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Illustration of Key Considerations Determining Hazardous Indoor Inhalation Exposures

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Illustration of Key Considerations Determining Hazardous Indoor Inhalation Exposures

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Abstract

Buildings can protect their occupants from outdoor hazards. In some cases, this protection can reduce hazardous exposures by an order of magnitude or more. The degree to which indoor exposures are reduced, relative to being outdoors, depends upon the specific building, hazardous material, and exposure pathway. This report illustrates how several key considerations interrelate to determine the building protection against indoor inhalation of outdoor airborne hazards. These considerations are the (1) outdoor plume duration, (2) loss of airborne material indoors, (3) rate at which outdoor and indoor air is exchanged, (4) importance of peak concentration to hazard toxicity, and (5) the time, after the outdoor plume has passed, that individuals exit (or ventilate) the building. This report focuses on “passive” building protection for inhalation exposures – the protection that buildings provide their occupants under normal operating conditions against outdoor inhalation hazards. With active measures, such as turning off building ventilation systems, building protection can be higher than the illustrative values shown here.

1.0 Introduction

Buildings can protect their occupants from outdoor hazards. The degree to which indoor exposures are reduced, relative to being outdoors, depends upon the specific building, hazardous material, and exposure pathway. In some cases, this protection can reduce hazardous exposures by an order of magnitude or more. Despite the increasing use of sheltering as a protective action, in some communities there is limited understanding of the building protection physics, particularly with respect to inhalation exposures.

This report aims to address this gap, in part, by illustrating how several key considerations interrelate to determine the building protection against indoor inhalation of outdoor airborne hazards, see **Table 1**. This report focuses on "passive" building protection for inhalation exposures – the protection that buildings provide their occupants under normal operating conditions against indoor inhalation hazards of outdoor origin. With active measures, such as turning off building ventilation systems before the outdoor plume arrives, building protection can be higher than the illustrative values shown here.

To illustrate these key considerations, and how they interrelate to outdoor and indoor inhalation exposures, we contrast the building protection against acute chlorine gas exposure to that of a particular radioactive noble gas. Chlorine is a common industrial chemical and significant atmospheric releases are known to occur. Radioactive noble gases, such as Xenon and Krypton, can be released during nuclear reactor accidents. We use ^{85}Kr (a low energy beta emitter) as the illustrative radioactive noble gas for this report. For other radioactive noble gases, e.g., ^{133}Xe, significant radiation exposures can occur without inhalation. For example, individuals can be exposed to gamma rays emitted by the passing cloud of radioactive material (external gamma exposure from cloudshine). As discussed in other reports, but not here, buildings can provide protection against these other exposure pathways as well [1], [2].

To enhance clarity for the reader, this report employs a simplified building protection model and parameter values. A broader, and more detailed, presentation of the key definitions, equations and graphics are provided in other reports (***Regional Shelter Analysis – Inhalation Exposure Methodology*** [3] and ***Regional Shelter Analysis – Inhalation Exposure Application (Particles)*** [4]) as well as in the related work of *Chan et al.* [5], [6].

Table 1. Key Considerations Determining Indoor Inhalation Exposures to Outdoor-Origin Airborne Hazards

Key Considerations Affecting Indoor Inhalation Exposures
Outdoor Plume Duration
Loss of Airborne Material Indoors
Rate at which Outdoor and Indoor Air is Exchanged
Importance of Peak Concentration to Hazard Toxicity
Time, After the Outdoor Plume Has Passed, that Individuals Exit the Building

2.0 Dynamics of Indoor/Outdoor Airborne Hazard Concentrations

The time-dependent indoor airborne hazard concentrations (C_{Indoor}) can be estimated from the outdoor airborne hazard concentration ($C_{Outdoor}$) using **Equation 1**.[1,2]

(Equation 1)

$$\frac{dC_{Indoor}(t)}{dt} = (L_{in-out} \cdot \lambda_{in-out})C_{Outdoor}(t) - (\lambda_{in-out} + \lambda_{internal})C_{Indoor}(t)$$

where

$C_{Indoor}(t)$ = indoor airborne hazard concentration at time t (g m^{-3})
$C_{Outdoor}(t)$ = outdoor airborne hazard concentration at time t (g m^{-3})
L_{in-out} = penetration fraction which is the fraction of the outdoor airborne hazard that penetrates indoors[3] via infiltration (dimensionless)
λ_{in-out} = air exchange rate between indoors and outdoors (h^{-1})
$\lambda_{internal}$ = indoor loss rate, e.g., deposition, radioactive decay (h^{-1})
t = time (h)

Figure 1 illustrates the dynamics of the outdoor (red) and the resulting indoor (blue) airborne hazard concentrations from a passing outdoor plume for the illustrative buildings discussed below. Note that:

The peak outdoor plume concentration is typically higher than the peak indoor concentration.

Indoor concentrations typically remain elevated well after the outdoor plume has passed.

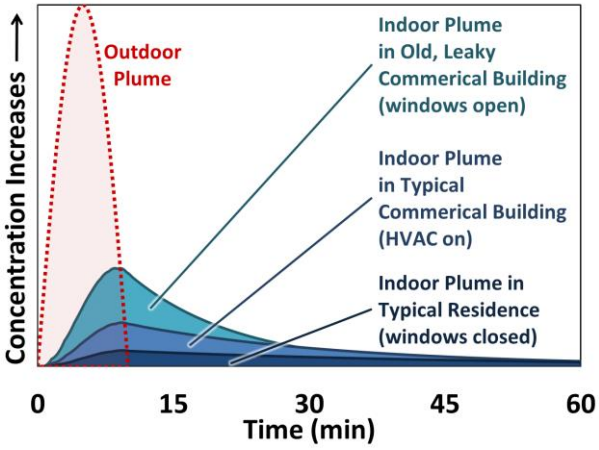


Figure 1. Illustration of outdoor and indoor chlorine gas concentration profiles resulting from plume passage

[1] This illustrative model neglects airborne material initially deposited (lost) to indoor surfaces and later re-emitted back into the air through resuspension, evaporation, and/or desorption. For some hazards, such as chlorine gas, re-emission is not significant over the time scales of interest [7]. For other hazards, such as nerve agents, desorption can be significant [8] and may need to be considered, see *Montoya et al*. [7] for more details.

[2] For reading clarity, the terms λ_{in} and λ_{out} used in ***Regional Shelter Analysis – Inhalation Exposure Methodology*** [3] have been replaced with $(L_{in-out} \cdot \lambda_{in-out})$ and λ_{in-out} in the present report.

[3] In some indoor air literature, this term is represented with a "P".

3.0 Illustrative Building and Airborne Hazard Parameter Values

The L_{in-out}, λ_{in-out}, and $\lambda_{internal}$ properties are known to vary by building type, the specific toxic material, weather, and local environment, see [4]. For discussion purposes, illustrative values are provided in **Tables 2a** and **2b**.[4] The values shown in **Table 2a-b** were used to calculate the indoor hazard air concentration profiles illustrated in **Figure 1**.

Table 2b defines three broad indoor loss categories: negligible, moderate, and substantial. Later discussions use these indoor loss categories to illustrate how building protection changes over a wide range of indoor losses. To provide the reader context, we list illustrative gaseous hazards for each indoor loss category. ^{85}Kr and chlorine gas, having negligible and moderate indoor losses, respectively, are used later to illustrate qualitatively different building protection considerations. The building protection for nitric acid gas, which has substantial indoor losses, is qualitatively similar to chlorine and so is not discussed further.

Besides gases, airborne particles, e.g., $PM_{2.5}$, PM_{10}, and larger particles, are another class of hazardous inhalation exposures. Airborne particles behave indoors in an analogous manner to the illustrative gaseous hazards discussed here [4]. For context, indoor losses ($\lambda_{internal}$, L_{in-out}) vary with particle size but can fall within the same range as shown **Table 2b**. Smaller respirable particles correspond to smaller indoor losses while larger particles have larger indoor losses. Indoor losses in buildings with air filtration systems can be even higher than those shown here – even for smaller particles.

Table 2. Illustrative building type air exchange rates and airborne hazard loss parameters.

a. Building air exchange rates

Illustrative building type	Indoor/Outdoor air exchange rate (λ_{in-out} in h^{-1})
Newer, energy efficient, residential building	0.2
Typical US residence	0.5
Typical US commercial building	1.5
Old, leaky commercial building	4

b. Airborne hazard loss parameters

Indoor loss category	Illustrative hazard	Penetration fraction (L_{in-out}, dimensionless)	Indoor loss rate ($\lambda_{internal}$ in h^{-1})
Negligible	^{85}Kr	1	0
Moderate	Chlorine gas	0.9	1
Substantial	Nitric acid gas	0.8	5

[4] Nominal λ_{in-out} values are based on [9]. The values for $\lambda_{internal}$ in **Table 2b** were derived assuming an indoor deposition velocity of 10^{-4} m s^{-1} for chlorine gas and $7x10^{-4}$ m s^{-1} for nitric acid and a room surface to volume ratio of 2 m^{-1} [10], [11]. These values are broadly consistent with the values in [6]. Penetration fraction values, L_{in-out}, are known to depend upon the details of the building air leakage and the airborne hazard (nominal values are provided here and may be updated as new information becomes available).

Figure 2 illustrates how indoor exposures that result from an outdoor toxic plume depend, in part, on the indoor losses. This illustration is for a typical US residence (λ_{in-out} = 0.5 h^{-1}) for short and long duration (10 min and 8 h, respectively) outdoor plumes. For context, **Figure 1** shows the same short duration outdoor plume with moderate indoor losses and different building ventilation rates. Note that the vertical axis for the upper left inset chart is expanded to better illustrate the indoor concentration profiles – partly truncating the outdoor plume amplitude visibility.

A few potential airborne hazards have negligible indoor losses (blue line). Indoor exposures are initially lower than outdoor plume exposures, but eventually the two exposures become identical. This is shown in the bottom row of **Figure 2** panels where the indoor (blue) exposures converge to the outdoor (red) exposures within a 24 h time period.

Other airborne hazards have significant indoor losses (black line). For these hazards, indoor exposures always remain less than outdoor exposures. This is shown in the bottom row of **Figure 2** panels where the indoor (black) exposures remain well below the outdoor (red) exposures even after 24 h. Note the large differences in total exposures between the two outdoor plume durations, as illustrated by the integrated exposure values labeling the right-hand end of each exposure curve.

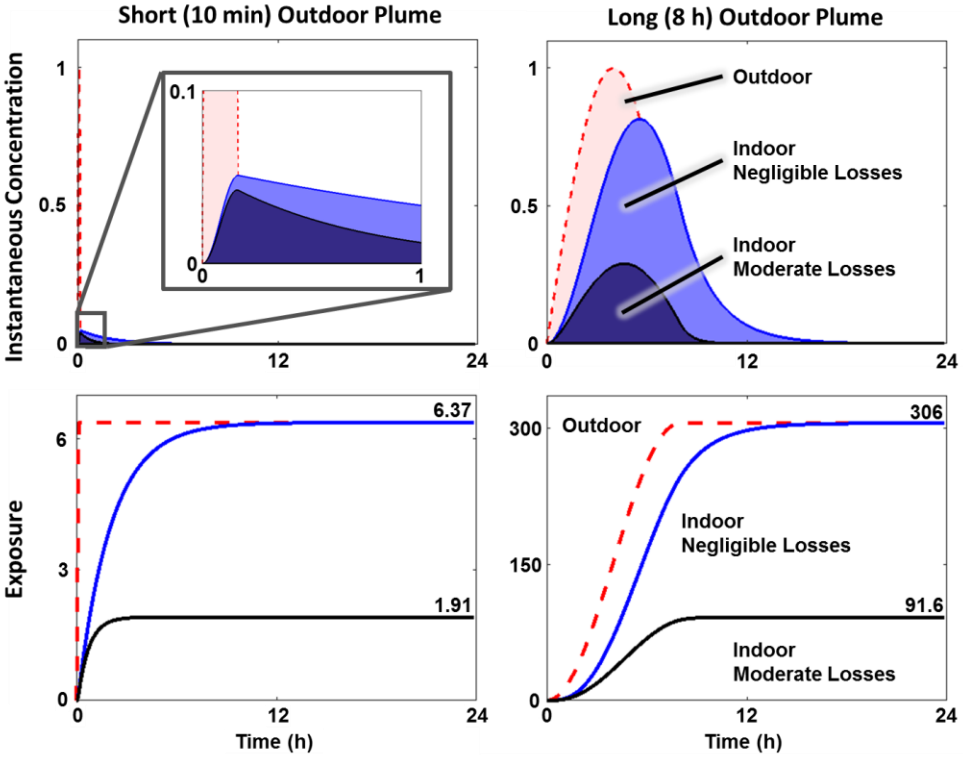


Figure 2. Concentration and exposure time-series for outdoor and indoor plumes in a typical US residence (λ_{in-out} = 0.5 h^{-1}). The left column of panels presents results for a short duration outdoor plume (10 min). The right column of panels presents the corresponding results for a long duration outdoor plume (8 h). The top row presents the concentration time-series for select indoor loss categories, see Table 2b. The bottom row presents the corresponding exposure (time-integrated airborne concentration which is equal to the toxic load with n = 1). Labels listed in the right column also apply to the left column. The outdoor plume is a sine wave with a period equal to twice the plume duration and the indoor plume is calculated from the outdoor plume and Eq. 1.

4.0 Toxic Load Exposure Metric

For some inhalation hazards, health effects are simply related to the total exposure, i.e., the time-integrated air concentration, an example of which is shown in **Figure 2**. On the other hand, for some toxic chemicals, health outcomes depend sensitively upon the peak concentrations. For these chemicals, there are a variety of mathematical models that estimate the health effects that rely on exposure metrics other than the total exposure.

To illustrate the importance of peak concentration sensitivity with respect to building protection, we use the ten-Berge toxic load equation [12], shown in **Equation 2**, as the exposure metric. A separate health effect model is used to relate the ten-Berge toxic load to the probability of a specific health outcome. The ***Regional Shelter Analysis – Inhalation Exposure Methodology*** [3] report provides more detail on other exposure metrics and their relation to health effect models.

(Equation 2)

$$Exposure = Toxic\ Load = \int_0^\infty C^n(t)dt$$

where

$C(t)$ = indoor or outdoor airborne hazard concentration at time t (g m^{-3})

n = toxic load exponent (dimensionless), and

t = time (h)

As can be seen in **Equation 2**, toxic load takes the form of an exponent on the hazard concentration. The value of the toxic load exponent determines how much more toxic high concentration (peak) exposures can be relative to low concentration exposures. Higher toxic load exponents reflect increased peak concentration toxicity. The appropriate choice of the toxic load exponent depends on the health effect model, specific airborne hazard, and health effect of interest [12], [13]. When the toxic load exponent (n) equals 1, the toxic load equation reduces to the more familiar exposure equation known as Haber's Law (as illustrated in **Figure 2**), where exposure is given by time-integrated concentration.

We use **Figure 3** to illustrate how different toxic load exponent values change the degree to which the exposure depends on peak concentrations (this is discussed on the next page). In **Figure 3**, the solid line shows an outdoor airborne chemical concentration measured at 1 s intervals.[5] The dashed line shows the corresponding 30-min time-averaged outdoor airborne chemical concentration. Note that the peak concentration of the 1 s data is a factor of ten higher than the 30-min time-averaged concentration.

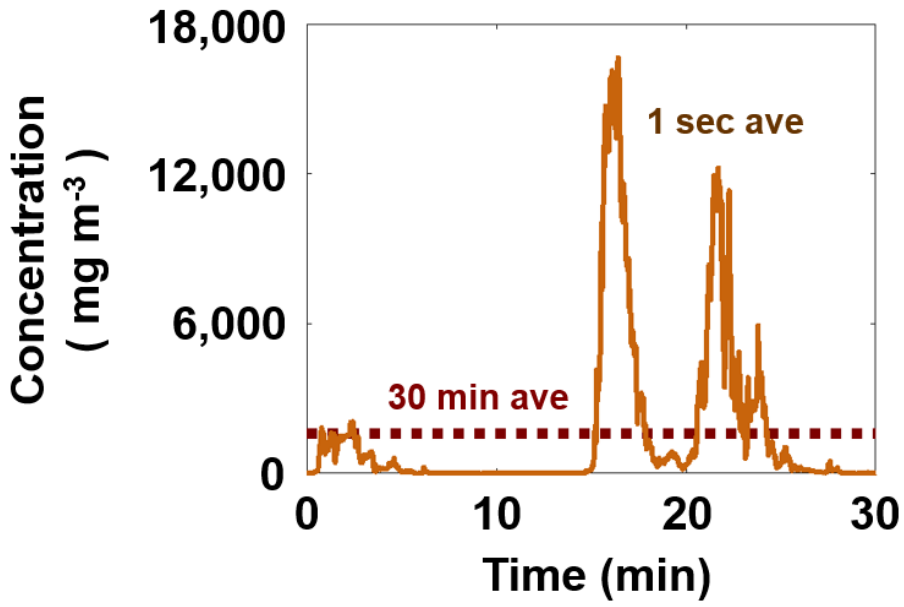


Figure 3. Concentration profile for an airborne chemical plume measured at 1 s intervals (solid orange line) and the equivalent time-averaged over 30 minutes (dashed red line)

[5] To facilitate discussion, the values shown in **Figure 3** are linearly scaled from those measured.

4.1 Radioactive Noble Gases

Many radiation health effect models relate injury to the time-integrated radiation exposure – which is equivalent to a toxic load exponent (n) of 1 [3]. Some chemical health effect models also use time-integrated airborne chemical concentrations as the exposure metric of interest. These models are said to follow Haber's Law. When the toxic load exponent (n) equals 1, the exposure is equal to the time-integrated airborne hazard concentration and the toxic load is identical for the 1 s and 30-min averaged data.

4.2 Reactive Toxic Industrial Chemicals

The acute toxicity of many reactive toxic industrial chemicals is particularly sensitive to peak concentrations.[6] For example, the *Sommerville et al.* health effect model [14] uses a toxic load exponent of 2.75 for acute chlorine gas exposures that lead to serious injury or death.

Furthermore when the toxic load exponent (n) is greater than 1, the exposure (and so health effects) depends sensitively on the concentration time series. Indeed, two different airborne hazard concentration time series can have the same time-integrated airborne hazard concentration, but considerably different toxic load values (and consequently different numbers of people affected). For example, the illustrative case shown in **Figure 3** has the same time-integrated concentration, but the toxic load for the 1 s data is 20 times greater than for the 30-min averaged data (assuming the plume is chlorine with n = 2.75). For a toxic gas like hydrogen sulfide, where n = 4.2, the difference is even greater.

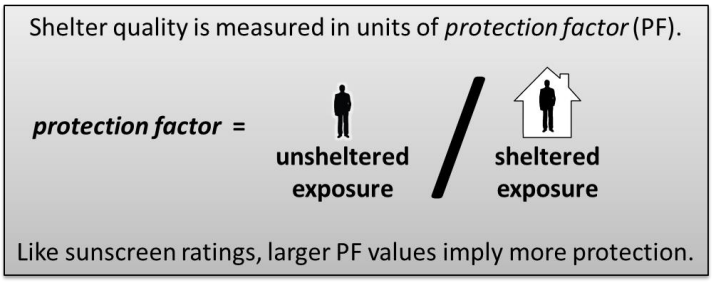
It should be noted that toxic load health effect models are typically developed assuming that exposure concentrations remain constant over a period ranging from several minutes to several hours. The use of highly time-resolved chemical exposure data, such as the 1 s data shown in **Figure 3**, to estimate health outcomes remains an area of active research [13], [15]. Indeed for some chemicals, such as carbon monoxide, health effect model parameters, including the toxic load exponent, are known to vary with the exposure duration (averaging time) [15].

For these hazards, response strategies that reduce peak concentrations, such as going or remaining indoors, can significantly reduce population exposures (toxic loads). This point is illustrated in **Figures 1** and **2** above - where the indoor peak concentrations are much lower than the outdoor peak concentrations. Building protection and response strategies are discussed in more detail below.

[6] Note that relatively non-reactive chemicals, such as carbon monoxide, can also be toxic.

5.0 Building Protection Definition

The protection buildings provide their occupants can be measured in units of protection factor. Protection factor (PF) is defined as the ratio of the unsheltered (outdoor) to sheltered (indoor) exposure. Similar to sunscreen and personal protective respirator rating systems, higher protection factor values indicate lower exposures and thus increased protection.



6.0 Building Protection Rules of Thumb

The model developed in this report illustrates several important points with respect to how well buildings protect indoor individuals from hazardous outdoor plumes. These points are listed below and are depicted in **Figure 4** which shows illustrative building protection values for a wide range of buildings, airborne hazards, and outdoor plume parameter values.

In each individual panel of **Figure 4**, the x-axis represents the range of the importance of peak airborne hazard concentrations to the hazard toxicity, i.e., the toxic load exponent n. The y-axis represents the building protection factor, i.e., the ratio of outdoor to indoor exposure. The different line color shading in the figure, ranging from dark to light, indicates a series of different indoor/outdoor air exchange rates (λ_{in-out}), corresponding to 0.2, 0.5, 1.5, and 4 h^{-1} respectively. Each line in the panel graphs represents one of the four illustrative building types discussed in **Table 2a**. For additional context, the airborne chlorine and radioactive noble gas (^{85}Kr) building protection values are shown as diamonds and circles in the middle and left column panels, respectively.

For this illustration, individuals are assumed to be inside before the outdoor plume arrives and stay inside the building for 24 h. Note that **Figures 1** and **2** presented earlier show the time-series for the outdoor and select indoor hazard air concentrations corresponding to the airborne chlorine gas exposure case (moderate indoor losses) shown in the middle column of **Figure 4**.

In the rare case of an inert gas with negligible loss mechanisms (e.g., ^{85}Kr), indoor exposures are initially lower than the outdoor plume, but eventually the long term time-integrated indoor exposure would approach the outdoor exposure, except as discussed below in the *(7.0 Ending Shelter)* section.

Building protection *improves* with:

1) *Increasing indoor losses ($\lambda_{internal}$, L_{in-out})*

   The faster the airborne hazard interacts with materials inside the building or while in transit through the building shell, the less toxic material remains airborne indoors and the more inhalation protection buildings provide their occupants, see **Figure 2**.

2) *Increasing sensitivity to peak airborne hazard concentrations (n)*

   Buildings reduce peak concentrations of airborne hazards, see **Figures 1** and **2**. As a consequence, buildings provide increased protection to their occupants as peak concentrations become more toxic, i.e., as the toxic load exponent increases.

Building protection *decreases* with:

1) *Longer outdoor plume duration*

   Longer duration outdoor plumes allow more time for additional toxic material to infiltrate indoors.

   Therefore when indoor losses are present and/or inhalation toxicity is particularly sensitive to peak concentrations (i.e., n > 1), longer plume durations decrease the protection buildings provide their occupants relative to shorter plume durations.

2) *Higher indoor/outdoor air exchange rates (λ_{in-out})*

   The faster contaminated outdoor air enters the building, the higher the indoor concentrations become.

   Therefore when indoor losses are present and/or inhalation toxicity is particularly sensitive to peak concentrations (i.e., n > 1), buildings with high indoor-outdoor air exchange rates provide less protection to their occupants relative to buildings with low indoor-outdoor air exchange rates. We note that increasing the indoor/outdoor air exchange rates after the plume has passed, i.e., ventilating the building with clean outdoor air, can increase the building protection, although, as discussed in the next section, the degree of increase can depend on the hazard.

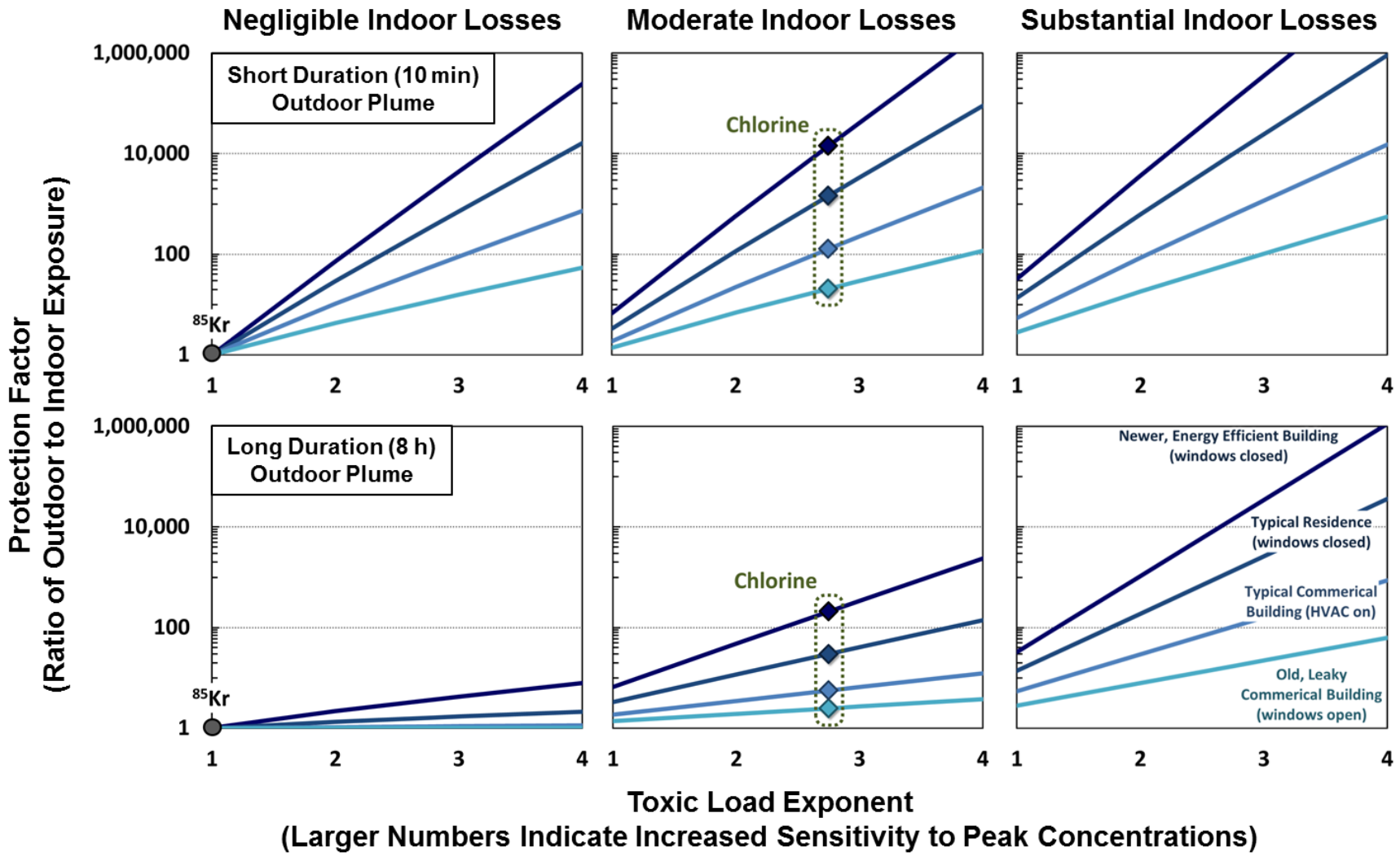


Figure 4. Building protection factors for a 24 h integration time for illustrative building types and airborne hazards. The top row of panels presents results for a short duration outdoor toxic material plume (10 min). The bottom row of panels presents the corresponding results for a long duration outdoor plume (8 h). Each column of panels represents a different indoor loss category ($\lambda_{internal}$, L_{in-out}) corresponding to the values provided in Table 2b. Line labels listed in the bottom right panel also apply to the other panels. The outdoor plume is a sine wave with a period equal to twice the plume duration and the indoor plume is calculated from the outdoor plume and Eq. 1.

7.0 Ending Shelter

Sheltering, defined as going or remaining indoors while hazardous outdoor conditions are (potentially) present, is a well-established protective action. However at some point, indoor individuals will leave the building, i.e., end sheltering. In this simplified conceptual model, optimally individuals should leave the building when indoor concentrations become higher than outdoor concentrations, see **Figures 1** and **2**. Alternatively, the building could be ventilated with clean, outdoor air by (a) opening windows/doors and/or (b) using the HVAC system to rapidly exchange indoor/outdoor air after the outdoor plume has passed. Note that the building protection examples provided here are based on normal building operations during the event, e.g., the HVAC systems are not turned off.

The benefits to ending shelter in a timely fashion greatly depend on the building and hazard characteristics.[7] This is illustrated below in **Figure 5** using two different types of hazards.

Radioactive Krypton 85 (^{85}Kr)

Ending shelter in a timely manner is important to obtain significant benefits for the case in which the inhalation hazard is not lost within the building. Indeed, when the hazard toxicity depends solely on the time-integrated airborne concentration, e.g., a radioactive noble gas such as ^{85}Kr that has an effective toxic load exponent of 1, remaining indoors well after the plume has passed results in no building protection, see **Figure 2**.

The top panel of **Figure 5** illustrates this case by showing that the protection factor approaches 1 (no protection) within 1 to 8 hours after the outdoor plume has passed, depending upon the ventilation rate. Exiting the building shortly after the plume has passed – assuming it is safe to do so – results in the largest building protection factor. At the same time, buildings with smaller air exchange rates reduce the importance of ending sheltering immediately after the outdoor plume has passed.

Reactive Toxic Industrial Chemicals

Ending shelter in a timely manner is less important when sheltering from inhalation hazards, such as chlorine, that are (a) readily lost within the building and/or (b) whose toxicity depends strongly upon the peak concentration (toxic load exponent > 1), see **Figure 2**.

The bottom panel of **Figure 5** illustrates this case by showing the protection factor remains elevated (> 1) after the outdoor plume has passed.

Thus much of the benefit of sheltering within a building will remain even if individuals end sheltering many hours after the outdoor plume passes by. Indeed for this case, the building protection factor essentially does not change with time after the first hour.

[7] It may also depend on other considerations, including the potential for secondary or lingering outdoor plumes or other hazards. These considerations, while potentially important, are beyond the scope of this discussion.

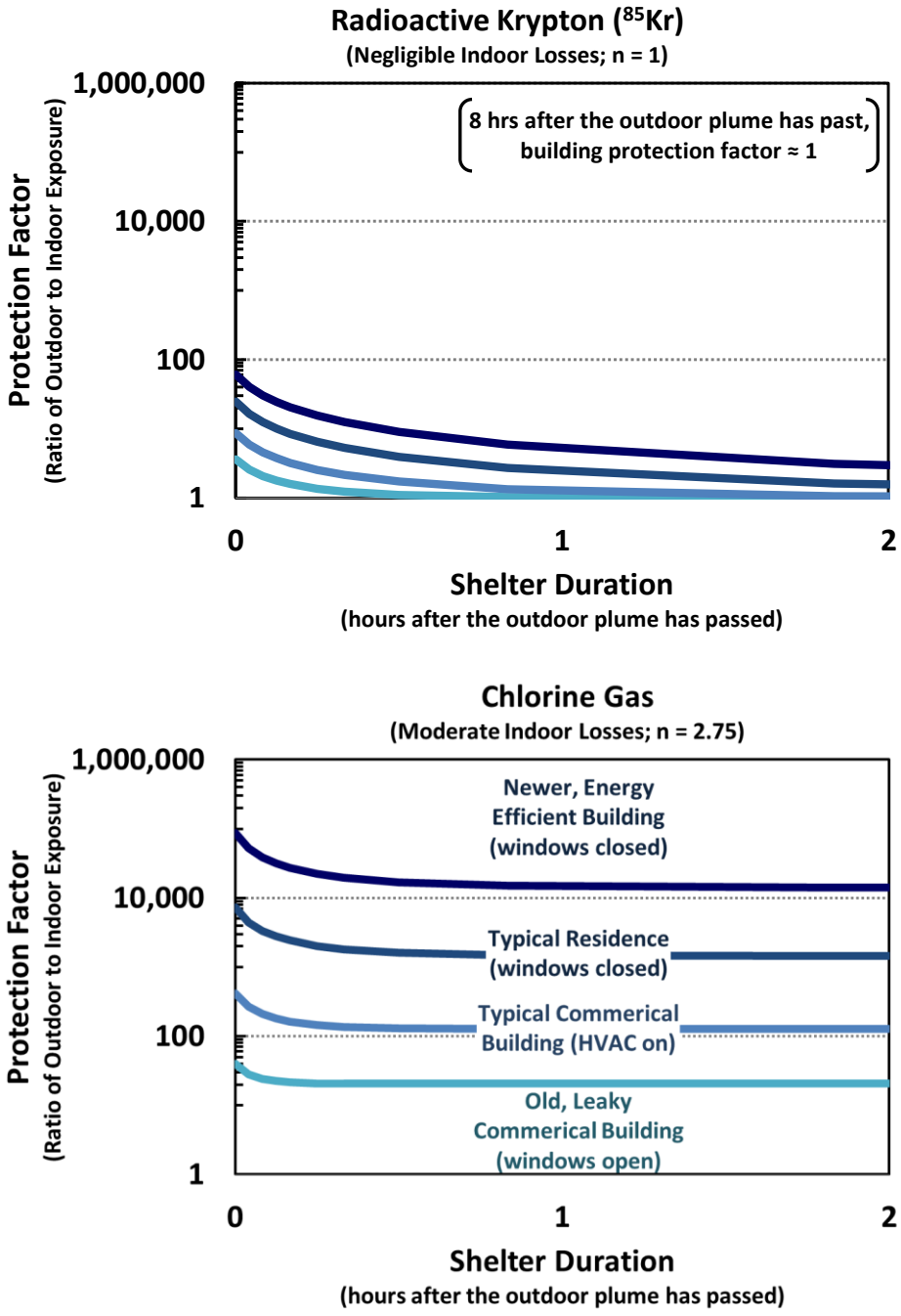


Figure 5. Building protection factors as a function of time spent in a building after a 10 min duration outdoor plume has passed. The top panel presents the building protection for a hazardous gas, such as ^{85}Kr, that has no indoor losses and whose toxicity depends on the time-integrated airborne hazard concentration (n = 1). The bottom panel presents the corresponding building protection for chlorine gas which has moderate indoor losses and an acute toxicity sensitive to the peak chemical concentration. Line labels shown in the bottom panel also apply to the top panel. The outdoor plume is a sine wave with a period equal to twice the plume duration and the indoor plume is calculated from the outdoor plume and Eq. 1.

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Attestations

Ethics statement

No humans or animals were used this in work

Data accessibility

No primary data were used in this analysis.

Competing interests

The authors have no competing interests for the material provided in this manuscript beyond (a) being and/or previously employed at our respective organizations and (b) receiving funding from the acknowledged sources.

Author's contributions

Michael Dillon (MBD) was responsible for the report concept and design, theory and manuscript development, and revision.

Richard Sextro (RGS) contributed to the theory development, manuscript development, and revision of this report.

All authors give approval for publication.

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