comprehensive emergency response plans within these districts. Title III also requires fixed facilities to notify the emergency personnel in the community if a certain minimum quantity of a hazardous substance is released and if areas outside the facility are likely to be affected. The facility must provide specific information about the release, including the chemical or substance name, and indication as to whether the substance has been designated as an extremely hazardous substance, an estimate of the quantity released, time and duration of the release, and information on any known or anticipated health risks.

The emergency response plan and the information about the release will be the basis for the response action, which will typically be led by a fire or police chief. The ultimate decision between in-place protection and evacuation usually rests with a local elected official — the mayor, city manager, or a county executive. Once this decision is made, instructions will be issued to the public. The success of the protective action will of course depend on whether the public has been well-prepared and on whether the instructions are communicated effectively.

Past research findings

Various facets of the subject of in-place protection as an alternative to evacuation have been examined in the research literature. Some of this work was done in the context of nuclear power plant accidents, some in the context of the possible impacts on civilians of accidents occurring during the disposal of chemical munitions, and some, of course, in the context of industrial chemical accidents.

Overview

In the nuclear field, Anno and Dore [1] performed an early study for the U.S. Environmental Protection Agency (EPA) on the effectiveness of in-place protection as a shield against releases of gaseous radioactive material, and Aldrich and Ericson [2] later contributed an analysis of how well buildings protect against the infiltration effects of such releases, taking into account the multi-compartment nature of structures. Guidelines for developing radiological emergency response plans, published shortly thereafter by the Nuclear Regulatory Commission [3], specifically include consideration of in-place protection. More recently, an extensive report by Lindell et al. [4] addressed many of the considerations for planning and decision-making that are common to both nuclear and non-nuclear emergencies.

The chemical stockpile disposal program of the Department of the Army has also spawned some interesting and relevant research. A report by the U.S. Army Engineer Division in Huntsville, Alabama [5] broadly discusses a number of aspects of emergency response management for fixed facilities and transportation accidents, including protective actions, such as in-place protection. And a recent investigation by Chester [6] examines in more technical depth the measures that can be taken to protect against acutely toxic vapors, including the use of various kinds of respiratory filtration devices.

As far as industrial chemical accidents are concerned, the research on protecting the public from toxic vapor clouds by in-place protection is represented by a number of articles and reports. The paper by Buschmann [7] reports on some empirical results from early Dutch experiments on the dispersion and infiltration of toxic gases into buildings. Three papers from the British Health and Safety Executive, by Purdy and Davies [8] and Davies and Purdy [9,10], deal with many of the technical factors that bear on emergency planning and risk assessment in toxic gas incidents. Prugh's article [11] suggests ways to combine information from various data sources to estimate the impacts of toxic vapors under different response scenarios, and an article by Wilson [12] describes a number of theoretical and experimental results on vapor cloud behavior and infiltration which suggest that in-place protection is almost always better than evacuation. Appendix H of the document *Technical Guidance for Hazard Analysis*, prepared by EPA in collaboration with the Federal Emergency Management Agency (FEMA) and the U.S. Department of Transportation (DOT) [13], lists the factors to consider in choosing a protective action in the event of a release of an extremely hazardous substance. The most recent contribution to this body of research is the checklist for decision-making and the supporting material that were developed for the National Institute for Chemical Studies [14].

In-Place protection vs. evacuation

In-place protection can provide shelter during a toxic chemical release emergency by virtue of the fact that buildings supply a reservoir of clean air and shield the occupants from direct exposure to the tainted air outside. Because of infiltration, in-place protection will not eliminate the threat entirely, but it will at least reduce the outdoor concentration, resulting in lower indoor exposure to its occupants for a prolonged length of time.

In-place protection has other advantages too. Jann [15] observed that even when the choice of a protective action has not yet been made, in-place protection should be the initial response because it provides protection while the emergency situation is being assessed and, if evacuation is anticipated, while mobilization is taking place. Wilson [12] argues that in-place protection is especially effective when the chemical's maximum peak concentration (rather than the time-integrated dose) is the greatest concern for human health. He notes that outdoor concentrations of vapor clouds do not follow a smooth trajectory, but that they fluctuate widely due to atmospheric turbulence, and since buildings tend to dampen those fluctuations, the peak value is much lower indoors.

Evacuation may be the preferred choice when there is a threat of harm but no release has occurred yet, or when the release threatens to create a large explosion or fireball (Davies and Purdy [10]). Also, evacuation may be preferable for a small, slowly developing leak that has the potential to escalate into a larger release (Chester [6]). However, evacuation is a safe alternative only when it can be completed prior to the time when a vapor cloud reaches a populated area. The time needed for evacuation depends on numerous factors, such as the size and the density of the area to be evacuated, the time of day, the weather conditions, the road network, and the effectiveness of the evacuation plan. A total evacuation can easily take several hours. In comparison, the time it takes for in-place protection will generally be considerably less, and if the public has been educated to recognize warning signals, in-place protection can begin almost immediately. Anno and Dore [1] estimate that the time for the public to react to such a warning would range from only a few minutes to half an hour.

Effectiveness of in-place protection

The infiltration rate of a structure, measured in terms of the amount of outdoor air exchanged with indoor air per hour, is the most important factor in determining the effectiveness of in-place protection. In his experiment, Buschmann [7] released a tracer gas for a duration of 10 minutes on the windward side of a test house and then compared the indoor and outside concentrations of the gas. He found that the indoor concentrations were about 1/10 the outside values for a room on the windward side of the house and about 1/20 for a room on the leeward side. In a second experiment, gaps around door and windows were sealed with paper and tape. These measures reduced the indoor concentrations to 1/30 and 1/50 of the outdoor concentrations on the windward and leeward sides, respectively.

For any given infiltration rate, the amount of protection provided by a structure will depend on the length of time the inhabitants remain indoors after the vapor cloud has passed. Because airborne chemicals can dissipate rapidly outdoors and buildings can act as reservoirs of contaminated air, the act of leaving the structure once the cloud passes greatly reduces one's exposure (see, e.g., Wilson [12]). This is especially important when the cumulative dose rather than the peak dose presents the greater harm. If inhabitants remain sheltered too long, they could end up being exposed to a higher cumulative dose than they would have received outside.

The effectiveness of in-place protection can be enhanced by taking additional precautions. Aldrich [2] indicated that significant reductions in the inhalation dose of radionuclides can be achieved by retreating to basements or interior rooms. Measurements by Warren and Webb [16] showed that infiltration rates in homes are lower for large rooms such as living rooms and bedrooms than for kitchens and bathrooms. By using a tracer gas to measure infiltration rates of several buildings at an industrial plant, Jann [15] found that vestibule exterior doors and weatherstrip seals could reduce infiltration rates by at least a factor of 3, and that a tenfold reduction could be achieved by more extensive remedial measures. Anno and Dore [1] determined that impromptu respiratory protection, i.e., covering the nose and mouth by a handkerchief or towel, can reduce inhalation of a radioactive gas by a factor of 10. The installation of a charcoal air filtration system is a more permanent precaution; the effectiveness of such systems has been reviewed by Chester [6].

Automobiles generally provide poor protection from toxic gases because passenger compartments are not airtight, according to Peterson and Sabersky [17], who estimated the infiltration rate of an idling vehicle with the windows closed and the air-conditioning system off to about 24 air changes per hour (ACH), and found that this value increases linearly with vehicle speed. At 55 mph, for instance, they estimated the rate to be 38 ACH. In other research, Jann [15] found that automobiles have "very low" infiltration rates when the car is stationary and closed up and the engine is off.

The guidance prepared by EPA, FEMA and DOT [13] to help local communities carry out their responsibilities of Title III includes some general considerations for choosing between in-place protection and evacuation during chemical releases emergencies. In addition to presenting some of the advantages and disadvantages of in-place protection and evacuation, it provides a comprehensive list of factors that should be considered, including: the physical and chemical properties of the hazardous material; the health effects from short-term exposure; the material's dispersion pattern; atmospheric conditions; media to which the material is released; and the size, duration and rate of release, as well as any projected changes in the release rate.

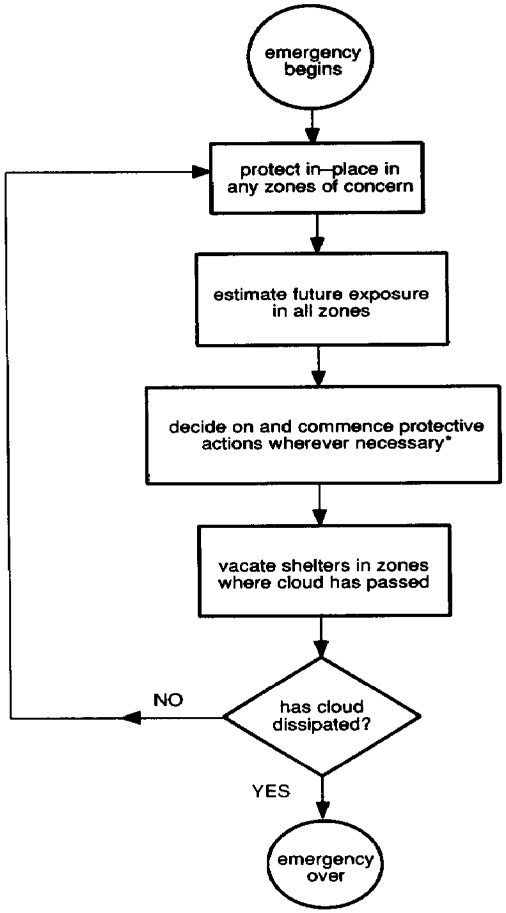
In developing a detailed checklist of the factors that might influence an emergency manager's decision to protect in-place or evacuate, the methodology provided by the National Institute for Chemical Studies [14] carries the guidance process one step further. It groups these factors into six categories: chemical characteristics, population aspects, meteorological conditions, response resources, communications, and time factors. The checklist helps the decision-maker to identify quickly which factors should be considered in the decision and to assess the relative importance of these factors to the decision.

The decision process

Figure 1 shows a flowchart for the sequence of determinations, decisions and actions that are needed to protect the public during a toxic vapor cloud emergency. It is consistent with similar decision processes that have been described by Perry and Mushkatel [18] and by Lindell et al. [4], but is more specific to this kind of emergency and more specific about the nature of the components of the decision process. (Note that this discussion does not specifically address the mitigation of the release and the complications introduced by the possibility of fire or explosion, which are extremely important considerations in practice.)

Starting at the time when the emergency begins, this flowchart tracks the impact of the actual or possible release upon all the potentially vulnerable zones in the area until the threat has passed. Initially, in-place protection should be used in any zones that are already exposed and in any others where it is needed as a precaution. The next concern is to estimate future exposure based on the projected size and direction of the release and its anticipated impacts, which then leads to protective action decisions for the potentially threatened zones and to the implementation of those decisions. Any previous decisions and actions regarding the affected zones may need to be revised and interrupted as a result. The next action is to vacate the shelters used in any zones where the cloud has passed, due to the buildup of toxic vapors indoors. If it is then determined that the cloud has dissipated and ceases to be a threat to any zone, then the emergency is over; otherwise attention returns to the need to protect in-place in any exposed zones, and so on.

Monitoring, detection, warning, communication, control, and advanced planning are obviously important factors in the successful execution of this decision process. At the heart of the process, of course, is the critical choice between the options of in-place protection and evacuation. This decision depends on whether staying indoors will offer adequate protection throughout



[*revise previous decisions and interrupt ongoing actions if necessary]

Fig. 1. Public protection in a toxic vapor cloud emergency.

the duration of the emergency (possibly taking extra precautions to reduce infiltration and its effects) and on whether there is sufficient time to safely relocate everyone involved to someplace else before the anticipated cloud reaches them.

These are straightforward choices in principle, but in practice a number of the factors that bear upon the determination of "adequate protection" and "sufficient time" need to be evaluated before a decision can be reached. The decision process can be expedited and made more reliable by evaluating as many of these factors as possible in advance, and by instituting a procedure to be used during the emergency that systematically accounts for all the relevant factors and provides a guide for selecting the best protective action.

Such a procedure would first of all permit the toxic concentration of the vapor cloud to be estimated as a function of time for each potentially exposed zone, which would then enable the indoor concentration over time to be estimated if the inhabitants of the zone were to be protected in-place. These estimates would be based on information about the chemical in question, the nature of the release (including its source, its size and its duration), the meteorological conditions (including atmospheric stability, temperature and wind conditions), and the different infiltration rates of the structures in the zone. Additional information about the emergency mobilization capabilities and transportation characteristics of the zone would then be used in the envisioned procedure to estimate the time need to evacuate each zone. Finally, the most appropriate protective action for each zone would be determined by means of the kind of decision aid described in the following section, which would be used to: (a) compare the estimated maximum indoor dose to an established critical level, and (b) compare the estimated time at which the anticipated cloud will arrive to the estimated time needed to evacuate the zone.

A protective action decision aid

The four quadrants of the diagram in Fig. 2 indicate the most appropriate protective action, given the values of maximum indoor dose, d_i and the time of arrival of the toxic cloud, t_a. This decision aid is intended to apply to one protective action zone at a time, and the variables d_i and t_a can be understood to refer either to the most vulnerable structure that will be used for in-place protection in the zone, or to a "representative" structure, depending on how conservative the judgement is supposed to be. The dose may be measured in terms of the toxic concentration in the air (ppm) or the cumulative, time-integrated exposure to such a concentration over time (ppm min).

The critical value of the dose for the purpose at hand is denoted by d^*, which might be based on IDLH[1] level or the LC_{50} of the chemical. The critical value of the arrival time of the cloud is t^*, which is the estimated time by which the zone could be fully evacuated. These values define the four quadrants separated by the dotted lines. When quadrant 1 applies, because $d_i < d^*$ and $t_a < t^*$ (the maximum indoor dose is expected to be *below* the critical level and the cloud is expected to arrive *before* the evacuation can be completed), then in-place protection is the most appropriate protective action. If, however, quadrant 2 applies, because $d_i < d^*$ and $t_a > t^*$ (the dose is low but the cloud will arrive *after* evacuation is completed) then either protective action would be appropriate, and the choice might hinge on other considerations instead (e.g., evacuation would be more disruptive but also more protective in the event that the projected dose was underestimated.). Quadrant 3 applies when $d_i > d^*$ and $t_a > t^*$ (the maximum indoor dose is expected to be *above* the critical value and the cloud is expected to arrive *after* the evacuation is completed), in which case evacuation is the preferred option. Finally, when quadrant 4 applies because $d_i > d^*$ and $t_a < t^*$ (the dose is high and the cloud will arrive *before* the evacua-

[1]IDLH means Immediate Danger to Life and Health.

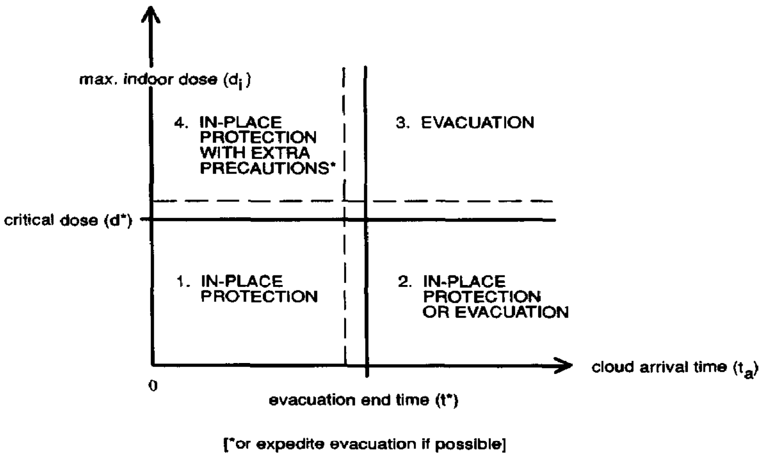


Fig. 2. A protective action decision aid.

tion is completed), which is the worst possible situation to be in, and regardless of whether in-place protection or evacuation (i.e., rescue) is selected, extra precautions for respiratory protection should be taken to guard against the high toxic concentrations indoors and out.

Some accompanying comments are in order. First, the decision boundaries at d^* and t^* shown by the dotted lines in Fig. 2 have been shifted to the positions shown by the solid lines to provide a margin in the face of uncertainty. Uncertainty in the values of the parameters d^* and t^*, and in the on-scene estimates of the variables d_i and t_a, is probably the most serious obstacle to rational protective action decision-making. Second, in the last case described, it might be more effective to undertake an "expedited" evacuation of the most vulnerable shelters instead of relying on the use of extra precautions while using in-place protection. Third, the "wait-and-see" option of placing an area on alert — instead of either evacuating or using in-place protection — has not been included. This might be the most appropriate action when t_a is large. Fourth, the risks and costs associated with the options have not been addressed.

Dose estimation

Two frequently used models for the propagation and infiltration of a toxic vapor cloud can be used to estimate the maximum indoor dose d_i, based on the rise and fall of the corresponding toxic indoor concentration. The first one, shown in Fig. 3(a), depicts a "top-hat" form for the progression of the outdoor concentration over time. This form is descriptive of the effect that a vessel rupture releasing a toxic cloud would have on a nearby zone. In Fig. 3(b), the outdoor concentration is shown as an exponentially decreasing function of time, which is a description of the effect on a nearby zone of a toxic cloud emanating

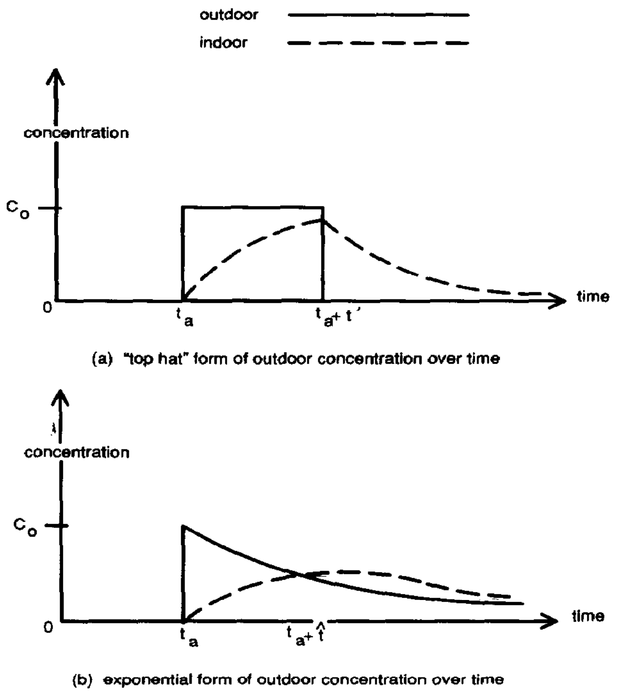


Fig. 3. Outdoor and indoor toxic vapor concentration over time.

from a ruptured pipeline. The dotted line in each case shows the rise and fall of the indoor concentration as the cloud passes by.

Mathematically, as discussed by Davies and Purdy [9], the first situation is described as follows. The rate of change in the indoor concentration $C(t)$ at t minutes after t_a is equal to the effective infiltration rate λ times the difference between the outdoor concentration C_0 during cloud passage and the indoor concentration $C(t)$:

$$\frac{dC(t)}{dt} = \lambda[C_o - C(t)] \tag{1}$$

which yields upon integration

$$C(t) = \begin{cases} C_o[1 - e^{-\lambda t}] & \text{for} \quad t < t' \\ \hat{C}e^{-\lambda(t-t')} & \text{for} \quad t > t' \end{cases} \tag{2}$$

if the cloud completes its passage at t' minutes after t_a, where $\hat{C}$ is the peak indoor concentration:

$$\hat{C} = C_o[1 - e^{-\lambda t'}]. \tag{3}$$

In contrast, for the second situation, as discussed by Wilson [19], the outdoor concentration is an exponentially decreasing function of time:

$$C_o(t) = \hat{C}_o e^{-\mu t} \tag{4}$$

where $\hat{C}_o$ is the peak outdoor value, occurring when the cloud first arrives, and μ is the decay rate. Then replacing C_o by $C_o(t)$ in the differential equation for $dC(t)/dt$ and solving, we now have:

$$C(t) = \hat{C}_o \frac{\lambda}{\mu - \lambda} [e^{-\lambda t} - e^{-\mu t}], \tag{5}$$

which has its peak at $\hat{t}$ minutes after t_a, where

$$\hat{t} = \frac{\ln \mu_o - \ln \lambda}{\mu - \lambda}, \tag{6}$$

so that the peak indoor concentration in this case is $\hat{C} = C(\hat{t})$.

If the physiological response of individuals to the chemical in question is such that the magnitude of the health threat is determined by the peak indoor concentration, then the maximum indoor dose d_i takes on the value of $\hat{C}$ associated with one or the other of the expressions for $C(t)$ above and the critical dose d^* is assigned a standard value such as the IDLH. If, however, the determinant is not the peak but the *cumulative* indoor concentration, then d_i must be calculated either by integrating the time-varying concentration $C(t)$ over the anticipated duration of exposure Δt or, less exactly, by multiplying the estimate of the average level of indoor concentration by Δt. In that case, d^* would instead be assigned a value such as the LC_{50} for the given duration.

Table 1 presents the IDLH values and, for exposures of 10 minutes and 30 minutes, the LC_{50} values reported by Harris [20] for ten different toxic gases. Ten Berge et al. [21] explain how probit analysis is used to derive LC_{50} values from inhalation toxicity experiments and they discuss refinements to the dose calculation process.

The value of the infiltration rate (sometimes referred to as the ventilation rate or the air exchange rate) that appears in the expressions for $C(t)$ depends primarily on the design and construction of the structure and the weather conditions. As one would expect, buildings in cooler climates typically lower infiltration rates than those in warmer areas because of weatherproofing and older buildings tend to be leakier than newer buildings. Infiltration rates can vary widely even among buildings within the same community, according to Aldrich [2].

A study of residential structures in Maine showed rates varying from 0.78 to 1.99 ACH (see Grot [22]), which can increase by a factor of 4 when the windows are open. For the U.S. as a whole, Nazaroff et al. [23] report that the range is 0.2 to 2.0 ACH. The general residential estimates given in the ASH-

TABLE 1

Critical values for some toxic gases (concentration, in ppm)[a]

Gas	IDLH values	LC_{50} values	
		10 min	30 min
$COCl_2$	2	72	24
Cl_2	25	433	250
HCN	60	597	277
MIC	20	620	115
Br_2	10	651	376
H_2S	300	950	441
HF	20	992	331
SO_2	100	1882	627
HCl	100	5555	1850
NH_3	500	20000	11540

[a]Source: Harris [20].

RAE handbook [24] are 0.5 ACH without windows or exterior doors, 1.0 ACH when windows or exterior doors are on one side only, and 1.5 ACH when they are on two sides. For non-residential structures, Grot and Persily [25] found that U.S. federal office buildings have infiltration rates ranging from 0.2 to 0.7 ACH, while Purdy and Davies [8] reported that in England, the rates vary from 3 to 5 ACH for factories, to values of 5 ACH for office buildings and schools and hotels, 8 ACH for department stores, and 10 ACH for hospitals.

For a given type of structure, the speed of the wind and the difference between indoor and outdoor temperatures will increase the infiltration rate. Simple formulas showing that λ increases linearly with wind speed and that λ goes up with the square root of the temperature differential were developed by Dick and Thomas [26]; a more complicated approach to estimating the nature of these dependencies was developed by Coblentz and Achenbach [27] and adopted for use in the U.S. Coast Guard's vulnerability model. To illustrate the dose estimation procedure, suppose for example that a chlorine cloud is moving at the rate of 5 mph (8 km/h) toward a housing development where the homes have an infiltration rate of 0.9 ACH and that, by the time it reaches the first houses, the cloud will have a concentration of 100 ppm and will be 1000 feet across in the direction of travel. Then a house that measures 100 feet deep in that direction will be exposed for 2.5 minutes. Assuming that the outdoor concentration over time has a top hat form, the indoor peak will be less than 4 ppm, which is below the IDLH value of 25 ppm in Table 1. If this criterion were used, then evacuation would not be called for, except as a possible precaution.

Evacuation time estimation

The time t^* at which the evacuation of an area can be expected to be completed depends on how long it takes to make the decision, to notify the people who are to be evacuated, and to see that they move or are moved to a different location. This is obviously a complex undertaking that even with the best of planning is subject to complications that make it difficult to predict when the action will be completed. Nevertheless, it is important both for planning and emergency response to be able to estimate the time needed to evacuate an area.

Once the decision to evacuate is made, the two actions to be taken are warning and execution. A recent investigation by Sorensen [28] provides some "best guesses" about the times required to reach the public with a warning message, assuming adequate resources and a good warning plan. These estimates indicate that it might take as long as two-and-a-half to three hours to warn 90% of the public through door-to-door contact, but only 20 to 35 minutes by using sirens or alarms along with emergency broadcasting. These are averages, assuming good weather and well-maintained systems. Estimating the time needed to execute an evacuation is more problematic because it depends on the means of transportation, the geometry and capacity of the transportation network, the overall population density, the weather conditions, and the needs of special populations such as hospital patients. The study by Urbanik and Desrosiers [29] found the median estimated evacuation time for the area within a ten-mile radius of 52 nuclear plants (excluding warning time) to be 1.8 hours for the permanent population only, with a range of 0.3 to 6.0 h. Estimates of the total warning and evacuation time for the entire body of people in the area, including special populations, ranged from 1 h to 21 h, with a median of 5 h. Data from the major chlorine tank car derailment in Mississauga, Ontario indicate, according to Sorensen [28], that almost 90% of the population was evacuated 45 minutes after being warned, and the same source suggests that a total time of 130 min for warning and 60 min for evacuation is a reasonable estimate for a "normal" scenario. Sophisticated traffic models such as I-DYNEV (see FEMA [30]) and MASSVAC (see Hobeika and Jamei [31]) have also been developed as a means to estimate evacuation times by simulating traffic flow patterns away from the hazard. They are useful aids to evacuation planning, but as Sorensen et al. [32] point out, more research is needed to validate these models based on real-world data.

Conclusions

Figure 4 summarizes the information required for the process of deciding on the most appropriate protective action in a toxic vapor cloud emergency, and shows how this information needs to be factored into the formulation of answers to the two fundamental questions that must be addressed. These ques-

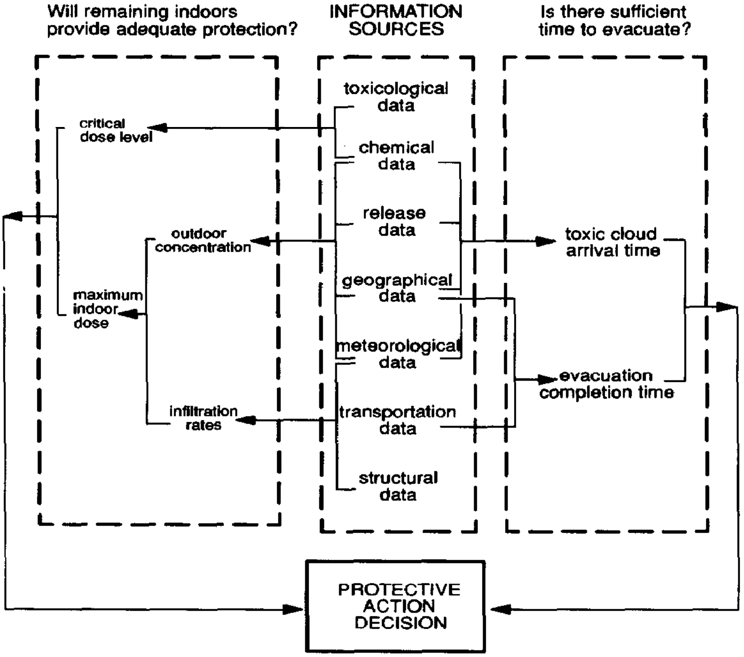


Fig. 4. Representative flow of information into the protective action decision.

tions are: (1) will in-place protection provide adequate protection? and (2) is there sufficient time to evacuate?

The list of considerations in Appendix H of the guide for hazards analysis published by EPA, FEMA and DOT [13] and the proposed checklist in the recent report on public protection of the National Institute for Chemical Studies [14] provide useful guidance for enumerating and accounting for the factors related to identifying and organizing this kind of information, but more needs to be done along the lines suggested in this paper to develop a decision aid to routinize the use of quantitative guidelines for protective action decision-making.

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