# Air Infiltration and Ventilation Centre
# Ventilation Information Paper
# Sheltering in Buildings from Large-Scale Outdoor Releases

W.R. Chan, P.N. Price, A.J. Gadgil

## 1. Introduction

Intentional or accidental large-scale airborne toxic release (e.g. terrorist attacks or industrial accidents) can cause severe harm to nearby communities. Under these circumstances, taking shelter in buildings can be an effective emergency response strategy. Some examples where shelter-in-place was successful at preventing injuries and casualties have been documented [1, 2]. As public education and preparedness are vital to ensure the success of an emergency response, many agencies have prepared documents advising the public on what to do during and after sheltering [3, 4, 5]. In this document, we will focus on the role buildings play in providing protection to occupants.

## 2. How effective is sheltering?

The sudden nature of a terrorist or accidental release means that there is often not enough time to safely evacuate the nearby communities. The remaining option is to take shelter until the toxic plume has dispersed. The obvious advantage of staying indoors is that there is a reservoir of clean air contained in buildings. Even though buildings are not airtight, building envelopes restrict the transport of the toxic pollutant to the indoors. The result is that the indoor concentration will increase much slower and remain low relative to the outdoor concentration.

### 2.1 Outdoor-indoor air exchange

When sheltering in buildings, doors and windows should be closed, and ventilation and exhaust fans should be off to minimize air exchange with the outdoors. In such cases, the air change per hour (ACH) is determined by uncontrolled air leakage across the building envelope (*Figure 1*). Air infiltration is a function of the leakiness of the building, and the differential pressures across the envelope, which are caused by indoor-outdoor temperature difference and the forces exerted by wind.

Air infiltration rates can vary from less than 0.1 ACH for a tight house under mild weather conditions to over 1.5 ACH for a leaky house under severe weather conditions (*Table 1*). These values are derived from air leakage measurements of residential houses in the US [7]. Houses in countries where the climate is more severe, such as Sweden, Norway, and Canada, tend to be more airtight than the values presented here [8].

*Figure 1: Uncontrolled air leakage, known as air infiltration, across the building envelope of a house.[1]*

| Weather condition | Wind speed [m/s] | Indoor-outdoor Δ temperature [K] | Δ Pressure across building envelope [Pa] | Air infiltration [ACH] | | |
|---|---|---|---|---|---|---|
| | | | | Tight house | Typical house | Leaky house |
| Mild | 2 | 5 | 0.2 | 0.07 | 0.1 | 0.4 |
| Moderate | 5 | 15 | 1 | 0.2 | 0.3 | 1.0 |
| Severe | 7 | 25 | 2 | 0.3 | 0.5 | 1.6 |

*Table 1: Typical normalized leakage and air infiltration rate of US residential houses estimated using LBL Infiltration Model [6] under different weather conditions.*

For a conserved contaminant, indoor concentration during sheltering can be predicted using the air infiltration rate and the outdoor concentrations (*Figure 2*). Houses with high air infiltration rates (e.g. 1 ACH) will permit larger amounts of the toxic material to enter indoors as the outdoor plume arrives. However, due to the rapid exchange with the outdoors, the indoor concentration will also decay much faster compared to tighter houses after the outdoor plume departs. If shelter-in-place were maintained in all houses for sufficiently long time, the indoor exposure (time integrated concentration) would eventually approach the outdoor level assuming no toxic material is lost while entering and within the building. Therefore, termination of shelter-in-place is an important part of the overall sheltering strategy in order to minimize exposure.

[1] Used with permission of US EPA ENERGY STAR®.

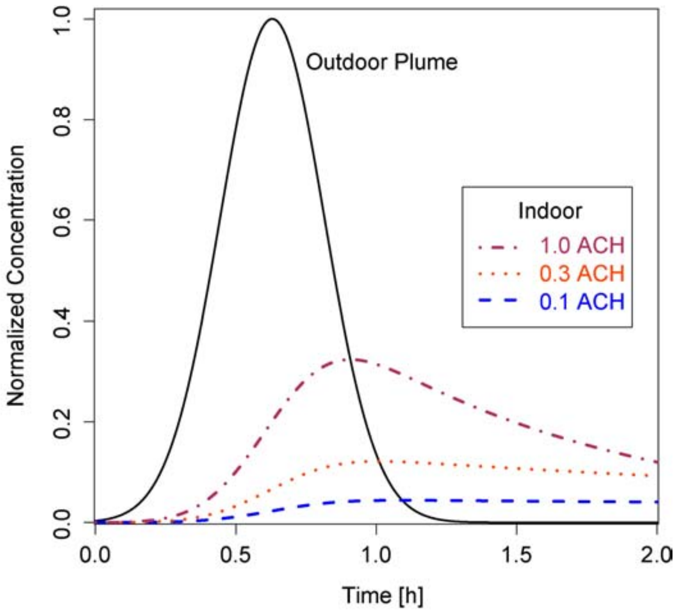



*Figure 2: Indoor concentration profiles for a well-mixed dwelling at different air exchange rates. The concentrations shown are normalized to the peak outdoor concentration.*

**2.2 Removal mechanisms**

Mechanisms by which toxic materials are removed by buildings further decrease the indoor concentration of the toxic material. Building envelopes can remove some bio-aerosols (typical size range 1 to 5 μm) as they infiltrate through cracks. The penetration factor, defined as the fraction of contaminant in the infiltrating air that passes through the building envelope, has been found to be close to 1 for particles that are 1 μm in diameter [9]. Experimental study also suggests that particles larger than 5 μm can have a significantly lower penetration factor in houses with tighter construction [10]. Building envelopes can therefore offer some, but not substantial, protection from outdoor bio-aerosol plumes.

Once inside buildings, bio-aerosols can deposit out of the air onto surfaces. For 1 to 5 μm particles, the loss rate by deposition is equivalent to having an additional fresh air supply of 0.1 to 1 ACH [11]. *Figure 3* shows the indoor concentrations at different loss rates. At a loss rate of 1 $h^{-1}$, the indoor concentration drops to less than 1% of the outdoor peak concentration several hours before the no-loss case does. On the other hand, a loss rate of 0.1 $h^{-1}$ has little effect on the indoor concentration. Resuspension of particles, a process not considered here, can reintroduce deposited particles into the air and changes the airborne concentration.

The penetration factor of gases is highly dependent on the pollutant-surface reaction probability, which is defined as the ratio of removal rate to the collision rate of the gaseous species on the surface [12]. However, sorption to indoor surfaces, which may include adsorption, absorption, and chemical binding, is likely to be the dominate removal mechanism for chemical agents. Similar to particle deposition, loss rate by sorption is also highly sensitive to the level of furnishing and other indoor conditions. Sorbed chemicals can also slowly desorb from surfaces. Room-scale experiments indicate that the sorption loss rate of $NH_3$, $Cl_2$, $SO_2$, sarin, and VX are equivalent to having an additional fresh air supply of 1 ACH [13, 14, 15], which is significantly more rapid compared to the typical air change rate of 0.3 $h^{-1}$.

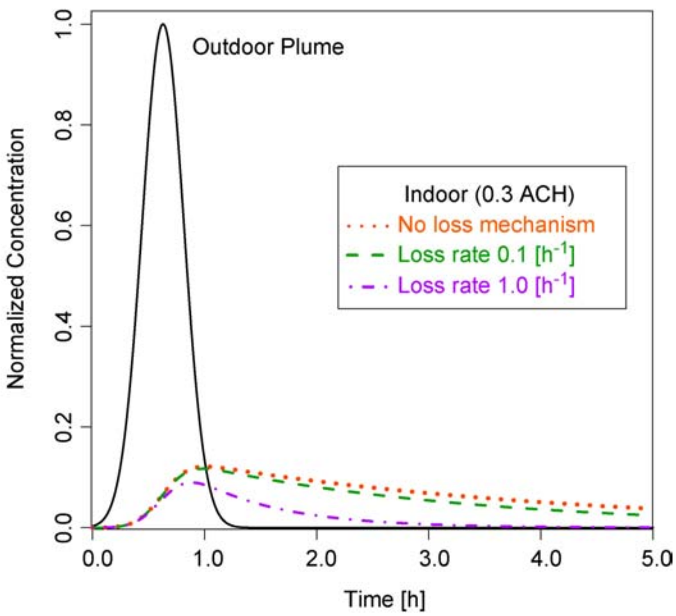



*Figure 3*: *Indoor concentration profiles for a typical dwelling with different loss rates. The concentrations shown are normalized to the peak outdoor concentration.*

**2.3 Health effects**

Health effects of many chemicals are best described by the "toxic load rate". Toxic load rate is the airborne concentration of the chemical raised to an appropriate exponent. For an agent with a high exponent (e.g. $H_2S$ has an exponent of 4, some nerve agents have an exponent of 2), exposure to high concentration for a short time is worse than exposure to a lower concentration for a proportionally longer duration of time. This non-linear dose-response characteristic means that sheltering is very effective in preventing injuries and fatalities because the indoor concentration remains much lower than the outdoor during the release (*Figure 2*). After the plume has passed, the indoor concentration rises above the outdoor. Therefore, sheltering should be terminated by opening windows and doors to avoid prolonged exposure to the residues that remain indoors. The exact timing of termination will depend on the characteristics of the release as well as the protectiveness of buildings against the agent. In general, termination time is most critical if sheltering in leaky buildings from a highly concentrated puff release of an agent that does not undergo deposition or sorption indoors.

## 3. Role of ventilation systems

Most commercial buildings have some form of heating, ventilating, and air-conditioning system (HVAC) that includes an air-filter to remove particles, and in some cases an air-cleaner to remove gases. For bio-aerosols in the size range of 1 to 5 μm, many air-filters might have limited collection efficiency depending on the particular design and loading on the filter [16]. Commonly used air-cleaning media is even less effective against most chemical warfare agents. Special chemically active sorbents might be needed to achieve significant removal. Filter or sorbent bypass is another problem that can limit the efficiency of such system. Furthermore, operation of the ventilation system can increase the overall air exchange with the outdoors which is undesirable during sheltering. The default advice is therefore to shut down the mechanical ventilation system and bathroom exhaust fans in response to an outdoor release [17]. Intake and exhaust dampers should also be fully closed.

Commercial buildings further differ from small residential buildings because the air within the former cannot be considered well-mixed throughout the building. Consequently, the indoor concentrations in various parts of the building will depend also on the interzonal airflows [18] and will not be uniform throughout the building (*Figure 4*). When the HVAC is operating, transport of the contaminant within the building is determined by the airflow directed by the air handling units and duct systems. Typically, air is rapidly mixed within a zone, but airzones are designed to be isolated from one another. When the HVAC is turned off, the overall airflow and within-zone mixing is much reduced. However, the contaminant can now spread throughout the entire building with time. Under such circumstances, indoor concentrations can vary greatly depending on the weather conditions and the air leakage pathways of the building.

## 4. Proactive measures

Apart from closing all doors and windows, and turning off ventilation systems, a range of measures can be taken to make buildings more protective from an outdoor release (*Figure 5*). Simple taping of doors and vents, and plastic sheet over windows can reduce air infiltration to some extent [19], particularly when an interior room is chosen for the sheltering. More permanent modifications can include weatherization techniques such as caulking to improve the airtightness of residential dwellings [20]. Larger and more vulnerable buildings might install a filtration system to supply clean air at a positive pressure that can prevent contaminated air from leaking in. Active filtration can also take the form of a stand-alone air purifying unit containing HEPA and activated carbon filters [21, 22].

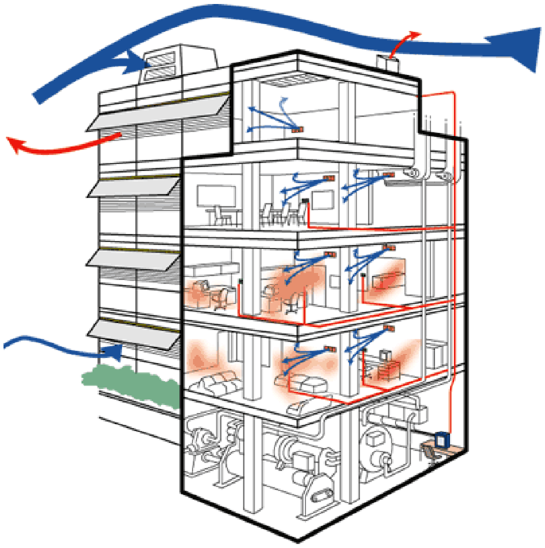


*Figure 4: Complex airflow pathways in a commercial building leading to multizone condition.*

*Figure 5: Examples of some proactive measures: duct tape/plastic sheet, weatherization, and air purifier.*[2]

## 5. Discussion

While the idea of shelter-in-place is straightforward, challenges remain in characterizing the benefits of sheltering under realistic scenarios. Large variability in building characteristics means that there is a range of shelter-in-place effectiveness. There are also considerable uncertainties owing to the limited

---

[2] Used with permission of Sedgwick County Emergency Management (left), Big Five's Weatherization Program (center), and Morrow County Oregon Emergency Management Office (right).

understanding of some of the indoor transport mechanisms and fate of airborne toxic materials. Even so, past experiences and preliminary investigations have pointed to shelter-in-place as a promising emergency response strategy.

Illustrated in *Figure 6* is a simulation of the expected harm reduction from sheltering for a community in Albuquerque from a hypothetical large-scale chlorine gas release [23]. Air infiltration rates of the houses are estimated based on the air leakage characteristics and the weather conditions during the release. Estimation of sorption to indoor surfaces is also included. At the end of the 4-hour release, the area at risk of life-threatening effects is an order of magnitude smaller if people were sheltering indoors for the duration of the release than if everyone were outdoors. Sheltering can be even more effective than shown here for releases of a shorter duration, and if suitable proactive measure and strategy is deployed.

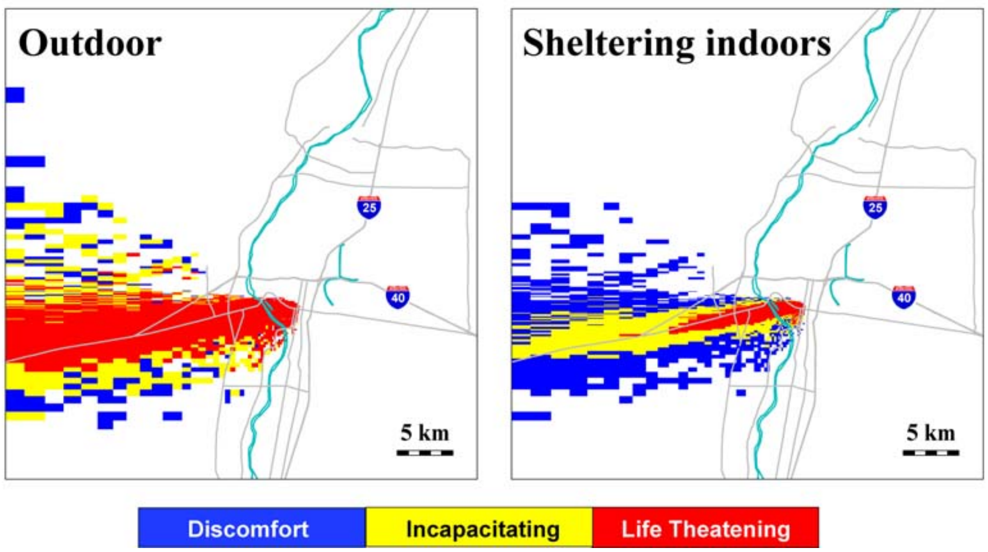



*Figure 6: Predicted health effects based on US EPA's Acute Exposure Guidelines [24] of a hypothetical 4-hour chlorine gas release in Albuquerque if shelter-in-place is implemented (right) compared to if everyone is outdoors (left).*

**6. Conclusion**

- Under most circumstances, shelter-in-place is an effective response against large-scale outdoor releases. This is particularly true for release of short duration (a few hours or less) and chemicals that exhibit non-linear dose-response characteristics.
- The building envelope not only restricts the outdoor-indoor air exchange, but can also filter some biological or even chemical agents. Once indoors, the toxic materials can deposit or sorb onto indoor surfaces. All these processes contribute to the effectiveness of shelter-in-place.
- Tightening of building envelope and improved filtration can enhance the protection offered by buildings. Common mechanical ventilation system

present in most commercial buildings, however, should be turned off and dampers closed when sheltering from an outdoor release.

- o After the passing of the outdoor plume, some residuals will remain indoors. It is therefore important to terminate shelter-in-place to minimize exposure to the toxic materials.

## 7. Acknowledgement

The authors would like to thank Remi Carrie, Buvana Jayaraman, David Lorenzetti, and Peter Wouters for their reviews. This work was supported by the Science and Technology Directorate of the Department of Homeland Security, and performed under U.S. Department of Energy Contract No. DE-AC03-76SF00098.

## 8. References

[1] "Sheltering in Place as a Public Protective Action", National Institute for Chemical Studies, 2001: http://www.nicsinfo.org/shelter%20in%20place.pdf

[2] Mannan MS, Kilpatrick DL, "The Pros and Cons of Shelter-in-Place", Process Safety Progress, Vol. 19 (4), p. 210, 2000.

[3] Shelter-in-Place Information Center, National Institute for Chemical Studies: http://www.nicsinfo.org/SIP%20Center.htm

[4] American Red Cross: http://www.redcross.org/services/disaster/beprepared/shelterinplace.html

[5] Emergency Management Center, Oak Ridge National Laboratory: http://emc.ornl.gov/index.html

[6] Sherman MH, "Air Infiltration in Buildings", PhD Thesis, University of California Berkeley, CA, 1980.

[7] Chan WR, Price PN, Sohn MD, Gadgil AJ, "Analysis of US Residential Air Leakage Database", Lawrence Berkeley National Laboratory, LBNL-53367, 2003: http://eetd.lbl.gov/ied/apt/pubs/Leakage.pdf

[8] Sherman MH, Chan WR, "Building Airtightness: Research and Practice", Lawrence Berkeley National Laboratory, LBNL-53356, 2003: http://epb1.lbl.gov/EPB/Publications/lbnl-53356.pdf

[9] Liu DL, Nazaroff WW, "Particle Penetration Through Building Cracks", Aerosol Science and Technology, Vol. 37, p. 565-573, 2003.

[10] Thatcher TL, Lunden MM, Revzan KL, Sextro RG, Brown NJ, "A Concentration Rebound Method for Measuring Particle Penetration and Deposition in the Indoor Environment", Aerosol Science and Technology, Vol. 37, p.847-864, 2003.

[11] Thatcher TL, McKone TE, Fisk WJ, Sohn MD, Delp WW, Riley WJ, Sextro RG, "Factors Affecting the Concentration of Outdoor Particles Indoors (COPI): Identification of Data Needs and Existing Data", Lawrence Berkeley National Laboratory, LBNL-49321, 2001.

[12] Liu DL, Nazaroff WW, "Modeling Pollutant Penetration across Building Envelopes", Atmospheric Environment, Vol. 35, p.4451-4462, 2001.

[13] Singer BC, Destaillats H, Hodgson AT, Revzan KL, Sextro RG, "Indoor Sorption of Surrogates for Sarin and Related Chemical Warfare Agents", Lawrence Berkeley National Laboratory, LBNL-54992, 2004.

[14] Karlson E, Huber U, “Influence of Deposition on the Indoor Concentration of Toxic Gases”, Journal of Hazardous Materials, Vol. 49, p. 15-27, 1996.

[15] Grøntoft T, Raychaudhuri MR, “Compilation of Tables of Surface Deposition Velocities for $O_3$, $NO_2$ and $SO_2$ to a Range of Indoor Surfaces”, Atmospheric Environment, Vol. 38, p. 533-544, 2004.

[16] “Guidance for Filtration and Air-Cleaning Systems to Protect Building Environments”, Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, 2003: http://www.cdc.gov/niosh/docs/2003-136/pdfs/2003-136.pdf

[17] Advice for Safeguarding Buildings Against Chemical or Biological Attack, Indoor Environment Department, Lawrence Berkeley National Laboratory: http://securebuildings.lbl.gov/

[18] Multizone Simulation, Airflow and Pollutant Transport Group, Indoor Environment Department, Lawrence Berkeley National Laboratory: http://eetd.lbl.gov/ied/apt/APT_tMS.html

[19] Sorense JH, Vogt BM, “Will Duct Tape and Plastic Really Work? Issues Related to Expedient Shelter-in-Place”, Oak Ridge National Laboratory, ORNL/TM-2001/154, 2001: http://emc.ornl.gov/EMCWeb/EMC/PDF/TM_2001_154_duct_plastic.pdf

[20] Weatherization Assistance Program, Energy Efficiency and Renewable Energy, US Department of Energy: http://www.eere.energy.gov/weatherization/

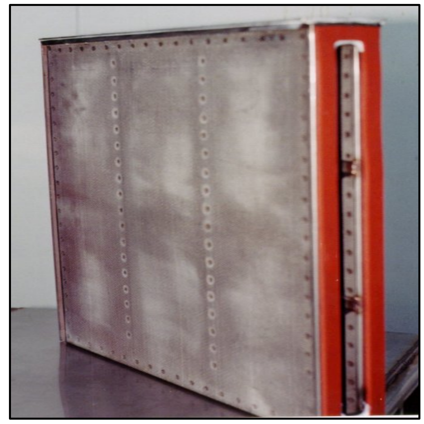
[21] Blewett WK, Arca VJ, “Experiments in Sheltering in Place: How Filtering Affects Protection Against Sarin and Mustard Vapor”, Edgewood Chemical Biological Center, Aberdeen Proving Ground, 1999.

[22] National Institute for Chemical Studies News, Vol. 12, 2003: http://www.nicsinfo.org/nn0203.pdf

[23] Chan WR, Price PN, Gadgil AJ, Nazaroff WW, Loosmore G, Sugiyama G, “Modeling sheltering-in-place including sorption on indoor surfaces”, American Meteorological Society Annual Meeting, Seattle, 2004: http://ams.confex.com/ams/pdfpapers/73459.pdf

[24] US EPA, Office of Pollution Prevention & Toxics, Acute Exposure Guideline Levels (AEGLs): http://www.epa.gov/oppt/aegl/chemlist.htm

# M49 FIXED INSTALLATION FILTER (FIF)



**120 CFM Filter Tray**

## Description:

The M49 FIF is comprised of modular, stainless steel 600 cubic feet per minute (CFM) and 1200 CFM gas filters, which can be stacked in parallel for a larger airflow capacities. Each gas filter contains refillable, 120 CFM gas filter trays (5 trays per 600 CFM; 10 trays per 120 CFM filters). The FIF is a stainless steel gas filter containing ASZM Teda Carbon – chrome-free, non-hazardous material.

Typical FIF systems operation consist of three stages: (1) a pre-filter to collect large particles size dust, (2) a high efficiency particulate air (HEPA filter to collect sub-micron size particles, and (3) a gas filter to filter toxic vapors and gases. Though such systems are installed within the existing ventilation ducts, a separate blower system must be installed to accommodate the extra static head present in the collective protection filter system. The HEPA filter will protect against nuclear and biological particulate matter; the gas filter will protect against chemical agent vapors.

## Mission:

The (FIF) is designed to provide a protective environment against nuclear, biological and chemical (NBC) warfare agents for chemical-hardened fixed shelters, office command control, medical, rest and relief, underground shelters during life support operations and a variety of other critical applications, allowing personnel to perform their duties unencumbered by individual protection equipment.

## User:

U.S. Air Force, U.S. Navy, U.S. Marine Corps, U.S. Army

**1200 CFM Gas Filter**

## Capabilities:

- Provides effective filtration at a temperature range from –25°F to +125°F.
- Low filter pressure drop (1 iwg for 1200 CFM and 0.7 iwg for 600 CFM).
- 120 CFM filter trays are modular, refillable, and reusable.
- Stainless steel construction is completely decontaminable.
- Filter trays packaged for long-term storage without degradation.

Additional information on this system can be obtained by directing your inquiries to Joint Project Manager, CBR Collective Protection, 17320 Dahlgren Road, Dahlgren VA, 22448-5100 or by telephone at (540) 653-2719 or DSN 249-2719, or by fax to (540) 653-2881.