Public Health England

Protecting and improving the nation's health

Chemical Hazards and Poisons Report

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Protective actions during chemical incidents and fires: evacuate or shelter-in-place?

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Public Health England
Wellington House
133-155 Waterloo Road
London SE1 8UG
Tel: 020 7654 8000
www.gov.uk/phe
Twitter: @PHE_uk
Facebook: www.facebook.com/PublicHealthEngland

Prepared by: Jim Stewart-Evans
For queries relating to this document, please contact: james.stewart-evans@phe.gov.uk or chapreport@phe.gov.uk

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Editorial

Jim Stewart-Evans
Environmental Hazards and Emergencies Department, Centre for Radiation, Chemical and Environmental Hazards, Public Health England
Email: james.stewart-evans@phe.gov.uk

Introduction

Public Health England's (PHE's) health protection remit includes protecting the public from threats to their health from infectious diseases and environmental hazards, which include incidents involving the release of chemical or radiological material. PHE fulfils its role by providing independent impartial advice and information to the general public, health professionals such as doctors and nurses, emergency responders, and national and local government. This advice requires specialist knowledge of the impacts of environmental, chemical and radiological hazards on human health.

Releases of airborne chemicals can rapidly affect wide areas, leading to exposures that can harm public health. The preparedness for, and response to, emergencies aims to prevent, or minimise, adverse health outcomes such as injuries and deaths. This is achieved through interventions to prevent, or minimise, public exposure. In England, standard shelter advice to "Go In, Stay In, Tune In" is commonly issued to the public by the emergency services and responding organisations during chemical incidents and fires. Depending on the nature of the incident, responders may evacuate those persons at highest risk. In practice, this often applies to a limited number of properties or areas nearest to the incident location, whilst sheltering advice applies to much wider areas.

Public sheltering and evacuation are accepted and commonly used protective strategies. To optimise preparedness and response, emergency planners and responders must understand the factors determining the effectiveness of these strategies, and decision-making and implementation must be evidence-based.

This special edition of the Chemical Hazards and Poisons Report summarises the findings of a review of scientific literature and guidance related to sheltering, evacuation, and associated interventions to protect public health during chemical incidents and fires. As such, it is a review and does not constitute UK policy or doctrine.

The scope of this special edition

This special edition discusses factors that affect shelter and evacuation effectiveness during chemical incidents and fires, but it is also relevant to other types of airborne hazard. It focuses on the acute phase of incidents involving an airborne release; this is defined as the period before, during and after a release when there is an immediate threat to people's health. Longer-term considerations, such as chronic (long-term) risks to health, are mentioned where they are relevant to actions or decisions taken during the acute phase.

In terms of interventions to protect public health, we focus on the established principal options to prevent or minimise population exposure: sheltering and evacuation. Decontamination of people who have been exposed and contaminated, whilst a valid action to protect public health, is addressed by separate guidance [1-3], as is recovery and environmental remediation following chemical incidents [4 5].

An overview of protective strategies

Sheltering-in-place

"Sheltering-in-place" (SIP) or, in the context of this special edition, "sheltering", describes a situation whereby a person stays or moves indoors to decrease their exposure to a hazard that is outdoors. It should not be confused with relocation of members of the public to evacuation centres, which are sometimes described as "shelters" in guidance documents.

Following a release of a hazardous substance to air, a cloud or "plume" may travel downwind towards a building. As the plume reaches the building, the outdoor concentration rises, and the indoor concentration also rises: the substance enters the building as air from outdoors replaces air indoors due to infiltration. However, restricted air exchange and physicochemical attenuation mean that the concentration indoors remains comparatively lower. This protects people indoors from the higher outdoor concentrations. The level of protection diminishes with time. If there is a high infiltration rate, the concentration indoors rises more rapidly.

After the plume has passed the building, the air outdoors returns to an ambient concentration, but the air indoors will still contain some of the substance which entered when the plume was present. At this point the concentration indoors will be higher than outdoors.

A successful sheltering strategy requires that 2 distinct actions are taken without delay to maximise the passive protection a building provides. These are:

- reducing the indoor-outdoor air exchange rate before a plume arrives – this is achieved by closing windows and doors and turning off fans, air conditioners and heaters

- increasing the indoor-outdoor air exchange rate as soon as the plume has passed – this is achieved by opening windows and doors and turning on fans and ventilation to ventilate the building

Three additional variants of SIP are described in the literature:

'Enhanced SIP'
Enhanced SIP is when weatherisation techniques are applied to a building before an emergency to permanently reduce the rate at which air enters the structure. It is sometimes used around hazardous industrial sites to improve the effectiveness of residential SIP. Weatherisation techniques are also used more generally to improve the energy efficiency of buildings (for example, sealing doors, windows and attic hatches).

'Expedient SIP'
Expedient SIP is when measures are taken to reduce the rate at which air enters a single room used as a shelter during an emergency. It is most effective when people are prepared for it in advance. Emergency measures include taping around doors and windows and covering vents and electrical outlets with plastic sheeting. Creating and moving into an expedient shelter is most effective in advance of a hazardous plume impacting the building, implementation after a release has reached a building can greatly reduce the potential for additional protection.

'Pressurised SIP'
Pressurised SIP is when outdoor air is drawn into a shelter through a filter to remove pollutants. This filtered air creates a positive pressure inside the shelter so that clean air leaks out instead of contaminated air leaking in. This method prevents the infiltration of outdoor air into the shelter and offers the highest level of protection. It is not a strategy that can be readily used by the general public and is most relevant when considering buildings specifically designed to be used as shelters.

Evacuation

Between 1970 and 1998 a total of 3 million people worldwide were evacuated in response to chemical incidents [6]. Cabinet Office guidance from 2006 [7] explained that "The purpose of evacuation is to move people… away from an actual or potential danger to a safer place. For this to happen safely there need to be plans not just for alerting people and moving them, but also plans to shelter and support them through to their eventual return and recovery." Evacuation can be precautionary (that is, occur before a release has occurred) or reactive (in response to an existing threat). Responders often use the term "evacuation" to mean a managed evacuation that responders facilitate. However, guided dispersal and self-evacuation of the public are also options. These 3 variants of evacuation are summarised below:

Assisted/facilitated evacuation
Managed evacuation involves an active intervention by authorities to move people away from danger. This requires prior planning, transport and personnel to undertake successfully.

Dispersal
Dispersal is a form of evacuation in which people are simply directed away from the real or perceived source of danger [8]. Any form of evacuation is likely to include some dispersal – this is illustrated by the commonplace practice of setting up cordons, manned by police who direct traffic away from the site of an incident.

Self-evacuation
People may evacuate themselves, moving from danger on foot or using available transport.

Complementary actions

Complementary actions are not always viable and introduce additional considerations and issues, but they can sometimes offer additional protection. They include:

- the use of residential air filter systems
- breathing through masks, wet or dry towels or handkerchiefs

Choosing between shelter and evacuation

Sheltering can be implemented rapidly. In some circumstances, evacuation may be advisable, such as:

- when there is an immediate risk to surrounding properties (for example, from fire or explosion)
- when people can be evacuated prior to an exposure taking place (for example, before a release has occurred or before it has moved to their location)
- when an incident is likely to be prolonged (for example, when the risk associated with sheltering exceeds the risk associated with evacuation, though this is difficult to predict)

Articles within this special edition

Emergency preparedness and response (including the stages of information-gathering; exposure and risk assessment; decision-making; and implementation) are considered in:

- case studies of incidents in which sheltering or evacuation was implemented, and factors that affected outcomes, both within England and abroad
- the relationships between shelter and evacuation effectiveness and physicochemical and toxicological properties of a hazardous airborne chemical, population characteristics and building (that is, shelter) characteristics
- the assessment of outdoor and indoor exposure and use of environmental monitoring and modelling
- the characterisation of risks and use of health guideline values to inform risk assessment
- decision-making and implementation of sheltering and evacuation strategies
- effective communication and implementation of protective actions
- the role of emergency preparedness in facilitating sheltering and evacuation during emergency response

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Incidents involving sheltering and evacuation

James Isaac, Jim Stewart-Evans
Environmental Hazards and Emergencies Department, Centre for Radiation, Chemical and Environmental Hazards, Public Health England
Email: james.stewart-evans@phe.gov.uk

A review of the literature

There are many reports of shelter-in-place (SIP) and evacuation strategies being used during chemical incidents. Different countries have historically favoured one protective action over the other. Whilst it has become common practice in the UK and Europe to emphasise SIP in response to chemical incidents [1-4], emergency responders in the US have more commonly used evacuation [5,6].

Sorensen [7] investigated the use of evacuation during the response to chemical incidents occurring in the US between 1980 and 1984, using data from news reports. The study found that the 4 most common causes of evacuation were:

- releases from chemical manufacturing plants
- releases from industrial sites using chemicals
- chemical road tanker accidents
- train derailments

The physiochemical properties of a released chemical can influence the protective action taken. In the US, evacuation has been reported as less likely for incidents involving chemicals with lower vapour pressures, such as sulphuric acid and sodium hydroxide [6]. Saw et al. [8] examined reports from the US Hazardous Substances Emergency Events Surveillance (HSEES) system[1], finding a lower proportion of protective action orders for incidents involving pesticides and agricultural chemicals. This was partly attributed to their occurrence in remote rural locations.

In comparison, Weisskopf et al. [9] showed that evacuation was more likely following the release of ammonia, which has a relatively high vapour pressure, than for any other chemical, accounting for 26% of incidents in the State of Wisconsin that resulted in

[1] This program ran between 1990 and June 2009 and has since been replaced by the National Toxic Substance Incidents Program (NTSIP)

evacuation. The authors observed that whilst the greatest risk factor was the quantity of ammonia released, almost as many small-scale releases led to evacuation as large-scale releases.

Public Health England's (PHE's) predecessor organisation, the Health Protection Agency (HPA) [10 11], previously reviewed chemical incidents related to industrial sites in England and Wales regulated under the Control of Major Accident Hazard (COMAH) Regulations [12]. Between 2005 and 2011, sheltering was more commonly advised than evacuation; most evacuations were due to risks close to the source, from explosion or fire, rather than the wider area being at risk from an airborne chemical hazard.

Case studies of SIP and evacuation strategies tend to focus on the outcomes of a single strategy. South et al. [13] carried out a technical assessment of the effectiveness of evacuation and SIP in response to a potential release of hydrogen sulphide. It concluded that SIP is the most suitable strategy in response to an incident involving an unpredictable toxic gas release, when the predicted release duration is unknown. This is based on the assumption that most releases are likely to be of short duration and mitigated by prompt action at the source (process shutdown, depressurisation, use of safety valves etc); hence, the greatest risk is from short-term exposure. The authors noted that sheltering does not preclude the use of evacuation; sheltering may be used as a first, protective, pre-evacuation measure in situations where there is a release that turns out to be prolonged. In such cases, it is important to consider the implications of different strategies for people's exposure.

The effectiveness of sheltering and evacuation in past chemical incidents

Case studies of successful sheltering

South et al. [13] refer to 3 examples of incidents involving the release of gas clouds (2 ammonia releases and a sulphur trioxide release) where SIP successfully prevented injury, whereas evacuation could have potentially led to harmful exposures. Following the accidental release of hydrogen fluoride gas from a reactor in Texas, modelling was used to estimate the direction of the release and environmental concentrations [14]. Comparison of environmental concentrations with Emergency Response Planning Guidelines (ERPG) supported a sheltering strategy. The plume passed through a residential area, and observations of damage to outdoor vegetation were consistent with predicted concentrations.

Woodhouse [15] described a hydrogen chloride gas release at an industrial site in Cheshire, England, in 2000. The population around the site was first alerted when the site siren was sounded, and the emergency services worked with the local media to advise the public to shelter. Although there was a visible gas cloud in residential areas, only a small number of casualties with minor symptoms were reported, and it was concluded that prompt advice to shelter had minimised impacts.

Case studies of problematic sheltering

After a railroad accident in Graniteville, South Carolina, in 2005, chlorine gas quickly reached residents. Evacuation was considered to be the best option, despite the fact that people would have to evacuate through the gas. However, delays in giving evacuation advice resulted in a large number of the sheltering population experiencing adverse health effects [16]. A similar case involved a chlorine release from a rail tank car unloading operation in Missouri [17].

Baxter et al. [18] described a fire at a waste plastics site in England. In this incident the police initially made a decision not to evacuate residents. However, this decision was reviewed on the third day of the fire when the weather changed and smoke began to affect nearby residential areas. The authors concluded that evacuation may be advisable during prolonged incidents, as the state of the fire or release and weather conditions could change unexpectedly, and there is potentially a longer duration of exposure. Advance planning is required to ensure that people can be moved during favourable conditions.

Case studies of successful evacuation

Scoville et al. [19] described a successful large-scale evacuation following a white phosphorus release caused by a train derailment in Miamisburg, Ohio in 1988. The decision to evacuate 12,000 to 17,000 people was informed by the results of air monitoring, which indicated that elevated levels of particulates and phosphoric acid were present.

The Police Department divided the city into sectors and coordinated transport to pre-arranged evacuation centres, assisted by emergency support groups who provided bedding and food, with the help of local restaurants. Approximately 170 people were admitted to hospital with symptoms of shortness of breath, burning eyes and nausea. The overall success of the mass evacuation was attributed to effective training of local fire fighters, thorough emergency planning and good organisation and coordination of responders.

Case studies of problematic evacuation

The 2005 railroad chlorine spill in Graniteville [16] illustrated the challenge for a small town to handle a large-scale evacuation. Uncertainty regarding whether to shelter or evacuate, and what evacuation routes would protect or harm people, led to delays in issuing evacuation advice, while sheltering populations suffered health effects from exposure to chlorine gas. The authors emphasised the need for better chemical emergency preparedness – a key requirement was knowledge and understanding of the chemical hazard involved – and the importance of identifying local risks and engaging and educating the surrounding population.

The Graniteville incident occurred at night, which hampered the response and public communication. This has been a complicating factor in other incidents; McNaught et al. [20] described how emergency services, public health professionals and the local authority considered the feasibility of night-time evacuation of local villages. Other factors can complicate evacuation. Suburban areas with constricted road networks may be particularly difficult to evacuate; this has been demonstrated during wildfire incidents when the rapid spread of fires has blocked roads out of the affected area [21].

Kaszniak and Vorderbrueggen [22] described how an evacuation was started and then, subsequently, cancelled more than 9 hours after the incident began. Following an uncontrolled release of a vapour cloud of allyl alcohol and allyl chloride into the Dalton area of Georgia in 2004, the Fire Department issued an evacuation notice for all residents within a half-mile radius of the source facility. In an attempt to evacuate residents, emergency responders entered the area affected by the vapour cloud without personal protective equipment (PPE). Residents and emergency responders were subsequently exposed to toxic vapours, and some required hospital treatment. One hundred and fifty-four individuals required decontamination and treatment for symptoms of respiratory distress and skin and eye irritation. The investigation into the incident found that methods to promptly alert the public and keep them informed during the evacuation were ineffective. It was unclear to residents when the evacuation order was lifted, causing confusion and delaying residents' return to their homes. When people returned, there were no guidelines for decontaminating personal belongings and food.

It is difficult to determine what the public response will be to an evacuation order. Rogers and Sorensen [23] considered the effectiveness of warning systems for evacuation orders for 2 chemical transportation accidents in the US. The most frequent response was for recipients to disregard information. Although compliance rates are not well documented, there is evidence that in situations where both shelter and evacuation have been advised, compliance with the recommendation to shelter has not been high [21].

Cross-sectional health studies that compare shelter and evacuation outcomes

Few published case studies and reviews allow for a direct comparison between sheltered and evacuated populations. However, some cross-sectional studies have compared health outcomes experienced by sheltering and evacuated populations. Their general approach is to use questionnaires after the event; a common challenge is in determining exposure levels. Two such studies involved communities affected by the smoke produced by factory fires [1 24].

Kinra et al. [1] compared sheltered and evacuated populations following a partial evacuation in response to a fire at a plastics manufacturing plant in Devon in 1999. Four hundred and seventy-two residents were evacuated, and 1,278 others were advised to stay in their homes. A questionnaire survey was used to compare early health outcomes, and statistical analysis found that evacuation did not confer any additional health benefit over SIP. Indeed, evacuated residents appeared to have worse health immediately following the incident than those that sheltered: twice as many evacuees experienced mild respiratory, skin and eye irritation when compared to those sheltering, although symptoms did not persist.

The study concluded that direct exposure to smoke was a more important determinant of ill health than cumulative exposure to smoke (that is, shorter exposures to higher concentrations of products of combustion was worse than longer exposures to lower concentrations), which is consistent with the findings of other studies [25 26].

An evaluation of community evacuation was undertaken following a fire at an electroplating plant in Pennsylvania in 1987 [24]. Fifteen thousand people were directed to leave their homes. The symptoms reported via a household survey were relatively mild, of short duration and consistent with acute exposure to acidic aerosols. For those residents that did not evacuate, 11% reported symptoms, compared with 20% of those who did leave their homes. However, these proportions were not statistically significant as the evacuation compliance rate was very high (98%) and relatively few people sheltered. The authors acknowledged that mass evacuation may generate other hazards in addition to the original threat.

Sheltering and evacuation decisions and their implementation in England

PHE undertook a rapid review of logged chemical incidents and fires occurring in England and Wales over a thirteen-month reporting period (from 1 November 2011 to 30 November 2012), searching incident logs for keywords related to protective actions. Of 126 log entries screened as potentially relevant, evacuation was reported in 69 cases, sheltering in 21, both evacuation and sheltering in 16, and in 20 cases no action was taken (for example, sheltering or evacuation was mentioned but not implemented).

Table 1 describes the types of incident associated with protective actions; the 14 deliberate releases included 8 cases involving intentional self-harm using chemicals. There were few transport incidents; however, this may have reflected the short review period.

Table 1. Incidents associated with protective actions

Type of incident	Cases
Fires	45
Airborne releaes	43
Releases to ground or water	16
Deliberate releases	14
Explosions	5
Chemical contamination	3

In the majority of incidents, initial decisions to evacuate or shelter were made by the emergency services before public health professionals became involved. Mention of evacuation in logged incidents primarily related to evacuation of the premises where an incident occurred, initiated by the emergency services or self-evacuation of employees or residents. A precautionary approach was often taken by the emergency services during the initial stages on an incident, with nearby buildings evacuated if they could be at risk.

Most (26) of the 37 logged incidents in which sheltering took place were fires. In fire scenarios, precautionary SIP was issued (for example, door-to-door or through media messages) by the emergency services, advising local populations nearby and downwind to shelter indoors to minimise their exposure to smoke.

There were 3 incidents during the review period in which a multi-agency Air Quality Cell (AQC) [27] was convened to coordinate real-time air monitoring and interpret local air quality data. In these 3 incidents (all involving waste materials), the potential for a prolonged incident was recognised. Monitoring results informed decisions regarding the need for initial and continued sheltering and the termination of sheltering once there was no longer a significant risk.

Key points

- countries have different preferences for sheltering and evacuation
- chemicals with high vapour pressures, such as ammonia, may be more likely to provoke evacuation than chemicals with low vapour pressures
- sheltering has been used successfully during short-lived incidents; in some longer-lived incidents, it has been less effective
- people may be exposed to an outdoor hazard whilst evacuating. Large-scale evacuation can pose significant resource requirements and requires good prior emergency preparedness
- a range of factors affect the success of sheltering and evacuation strategies

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Factors affecting shelter and evacuation effectiveness

Jim Stewart-Evans
Environmental Hazards and Emergencies Department, Centre for Radiation, Chemical and Environmental Hazards, Public Health England
Email: james.stewart-evans@phe.gov.uk

Introduction

Sheltering and evacuation strategies aim to prevent or minimise population exposure to an airborne hazard and its consequences. Three broad areas are relevant when considering exposure. These are:

- environmental dispersion, which determines outdoor exposures
- the relationship between outdoor and indoor exposures
- the effects of exposure on people's health

Communication, public behaviour and emergency preparedness affect the success of implementing the chosen strategy and are dealt with in later articles.

Incident and hazard characteristics

An incident's characteristics determine the concentration of a substance in the outdoor environment and the potential exposure duration. They can often be described by emergency responders at the scene and include:

- the type of incident, for example
    - a short or long-lived fire, producing products of combustion (smoke)
    - an instantaneous release, such as the catastrophic failure of a storage tank
    - a continuous release, such as a prolonged leak from pipe-work
- environmental conditions and storage conditions (such as refrigeration or pressurisation), which may affect substances' behaviour when released
- the quantity of the substance(s) involved – larger quantities can produce higher environmental concentrations over wider areas
- the rate of combustion or release – higher release rates produce higher environmental concentrations more quickly
- the duration of release, which determines the potential duration of exposure – sheltering can become less effective during prolonged releases

- mitigation measures taken at the scene to reduce a substance's environmental concentration (for example, containment, neutralisation, blanketing, or use of water, misting sprays or foam cover)
- the location of the incident relative to the location of members of the public
- dispersion (spatial movement and distribution) of the substance(s) from the source, which, for releases to air, is primarily driven by meteorology and topography (including the density, layouts and forms of urban areas) – outdoor (and indoor) concentrations are generally highest close to the source [1]
    - critical meteorological conditions include wind speed, wind direction, temperature, and atmospheric stability [2,3]. Wind speed and direction determine which areas will be affected and how long it will take an airborne hazard to reach them. They also influence the rate of ingress of outdoor hazards
    - light winds and stable conditions can give rise to high ground-level concentrations [2]
    - inversion conditions may cause a chemical plume to travel closer to the ground and dissipate less rapidly [2] or, in the case of large fires with high-altitude plumes, inversion conditions may slow a cooling plume's return to ground level
    - dispersion is also influenced by the nature of the surrounding built environment [4]

Physicochemical properties

A substance's physicochemical properties affect its environmental concentration and the type(s) of hazard that it poses, so that:

- gases are readily dispersed in air – solids and liquids are less likely to become airborne, although powders, vapours and aerosols may be wind-blown or carried by buoyant smoke plumes during fires
- smaller, lighter particles and droplets are carried further and deposited less readily
- vapour pressure and temperature influence the rate at which a substance evaporates and its subsequent concentration in air – volatile substances are more likely to evaporate at relatively low temperatures, and materials with higher volatility are more likely to enter structures [5]
- raised temperatures may encourage evaporation or decomposition
- reactive substances that are inherently unstable and susceptible to rapid decomposition, and substances capable of reacting alone or with other substances, may generate gaseous products of reactivity – these may be more hazardous than the original substance
- flammable or explosive hazards may preclude sheltering in affected areas
- a gas's density (and concentration) influences its dispersal – gases which are lighter than air will disperse upwards with time, while those heavier than air are more likely to travel close to the ground and be affected by topography

- the environmental persistence of a substance influences the potential exposure duration and can be a longer-term consideration – persistent substances may require environmental decontamination [6 7]

Toxicological properties

Chemical toxicity has a number of implications for sheltering and evacuation decisions. These are:

- substances that are toxic via inhalation and dermal absorption are most likely to present a risk in the event of an airborne release
- for any single release 2 determinants of toxicity are relevant: exposure concentration and exposure duration
    - higher exposure concentrations and longer exposure durations increase the likelihood of adverse health effects
- toxicity affects the concentration and duration of exposure that can be tolerated and, hence, the timescales of sheltering or evacuation
    - highly toxic substances may cause health effects at lower concentrations and exposure durations. There is less time to implement a protective strategy and shelter or evacuate before exposure will lead to effects
- adverse health effects can reduce people's ability to evacuate, shelter or remain in shelter
- exposure may lead to immediate or delayed health effects: the risk of longer-term effects (for example, carcinogenicity) may preclude prolonged sheltering
- health guidelines, standards and exposure thresholds can inform decision-making: if exposure will not exceed health-based guidelines or standards then impacts are unlikely and protective action may not be required

Haber's Law, as summarised by Maynard [8], describes the relationship between the exposure concentration and duration required to produce a given toxicological endpoint (for example, mortality). It can be used to determine the effect of exposure concentration and duration when the toxic effect is linear, where doubling the concentration or duration of exposure will halve the time taken for an adverse effect to be seen.

However, it does not apply to all chemicals and toxicological endpoints. A number of chemicals – such as many chemical warfare agents, locally irritant gases and systemically acting vapours – have been found to deviate from Haber's Law, and it is widely accepted that for some chemicals time-integrated concentrations are not a good indicator of effects such as mortality [8-11]. Total exposure (dose), and the effect produced by that exposure, is still the most important variable, but this effect is often non-linear.

For many chemicals, the exposure concentration will eventually determine the effect, and this is not simply a combination of concentration and exposure time. The "toxic-load exponent" or "*n* value" is a chemical-specific parameter that characterises the dose-response relationship [10]. It can be used to calculate "toxic load" (TL), a metric that recognises that chemicals elicit different responses over different concentrations and timescales.

For any given chemical, when the load exceeds a certain limit, adverse health effects are likely to occur – this is called the "toxic load limit" (TLL), and the concept is fundamental to the derivation of many guideline levels for acute exposure during emergencies, such as Acute Exposure Guideline Levels (AEGLs) [8], associated with discomfort, disability and death.

It is important to note that whilst published *n* values and TLLs [12] provide health-effect thresholds that can be used to evaluate the effects of different exposure concentrations and durations of exposure, there are significant uncertainties associated with limited human and animal toxicological assessment data and its extrapolation and use [8 13]. *n* can vary according to the toxicological endpoint considered, and for some chemicals, *n* may not be constant with time [8].

Population characteristics

Population characteristics partly determine a population's capability to shelter or evacuate and the likelihood of exposure and health effects.

The direction and distance of people and buildings from the source of an airborne hazard has a large bearing on whether exposure will take place: those downwind closest to a release are likely to be at highest risk. The number of people that may be exposed depends on the size and nature of the area affected (for example, its population density). As well as the scale of potential impacts, this can affect the feasibility of a managed evacuation. However, densely populated urban areas tend to have more infrastructure and resources to support large-scale warning and evacuation: this runs counter to a common perception that evacuation takes much longer in built-up areas [2].

Studies have found that people typically spend up to 90% of their time indoors [14-19]. People are, therefore, generally more likely to be indoors than outdoors [20], depending on variables such as the time of day and weather. People who are already indoors can potentially shelter more quickly and effectively, although communication and implementation may be problematic at night when people are sleeping.

Vulnerable individuals may spend an even larger proportion of their time in the home [21 22]. Children, the elderly and people who have pre-existing medical conditions are also more likely to be affected by exposures to harmful substances. People at greatest risk from acutely toxic inhalation exposures are those with cardio-respiratory disease and those in frail health, including a proportion of the elderly. These susceptible groups are less able to tolerate high concentrations and prolonged exposure durations; consequently, sheltering may offer them a shorter period of protection and evacuees may be affected more quickly if there are harmful concentrations outdoors.

Some people may be less able to implement evacuation or shelter advice: it may be difficult for them to close doors and windows and turn off ventilation or to evacuate. Thus, mental and physical incapacity can hamper effective sheltering or evacuation, and assistance may be required from others. During prolonged incidents, people who require prescription medicines or specialist care may need to leave shelter or have those medicines or care delivered to them.

Some types of building require individual consideration by risk assessors [2]. Institutional premises, such as schools, nursing homes and hospitals, are readily associated with the presence of susceptible populations. Commercial and leisure facilities and transport infrastructure will contain a proportion of vulnerable individuals. Additional considerations can affect the feasibility and effectiveness of sheltering or evacuation: prisons and recreational grounds, for example, can be problematic because one of evacuation or shelter is strongly favoured, with the other a last resort. If people are outdoors at the time of an incident and cannot readily shelter, dispersal or self-evacuation may be preferable.

Complementary actions

Complementary actions can enhance the effectiveness of sheltering and evacuation strategies. They include:

Expedient sheltering

During incidents in the US, the public may be advised to take additional measures to reduce infiltration. The Federal Emergency Management Agency website advises people to seal the windows, doors and air vents of their chosen shelter room using plastic sheeting and duct tape [23].

Proper sealing, which may take an average of 35 minutes to implement, can make a substantial difference in the effectiveness of a shelter room by increasing airtightness and reducing air exchange [24]. Placing a wet towel under the door might reduce air infiltration, depending on the size of the opening, and is a measure that is widely cited in sheltering literature [25], but in itself is not as effective as proper sealing [26].

The success of expedient measures in reducing infiltration is reliant on rapid implementation [26]. It requires prior emergency preparedness, otherwise people are unlikely to have the capability to implement it [27].

Portable filter systems

The use of portable residential filter systems has the potential to reduce indoor concentrations of particulate matter [28-30] and is advised in US wildfire guidance, though integral filters in building ventilation systems are thought to be more effective [31]. Filter effectiveness partly depends on the filter flow rate relative to the infiltration flow rate of the building; for wildfires Lipsett [31] advised that units should be sized to filter 2 to 3 times the room volume per hour. Chan et al. [11] noted that portable filters can be costly and time-consuming to deploy, which may limit their use in practice.

Running water

The use of water to mitigate the release of water-soluble airborne substances is a technique sometimes used at the scene of an incident by industry and fire-fighters. Fthenakis [32] found that water-spraying was effective at controlling highly water-soluble gases (for example, hydrogen fluoride and ammonia), but did not substantially reduce moderately water-soluble gases (for example, sulphur dioxide).

People calling the emergency services have been advised to shelter in bathrooms with running water during some past incidents in the US [33]. Tarkington et al. examined the effect of a running a bathroom shower on ammonia levels, suggesting that this can substantially reduce ammonia exposure and that by combining strategies (that is, also breathing through a wet towel, see below), inhalation of ammonia gas can be reduced one hundred-fold, even during prolonged exposure periods and at high exposure concentrations. The authors suggested that their findings would apply to other water-soluble chemicals such as hydrogen chloride, hydrogen fluoride and ethylene oxide; this strategy would, however, be less effective for chlorine and relatively insoluble gases such as phosgene [27].

Improvised respiratory protection

Some countries routinely advise the public to use improvised respiratory protection during some types of incident [34 35]. Breathing through towels, handkerchiefs and similar materials can offer some protection against inhalation of particulate matter and aerosols during short-lived incidents. Leakage around materials held to the face is an important determinant of the level of protection [33 36-39]. Sorensen and Vogt [36] summarised studies examining respiratory protection, finding that dry materials reduced aerosols by a factor of 30 across the range of aerosol sizes studied, but did not reduce vapour concentrations. Thicker material increased the protection from filtration but made the material more difficult to breathe through. Wet cloths offered a lower level of protection but were effective at removing reactive gas. Dampened materials can provide additional protection against the inhalation of water-reactive or soluble substances, including vapours and gases [33 36 38 40-42]. Damp cloths must be rinsed out once saturated to sustain protection over time.

Improvised respiratory protection is only likely to provide protection from relatively low concentrations and for short exposure periods [39], and offers little protection from low-solubility or low-reactivity gases. Whilst its use may be beneficial during fires [36], the use of masks and respirators by the public may be considered a last resort after other methods of exposure reduction have been implemented [31 43 44].

Key points

- the characteristics of an incident determine the concentration of a substance in the outdoor environment and the potential duration of exposure
- a substance's physicochemical properties affect its environmental concentration and the type(s) of hazard that it poses
- chemical toxicity depends on the exposure concentration, exposure duration and dose-response relationship and has a number of implications for sheltering and evacuation decisions
- population characteristics partly determine a population's capability to shelter or evacuate and the likelihood of exposure and health effects
- complementary actions can enhance the effectiveness of sheltering and evacuation strategies

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Factors affecting sheltering effectiveness

Jim Stewart-Evans
Environmental Hazards and Emergencies Department, Centre for Radiation, Chemical and Environmental Hazards, Public Health England
Email: james.stewart-evans@phe.gov.uk

Introduction

Sheltering aims to prevent or minimise population exposure to an airborne hazard and its consequences. This article discusses key factors that influence sheltering effectiveness: building characteristics and air exchange, chemical dose-response, and timing.

Building characteristics

Hall and Spanton [1] considered the ingress of external contaminants into buildings, surmising that building characteristics affecting ingress include height, internal volume, complexity, and permeability. Permeability – a measure of how inherently well (or badly) sealed a structure is – is one of several factors that determine a building's air exchange rate [2-7].

Building characteristics: air exchange

Buildings typically have 3 different methods of air exchange [8]. These are:

- forced mechanical ventilation
- natural ventilation through open trickle vents, windows and doorways
- infiltration through unintentional openings (air leakage)

The air exchange rate is derived by dividing the total volume of air added to or removed from a space over a given period of time ($m^3\ h^{-1}$) by its volume (m^3). It is usually expressed as air changes per hour (ach or acph[2]).

Whole-building air exchange rates provide an overall measure of air exchange. The lower the air exchange rate, the lower the rate of ingress of an outdoor hazard. Indoor exposure is also influenced by internal air exchange between the different floors and rooms of buildings.

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[2]ACH are used in UK Building Regulations, but note that some studies express air exchange as h^{-1}

Building characteristics: air exchange – ventilation

Purpose-provided ventilation may be delivered using natural, mechanical or mixed-mode systems. An air exchange rate of at least 0.5-1 acph is a common target. In summer months, when windows and vents are open, air exchange rates can be twice as high as in winter.

The vast majority of UK residences are naturally ventilated. Ventilation can be reduced by closing trickle vents and controllable ventilation openings (including windows and doors). Recently built houses show an increasing trend towards the use of mechanical ventilation. Guidance exists to help people use ventilation systems efficiently [9], but there is evidence that people's understanding and maintenance of them is poor.

In a sheltering scenario people are advised to turn off ventilation systems and to close windows and doors. The US Federal Emergency Management Agency (FEMA) [10] states that, in most cases, air conditioners and combustion heaters should not be operated either. These actions lower the air exchange rate. It may be possible to shut the supply air (that is, inflow) off completely and operate some mechanical ventilation systems in recirculation mode. Mechanical ventilation can remain active if air intakes are unaffected by an outdoor hazard.

Building characteristics: air exchange – infiltration

Once ventilation is minimised, air exchange is driven by infiltration, whereby outside air leaks through cracks and gaps in a building's fabric. Infiltration occurs at the same time as exfiltration. Flow rates depend on a number of factors [11], including:

- location, size and nature of openings (for example, cracks and purpose-provided openings)
- local wind speeds and pressure coefficients
- inside and outside (air) temperature
- the nature of flow paths within a space (where air moves)
- the flow regime (how air moves)

Building characteristics: air exchange – permeability

All buildings have some level of permeability. Factors that influence airtightness include the building's age, number of storeys, size and complexity, quality of site supervision and workmanship, floor type, type of walls and ceilings, number of attic accesses, presence of fireplaces, insulation of electrical outlets, drying out of the structure over time, and the season [2 6 12-14]. Some nominally "leakier" construction types (for example, timber, masonry and reinforced concrete-framed) have higher permeability than others (for example, precast concrete panels) [6 14 15].

Air leakage is defined as the uncontrolled flow of air through gaps and cracks in the fabric of a building. The greater part of “background air leakage” may be associated with myriad cracks and gaps in the structure, rather than the cracks around doors and openable windows [6 14]. It is generally expressed in terms of the leakage of air (m^3/hour) in or out of the building per square metre of building envelope, reported at a pressure differential of 50 Pascals between the inside and outside of the building (m^3/($h.m^2$)@50Pa).

Flats tend to be more airtight than other dwellings of equivalent area, as they are more likely to have solid intermediate floors, fewer external door and window openings and fewer service penetrations for pipes and cables [16]. Warehouses and small footprint, short height buildings may have higher permeability than large, tall buildings [15], but the relationship between airtightness and the number of storeys appears inconsistent [16 17].

The implications of permeability for sheltering during acute incidents

Tighter buildings can reduce the rate of ingress of outdoor hazards and the exposure of sheltering occupants during incidents. Chan et al. [18] found that tighter buildings (comparing 0.2 acph to 2 acph) could be twice to 4 times more effective at reducing toxic load.

In the UK, the relationship between building age and airtightness is not linear: older houses are not necessarily leakier. Homes built since about 1980 are more airtight on average than those built since the 1930s, but the range of values is very wide [6]. A trend of increasing airtightness is seen in UK homes built since 1995 [19], with further improvements seen since 2006 [14]. In the US, Chan et al. [20] found a relationship between airtightness and household income, observing that lower income households tended to reside in less airtight houses.

Building characteristics: air exchange – wind speed and direction

Wind causes pressure differences between the inside and outside of buildings. Air is drawn in through the windward face (infiltration) and leaves the dwelling via the leeward face (exfiltration) [21]. During incidents, higher wind speeds can increase the pressure difference and the infiltration rate, but they can also disperse hazardous plumes more quickly.

There is a fairly linear increase in infiltration with increasing wind speed [1 12]. 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 so on. Variable winds will generate variable flow rates.

The prevailing wind direction versus the characteristics of the building seal also influences infiltration: for example, a building may have higher infiltration when there is a west-to-east cross-flow rather than a north-to-south flow [22]. In tall buildings, the indoor-outdoor pressure difference can vary significantly with height [15].

Shielding by local terrain and obstacles, such as other buildings and vegetation, can lower wind pressure on the building envelope [1 20 22]. If there is a high level of turbulence the wind pressure is less consistent, leading to lower infiltration [22].

Building characteristics: air exchange – temperature

Temperature affects air exchange kinetics, both within a property and between the property and the outdoors [4]. Temperature-driven flows are highly variable, as both the indoor and outdoor temperatures vary throughout the day and across the seasons [11]. Infiltration increases as the temperature difference between outdoors and indoors increases. Limited data suggest that a temperature differential of 11°C (20°F) will double the infiltration rate, and 33°C (60°F) may triple or quadruple the infiltration rate [12]. However, Sorensen et al. [12] state that the relative importance of temperature is minor in comparison to other factors.

Temperature differences create a stack effect. In the UK, the outdoor air temperature is nearly always lower than the indoor air temperature [16]. Warm air is more buoyant than cold air, and buoyant air rises by convection. This effect draws in cooler air at the bottom of a building (infiltration), which is felt as cold draughts inside. The pressure caused by the temperature and resulting air density differences pushes warm air out of cracks and gaps in the envelope of the upper portion of the building (exfiltration). The effect is greater if the temperature differential is higher [21], if the ceiling is particularly leaky or windows above the ground floor are unsealed [23]. During summer or warmer outdoor-to-indoor conditions, the air infiltration and exfiltration airflow is reversed, and cool air falls through the building.

Hall and Spanton [1] note that “increasing [building] height increases both the buoyancy forces and the wind speed to which a building is exposed, generally increasing ventilation rates”. The authors note that multiple floors can lead to a stepped vertical pressure profile, following the floor levels. Structures like ventilation ducts, lift shafts and stairwells tend to enhance stack-effect pressures and vertical airflow connectivity. In a building with airtight separations at each floor, each story acts independently such that the stack effect is discontinuous [15 24].

Indoor heating systems affect temperature-driven infiltration. Open fireplaces with a large rate of airflow out of the chimney can induce significant air-exchange [22]. The effect of heating on infiltration in sheltering scenarios was examined by Sirén [25], whose study found that although the overall effect is quite small, turning off heating systems can still offer protection if there is enough time for indoor temperatures to fall.

The implications of air exchange for sheltering during acute incidents

Air exchange rates inform estimates of building protection factors, levels of exposure reduction and shelter effectiveness. Schmidtgoessling [26] presented a general rule: if air change rates are halved, peak indoor concentrations are reduced by a factor of 1.5. Table 2 shows the relationship between sheltering time, air change rate and dose reduction factor (DRF). A DRF of 0.50 means that the indoor dose ($c^n.t$) is 50% of the outdoor dose. Shorter sheltering durations and lower air change rates are associated with the highest levels of protection (that is, the lowest doses).

Table 2. The relationship between air exchange and dose reduction factor[3]

Air Exchange Rate (acph)	Dose Reduction Factor (DRF)				
	30min	1h	2h	5h	10h
0.1	0.03	0.05	0.09	0.21	0.37
0.5	0.12	0.22	0.37	0.64	0.80
1	0.22	0.38	0.57	0.80	0.90
5	0.66	0.82	0.91	0.96	0.98
10	0.83	0.92	0.96	0.98	0.99

Building characteristics: attenuation

Deposition, condensation, reaction with building materials, and the potential filter-effect of passage through a building's structure can all affect the indoor concentration of a substance. Chemicals may interact with a range of external and internal surfaces, such as bricks, concrete, glass, plastered walls and interior furnishings, such as carpets and curtains. Chan et al. [20] observe that "interactions can occur through several mechanisms including redox reactions, acid–base reactions, hydrolysis, and sorption." Such interactions can increase or decrease the concentration [27].

Studies that have investigated attenuation effects have found that they can substantially increase the protection offered by sheltering [25 28-32].

[3] Where dose-response is linear (that is, the chemical toxic-load exponent 'n' = 1)

The choice of building

Sheltering in leaky buildings or buildings with active ventilation systems is less effective. It is, consequently, inadvisable to shelter within structures such as sheds, huts or tents for all but the briefest periods unless there is no alternative. Semi-open structures such as stadia offer very little protection because they cannot be sealed.

Vehicles offer a lower level of protection than residential buildings as they tend to have higher rates of air exchange, especially if they are moving. As a last resort it may be feasible to shelter within vehicles for short periods while taking measures to reduce infiltration (for example, by closing windows and vents).

Buildings with multiple rooms and multiple storeys can offer more protection than single-room single-storey structures. Larger buildings have higher internal volumes, which act as a reservoir to increase the dilution of incoming contaminants, and internal movement of contaminants can be slowed within complex structures [33-35].

The choice of shelter room

Air flows between rooms within a property are governed by ventilation and infiltration and exfiltration flows. Without sealing measures, bathrooms may offer no additional protection than the rest of a house due to higher infiltration [33]. Closing doors and choosing an appropriate shelter room with internally-facing walls can potentially decrease dose by an additional 50% [25].

Typical advice within the UK is to move upstairs to a room on the opposite side of the house from an incident [36]. Sirén [25] found that the lowest doses over a 12 hour period usually occurred on the second floor and the leeward side of a building. Other sources state that there is no substantial advantage in a room on the higher floors of a low-rise building [37].

The additional protective effect of a good shelter room is greatest in reducing exposure in the short-term. It may not substantially reduce cumulative exposure in longer-term incidents, as indoor concentrations in buildings and shelter rooms tend towards outdoor concentrations over time.

Dose-response

Dose is a function of exposure concentration and duration. As indoor concentrations tend towards outdoor concentrations over time, the indoor dose will tend towards the outdoor dose in the longer-term. The effectiveness of sheltering depends on the level of exposure versus health-effect thresholds. These are derived from information on chemical toxicity and dose-response for the effects of concern. Depending on the available data, the dose-response for acute effects, which are likely to be the main concern when sheltering is being considered, may be characterised by a chemical's toxic-load exponent, *n* (described in the preceding article in this edition).

Typically, inhalation of a very high concentration for a short time is much worse than inhalation of a lower concentration for a long time, even if the time-integrated dose is the same in both cases [15]. Non-linear dose-response relationships (where $n>1$) imply a substantial reduction in toxic load from lowering the peak exposure concentration, which means that sheltering can be particularly effective for short-duration releases of chemicals because the dilution of outdoor air mixing with indoor air reduces the peak concentration indoors [18 38]. In such cases, delays in terminating sheltering will cause little extra harm, providing the plume has passed, since most protection has already resulted from the lower peak exposure concentration indoors during the passage of the plume. However, for chemicals with linear dose responses (that is, $n=1$), it can be more important for people to shelter promptly and terminate sheltering once a plume has passed, in order to minimise their cumulative exposure.

In practice, risk assessment is based on comparison of exposures with exposure thresholds for relevant health endpoints derived from chemical-specific toxicity data. Thus, *n* values cannot be interpreted in isolation; health effects are dependent on whether exposure reaches exposure thresholds associated with adverse effects.
As a general rule, sheltering can be an effective mechanism for reducing exposure to peak concentrations over a limited time, but it may be less effective at reducing cumulative exposure over a longer time period as the concentrations build up indoors [12 18 20 38-40].

Timing

Three time periods are relevant when sheltering from an airborne hazard. These are:

- the period before a hazard reaches a building, for example, before a plume arrives
- the period during which the hazard is outside, for example, while a building is in the plume
- the period after the hazard has passed, for example, after a plume has moved away

It is desirable to minimise air exchange before a substance reaches a building, as this maximises the protection offered by sheltering. Delays in turning off ventilation and reducing infiltration can significantly reduce shelter effectiveness [15 20 38 41-43], particularly for non-sorbing chemicals with linear dose-responses [20]. In prolonged incidents such as long-running fires, the effect of delayed sheltering is less significant to people's overall (cumulative) exposure. In some cases sorption can offset the loss in effectiveness caused by delayed sheltering [15].

A number of organisations and studies have estimated the limit at which sheltering indoors might cease being effective at protecting people if levels of exposure outdoors remain hazardous for a prolonged period (that is, exposures outdoors remain high enough to cause morbidity or mortality). These range from 30 minutes to a few hours [8, 44-48]. Sheltering for longer periods remains viable, particularly if outdoor exposures are lower and/or intermittent, and the effectiveness of sheltering must be considered on a case-by-case basis.

Once an outdoor hazard has passed, the best time to stop sheltering is when outdoor concentrations become lower than those indoors. Maximum protection is attained by increasing the air exchange rate at this point (that is, turning ventilation back on and opening windows and doors) [20 38 49 50]. This is particularly important for non-sorbing chemicals with linear dose-responses.

Tighter buildings can slow the escape of substances that build up indoors, which can turn an initial advantage into a liability. If sorption of chemicals to indoor surfaces occurs and is reversible, Chan et al. [20] state that the amount of a toxic chemical that desorbs from surfaces into indoor air is relatively small over the course of a few hours after a release has stopped. The authors found that shelter effectiveness remains essentially unchanged with respect to termination time for sorbing chemicals. If indoor exposure presents an on-going risk once an outdoor hazard has passed, then people should exit the building into clean air whilst the building is ventilated [45].

Prompt ventilation after a plume has passed is most relevant in short-lived incidents. For longer release durations, higher air exchange rates (whereby indoor exposure concentrations and doses become similar to those outdoors) or higher attenuation rates (whereby rates of deposition, sorption etc significantly reduce exposures), the reduction in exposure due to ventilation after an outdoor hazard has passed can become negligible [50].

Key points

- the effectiveness of sheltering decreases over time due to the ingress of external hazards
- air exchange is the most important factor determining ingress and exposure indoors
- air exchange is determined by ventilation and infiltration, which itself depends on factors such as a building’s permeability, the wind speed, and the outdoor-indoor temperature differential
- attenuation effects and the choice of building and room in which to shelter can significantly affect the effectiveness of sheltering
- prompt initiation and termination of sheltering can maximise its effectiveness, particularly in short-lived incidents and for chemicals with a linear dose-response

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Factors affecting the effectiveness of evacuation

Lydia Izon-Cooper, Jim Stewart-Evans
Environmental Hazards and Emergencies Department, Centre for Radiation, Chemical and Environmental Hazards, Public Health England
Email: james.stewart-evans@phe.gov.uk

Introduction

Evacuation aims to prevent or minimise population exposure to airborne hazards and its consequences. This article discusses key factors that influence the feasibility and effectiveness of evacuation during chemical incidents and fires.

Evacuation: feasibility

Evacuation is almost always advised rather than imposed. Its effectiveness relies heavily on emergency planning and prior communication [1]. Historical incidents have shown that out-of-date emergency plans can significantly hinder the effectiveness of evacuation [2]; people may be less inclined to leave their homes if they are not aware of a specific evacuation plan in advance [3].

Key vulnerabilities and capacities should be considered when determining the practicality and feasibility of evacuation, including: availability and suitability of transport; adequacy of transport routes and networks; time constraints associated with evacuating different populations; mobility and special needs of the population; size of the population (as it will be easier to evacuate a small discrete population compared to a large dispersed population, for example); physical considerations such as weather conditions; and whether there are concurrent or related disasters or incidents (for example, flooding or earthquakes) that introduce additional hazards.

Evacuation: feasibility – transport

A questionnaire sent to residents near the Berkeley nuclear power station indicated that 95% of those questioned would use private motor vehicles in an evacuation [4]. However, evacuation may require the provision of vehicles by emergency responders or supporting organisations; it may not be possible to evacuate some groups without specialist transport (for example, ambulances). It has been suggested that, during an evacuation, public transport should be reserved for the least mobile members of the population [5] and those with special requirements. If people do not have access to mass transit, personal or community vehicles then their speed and range of evacuation can be greatly reduced. Longer evacuation times can increase exposure whilst evacuating.

The transport network (for example, the road or rail network) must also be able to support the volume of traffic. Road conditions and traffic flow affect evacuation: poor weather and congestion can increase evacuation time. Physical barriers (such as lakes, rivers or hilly terrain) can result in movement being channelled in particular directions, and it may be difficult for people to move away from a plume, or the path of a plume, thus increasing exposure to an airborne hazard. Open road networks, where people can take a number of possible routes when evacuating, allow for freer direction of movement and can decrease evacuation time as traffic is not bottle-necked. Sorensen et al. [6] emphasise the importance of evacuation routes, using wildfires in Oakland, USA as an example where a single egress point was made inaccessible by fire.

Evacuation: feasibility – the needs of the population

The nature and needs of the population at risk can affect the logistical aspects of evacuation, such as the time required to communicate an evacuation message; the resources required to safely evacuate people; and the time required to conduct evacuation.

A study of protective action responses to hazardous chemical releases undertaken by Preston et al. [7], whilst acknowledging the complexities of evacuation and the need for good planning, asserted that “evacuation remains the mainstay for pre-hospital care to limit victims.” However, the evacuation of susceptible populations (that is, those more likely to be affected if they are exposed to hazardous chemical releases), such as residents of care or nursing homes, is more difficult than the evacuation of healthy adults. Other populations, such as residents of prisons and other detention institutes, pose their own issues.

Again, careful emergency planning is fundamental to the successful evacuation of vulnerable or susceptible populations, and it is clear that they require a managed evacuation. The physical and mental needs of evacuees must be considered during and after an evacuation. Continuous special care, specialist equipment or supplies of medication may be required. The population may not be mobile, requiring specialist transport; diminished physical capability can make it difficult for elderly or disabled people to evacuate, compared to mobile individuals [8]. A suitable onward shelter must be available for evacuees to move to.

The nature of some evacuees may preclude the use of shared evacuation shelters: for example, it would be inappropriate to evacuate a prison or hospital population to the same shared shelter as a school [9].

Evacuation: feasibility – risks to responders

Emergency responders and other response personnel face risks associated with potential exposure to chemical hazards, together with health and safety risks posed by any concurrent occupational or environmental hazards such as unstable structures, fires, explosions, or severe weather. A managed evacuation (that is, an evacuation carried out by emergency responders) may not be possible if there are concerns, or proven risks, regarding the health and safety of emergency responders and other supporting personnel. The World Health Organization [10] states that "the safety of emergency responders is crucial". This is recognised in the UK [11], though the over-riding priority is the safety of the public [12].

Evacuation: timing

The timing of evacuation is a key determinant of exposure to an outdoor hazard. In many incident scenarios, there will be a limited time window during which evacuation can take place before people are exposed to an outdoor hazard (that is, before a plume arrives at their location). If evacuation cannot take place within a 'safe' window, then evacuees may be exposed whilst they are evacuating (and, potentially, beforehand). The time taken to implement evacuation depends on:

- the time taken to make the decision to evacuate
- the time taken to communicate this decision to all those involved and the effectiveness of the communication itself
- (for a managed evacuation) the time taken to organise resources, including personnel, vehicles, onward shelter and any appropriate special care facilities or supplies for onward shelter (for example, medicines and medical equipment)
- the time taken for people to react and physically move to another location, be this via group transport or by individuals using their own vehicles (there are a number of factors which may affect evacuation time, such as the viability of transport routes) [13]

The time of day that an incident occurs can greatly influence the feasibility and effectiveness of evacuation. During the night, complicating factors may introduce significant delays, such as:

- delayed decisions due to slower or limited access to decision-makers and supporting command and control infrastructure
- complications in communicating with the public
- delays in the ability to obtain suitable transport and organise onward shelter
- difficulties evacuating during darkness

Evacuation: exposure whilst evacuating

Just as it is important to consider indoor exposures when considering sheltering, it is important to consider outdoor and in-vehicle exposures when considering evacuation [14]. If outdoor concentrations are higher than those indoors, evacuation may expose people to higher maximum concentrations and cumulative doses than they would have experienced if remaining in shelter.

Ideally, people should be evacuated away from, rather than through, areas affected by a hazardous plume; the feasibility of this depends on the specific scenario and local geographical and transportation considerations.

Exposure whilst evacuating may lead to debilitating health effects that hamper people's ability to evacuate. People at greatest risk from acutely toxic inhalation exposures include those with pre-existing cardio-respiratory disease and susceptible populations, such as children, pregnant women and the elderly.

Short-term exposure to high outdoor concentrations (such as may be experienced when evacuating through smoke) is more likely to lead to acute health effects than a longer-term exposure to lower indoor concentrations. Kinra et al. [15] observed that increased health effects may be seen when evacuations involve moving a population through an area of higher exposure (to smoke) for a short duration. They stated, "Our results show that direct exposure to smoke is a more important determinant of ill health than the cumulative exposure to smoke and these are consistent with those reported from other studies."

The significance of exposure, and its implications for evacuation, will depend on the toxicological properties of a given substance and must be considered on a case-by-case basis. In reality, balancing the chemical risks associated with exposure (indoors or outdoors) and non-chemical risks associated with evacuation is difficult and can rarely be done in a timely or satisfactorily quantitative way.

Evacuation: non-chemical risks

Evacuation carries risks associated with the stress of evacuation and temporary accommodation and physical risks associated with evacuating. Aumonier and Morrey [4] found limited data relating to the UK and more relating to the US. Although some factors, such as traffic accident statistics, may differ between the US and UK, the authors drew a number of general conclusions which were:

- risk associated with transport during an evacuation is likely to be lower than the everyday risk of road travel

- risk associated with preparation for evacuation and using a reception centre is difficult to assess, but is likely to exceed the daily rate of day-to-day domestic accidents, though by less than an order of magnitude
- stress-related illness caused by evacuation is also difficult to assess, as this stress is inseparable from the stress caused by fear of the incident itself
- self-evacuation may result in a considerably greater number of people evacuating than planned by the competent authorities – this means that the collective risk of evacuation is likely to be greater than planned, but it is not possible to separate self-evacuation as a response to the accident from that as a response to evacuation advice
- evacuation risks and costs must be balanced against the risk averted. The authors estimated a “most pessimistic” daily rate of fatality associated with evacuation in the UK to be 3×10^{-6}

Some studies indicate that there may be more psychological impacts associated with evacuation than shelter, possibly depending on the nature and vulnerability of the population [16 17]. Compulsory evacuation, in particular, may impart feelings of a loss of control and an inability to protect family and friends. Adverse effects on mental health after an evacuation can affect communities and place long-term demands on healthcare services. The potential for psychological effects can be reduced by good emergency planning and communication.

The Fukushima Daiichi Nuclear Power Plant accident provides a recent illustration of risks associated with evacuation. Whilst there were no deaths related to radiation or the explosions of the reactors, a number of studies have found adverse impacts on mental and physical health. For example, Tsubokura et al. [18] evaluated changes in the clinical parameters of 155 evacuees before and after the incident, finding substantial deterioration in clinical parameters related to lifestyle diseases and the presence of general psychological distress, though it is difficult to identify the exact cause of such outcomes.

In common with their increased susceptibility to chemical exposures, evacuation may pose particular risks for groups such as hospital inpatients and the elderly. The mental and physical burden of the forced evacuation from hospitals and nursing care facilities in the vicinity of Fukushima was the cause of a number of early deaths [19 20]. The vast majority of people that died were elderly: only 4% were below 60 years, while 67% were over 80 [21]. Where evacuation of vulnerable people is deemed appropriate, it must be carefully done and with medical arrangements in place before transfer [19].

Key points

- effective evacuation relies heavily on effective emergency planning and prior communication
- the feasibility of evacuation must be considered: it requires sufficient means of transport and viable evacuation routes and may require specific arrangements for some population groups
- exposure to an outdoor hazard may pose risks to responders and evacuees prior to and during an evacuation
- the timing of evacuation is a key consideration: evacuation should ideally take place within a 'safe' timeframe and during daylight
- evacuation poses additional physical and mental risks that must be balanced against the exposure risk avoided by evacuating rather than sheltering

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Exposure assessment

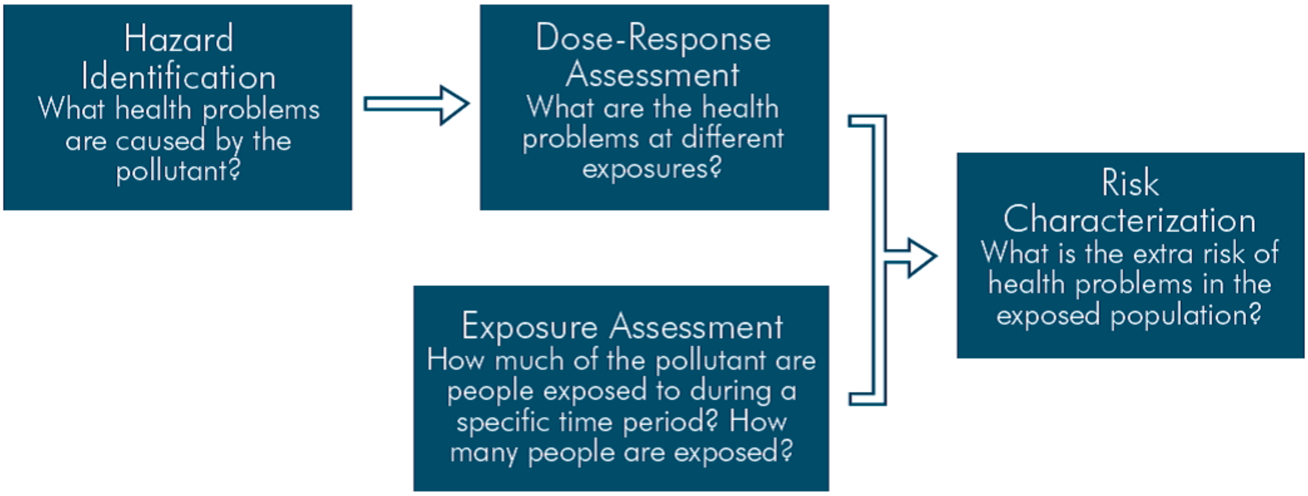
Laura Mitchem[1], Andrew Kibble[2], Jim Stewart-Evans[1]
[1] Environmental Hazards and Emergencies Department, Centre for Radiation, Chemical and Environmental Hazards, Public Health England
[2]Centre for Radiation, Chemical and Environmental Hazards (Wales), Public Health England
Email: laura.mitchem@phe.gov.uk

Introduction

This article focusses on exposure assessment in acute chemical incidents, which is informed by information from the scene and surrounding area of an incident, mapping of the affected area, environmental monitoring and modelling of dispersion and ingress.

Exposure assessment is part of a 4-step risk assessment process described by the World Health Organization (WHO) [1] and summarised in Figure 1.

Figure 1. The 4-step risk assessment process [1]



Geographic Information Systems (GIS)

Detailed maps and computer-based Geographical Information Systems (GIS) allow rapid identification and characterisation of populations in the vicinity of a hazardous airborne release. Spatially-referenced datasets such as the UK National Population Database can be used to estimate the number of people present (according to factors such as the time of the day and day of the week) and identify vulnerable populations (including schools, hospitals and care homes). Maps enable estimation of the distance of receptors from the source of a hazard, which influences how long a moving hazard may take to reach them or their potential level of exposure, which decreases with distance.

GIS mapping outputs can be enhanced through the incorporation and visualisation of basic meteorological information (such as wind speed and direction) or more detailed dispersion modelling outputs (in the UK, primarily provided by the Met Office). This can identify and characterise populations within predicted 'at risk' areas where sheltering and evacuation decisions will be most critical, and identify prospective locations for environmental monitoring.

Quantitative predictions of exposure over space and time, plotted on maps in comparison with health-based guidance levels, are most useful to risk assessors. There are a number of examples of emergency response organisations using an integrated approach that combines GIS maps and dispersion model outputs [2]; the tools adopted vary in their complexity.

Environmental assessment

Estimates of exposure are informed by the incident scenario; knowledge of the source-term, release duration and other characteristics; meteorology; locations of at-risk populations; feedback from the scene, such as visual observations of plume behaviour; and reports of health effects.

In order to characterise risk by comparing actual and predicted concentrations with health-based guidance levels, quantitative estimates of exposure are required. Monitoring and modelling can provide such estimates.

The 2 approaches are complementary: for example, dispersion models can predict where highest concentrations might occur at receptor locations and monitoring should be undertaken, whilst monitoring can be used to inform and improve modelling predictions. Monitoring and modelling can be used to target interventions and public communication and inform estimates of when exposure has or will begin and end; this is critical for prompt sheltering and prompt termination of sheltering once a plume has passed [2], as well as the estimation of safe periods in which evacuation can be carried out.

Environmental monitoring and sampling

Environmental monitoring may be carried out in the event of a chemical incident or fire to inform sheltering and evacuation decisions, but it is not always available, appropriate or timely. Indoor air quality monitoring during acute incidents is extremely rare. If monitoring is undertaken, risk assessors require interpreted air quality information promptly within the time-scale required to inform decisions; this can be a challenge because deployment, data sharing and interpretation takes time.

Monitoring can establish the nature of a hazard, indicate whether it is present at a level that necessitates protective action, and identify when a hazard has passed (and sheltering or evacuation can end). Because monitoring provides a near real-time or retrospective indication of exposure, it can best inform estimates of current or past exposure (and current and past risk). In some cases, it may be possible to make assumptions about future exposure based on monitored levels, for example, during prolonged releases where environmental concentrations are expected to remain similar in affected areas over time.

Shelter and evacuation decisions are rarely based on the results of monitoring alone, as there are a number of associated limitations. For example, a spot sample will provide an indication of chemical concentration at a single location at a given point in time; however, concentrations will vary spatially and temporally. Locating continuous monitoring equipment where public exposure is predicted to be highest can provide an indication of worst-case public exposures over time. For fire scenarios, consideration of fire lifecycles and smoke plume behaviour can help to determine the optimum stage of a fire in which to monitor pollutants (that is, when smoke plumes are most likely to reach the ground and exposure is likely to be highest). Other considerations include the capability of monitoring equipment to detect different chemicals, the level of detection and the accuracy of results.

Modelling

Predicting the effectiveness of sheltering-in-place (SIP) and evacuation requires models that address 3 aspects which are:

- an atmospheric dispersion model to predict outdoor concentrations and exposure levels
- an indoor air quality model to predict indoor concentrations and exposure levels resulting from outdoor concentrations
- a dose-response model to predict health effects resulting from exposure to the time-varying concentration [3,4]

Predicting outdoor exposures

The atmospheric dispersion of chemical releases, and subsequent outdoor concentrations and exposure levels, can be predicted using dispersion models.
In order to inform risk assessment during incident response, models must provide outputs rapidly.

A key advantage of dispersion modelling over monitoring is the ability to predict exposure before it happens. This is critical for prospective shelter and evacuation decisions; without an ability to predict future exposure, interventions are more likely to be reactive. In cases where exposure exceeds safe levels, a reactive approach may have significant consequences (that is, protective action may be too late to prevent adverse effects).

The immediate requirement of risk assessors is for a model to predict the area at risk downwind of a hazardous plume. This allows the buildings and population at risk to be identified so that public communication and on-the-ground actions can be focussed on the affected area. Quantitative estimates of exposure require prediction of outdoor chemical concentrations, spatially and temporally. These require incident-specific input information or assumptions before they can be prepared. Key input parameters that are required include:

- source term characteristics, for example
  - total mass or volume of chemical involved
  - type of storage (for example, refrigerated, pressurised, etc)
  - rate of release over time
  - circumstances of release: fire, spill, leak or explosion
  - mitigating actions taken on-site to reduce or control the release
- physicochemical characteristics of substances involved, for example
  - physical properties: form, vapour pressure, reactivity, solubility, density
  - flammability, decomposition and behaviour as a result of heat or ignition
- meteorology, for example
  - temperature, humidity, precipitation, wind speed and direction, atmospheric stability and mixing height
- topography, for example
  - flat and smooth surfaces, hills, urban environments and complex terrain

Early in an incident, information is limited, and detailed incident-specific information is unlikely to be available. In order to run a model, estimation of some inputs may be required, Generic source-term data can inform initial predictions; in some cases, emergency plans may have pre-examined possible incident scenarios.

Informing model predictions requires close communication between modellers and emergency responders at the scene (primarily the Fire and Rescue Service). The more detailed the model outputs, the more input information is needed. As incidents progress, more information becomes available; consequently, dispersion model predictions can and should be updated throughout the course of an incident.

Comprehensive inventories exist that list and describe existing models [5-7]. Model results are dependent on the input data, assumptions used and nature of the model itself.

Models differ in their complexity and input and output parameters, and interpretation of their outputs must account for each model's specific limitations [8 9], otherwise there is potential for the model results to be misinterpreted. Specific types of incident can introduce further complexities:

Fires: fires often occupy a significant surface area and are usually at ground level; thus, plume dispersion is subject to the effects of surface obstacles and pronounced wind shear. Hall and Spanton [10] explored the subject of fire plume dispersion in detail, making recommendations for best modelling practice while noting the use of different methods and models in practice.

Urban and complex terrain: predicting dispersion over and through complex terrain and urban environments is resource-intensive. Models must have sufficient resolution to account for local-scale dispersion and may require more detailed information about local wind speed and direction, which can be highly variable, and may be unavailable. Hall et al. [11] discussed dispersion over different scales in urban areas in more detail. The applicability of different approaches and their contribution to risk assessment has been considered by a number of reviews [8 12 13].

Dense gases: dense gases may show reduced dispersion: they can travel closer to the ground and may be channelled by dips in the ground and land contours. Releases of gases that are ordinarily lighter than air from refrigerated or pressurised containers may be heavier than air and thus behave similarly [14].

The suitability of a given model is dependent on the user's requirements. To inform risk assessment and decision-making during an emergency response, models must be tailored to the needs of risk assessors [15]. Risk assessors' main requirements are the ability to rapidly obtain representative model predictions, account for different exposure periods and compare predicted exposures to health standards.

Rapid models may be indicative at the expense of resolution or accuracy and vice versa. Slow or unwieldy models may offer improved predictions and are useful for emergency preparedness work but are less likely to be used during incident response.

A consistent approach and understanding of a model's capabilities and limitations is required when using modelling predictions to support shelter and evacuation decisions, especially during a multi-agency response. The use of different models by different agencies, or differing interpretations of the same model's outputs, may result in contradictory advice. Decisions about sheltering and evacuation are informed by all aspects of exposure assessment and cannot be based on modelling alone.

Predicting indoor exposures

A number of factors determine indoor concentrations following a hazardous airborne release; they are discussed earlier in this special edition. Given predictions of outdoor concentrations, the additional information required to model indoor concentration is, in essence, the air exchange rate and predicted loss due to attenuation [16]. A number of relevant software models exist, of varying levels of complexity [17-19].

Indoor concentrations are often predicted by simple mass balance, without consideration of attenuation [20]. Calculations are based on a well-mixed single box used to represent a typical residential property. The assumption of a single well-mixed zone is useful in order to estimate the broad scale of effects [21] and can be used when there is limited time or information to evaluate individual buildings at smaller scales. Outputs (that is, calculated indoor exposures) can be produced within a short timescale, but may over-predict chemical exposure if they do not account for attenuation. The choice of whole-building air exchange rate is a critical factor, as higher air exchange rates are associated with higher indoor exposures.

Models that go beyond a simple mass balance transfer require more extensive input parameters. Further assumptions may be required to account for temperature differentials and wind pressures. Building characteristics (such as permeability, volume, indoor area, number of rooms, etc) are required in order to account for different building types or individual buildings. Ventilation and air exchange models are described in more detail by Hall and Spanton [22] and Breen et al. [23].

The risk of pollutant ingress across an individual building's surfaces can be estimated based on pressure and concentration patterns [24 25]. More detailed numerical models, such as multi-zone or Computational Fluid Dynamics (CFD) methods, are required to estimate airflow and indoor concentration (and, hence, exposure) in and around complex structures [20 21 26]. Breen et al. [23] note that multi-zone models are typically not feasible for air pollution exposure assessments due to intensive data needs and the expertise required to use them. This limits their applicability during a chemical incident. Parker et al. [21] characterised the variability in exposures within multi-zone buildings to supplement assessments based on simple single-zone modelling results.

The use of modelling to predict indoor exposures can support shelter and evacuation decisions. Detailed modelling can be undertaken most readily as part of emergency preparedness, when there is more time to collect information and perform calculations. Hall and Spanton [22] concluded that "…in the practical application of ingress and internal exposure calculations there are significant uncertainties that arise naturally in every part of this complex calculation chain. In consequence the estimation of internal exposure to external pollutants is in most cases never likely to be very precise. This also suggests a law of diminishing returns in attempting more sophisticated calculations."

Key points

- exposure assessment informs risk characterisation and shelter and evacuation decision-making and implementation
- estimates of exposure are based on mapping, information from the scene, environmental monitoring, dispersion modelling, and health surveillance
- spatially-referenced monitoring and modelling outputs can provide quantitative estimates of exposure at different locations that can be compared to health standards in order to characterise risk
- predicting the effectiveness of SIP and evacuation using models requires 3 components: an atmospheric dispersion model, an ingress model, and a dose-response model
- decisions about sheltering and evacuation are informed by all aspects of exposure assessment and cannot be based on monitoring or modelling alone due to the associated uncertainties and limitations

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Risk characterisation

Andrew Kibble[1], Laura Mitchem[2], Jim Stewart-Evans[2]
[1] Centre for Radiation, Chemical and Environmental Hazards (Wales), Public Health England
[2] Environmental Hazards and Emergencies Department, Centre for Radiation, Chemical and Environmental Hazards, Public Health England
Email: andrew.kibble@phe.gov.uk

Introduction

This article focuses primarily on risks associated with acute (short-term) exposures to chemicals and products of combustion (smoke). It outlines approaches to assess the risk to health and how the effectiveness of sheltering-in-place can be evaluated.

Approaches to risk assessment during acute chemical incidents and fires in England and Wales

In the UK, assessment of the potential public health impacts of exposure to ambient air pollutants (that is, those commonly present in outdoor air) is based on comparison with a range of air quality guidelines or standards. These are principally the UK Daily Air Quality Index (UK DAQI) and World Health Organization (WHO) air quality guidelines and interim targets (WHO AQG and IT) [1]. For chemicals associated with industrial emissions, short-term (one hour) and long-term (annual average) UK Environmental Assessment Levels (EALs) are used in an environmental regulatory context [2].

If chemical concentrations exceed typical ambient concentrations during a chemical incident or fire, it may be necessary to use guidelines specifically intended for the risk assessment of short-term exposures to high concentrations. These include Acute Exposure Guideline Levels (AEGLs) developed for the US Environmental Protection Agency [3]. Other standards developed in the US include the National Institute for Occupational Safety and Health (NIOSH) Immediately Dangerous to Life and Health (IDLH) concentrations [4], the American Industrial Hygiene Association (AIHA) Emergency Response Planning Guidelines (ERPGs) [5], and the Subcommittee on Consequence Assessment and Protective Actions (SCAPA) Temporary Emergency Exposure Limits (TEELs) [6] and Chemical Mixture Methodology (CMM) [7].

In the absence of a formal risk assessment framework for public health interventions during large-scale fires and other chemical incidents with an impact on air quality in England and Wales, 4 potential options were developed for inclusion within a formal Health Protection Agency (a predecessor organisation to PHE) risk assessment framework. The options were not mutually exclusive and formed the basis for a risk assessment framework outlined below. Stewart-Evans, Kibble and Mitchem [8] set out how this framework can be used in practice in an evidence-based approach to risk assessment and risk management during prolonged fires.

National and international ambient air quality standards and guidelines

Ambient air quality guidelines are useful initial comparators for typical ambient air pollutants. However, their use as initial screening values during incidents is limited as they encompass a relatively small number of pollutants and are not intended for use in scenarios involving abnormally high concentrations and short exposure periods, having often been developed for 24-hour averages or annual averages associated with the risks of exposure to ambient levels over a lifetime. Consequently, exposures during incidents can be much higher than these standards.

Fires are often associated with extremely high but short-lived peaks of particulate matter (PM), often reaching levels 2-3 orders of magnitude above ambient air quality standards (for example, mg/m^3) in close proximity to the fire, usually for periods of less than an hour at a time. This presents an obvious problem, since the best evidence on the short-term effects of exposure comes from time-series studies based on 24-hour averages.

The WHO, in addition to setting a 24-hour guideline value for PM_{10} (PM, ≤10 microns in diameter) of 50 $\mu g/m^3$, has also developed a series of 24-hour averaged interim targets for developing countries that experience higher levels of ambient particulate matter [1]. During tyre fires in the UK, the highest WHO interim target value of 150 $\mu g/m^3$ as a 24-hour average has been used as a starting point for the consideration of protective actions, and the effectiveness of shelter has been considered at higher levels (from around 300 $\mu g/m^3$) categorised as 'hazardous' in wildfire guidelines and ambient air quality indices used during short-term episodes of poor air quality [9-12]. The exact concentration bandings used vary, and thresholds are generally lower when particulate matter is measured as $PM_{2.5}$ (fine PM, ≤2.5 microns in diameter).

Chemical guidelines developed specifically for acute exposure during emergencies

The US Department of Energy (DOE) maintains a data set of Protective Action Criteria (PAC) for use during emergency preparedness and response for uncontrolled releases of hazardous chemicals. PAC may be used during incident response to identify adverse health outcomes associated with different levels of exposure, estimate the consequences of predicted or actual exposure and to inform decisions about what protective actions should be taken. As part of emergency preparedness work, they can be used to plan an effective emergency response.

The PAC dataset includes 3 different types of public exposure guidelines: AEGLs, ERPGs and TEELs [13]. Each of these guidelines has 3 tiers of exposure values for each chemical; each successive level of exposure is associated with increasingly severe outcomes. The levels are:

- level 1 – mild, transient health effects
- level 2 – irreversible or other serious health effects that could impair a person's ability to take protective action
- level 3 – life-threatening health effects

Within this dataset, there is a general hierarchy with AEGLS preferred to ERPG and then TEELS.

AEGLs have been developed by the National Advisory Committee on Acute Exposure Guideline Levels for Hazardous Substances (NAC/AEGL), which was established following a request by the US Environmental Protection Agency (EPA) and US Department of Defence to develop scientifically credible short-term exposure limits (typically up to 8 hours) for approximately 400 to 500 acutely toxic substances [14].

PHE uses AEGLs to assess risks to public health during acute chemical incidents when ambient air quality guidelines are not applicable (because concentrations are far higher or because no ambient air quality guideline exists for the chemical in question). AEGLs are intended to protect most individuals in the general population, including those that might be particularly susceptible to the deleterious effects of exposure. However, it is recognised that certain, more susceptible, individuals could experience effects at concentrations below AEGL values.

TEELs differ from AEGLs and ERPGs by the methods and the sources of data used to develop them. AEGLs and ERPGs are derived from a review of primary sources (human health effect studies), and the values developed for each chemical are individually peer-reviewed. To produce interim values in a more timely fashion whilst maintaining high quality, TEELs are derived from secondary data sources (occupational limits or animal studies) using a peer-reviewed algorithm.

Emergency responders and planners may use different guidelines as though they are comparable, though there are differences in their derivation. Oberg et al. [15] reviewed key discrepancies between 2 of the most commonly used acute guideline levels: AEGLs and ERPGs. While they found similar differences between levels (that is, the gaps between tiers 1 to 2 to 3), indicating that both methodologies were highly precautious, they recorded significant differences between comparable values for individual chemicals. These differences were often large (as high as a factor of 3) and were seen for chemicals in common use, as well as less commonly encountered substances.

Differences appeared to be due to the choice of critical effect (ERPG levels include the detection of odour as a level 1 effect, whereas others do not) or the critical study used. The lack of consistent, standard criteria potentially hampers risk assessment, but no one methodology has produced guideline levels for all chemicals. Evaluation of different standards' applicability is required prior to their use.

For fires, particulate screening values developed for wildfires

Some countries, such as the US and Australia, have published air quality guidelines for wildfires and bush fires, when particulate levels are elevated and persistent. In common with air pollution indexes such as the UK DAQI, advice regarding protective actions, such as sheltering indoors and limiting physical activity, is associated with a series of exposure categories based on time-weighted concentrations of particulate matter [16-18].

The threshold concentrations that define different categories differ between countries and even within countries (for example, between various states in the US [18-20]). Evaluation of different standards' applicability is required prior to their use.

For prolonged fires, time-series coefficients to estimate impacts associated with exposure to particulates

The UK Committee on the Medical Effects of Air Pollutants (COMEAP) has considered time-series studies that link daily variations in PM_{10} and, increasingly, $PM_{2.5}$ with increases in mortality and hospital admissions for respiratory and cardiovascular causes. Its view is that the associations reported are likely to be causal. The Committee has previously recommended concentration-response relationships that may be used to quantify these short-term effects (for example, a coefficient of a 0.75% increase in mortality per 10 µg/m^3 increase in PM_{10}) [21 22]. Such coefficients have been used to predict global mortality attributed to acute and chronic exposures to smoke from wildfires [23].

During a prolonged fire of any type, coefficients derived from studies of large populations can be applied at a smaller spatial scale to calculate increases in mortality or hospitalisation risk in the wider population in an area potentially affected by smoke or particulates. Within small populations the impact will, inevitably, be small: not many deaths are expected ordinarily over short periods of time and exposure to particles will increase the existing rate by only a small amount.

The use of this approach to inform risk assessment during fires has been explored by Kibble et al. [24 25]. A theoretical example was given of a population of 1,000 exposed to 500 µg/m^3 PM_{10} (24-hour average) for 4 months during a prolonged tyre fire. This would be a very high level of exposure when compared to the ambient annual average concentration of PM_{10} in the UK (~25 µg/m^3). Assuming a background rate of death of

1% per year, 10 deaths per year could ordinarily be expected in this population. Using the time-series coefficient for all-cause mortality (0.75% increase per 10 µg/m^3 PM_{10}) the number of deaths associated with exposure to the increase in PM_{10} due to the smoke was calculated as:

Increase in PM_{10} x mortality coefficient x background death rate x exposure period = number of deaths

((500-25)/10) * ((0.75*(10/100)) * (4/12)) = 1.19 (rounded down to 1)

Thus, ignoring estimates of uncertainty, 1 extra death would be expected due to exposure to PM_{10} in the 4-month period in a population of 1,000. However, it must be noted that there are very large uncertainties in applying such calculations to small populations.

Defining an unacceptable level of chemical exposure and the need for protective action

Comparing exposure estimates to health standards can inform evaluation of the significance of exposure and assist prediction of impacts at population level. When considering the need for protective actions such as sheltering or evacuation, short-term exposures capable of causing irreversible injury or death (such as those indicated by AEGL-2 or AEGL-3 values) are clearly significant and require prompt action to protect health. It is less straightforward to define acceptability when transient, less serious health effects are involved or where small effects are calculated at the population level over longer exposure periods.

For incidents involving longer periods of exposure (days rather than hours) to chemicals, additional health standards, such as the Agency for Toxic Substances and Disease Registry (ATSDR) inhalation minimal risk levels (MRLs), are potentially applicable. They cover a range of different time periods: acute (1-14 days), intermediate (14-364 days) and chronic (≥365 days) [26].

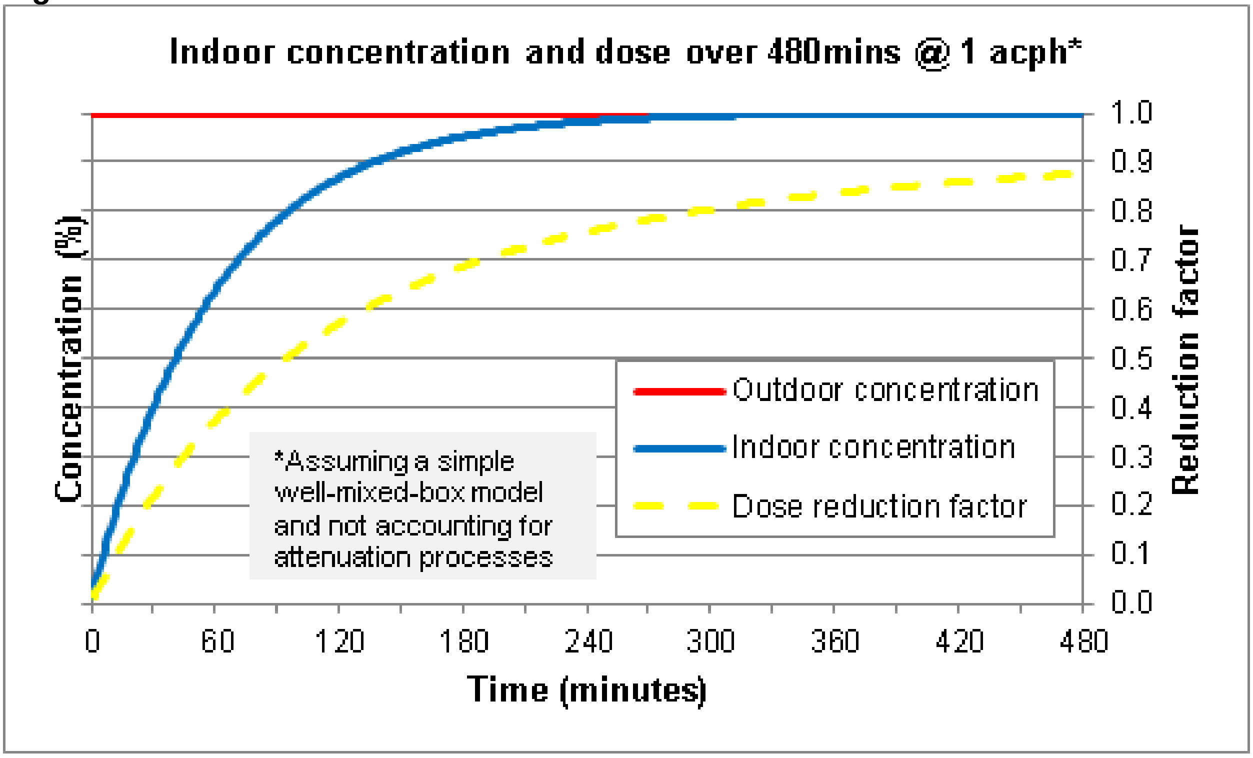
Evaluating shelter effectiveness: theoretical approaches in the scientific literature

Chan et al. [27] comment that one difficulty in quantifying shelter-in-place effectiveness is the lack of simple yet informative metrics. Shelter protection factors are measures of the relative exposure outdoors versus indoors and can incorporate evaluation of health effects. The use of shelter protection factors can potentially inform decision-making during emergency response [28] or be used to evaluate different protective strategies as part of emergency preparedness [29] [30].

Protection factors may be calculated:

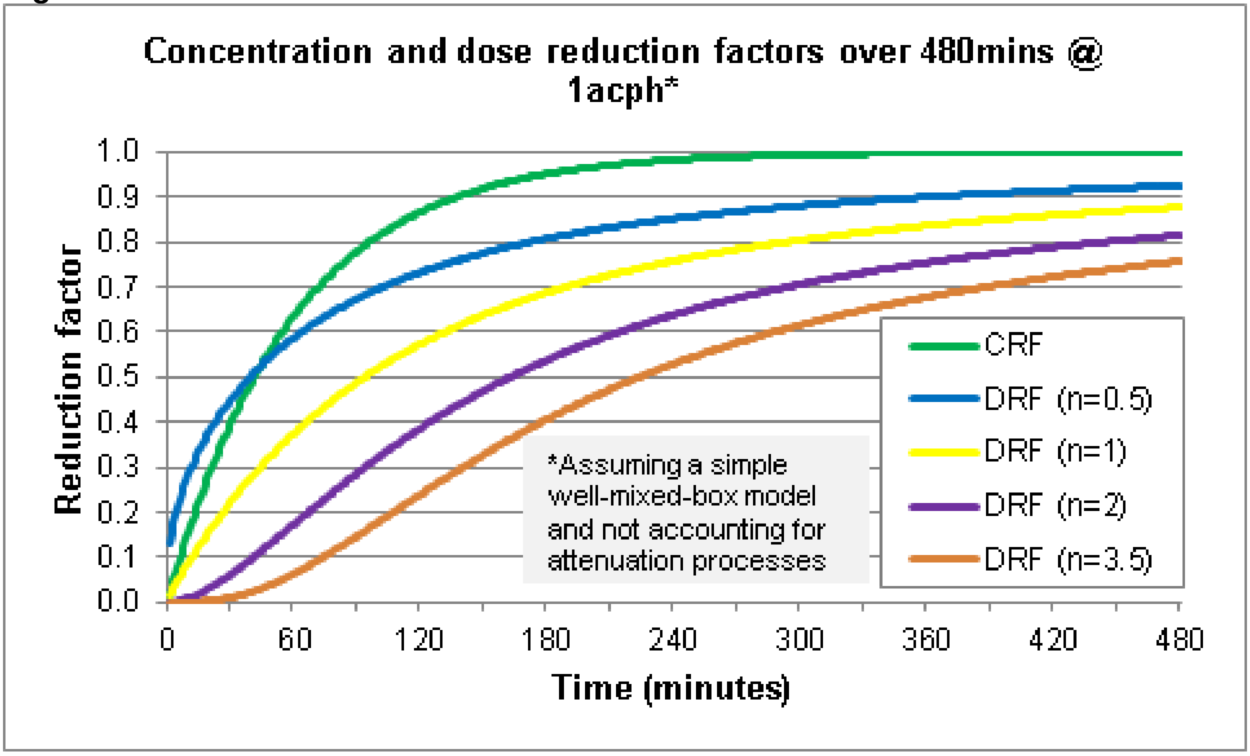
- using exposure concentration (for example, comparing the difference between the outdoor and indoor concentration of a substance at a given point in time) – for most hazardous materials the likelihood of a negative impact on health will depend on a cumulative measure of the concentration used as opposed to a peak value [31]
- using dose, a time-integrated measure of exposure (for example, comparing the difference between the cumulative outdoor exposure and cumulative indoor exposure over a given period of time) (see Figure 2, in which acph=air changes per hour) – some studies term “protection factor” as the ratio of the cumulative exposure outdoors over the cumulative exposure indoors; others use the reciprocal “dose reduction factor” (the ratio of cumulative exposure indoors over outdoors) [32]

Figure 2. Indoor concentration and dose



- using toxic load, a time-integrated measure of exposure that accounts for chemical dose-response (Figure 3, in which acph=air changes per hour, CRF=Concentration Reduction Facto or, n=toxic load exponent, a chemical-specific parameter that characterises the dose-response relationship) – toxicological assessments are not always incorporated into scientific papers that examine shelter protection; however, protection factors that account for both exposure and health effect thresholds can provide measures of shelter effectiveness that also characterise health impacts

Figure 3. Concentration and dose reduction factors



Toxic loads (TLs) and toxic load limits (TLLs) associated with adverse health endpoints and mortality have been used in the literature to calculate related metrics such as the toxic load reduction factor (TLRF); casualty reduction factor (CRF) (which requires the use of dispersion models to model community exposure); the safety-factor (SF), which is the maximum factor by which the exposure concentration can be multiplied without the exposed individual being subjected to potential adverse health effects; and the safety-factor multiplier (SFM), which is the ratio between outdoor and indoor safety factors [33 34].

Whilst these metrics are potentially useful, their use during an emergency response requires timely monitoring or modelling outputs and rapid calculation of the metrics themselves. This may not be practical during emergency response, and their use is more feasible as part of emergency preparedness, when there is more time to carry out detailed assessments. Additional toxicological considerations and caveats apply to the use of TLLs in practice: these are discussed in an earlier article in this edition.

Key points

- to evaluate risks associated with exposure whilst evacuating or sheltering, exposure models must be linked to health-effects models that account for chemical dose-response
- risk can be characterised by comparing time-averaged outdoor or indoor air concentrations to national and international ambient air quality standards and guidelines, chemical guidelines developed specifically for acute exposure during

emergencies, or particulate screening values developed for wildfires, and time-series coefficients can be used to estimate population-level impacts associated with longer-term exposure to particulates

- shelter protection factors are measures of the relative exposure outdoors versus indoors and can incorporate evaluation of health effects at an individual or population level
- short-term exposures capable of causing irreversible injury or death require prompt action to protect health
- the case for protective action is less straightforward when transient, less serious health effects are involved or when small effects are calculated at the population level over longer exposure periods

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Protective action decision-making and implementation

Jim Stewart-Evans
Environmental Hazards and Emergencies Department, Centre for Radiation, Chemical and Environmental Hazards, Public Health England
Email: james.stewart-evans@phe.gov.uk

Introduction

In order to make informed decisions regarding protective actions, a number of prior steps are needed in any risk assessment [1]. These include:

- determining the nature of the chemical released (that is, its toxicological and physiological characteristics)
- determining the type, rate and duration of the release
- determining prevailing and future meteorological conditions
- determining local topography
- determining the characteristics and susceptibility of the local population
- determining the characteristics of buildings that could offer shelter and protection from outdoor concentrations
- estimating the time available before the plume affects an area and the time available to issue and fully implement shelter/evacuation advice

This article outlines intervention principles, scenarios in which one of sheltering or evacuation is favoured over the other, existing sources of guidance, and considerations that are relevant when implementing a decision once it has been made.

Intervention principles

Studies have considered the various objectives of protective actions [2]. They can include:

- reducing exposure below specified levels (for example, below health guidelines or standards)
- avoiding or minimising injuries or fatalities
- avoiding or minimising *any* adverse effect (including mild and reversible effects)
- minimising the total number of people exposed
- minimising the exposure of those people subject to the highest risks

Objectives can involve difficult trade-offs: for example, Sorensen et al. state that "…policy makers must decide whether it is better to (1) minimize fatalities by having a large percent of the population exposed to a sub-lethal, 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."

Three key principles of radiological protection are recognised when planning for and responding to radiological incidents:

- intervention must be justified (that is, protective action should do more good than harm) [3]
- all possible efforts should be made to prevent serious deterministic effects (that is, to prevent health effects)
- the method, scale and duration of the protective action should be optimised in order to produce the maximum net benefit to the public. Optimisation may include employing all appropriate methods to warn and inform the public, identifying and protecting vulnerable groups such as children or the elderly, or seeking to minimise the risk of delayed, as well as immediate, health effects [4]

These principles are equally valid when considering protective actions in chemical incidents.

Risk-based interventions

Taking no action

The release of a harmful substance does not mean that harm will occur. The key question is "is there a risk?" [5]. If there is no risk (of adverse health effects), and the public are not threatened, then no protective action is necessary. In practice this may be difficult to judge. When faced with a potentially significant risk, precautionary protective action is advisable.

Sheltering

If an incident poses a risk to public health, sheltering is an effective protective action that can be implemented rapidly to reduce population exposure. The time taken by the public to respond is often cited in favour of shelter over evacuation [6,7]. For the majority of chemical incidents and fires, an initial decision to issue sheltering advice will be justifiable. Releases of hazardous substances that lead to indoor exposure concentrations and durations sufficient to lead to public injury or fatalities are, thankfully, rare. However, the effectiveness of sheltering must be considered on a case-by-case basis and is subject to review throughout the course of an incident.

Evacuating

In some circumstances evacuation may be advisable [2 8 9], such as:

- when there is an immediate risk to people and properties (for example, from fire or explosion) [10]
- when people can be evacuated prior to an exposure taking place (for example, before a harmful substance has been released, before a small rate of release becomes much larger or before a release can move to their location or a shift in wind affects a given area) [2 10-12]
- when the risk associated with sheltering will exceed the risk associated with evacuation (for example, when an incident is likely to be prolonged such that the protection offered by sheltering becomes insufficient [10 13])
- after an incident, if there is an unacceptable residual risk (for example, continued exposure due to extensive and persistent environmental contamination)

Chemical incident and fire scenarios

Incidents involving chemical releases tend to be one of 3 types: instantaneous (such as the failure of a storage tank or tanker, in which the entire inventory is lost in a very short time), continuous (such as a leak from a pipeline or slow release from a damaged tank) or intermittent (such as during a fire or discontinuous release, when the rate of release varies). Variable winds can also lead to changeable and intermittent exposures downwind.

In instantaneous chemical release scenarios there is a predisposition towards shelter. The release and, consequently, exposure durations are short-lived, and there is little time available to implement a protective strategy. Montoya et al. [14] state that accidental releases tend to have a single source and last for a short period of time (typically less than 60 minutes). Because it can be quickly implemented and is most effective for short-lived incidents, sheltering is usually preferable.

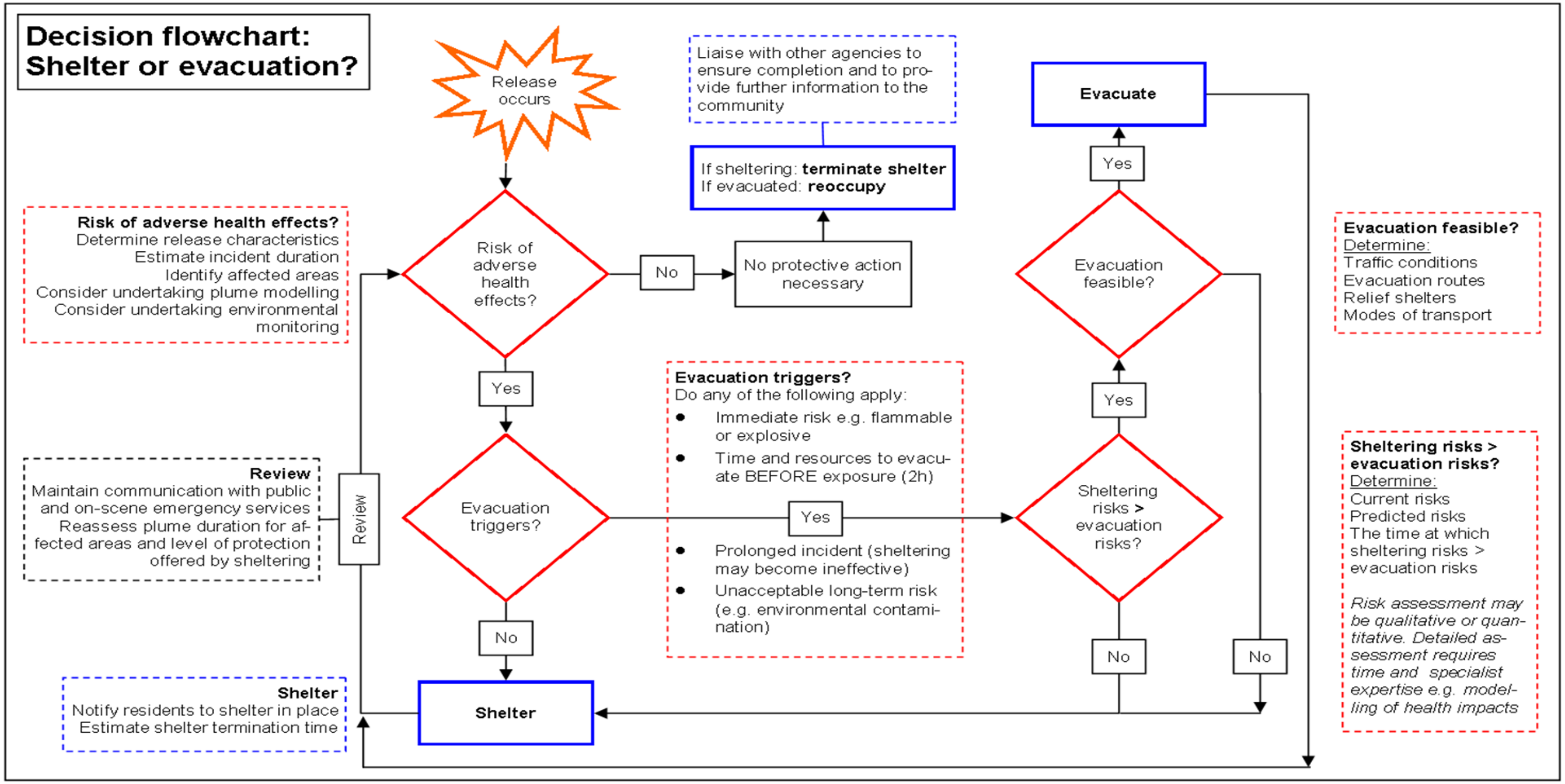
Intermittent or continuous releases can occur over longer durations, over which sheltering may become less effective. It is not possible to specify in advance an exact period beyond which sheltering will become ineffective: as discussed in previous articles in this edition, many factors affect this, and the prediction of indoor and outdoor exposures and health consequences in sheltering and evacuating populations, though possible, is complex. Within shelter and evacuation decision trees, written to assist the avoidance of fatalities and minimise exposure, Sorensen et al. [2] discuss how decision checklists could specify a plume duration (that is, hazardous levels outdoors) of less than 30 minutes being more ‘towards’ sheltering and over 120 minutes more ‘towards’ evacuation, with a “grey area” between 30 and 120 minutes where the decision outcome is unclear. Suggested durations vary: Australian guidance [9] considers sheltering appropriate for incidents of 1 hour or less and prompts consideration of evacuation for releases lasting over 4 hours.

In intermittent (for example, fire) release and exposure scenarios it may be possible for people to shelter downwind for longer periods of time, because buildings are not exposed to a consistently high outdoor concentration and, consequently, indoor exposures are lower. So too in cases where highly sorbing chemicals are involved or other attenuation factors are anticipated to lower indoor exposures. It remains important to consider all of the factors that affect sheltering and evacuation effectiveness and to make a decision based on the specific circumstances.

Guidance for decision-makers

A number of decision aids are available to help decision-makers assess an incident and make evidenced decisions regarding the most suitable protective action [1 2 5 9 11 15 16]. These range from simple qualitative checklists and decision trees, such as the flowchart in Figure 4, to complex computer decision tools. While a number of different approaches have been advocated, no single approach to decision-making for chemical incidents has achieved widespread acceptance based on validity, utility and effectiveness [2 5 17]. This is illustrated by the differing approaches suggested by existing guidance, in which there are different preferences for initial sheltering or evacuation, although a common consensus is that a comparative evaluation of risks is required to be able to come to a decision.

Figure 4. Decision flowchart: Shelter or evacuation?



Implementing a decision

Existing UK arrangements for multi-agency emergency response provide for implementation and public communication after a sheltering or evacuation decision is made [12] – communication is discussed in more detail in a later article.

Implementing sheltering

Key points from the literature for responders who are implementing shelter decisions are summarised below. In cases where there is combined shelter and evacuation (that is, one area is evacuated while another is told to shelter), issues associated with public perception and communication must also be addressed [1].

When implementing shelter:

- ensure that shelter advice is issued as soon as possible
- define the area in which protective action is required
- include instructions to undertake whatever complementary actions are appropriate
- keep reinforcing shelter advice once it is issued
- ensure that people are told when to stop sheltering

Ending sheltering

To encourage prompt termination of sheltering, emergency responders must obtain and communicate reliable information on when an outdoor chemical hazard has dissipated, and it is time to end the sheltering period, which may be informed by environmental monitoring and dispersion modelling predictions. Key points from the literature are:

- the optimum time to end sheltering will vary between properties – no one time is best for all [18 19]
- in some scenarios, such as when a plume is clearly visible, it may be possible to advise people to leave their shelter once a plume has clearly passed by and the outdoor concentration has reduced or approached zero [18]
- consider population distribution: it is unlikely to be homogenous – give appropriate consideration to areas of high population density and high-occupancy buildings [19]
- it may be possible to issue targeted instructions to discrete areas of population – if it is not feasible to stagger “stop sheltering” messages, blanket advice to all properties is required
- when prolonged sheltering is necessary against a large release, those who are located closest to the release source and who are highly exposed should exit shelters as soon as it is safe to do so – this can occur much sooner than the time at which no-one is expected to be exposed to harmful concentrations outdoors, which requires consideration of populations farther downwind

- in the absence of other criteria, consider ending sheltering when no casualties would be expected anywhere outdoors, but note that this may result in a considerable increase in dosage for people closer to the source
- detailed consideration requires prediction of dosage (compared against health standards) against downwind distance from a source, for different termination times [19]

Implementing evacuation

Key points from the literature for responders who are implementing evacuation decisions are summarised below. In cases where there is combined shelter and evacuation (that is, one area is evacuated while another is told to shelter), issues associated with public perception and communication must also be addressed [1].

When implementing evacuation:

- define the type and scale of evacuation (this should also be considered in the impact assessments that support evacuation decisions), for example
  - small/medium/large/mass scale evacuation, as classified by Cabinet Office guidance [12] according to the number of evacuees and resources required
  - evacuation via dispersal/self-evacuation/facilitated evacuation or combinations thereof
- define the area in which protective action is required
  - evacuation of an entire area, or evacuation of a smaller area with sheltering advised in the wider area [20]
  - evacuation should begin with those outdoors and near to the scene, then expand the area to be evacuated downwind and crosswind [16]
- ensure that evacuation takes place at (or around) the optimum time period (that is, ideally prior to any exposure taking place or, if responsive evacuation is necessary, whenever overall impacts are predicted to be lowest – it may be preferable to shelter for a defined period first before evacuating)
- include instructions to undertake whatever complementary actions are appropriate
- use any local, regional or national evacuation plans that exist

There are a number of methodologies available to calculate evacuation distances; they generally rely on a prior or real-time calculation of outdoor concentrations to determine a distance based on where the airborne chemical concentration will fall below a certain level [9,16].

Reoccupying after evacuation

Evacuees should remain in rest centres and evacuation destinations whilst acute (or chronic) threats to health exist. Adequate information is required to support a decision that an area is safe [10]. In support of a reoccupation decision, the literature suggests that:

- properties must be in a fit state for reoccupation and essential services must be provided
- there should be minimal residual environmental contamination that could pose a significant risk to health (for example, contamination of air, buildings, land, food or water, including water pipes)
- monitoring may be undertaken to confirm the absence of a chemical hazard

Key points

- protective actions must aim to prevent serious deterministic effects (that is, prevent health effects), should be justified (that is, do more good than harm), and should be optimised (that is, maximise benefits)
- sheltering is an effective protective action that can be implemented rapidly to reduce population exposure
- in some circumstances evacuation may be advisable, such as when there is an immediate risk, when people can be evacuated prior to an exposure, when the risk associated with sheltering will exceed the risk associated with evacuation, or if there is an unacceptable residual risk (for example, contamination)
- it is important to consider all of the factors that affect sheltering and evacuation effectiveness and make a decision based on the specific circumstances
- a range of existing guidance documents can assist decision-making and effective implementation of sheltering and evacuation strategies

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Communication and the public response

Nick Brooke[1], Jim Stewart-Evans[2]
[1] Chemical and Environmental Effects Department, Centre for Radiation, Chemical and Environmental Hazards, Public Health England
[2] Environmental Hazards and Emergencies Department, Centre for Radiation, Chemical and Environmental Hazards, Public Health England
Email: james.stewart-evans@phe.gov.uk

Introduction

Communication is a critical determinant of the effectiveness of shelter and evacuation strategies because it influences the speed and efficacy of the public response during emergencies. This article considers issues associated with the communication of shelter and evacuation messages once a decision has been made to implement them. Different civil alerting systems and technologies may be used to communicate shelter or evacuation advice. The content of messages and psychosocial factors influence how people respond to shelter and evacuation messages.

The importance of effective communication

Delayed communication and non-specific advice have been identified as risk factors in past incidents that led to casualties [1,2]. Unclear or conflicting public health messages risk misinterpretation [3], and if responders issue initial advice that is inaccurate or incomplete, it may subsequently have to be rescinded or changed [4]. Ineffective communication may lead to public confusion, anxiety and a lack of confidence in the responsible authorities [5,6]. This may reduce compliance with advice and reduce the effectiveness of sheltering and evacuation strategies.

Methods, timing and targeting of communication

Key communications objectives during an emergency response are to deliver accurate, clear and timely information and advice to the public so that they feel confident, safe and well informed. Messages must reach as many people as possible as quickly as possible.

Alerting, notification and interpretation are distinct stages of communication:

Alerting: making the public aware of imminent hazard (prompting people to seek more detailed information).

Notification: providing the public with more detailed information that includes instructions regarding protective actions (that is, shelter or evacuation instructions).

Interpretation: the messages taken by the public from the information provided – an important determinant of subsequent public behaviour [7].

Methods of communication

Early alerting enables people to take protective action and begin to access information about the incident through a variety of media as soon as possible. A civil alert system is "the primary mechanism by which the public receive warning of the presence of an emergency or hazard in their proximity" . The chosen approach must be able to communicate, during a catastrophic event with a short lead time, with [8]:

- static persons in their own dwellings
- static persons at their places of work
- travellers on foot
- travellers in vehicles
- travellers in remote locations wishing to know of events elsewhere

Methods of communicating during emergencies include mass media, the internet (including social networking sites and social media), route alerting (door-to-door or loudhailer), person-to-person (informal) communication, sirens, email, telephone alerting, information lines and leaflet drops. It is estimated that approximately 95% of people in the UK use a mobile phone. No one form of communication will reach an entire at-risk population and each has its advantages and disadvantages. The ideal public warning and informing package reaches as many of the at-risk population as possible, no matter where they are, what they are doing, or what time of day it is [9]. When communicating shelter and evacuation decisions, it is thus important to use all appropriate means – such as a variety of channels and existing community resilience networks – to reach all community groups and vulnerable people, particularly if a community's immediate safety is at risk [10]. Not only does this improve coverage, it means that if certain methods of communication become inaccessible, messages may still be received by other routes. The use of multiple alerting systems can also reinforce messages, so people are more likely to respond promptly.

Targeted communication

"Blanket" shelter or evacuation advice is commonly issued to the general public, but additional effort may be required to communicate with some populations or premises. Target audiences can include individuals with hearing or visual problems, the homeless, those who speak a non-native language, those on public transport, motorists, tourists, temporary workers and disabled people with reduced mobility.

Some vulnerable people will be widely dispersed in the community; others will be concentrated in premises such as hospitals, schools or nursing homes. Locations where vulnerable people are present may require targeted communications, as may areas that are particularly difficult to evacuate (such as prisons or hospitals) or shelter in (such as sports stadiums and open areas).

Whilst targeted communication can be used to supplement a wider shelter or evacuation message, it also provides for the possibility of advising sheltering in some areas and evacuation in others. However, it may be difficult or inadvisable to give mixed shelter and evacuation orders to different people living near to one another [11 12]. There are examples of incidents in which mixed shelter and evacuation orders undermined the effectiveness of protective actions. Following an explosion and chemical release in Arkansas, the US authorities advised residents within 2 miles of the source to evacuate but those between 2 and 3 miles away to shelter-in-place. Of those told to evacuate there was 90% compliance; however, 68% of residents who were advised to shelter decided to evacuate [11]. This has been described as “shadow evacuation”, for which informal routes of alerting are thought to be a major contributory factor.

Psychosocial factors

Psychosocial factors influence people’s decisions to evacuate or shelter after receiving advice or instructions to do so. Chemical incidents can generate a number of interrelated concerns and stressors, such as chemical exposure and contamination of individuals or property. Additional concerns regarding real and perceived risks are associated with sheltering and evacuation themselves [13]. People may fail to respond to public warnings to shelter or evacuate if they have special transport requirements or need to be warned in a different way [14].

Dombroski et al. [15] state that studies have generally suggested that public compliance with official warnings can be improved by integrating hazard detection with hazard communication, having pre-tested messages available and decentralising hazard responses. When averaged across different types of scenarios, the authors predicted 70-80% compliance with evacuation orders and 60-70%, slightly lower rates, for sheltering-in-place. Higher compliance (by 10%) was predicted for evacuation from a work location rather than from home, while the opposite was true for sheltering (that is, people were slightly less likely to shelter at work).

The provision of information plays a crucial role in managing the psychosocial aspects of a crisis. Rogers et al. [16] found that the prior provision of information increased the perceived credibility of official messages and reported levels of intended compliance. The public perception of risks, in combination with other factors, can be particularly powerful during environmental incidents such as industrial accidents or acts of terrorism [17]. In times of uncertainty, the public turn to the media when seeking information about potential threats. Public perception is influenced by information received from the media and messages from the emergency services [18]. Dombroski et al. [15] predicted that a sceptical media could reduce people's compliance with protective actions advice by 10%.

Psychosocial factors specific to evacuation

In areas in which evacuation is ordered or recommended, not everyone may participate in the evacuation. Roberson et al. [19] examined compliance with mandatory and voluntary evacuation orders for wildfires, finding that 10% of residents did not intend to evacuate if advised to.

Reasons for non-compliance include not having access to transport, having mobility impairment, not being able to afford to evacuate, needing to work, needing to provide care to people or animals, having a lack of trust in information provided by officials and assuming that the present location is safe (that is, that there is no need to leave). There is some evidence to suggest that older people may be more likely to remain in their homes following an emergency [20], even against official advice [21].

If evacuation is likely to be prolonged, people may be unwilling to close businesses or lose working time due to potential financial impacts. They may also have concerns regarding the potential looting of homes and businesses that make them less willing to evacuate [22]. Wherever possible, responders must reassure the public that properties will be safe and secure during the evacuation period. Developing and implementing a crime prevention strategy [23], and ensuring that the population are aware of it, can help to provide such reassurance.

Spontaneous or self-evacuation

Spontaneous evacuation or self-evacuation occurs when people evacuate without or before receiving an official instruction to do so. In some cases, this may be due to "shadow evacuation", as described previously. Cutter [24] found that evacuation decisions were directly influenced by the head of the household's perception of risk. Spontaneous evacuation may occur because of visual cues (for example, explosions), informal warning (for example, from family or friends) or due to prior knowledge or perception of a pre-existing hazard (for example, a nearby industrial site). Johnson and Zeigler [25] found evacuation decisions in the Three Mile Island incident were influenced by the location (distance and direction) of the home in relation to the source of the hazard. Families in which the head of household was under 35, those with young children, and those in which someone had completed 12 years of education were more likely to evacuate.

Return following an initial evacuation

Individuals may return to an evacuated area against official advice. For instance, following Hurricane Elena, 75% of evacuees took refuge relatively close to their homes (for example, at public shelters), which meant that re-entry to evacuated areas became a significant issue [26]. The attempted return of evacuees who have left important belongings or pets is well documented [22]; arrangements for pets and livestock must be considered in evacuation plans and communicated in evacuation messages [27].

Psychosocial factors specific to sheltering

Studies have examined barriers to sheltering-in-place, such as people being away from their homes (for example, at work or driving). In one study, 60% of participants said they would leave their shelter to check on family, friends or animals. This is most likely to occur when parents have children in nurseries or schools or if people must provide care for elderly parents or relatives [28-31].

Important factors affecting people's personal shelter decisions include whether:

- there is a risk of a hazard moving indoors
- there is access to critical medication and medical supplies
- basic needs are met (for example, appropriate bathroom facilities, tolerable temperatures, dietary requirements, etc)
- people feel safe in the company of others around them
- the neighbourhood is secure (for example, at risk of looting)
- there is access to a range of refreshments (including caffeine and alcohol)
- there is overcrowding of the shelter
- people feel that another location would be safer

Matuzsan [17] found lower rates of intended compliance with shelter, rather than evacuation, advice in chemical release scenarios. Higher intended compliance for both shelter and evacuation was noted for radiological release scenarios, potentially due to higher perceived risk. Pearce et al. [32] examined compliance with shelter advice in the UK and Poland after a hypothetical chemical spill, finding that participants were more likely to comply if they were at home when the incident happened. Coping appraisals (that is, perception of being able to cope) and trust were key predictors of compliance, but threat appraisals (that is, perception of a threat) were associated with non-compliance. Matuzsan [17] found that some residents were more likely to comply with sheltering instructions when they contained an explanation of why sheltering was necessary or information about wind speed and direction that allowed them to judge whether they needed to respond.

Who should deliver public messages?

If the public perceive a given organisation to be trustworthy, authoritative and credible, they are more likely to accept, and act on, information from that source [13 17]. A 2010 study found that the Fire Service was seen as most trustworthy, followed by the Police, when compared to the media, local government and people's friends [33]. A systematic review of the literature relating to CBRN (Chemical, Biological, Radiological and Nuclear) incidents in the US found that healthcare system workers such as family doctors, directors of health departments, health scientists and senior clinicians were preferred and trusted spokespeople [34].

Matuzsan [17] explored preferred sources of information for members of the public in evacuation and shelter-in-place scenarios for chemical and radiological releases, finding a fairly even split across all of the responding organisations (police services, fire services, local authorities, healthcare officials and national government officials) in shelter scenarios, with a preference for communications from the police in evacuation scenarios. The author noted that the public's trust in different sources of information may vary on an incident-by-incident basis. In order to have the greatest effect, messages should ideally be endorsed and propagated by as many different trusted sources as possible. To avoid conflicting advice, it is important that a coordinated, consistent message is given.

The content of shelter and evacuation advice

In the UK, "Go in, Stay in, Tune in" messages contain simple instructions to close doors and windows and to turn off air conditioning and ventilation in order to minimise air exchange [35]. More detailed messages developed in other countries address the choice of shelter room and actions that maximise the effectiveness of sheltering [36 37].

Various countries have developed generic and scenario-specific shelter and evacuation messages, and public information is available from a number of sources for use as part of emergency preparedness and emergency response. Some examples from the UK and internationally are listed in Table 3 below.

Table 3. Example information sources for shelter/evacuation advice

Country	Authors	Name (with hyperlinks)
UK	Cabinet office / local authorities	Shelter and evacuation guidance and local authority websites
US	Department of Homeland Security	Ready: Hazardous materials and chemical threats
Canada	Government of Canada	Get prepared
Australia	Australian Institute for Disaster Resilience	Evacuation planning handbook

Key points when communicating

- prompt warning and informing is critical because delayed communication has the potential to significantly reduce the effectiveness of sheltering and evacuation strategies. Communication must continue throughout an incident and include messages about when to end sheltering or evacuation
- a wide range of traditional alerting mechanisms such as route alerting (door-knocking and loudhailers) sirens, mass media and phone information lines may be used to communicate with the public following an incident. The additional contribution made by informal networks (for example, family, friends and social media) is significant in propagating messages
- the internet (for example, via social media) can be a valuable tool for communicating with the public during an incident
- following an incident, as many civil alerting systems as possible should be used. No one system is a “silver bullet” that can reach the entire “at risk” population. The use of different systems helps to reinforce shelter and evacuation messages
- people generally do not panic during an incident, but there are numerous psychosocial factors that influence whether people comply with emergency responders’ advice. Messages must be clear and barriers to communication must be addressed
- different groups of people often trust different sources, and people will always try to validate messages. Therefore, messages should ideally be repeated by as many different authoritative sources as possible, ensuring messages are consistent

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Chemical incident emergency preparedness

Jeff Russell, Jim Stewart-Evans
Environmental Hazards and Emergencies Department, Centre for Radiation, Chemical and Environmental Hazards, Public Health England
Email: james.stewart-evans@phe.gov.uk

Introduction

Emergency preparedness plays an important role in the delivery of effective sheltering and evacuation strategies during emergency response. It supports exposure and risk assessment, decision-making, communication and the public health response in major chemical incidents.

To prepare for an identified threat, the process of risk assessment and management within emergency preparedness aims to identify hazards, estimate the likelihood of exposure, calculate its consequences (or impact) and introduce steps to mitigate and manage risks – all before an incident takes place.

Preparedness efforts include the development of information and operational procedures for emergency responders. They also encompass education, training and awareness-raising – both of emergency responders and members of the public. This article summarises responder and public preparedness and its contribution to the effectiveness of protective actions such as sheltering and evacuation.

Responder preparedness

Pre-prepared information and decision-aids

There is little time during the initial response to an incident to collect information and make judgements about sheltering and evacuation. Pre-prepared information can reduce the time required in the response phase of an incident to collect and assess information, make a decision, communicate and implement it.

Information regarding the nature of chemical hazards can inform the risk assessment and incident management guidance can inform the operational response. There are a number of existing sources of such information [1,2].

Decision aids help decision-makers assess an incident and make evidenced decisions regarding the most suitable protective action. These range from simple qualitative checklists [3 4] and decision trees to complex computer decision tools.

Consequence modelling

Whilst it is not straightforward to predict the impacts associated with different incident scenarios to inform shelter and evacuation decisions in advance as part of emergency preparedness work, it is possible by using exposure models linked to health effect models, as described in a previous article in this special edition [5-10]. The ARGOS project generated "typical" incident scenarios, consequences and impacts for different locations, sources and quantities of chemicals [11].

When considering transport-related chemical incidents, whilst mobile sources may contain lower quantities (by volume or weight) than fixed sites, incidents can occur anywhere on the transport network. Predicted hazard ranges exist for different transport incident scenarios. They have been used to inform guidance to emergency responders on setting shelter and evacuation distances when responding to similar incidents [12].

The advantage of undertaking such work as part of emergency preparedness, rather than response, is that there is considerably more time available in which to predict exposure and assess risks. This can inform pre-emptive evaluation and decision-making about shelter and evacuation actions, and the preparedness work required to support their use during emergency response. The disadvantage, however, is that the relevance of such predictions to any given real-life incident scenario is uncertain.

Emergency plans

Emergency plans include responders' high-level plans for implementing sheltering or evacuation and site or scenario-specific emergency plans that may incorporate pre-prepared information, consequence modelling outputs and guidance regarding sheltering or evacuating the at-risk area. The existence, and use, of emergency plans during emergency response has the potential to improve the effectiveness of protective actions.

Operational guidance

Operational guidance is produced as part of emergency preparedness work in order to prescribe a consistent approach to emergency response. For example, in England, the Environment Agency published reviews and related guidance on the multi-agency approach to controlled burns [13]; furthermore, emergency services have overarching operational guidance that governs the actions that their organisations take at the scene of an incident, including protective actions such as sheltering or evacuation [14].

Effective sheltering and evacuation strategies can be specified and delivered through the implementation of emergency responders' operational guidance, along with emergency plans. In some countries, fire services' operational guidance prescribes a detailed approach to sheltering and evacuation decisions, based on predicting and mapping exposures during the emergency response. This reactive exposure and risk assessment and decision-making is informed by information compiled by prior research into factors affecting shelter effectiveness, such as representative building air exchange rates [15-17].

Public preparedness

Information, education, training and past experience can improve people's compliance with, and implementation of, shelter and evacuation advice. People can prepare resources in the home to support sheltering (for example, have duct tape and plastic sheeting ready, to be able to seal a shelter room) or evacuation (for example, having an emergency supply kit ready to take if one has to leave promptly).

Pre-prepared public information

People who understand the rationale behind shelter and evacuation, and who have access to information to answer their questions, are more likely to accept advice from emergency responders [18].

In terms of public awareness-raising campaigns for sheltering and evacuation, the UK public received information as part of the "Go In, Stay In, Tune In" campaign in 1999 and a 'Preparing for emergencies' booklet in 2004. A number of local authorities refer to this information on their websites; many local authorities and Local Resilience Forums have produced their own, more recent, resources, including training videos, to improve public preparedness for extreme events and evacuations [19-21].

Some countries such as the US, Canada and Australia have developed "one-stop" websites on which public information relating to major emergencies is prominently displayed and resources are provided. People are encouraged to learn about local hazards and to prepare family emergency plans and emergency kits. In many cases sheltering and evacuation are described in detail. The most well-developed pages are split into sections addressing general types of hazards or emergencies that people could be affected by (such as chemical or radiological releases), providing clear information on what to do before, during and after such emergencies. Another approach has been to include preparedness for emergencies in everyday learning at schools in order to help to improve public response.

When information is provided to the public, it is important that it is both understood and can be used by the individuals concerned. The US Redefining Readiness (RR)

Programme focussed on public engagement in emergency preparedness work, producing good practice guidance and materials for wider use [22-24].

Non-residential buildings are potential shelters during a chemical incident. Specific guidance has been produced in the US to assist building managers in protecting building environments from airborne chemical, biological or radiological releases [25-28]. Other US publications deal with the retrospective improvement of existing buildings to protect against terrorism [29].

It remains important to review and update pre-prepared public information and awareness-raising on an ongoing basis; this maintains public preparedness for major emergencies.

Key points

- pre-prepared information and guidance can reduce the time required by emergency responders in the response phase of an incident to collect and assess information, make a decision about sheltering and evacuation, and communicate and implement it
- there is more time available during the pre-emergency preparedness phase in which to predict exposure and assess risks. This can inform pre-emptive evaluation and decision-making about shelter and evacuation actions, but the relevance of prior predictions to any given real-life incident scenario is uncertain and must be considered during emergency response
- in some countries, fire services' operational guidance prescribes a detailed approach to sheltering and evacuation decisions during the emergency response phase, based on predicting and mapping exposures
- information, education, training and past experience can improve people's compliance with, and implementation of, shelter and evacuation advice
- it is important to review and update pre-prepared public information and awareness-raising on an ongoing basis; this maintains public preparedness for major emergencies

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Protective actions during chemical incidents and fires: evacuate or shelter-in-place?

Jim Stewart-Evans
Environmental Hazards and Emergencies Department, Centre for Radiation, Chemical and Environmental Hazards, Public Health England
Email: james.stewart-evans@phe.gov.uk

Introduction

Releases of airborne chemicals have the potential to rapidly affect wide areas, leading to exposures that can harm public health. Public sheltering and evacuation are accepted and commonly implemented protective strategies. Countries have different preferences for sheltering or evacuation: evacuation is more common in the US [1 2]; in the UK, standard advice to 'Go in, Stay in, and Tune in' is typically issued to the public during chemical incidents and fires and, depending on the nature of the incident, emergency responders may evacuate those persons at highest risk; usually those nearest to the incident.

Previous articles in this special edition have outlined the findings of a review of scientific literature and guidance related to sheltering, evacuation, and associated interventions to protect public health during chemical incidents and fires. This article provides a concluding summary for readers.

Evacuate or shelter-in-place?

Sheltering and evacuation have often successfully protected public health, but in some cases, they have been ineffective. Chemicals with a high vapour pressure, such as ammonia, and those released in large quantities or over prolonged periods are more likely to affect surrounding populations, and this can be a strong driver for evacuation [2 3]. To inform decisions, responders require rapid access to chemical information during incidents [4] and sufficient capabilities to undertake exposure assessment and risk assessment. Unsuccessful sheltering and evacuation strategies are often related to poor emergency preparedness, insufficient or delayed communication during the response phase, and slow decision-making.

Many factors determine the effectiveness of sheltering and evacuation, and considerations include the nature of the chemical released (for example, physicochemical and toxicological characteristics); the type, rate and duration of the release (for example, instantaneous, intermittent or continuous); prevailing and future meteorological conditions (for example, wind speed and direction); local topography (for example, complex terrain or dense urban areas); the characteristics and susceptibility of the local population (for example, population density, the presence of sensitive receptors such as schools, nursing homes or hospitals); the characteristics of shelter buildings and their implications for air exchange rates and indoor exposure (for example, airtightness, ventilation, internal volume and complexity); and the time available before the plume affects an area and the time available to issue and fully implement shelter or evacuation advice.

Two determinants of chemical toxicity are relevant to sheltering and evacuation scenarios: concentration and exposure time. Typically, inhalation of a very high concentration for a short time is much worse than inhalation of a lower concentration for a long time, even if the time-integrated dose is the same in both cases [5].

Non-linear dose-response relationships imply a substantial reduction in toxic load from lowering the peak exposure concentration, which means that sheltering can be particularly effective for short-duration releases of chemicals because the dilution of outdoor air mixing with indoor air reduces the peak concentration indoors [6 7]. For chemicals with linear dose responses, it can be more important for people to minimise their cumulative exposure.

In practice, risk assessment is based on comparison of exposures with exposure thresholds for relevant health endpoints derived from chemical-specific toxicity data. As a general rule, sheltering can be an effective mechanism for reducing exposure to peak concentrations over a limited time, but it may be less effective at reducing cumulative exposure over a longer time period as the concentrations build up indoors [1 6-10].

A successful sheltering strategy requires that 2 distinct actions are taken without delay to maximise the passive protection a building provides during a chemical emergency. The first is reducing the indoor-outdoor air exchange rate before a chemical plume arrives. This is achieved by closing windows and doors; turning off fans, air conditioners and combustion heaters; and taking other measures to reduce infiltration. The second is increasing the indoor-outdoor air exchange rate as soon as a plume has passed. This is achieved by opening windows and doors and turning on fans to ventilate the building. Both actions are dependent on prompt decision-making by emergency responders and prompt, effective communication between responders and members of the public.

The key considerations when evaluating sheltering effectiveness are infiltration (air exchange), attenuation (for example, deposition; condensation; reaction with built materials; and the potential filter-effect of passage through a building’s structure), indoor exposure concentration and duration, and dose-response. Sheltering is likely to be an effective initial protective action to take in the early stages of the emergency response to an incident involving an airborne release, when the predicted concentration and release duration is unknown. This is because many chemical releases in the UK tend to be of short duration and relatively low concentration. The principal advantage of sheltering is that it can be implemented more rapidly than evacuation. Its principal disadvantage is that the physical protection that it affords is quite variable [11]. However, sheltering does not preclude evacuation, and it can be used as a pre-evacuation measure in instances when there is a prolonged release.

Sheltering offers less protection over time as chemicals ingress indoors, and sheltering decisions can be finely balanced during prolonged incidents. A number of organisations and studies have estimated the limit at which normal sheltering from hazardous chemicals might cease to be effective: estimates range from 30 minutes to several hours [12-15]. This is a worst-case and such evaluations are not straightforward, particularly when outdoor concentrations are variable and if they do not pose an immediate risk (for example, during many fire scenarios). There are a number of additional measures that can potentially augment the protective effect of sheltering, such as ‘expedient’ sheltering within a sealed shelter room or the use of running water to reduce airborne concentrations of water-soluble chemicals. The effectiveness of sheltering is ultimately dependent on the incident scenario and on the significance of exposure.

Exposure assessment is informed by spatial mapping, environmental monitoring and modelling of outdoor and indoor exposures. Exposure estimates must then be compared to health-based standards in order to evaluate their significance; there are a number of potential approaches that include the use of guideline values developed for acute exposure during chemical emergencies.

A number of decision-aids are available to assist shelter and evacuation decisions, but there is no one commonly-accepted approach to decision-making. In some circumstances evacuation may be advisable, such as when there is an immediate risk to the public (for example, from fire or explosion); when people can be evacuated prior to an exposure taking place (for example, before a release has occurred or arrived at their location); or when a release is likely to be relatively large and/or prolonged (for example, when sheltering is associated with greater risk than evacuation). When evaluating evacuation, it is important to consider whether the risks associated with chemical exposure during evacuation – and the other non-chemical risks associated with evacuation – will be more or less significant than chemical exposure during sheltering.

Evacuation is not always feasible. The key factors when considering the practicalities and feasibility of evacuation are the availability and suitability of transport; the adequacy of transport routes and networks; the time constraints associated with evacuating different populations; population size, mobility and special needs; physical considerations such as weather conditions; whether there are concurrent or related events that introduce additional hazards; and the time of day. Evacuation takes time and can itself carry a significant risk. This is imposed by the stress of evacuation and temporary, often make-shift, accommodation and by physical risks associated with the process, including exposure while evacuating. Successful evacuation relies heavily on effective emergency planning and prior communication [4].

Responders' decisions regarding sheltering or evacuation require prompt and effective communication. Psychosocial factors can influence people's interpretation of, and compliance with, messages about protective actions. Delayed, unclear or conflicting messages and poor public compliance can reduce the effectiveness of protective actions. Clear messages are required from authoritative sources, and a range of communication systems are used by responders. A wide range of public information, template messages and educational material exists that can support proactive and reactive communication with the public regarding sheltering and evacuation.

Key points

- sheltering is an effective protective action that can be implemented rapidly to reduce population exposure
- in some circumstances evacuation may be advisable, such as when there is an immediate risk, when people can be evacuated prior to an exposure, when the risk associated with sheltering will exceed the risk associated with evacuation, or if there is an unacceptable residual risk (for example, contamination)
- it is important to consider all of the factors that affect sheltering and evacuation effectiveness and make a decision based on the specific circumstances

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