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Regional Shelter Analysis – Inhalation Exposure Methodology

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Abstract

During normal operations, buildings can protect their occupants from outdoor hazards, including airborne pollutants. Purposeful sheltering increases this protection. A long-term international research effort has advanced our knowledge of building protection physics. However, an operationally efficient, regional-scale methodology to account for US building protection effects is not available. Such a method is necessary because (a) the overwhelming majority of the US population is indoors at any given time and (b) a regional-level building protection methodology could better estimate populations truly at risk in emergencies, support improved decision-making (shelter vs. evacuation decisions), help guide resources towards those most at risk, and improve population level dose-response relationships, which are often derived by estimating ambient (outdoor) exposures and then tuning dose-response relationship parameters to best match the distribution of illness reports.

The Regional Shelter Analysis (RSA) methodology provides a comprehensive, yet operationally efficient method for population-based risk analyses. Specifically, it accounts for (a) building protection distributions (within and among different buildings) and (b) population postures (how people are distributed within and outside of buildings). It can generate predictions to support decision makers simultaneously on multiple operational levels, ranging from individual buildings and neighborhoods to larger regions. The method employs existing building and population databases and is compatible with many modern exposure and injury assessment tools.

This report develops the RSA methodology and discusses general operational considerations, with a focus on inhalation exposures. To place this work in the context of prior efforts and current initiatives, a focused literature review is provided that identifies the relevant literature, theory, scientific findings, and datasets from a variety of scientific fields. Planned follow-on reports will discuss (a) the external radiation exposure pathway and (b) specific RSA implementations.

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1. Introduction

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.[1] This report considers building protection from the inhalation exposure pathway, for airborne gases and/or particles.[2]

Because, on average, the US population spends about 87%, 8%, and 5% of their time indoors, outdoors, and in vehicles, respectively [1], it is essential that population-level public health and emergency response exposure and risk assessments incorporate an accurate building protection component. However, as discussed in the (*2. Historical Perspective*) section below, building protection considerations are often limited (or entirely omitted) in current exposure and casualty assessments. This may be due, in part, to the complexity of the problem, as a comprehensive solution needs to address building construction and operations, population distributions (both within individual buildings and among different buildings in a given region), exposure pathways, hazard dose-response relationships, and a variety of potential health outcomes. Regardless, US Federal exposure assessments may assume that exposed individuals are outdoors and

[1] Unless otherwise noted, we interchangeably use the term outdoors, unprotected, and unsheltered to simplify the discussion. Individual outdoor exposures can, and do, vary for a variety of reasons. The theory developed in this report is capable of handling regional variation in both outdoor and indoor exposures.

[2] We note that other exposure pathways exist, e.g., ingestion of contaminated food, which are not included in the present analysis.

so do not account for building protection considerations, e.g., [2]–[8].[3] Because of this, exposure assessments can over-estimate population exposures and risks – which is potentially problematic as protective actions could be applied to a much broader population than required. In situations in which only limited resources are available, the use of outdoor-only assessment models and / or imprecise building protection modeling could inadvertently allocate resources to low risk populations and so reduce the levels of assistance provided to the populations most at risk or most amenable to assistance [16], [17]. Further, population level dose-response relationships, often derived by estimating ambient (outdoor) exposures and then tuning dose-response relationship parameters to best match the distribution of illness reports, may underestimate an exposure hazard's true potency.

The Regional Shelter Analysis (RSA) methodology described here aims to partially address these issues. Initially developed as a stand-alone tool, elements of the RSA methodology are currently being integrated into operational emergency response models including the US Department of Energy National Atmospheric Release Advisory Center (NARAC) and US Department of Defense Hazard Prediction and Assessment

[3] The (a) US Environmental Protection Agency/National Oceanic Atmospheric Administration Areal Locations of Hazardous Atmospheres (EPA/NOAA ALOHA) and (b) US Department of Defense Hazard Prediction and Assessment Capability (DoD HPAC) models contains an optional (a) indoor exposure and (b) external radiation protection capabilities, respectively [9]–[13]. Similarly, the United Nations, US EPA, and the US Department of Energy, including the National Atmospheric Release Advisory Center (NARAC) model, provide optional, operational estimates to which indoor populations are shielded from outdoor radiological hazards [2], [14], [15]. All of these cases, except HPAC and NARAC which are in the process of upgrading their building protection capabilities, using elements of the RSA method, use single estimates for broad, building-class-based categories, e.g., residential vs. commercial buildings, rather than the more relevant protection factor distributions for detailed building classes or types.

Capability (HPAC). This RSA method thus represents a new, operationally feasible model that incorporates both building protection and population distributions - in contrast to most prior work, which has primarily focused on elucidating the processes and parameter values to assess (and improve) individual building protection.[4] The RSA methodology is intended to provide practical assistance to government officials in designing and implementing multi-hazard, multi-exposure pathway strategies that reduce population exposures to many important types of hazardous materials – both for emergency situations requiring rapid decisions, e.g., sheltering, evacuation, remediation, and/or relocation, as well as for public health responses to ongoing chronic hazardous exposures, e.g., [20]–[25]. Such an integrated analysis framework may be of practical use when minimizing acute (emergency) and chronic hazardous exposures through changes in the building protection and changing population locations. These could be accomplished in advance of actual emergencies through changes in zoning and building code standards; urban and transportation planning; and developing in advance plans for moving at-risk populations using sheltering, evacuation, and relocation strategies [7], [14], [15], [26], [27]. The RSA method is (a) spatial scale independent (suitable for use on scales ranging from individual rooms, buildings, neighborhoods, cities, to entire countries), (b) flexible (applicable to for radiological, chemical, and biological hazards), (c) compatible with current building and population databases as well as most current exposure and health effect models and measurements, and (d)

[4] As discussed further in the (*6. Discussion*) section, accounting for distributions of building protection can be critical for accurate assessments as the degree of protection provided by buildings can be highly variable, both within a given building and among different buildings, see [18], [19].

computationally efficient during operational use (the RSA methodology typically determines the distribution of indoor exposures by multiplying the outdoor exposure(s) by a set of predetermined linear scaling factors).

This report is part of a series of reports describing the Regional Shelter Analysis methodology and application. This report, which focuses on inhalation exposures, describes (a) prior key building protection and sheltering research, (b) the physical basis of building protection, (c) the general RSA methodology, which combines the protection provided by buildings with the population distribution within and among the different buildings, and (d) general, operational equations for calculating population impacts. **Supplemental Material S1** derives additional building protection factor equations suitable for certain important cases. Separate reports will (a) detail the application of the RSA method to inhalation exposures [19], (b) extend the RSA methodology to external gamma radiation exposures [28], and (c) illustrate, for planning officials and a general scientific audience, the key considerations that govern building protection against inhalation hazards [29].

2. Historical Perspective

This section provides the historical context of both (a) the scientific understanding of building protection against hazardous materials and (b) the use of building protection, including sheltering, within the context of public policies and practice. Historically, this information has been developed in disparate fields and therefore this section is divided into subsections based on the hazard of interest: (a) radiological, (b) acute chemical, (c) chronic chemical (i.e., air quality), and (c) biological airborne hazards. In this section, we make particular note of (a) key theoretical concepts and (b) the strengths and weakness of existing theory and data. Prior building protection approaches are reviewed here at a general level. The (*5. Hazard-Specific Health Effect Considerations*) section below (a) provides more detail on the current, hazard specific approaches and (b) explains how these approaches relate to the RSA methodology. We note that due to the large volume of prior work, this report highlights key literature and data, but does not provide a comprehensive review of all prior work.

2.1. Radiological Inhalation Hazards

In the 1950s, the US government initiated a civil defense program intended to mitigate the consequences of a nuclear explosion on its homeland [30]. The principal focus of that program was the mitigation of the hazard posed by fallout radiation, i.e., external gamma radiation. A companion report summarizes this literature and related studies [28]. Starting in the late 1960s, the nuclear fallout shelter assessment capabilities were adapted and extended for use in planning for, responding to, and remediating nuclear power plant (NPP) accidents and radiological dispersal devices (RDD). As part of that

extension, *Slade* [31] provided the initial theoretical basis for assessing building protection from the inhalation of radioactive gases and airborne particles [31]–[34]. These early efforts may have had limited utility due, in part, to the limited understanding of many practical details, such as the specifics of indoor losses of airborne hazardous materials through mechanisms including, but not limited to, deposition to indoor surfaces. These limitations, and the practical difficulty of accurately estimating building protection for a specific location, resulted in the early guidance that expressed strong concern about the practical feasibility of obtaining any benefit (or accurately estimating the exposure reduction) from sheltering within a building [32], [35].[5] During this period, shelter came to be regarded as a low-cost, low-risk alternative for situations in which evacuation was not appropriate, e.g., severe weather, damage to transportation infrastructure, immobile populations (e.g., the injured, institutionalized, and/or elderly), and/or insufficient evacuation time [35]. Improvements in scientific understanding and a desire for a consistent, all-hazards response have resulted in the modern guidance that recommends shelter be considered in a broader array of situations, often in concert with other protective actions including evacuation [14], [15], [36].

[5] As one example, early researchers were concerned about the perceived importance and practicality of ending shelter, e.g., opening windows/doors, when the outdoor plume has passed. For certain airborne hazards, such as radioactive noble gases, the failure to stop sheltering in a timely manner can result in no inhalation protection. We note, however, that buildings continue to provide protection against gamma rays (external exposure) from the passing airborne radioactive cloud, the dominant radiation exposure pathway for some radioactive noble gases. In addition, buildings provide significant protection against other classes of hazards, such as airborne particulates, that have significant indoor losses even if sheltering ends well after the plume has passed. See *Illustration of Key Considerations Determining Hazardous Indoor Inhalation Exposures* [29] for more detail.

This historical trend in planning policy parallels the use of shelter as a protective action in responding to NPP accidents. The response to the Three-Mile-Island accident used evacuation as the primary protective action [37]. Similarly, sheltering was not significantly used during the response to the Chernobyl accident [38]; however, *Likhtarev et al.* [39] estimates that its use would have halved the collective radiation dose for individuals within 30 km of the reactor and it is reasonable to expect that individuals who were indoors for all or part of the time that the radioactive plume passed by experienced reduced radiation exposure relative to those standing outside, Subsequent research supports this view and recommends more nuanced shelter-evacuation strategies depending on the extent of the release and other relevant conditions [36]. The response to the Fukishima accident used a combined shelter-evacuation strategy in which populations at successively greater distances from the NPP were initially sheltered and later evacuated [40], [41].

We note that despite the known importance of the inhalation exposure pathway in many radiation exposure scenarios [15] and the increased use of shelter as a protective action, improving currently available building protection estimates for radiation inhalation exposures is not typically prioritized for future capability, e.g., [42]. Indeed even retrospective dose assessments, such as for Fukushima [43], neglect building protection benefits during the response (plume) phase.

2.2. Acute Chemical Inhalation Hazards

Beginning in the mid-1980s, there was a marked increase in toxic chemical related shelter research with the aim of developing (a) more accurate consequence assessments and (b) effective response strategies. This surge of interest was due, in large part, to the increasing concern that an accidental chemical release could harm people living near a major industrial facility, the US chemical weapon stockpile, or along transportation routes, see [27], [44]–[49] and references therein. These scenarios, in contrast to the NPP scenarios discussed above, often assumed that there was limited time to warn at risk populations, greatly reducing the utility of evacuation as a protective action [45], [47], [50]. Research during this period also recognized that buildings provide particularly effective protection against outdoor airborne hazards when the health effects of these hazards depends sensitively upon peak concentrations [51], see also *Illustration of Key Considerations Determining Hazardous Indoor Inhalation Exposures* [29]. As such, casualty reduction research and guidance development focused on sheltering based strategies, both with respect to (a) devising building modifications and practices that enhance occupant protection (e.g., temporary, expedient, and enhanced shelter practices; safe rooms) and (b) designing population warning systems [27], [52]–[59].[6]

[6] Retrospective analysis of major events shows the potential community advantage of effective shelter from hazardous releases. In the 1984 Bhopal India chemical release incident, significant casualties occurred in part because the population was unwarned and the typical light residential building construction provided little protection. In contrast the large scale urban petroleum storage tank explosion and fire in Hertfordshire, UK in 2005 caused significant physical damage to the surrounding communities; however there were no deaths and only 43 injuries due to an effective shelter-evacuation strategy [60].

The dispersion of outdoor, airborne chemicals over population centers and their associated built environment(s) remains a major ongoing concern, e.g., [60]–[62]. Specific events are often tracked and include atmospheric chemical releases due to transportation accidents and chemical releases from fixed industrial sites (including unintentional releases due to power failure, equipment malfunction, explosions, fire, and natural disasters) [63]–[70], volcanos [71]–[73], and wildfires [74]–[77]. This collective experience has also provided the foundation for chemical emergency response guidance documents, public health risk assessments, mitigation planning, and abatement efforts, e.g., [60]. More recently, researchers have focused on characterizing how indoor air concentrations (and thus building protection) depend on the degree to which various airborne materials are lost to indoor surfaces (deposition, sorption) and, to some extent, are potentially re-emitted back into the air through resuspension, evaporation, and/or desorption, e.g., [78] and references therein.

Modern national and international level chemical hazard emergency response guidance recommends sheltering as a protective action, e.g., [7], [27], [60], [79], and sheltering is also recommended in authoritative reviews of medical emergency response to chemical emergencies, e.g., [80]. Assessments of the protection afforded by generic buildings are not uncommon as (a) several chemical hazard modeling programs, e.g., NOAA ALOHA, allow their users to estimate indoor exposures for individual buildings [9] and (b) advanced capabilities exist to estimate building protection for specific buildings and chemicals, e.g., [81], [82]. However, there have been few studies that have considered

the range of building protection estimates associated with typically encountered buildings or cities. The notable exceptions are (a) the *Barrett and Casman* [83] cost-benefit analysis of shelter-in-place improvements and (b) the *Chan et al.* [84], [85] method that estimates the distribution of US shelter-in-place efficacy for residential and office building types. Neither example is in wide operational use. Finally, unlike the situation with radiological hazards, we are unaware of any current formal, officially established guidance in this area for building protection estimates.

Sheltering strategies are also recommended for ambient exposures that convey imminent danger of major acute health effects. For example, in wildfire emergencies acute smoke inhalation injuries and fatalities are a primary concern, although more chronic health effects may also occur [75], [86]. As a consequence, sheltering is recommended against atmospheric smoke inhalation [74], [87]. Indeed, wildfire public health guidelines recommend high-risk localities establish community-level Cleaner Air Shelters - such as large commercial buildings, educational facilities, shopping malls – i.e., built environments with effective air conditioning and particle filtration capabilities [74]. The relative merits of sheltering vs. evacuation strategies for wildfire scenarios has also been reviewed [88], [89]. Currently efforts are also underway to improve wildfire protective shelter designs on a community as well as an individual level [90]–[92].

2.3. Air Quality Hazards (Including Airborne Chronic Chemical Hazards)

Air quality (AQ) problems, and the need to control them, have been recognized since antiquity [93]. Ancient, medieval, and modern societies have all faced AQ issues related to urbanization [94]–[96]; energy generation, e.g., combustion byproducts [97], [98];[7] and industrial activity, e.g., heavy metals aerosols [100]–[102]. However, it was only after WWII that the concerted scientific effort to address air quality began, in part, as a response to a series of serious air pollution incidents.[8] As discussed in *Stanek et al.* [106] and *Bachmann et al.* [109], these serious events occurred against a background of preexisting concerns about urban air quality and both sets of experiences informed the modern US air pollution legislation and standards first established in the 1970's. The US air pollution efforts have focused primarily on reducing the frequency and intensity of hazardous conditions by first identifying a key set of (criteria) pollutants[9] and then reducing their source emissions, or their precursors, into the atmosphere. This approach has posed significant scientific, regulatory, and implementation challenges as the actual toxic exposure received is often the result of individuals moving within temporally and spatially varying mixtures of toxic airborne species. Furthermore, these pollutants, or

[7] Some of the long struggle in London, UK to control toxic urban air pollution from high sulfur content coal combustion has been graphically documented [99].

[8] Specifically the 1948 Donora, PA industrial air pollution emergency; the emergence of noxious photochemical smog in the Los Angeles basin in 1943-1946; and the London Fog Emergency of 1952 [103]–[106]. Of some 14,000 persons in Donora, an estimated 43% became ill, 1,380 of them severely, and 400 required hospitalization. There were 20 acute deaths. The 1952 London "Fog" was a larger scale event and air pollution-related deaths were estimated at 4,000, but this may have been three times higher [105], [107]. Industrial chemical disasters have continued to trigger new regulatory standards since these initial earlier events, see Table 2 in *Blakey et al.* [108].

[9] Key pollutants of interest include, but are not limited to, $PM_{2.5}$ and PM_{10} (airborne particulate matter with aerodynamic diameters less than 2.5 and 10 microns, respectively), SO_2, NO_2, CO, O_3, and airborne metals such as lead [109].

their precursors, often originate from multiple and/or diffuse sources rather than from a single, well-defined release location.

In response to these challenges, research efforts have contributed to developing the scientific infrastructure prerequisite to population-based AQ exposure and risk assessments. Significant developments include increased understanding of atmospheric (tropospheric) chemistry and physics, e.g., [110]; models that predict gas and particle transport within the atmosphere, e.g., [5], [111], [112], and indoor environments [81], [82]; air and pollutant exchange between the indoor and outdoor environments, e.g., [84], [85], [113]–[120]; population-level databases of the distributions for human activity patterns, e.g., [1], [121], [122]; methodologies for simultaneous indoor, outdoor and personal level exposure monitoring, e.g., [25], [123]; characterization of the major health effects of low and high concentration atmospheric chemical exposures, e.g., [124], [125]; and methods to reduce indoor exposures to outdoor origin pollutants, e.g., [126], [127].

The earliest air quality health effect studies measured ambient outdoor pollutant concentrations and inferred health effect outcomes without explicitly considering the built environment [128], [129]. This approach is less sensitive than studies that incorporate building protection factor adjustments or personal-level air monitoring. However, it remains in general use in epidemiology [124], [130]–[132] and is sufficient to establish general-level associations between ambient (outdoor) air toxics exposures and human morbidity, mortality and many specific health effects, see the (*5.2. Chemical*

and Air Quality Hazard Health Effects) section. Subsequent research, including work in the related fields of indoor air quality and building energy efficiency, have established that, relative to being outdoors, indoor individuals can be exposed to significantly less outdoor-origin pollutants, see [133], [134] and references therein. [10] Several authors have compiled summaries of observed ratios of indoor to outdoor airborne hazard, primarily particulate, concentrations – which are often used as surrogates for building protection against outdoor-origin hazards, e.g., [137], [138]. However the interpretation and use of these datasets is challenging since (a) significant indoor emissions exist in particular instances , (b) building protection can vary significantly with particle size – requiring often unavailable finely resolved particle size measurements, and (c) a commonly used analysis approach can result in biased results [139]. More rigorous experimental techniques exist based on the specific mechanisms by which outdoor airborne pollutants are transported indoors as well as estimates of many of the relevant parameter values [24], [120], [133], [134], [140].[11] These techniques broadly agree with modeling approaches, e.g., [141], [142]. Due to the known importance of the built environment in reducing exposure to ambient atmospheric hazards, more AQ scientific research studies now incorporate some form of building protection into models and risk

[10] Indoor air quality is a significant parallel body of scientific work, e.g., [135]. While indoor-generated gas and aerosol hazards are beyond the scope of this report, they can pose substantial health risks – sometimes causing indoor pollutant concentrations to exceed outdoor concentrations and even dominating the overall health risk for indoor individuals [133], [135]. This has been observed for many pollutants including NO_2, $PM_{2.5}$, and PM_{10} [133], [134], [136].

[11] These include building-specific infiltration and penetration factors; meteorological factors (building pressurization effects, temperature, and humidity); indoor particle deposition and resuspension rates, absorption, desorption; air exchange rates and filtration factors, among others. A companion report [19] provides an analysis of these mechanisms and key parameters as well as improved estimates of building protection for a variety of US building types.

assessments at both local community and regional scales, e.g., [22], [25], [123], [143]–[146]. These studies typically use locally relevant building protection estimates. Two notable exceptions are (a) the National US Air Toxics Assessment which analyzes US population-level acute and chronic health effects in relation to ambient air exposure concentrations for more than 100 toxic airborne chemicals and uses national protection estimates [147], [148][12] and (b) an assessment of the spatial distribution of UK residential indoor exposures to both outdoor and indoor origin air quality hazards [145], [146].

Population sheltering strategies and existing population building protection factor distributions have had a limited role in public health and emergency planning for air pollution. Formal air pollution monitoring of criteria pollutants and public hazard advisories have been in use in the US since 1976 when the Pollutant Standards Index (PSI) was introduced [151]–[153]. Currently the US Air Quality Index (AQI), the successor to the PSI, provides advisories for criteria pollutants [154], [155] and there are similar indices in many countries [156], [157]. The US Environmental Protection Agency primarily recommends reduction in physical activity level, i.e., reducing individual breathing rates and thus net inhalation exposures, when AQI levels are unhealthy [154], [155]. We note, however, that indoor sheltering is recommended for sensitive groups (asthmatics and persons with respiratory illness) when particulate pollution is at

[12] The US Environmental Protection Agency Hazardous Air Pollutant Exposure Model (HAPEM) used for the NATA study provides a framework for nationally representative estimates of building protection (termed microenviroments), but is limited by input data availability and analysis complexity [136], [149], [150]. See the (*5.2 Chemical and Air Quality Hazard Health Effects*) section below.

hazardous levels [155], [158]–[160]. In addition, national-level public health sheltering guidelines exist for persons with allergic sensitization to pollen, a condition that affects a significant fraction of the US population [161]–[164]. When outdoor pollen counts are high, these guidelines advise sensitive individuals to stay indoors and to close windows, preferably remaining in an air-conditioned environment.

2.4. Biological Inhalation Hazards

Airborne particles containing biological material can originate outdoors, infiltrate indoors, and be inhaled by building occupants, e.g., [165]. The fungal pathogen species *Aspergillus*, including *fumigatus* and *flavus; Histoplasma capsulatum;* and *Coccidioides immitis* are important examples, with *Aspergillus* species posing a particularly severe risk for institutionalized and/or immune compromised individuals [166]–[173]. Significant effort has gone into medical facility construction design and protective measures to reduce the degree to which airborne infectious particles will be inhaled by building occupants - and so reduce the probability of hospital infections, e.g., the US Centers for Disease Control and Prevention guidelines [174], [175]. There is also concern for bioterrorism impacts and the risks associated with biomedical laboratories [59], [176]–[183]. In the event of an airborne biological hazard, sheltering is an accepted protective action for humans [184] and has been contemplated for livestock protection [185]; but it is not emphasized within current US guidance [184]. However, as previously noted, modeling capabilities exist that can be used to estimate building protection for specific buildings, e.g., [81]. For context, *Yuan* [182] suggests that typical residences and commercial buildings reduce biological inhalation exposures by a factor of 2 and 50, respectively.

For biological hazards, the authors are unaware of any accepted guidance that provides broadly applicable estimates for the appropriate choice of building protection beyond those discussed in the (*2.1. Radiological Inhalation Hazards*) section above – although we note that the current literature does contain useful data for individual site-specific

studies of selected bioaerosols, for example comparisons of ambient atmospheric pollen concentrations to their indoor levels at selected sites [186]–[188] and site-specific studies of outdoor vs. indoor concentrations of other bioaerosols [189]–[191]. Indeed despite its known relevance to understanding (and potentially managing) disease outbreaks that extend many kilometers downwind from a source of airborne pathogens, including but not limited to *Legionella* [192]–[195] and *Coxiella burnetii* (Q-Fever) [196]–[200]; building protection does not appear to be considered in most biological hazard risk assessments. For example, in a recent comprehensive review of the existing pathogenic, bio-aerosol dispersion modeling literature, only two studies were included that considered the degree to which indoor individuals may be exposed to different levels than outdoor individuals and no general theory was discussed [201].

2.5. Building Characteristics, Populations, and Geographic Distributions

An RSA exposure assessment requires characterizing (a) the building protection of different occupied buildings, (b) the variation of protection within any given building as well as (c) the distribution of people among and within different building types, e.g., see [202]–[205]. The first two items require identifying and characterizing key building attributes, see the (*3. Building Protection Physics*) section. The latter requires understanding the purposes for which the building is used (also called occupancy). Complicating the calculations further, each of these factors can vary over time. For example, building operating conditions can change; and many cities have a daily migration pattern between outlying residences and commercial buildings in the urban core. There is currently a substantial, yet incomplete, set of databases to estimate these parameters, which are summarized here to provide context to the later development of the RSA method.

Prior research on time use has tracked where and how people spend their time during a normal day. As previously mentioned, these studies have been performed over many decades and in numerous countries, e.g., [121], and provide the foundation for characterizing the degree to which different types of buildings are occupied at various times. Natural hazard, e.g., earthquake, planning and response tools have extended these time use study results by correlating time use categories with the geographical distribution of building structural characteristics. *Brzev et al.* [206] and *Gamba* [207] provide a recent survey of global, regional, and local building databases (for the purposes of earthquake risk assessment) including key considerations on their use

within an integrated analysis framework similar to that discussed here. We note that more detailed population estimates, either through examining individual building databases or harvesting social media, e.g., [208], are becoming available.

To provide the reader context for this report, we summarize here a few notable examples of local and regional building databases that provide structural and/or population attributes. The US Geological Survey's Prompt Assessment of Global Earthquakes for Response (PAGER) system provides estimates of how global populations are distributed into each of 89 model building types (e.g., small, lightweight wood frame; unreinforced masonry) and 2 building occupancy types (i.e., residential, non-residential) within the urban and rural regions of each country [209]–[212]. The related US Department of Homeland Security HAZUS model provides similar, but higher fidelity, estimates for US populations with 45 building construction and 33 building occupancy types delineated at US Census tract and Census block scales [58], [213]–[215]. [13] The US Census, US Department of Energy, US Environmental Protection Agency, and independent researchers provide additional, supplemental information on US residential and commercial building properties and occupancy, although many of these sources have limited geographic distribution information [118], [216]–[222]. In other countries, similar broad area information is also available [207]. Finally, detailed construction and occupancy information on large numbers of individual buildings is

[13] Nominally HAZUS has 36 distinct building construction types. However, 6 building types may have basements. In this report we have separated the buildings with basements into separate building types. HAZUS also defines outdoor and transportation (commuting) locations.

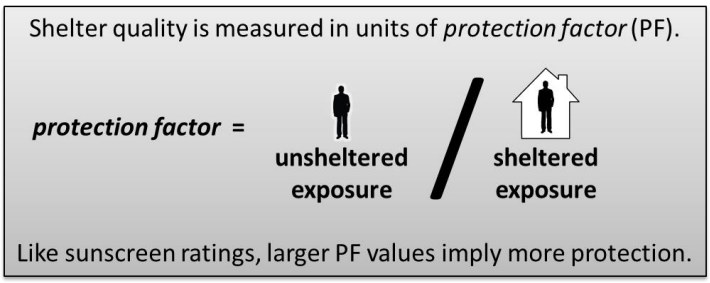
available for some locations. For example, local municipalities within the US often collect detailed occupancy, construction, and geographic location information for the purposes of assessing property taxes (the amount, type [e.g., year built, square footage, occupancy category], and quality of these data varies widely). Similarly, significant effort has gone into characterizing building stock for the purposes of energy efficiency. While access to this information can be limited, publicly available and research focused examples do exist, e.g., [223], [224]. Notably, this type of data has recently been adapted to estimate building protection for approximately 11.5 million UK residences [145], [146].

The authors are unaware of general estimates of the distribution of people within buildings. The number of people that can be present in a given room is well known to vary with room use and the maximum allowed population densities (occupancy loads) have long been codified within building construction and fire codes, e.g., (a) Table 1004.1.2 in the International Building Code and (b) Table 7.3.1.2 in the Life Safety Code [225], [226]. A limited number of building occupancy load surveys, such as [227] and references therein, have characterized typical (as opposed to maximum) occupancy loads (see also the occupancy discussion in [118]). When coupled with building floor plans and expert judgment, maximum and typical occupancy load estimates provide insight into the relative distribution of people within a given building. We note that, analogous to regional population distributions, building population distributions may vary with time, e.g., workday vs. weekend; night vs. day; and population posture (e.g., normal use vs. shelter in place).

3. Building Protection Physics

3.1. Building Protection and Assessment Metrics

The Regional Shelter Analysis methodology measures protection in terms of protection factor and transmission factor (see **Equations 1a** and **1b**). *Protection factor* (PF) is defined as the ratio of the unsheltered to sheltered exposure.[14] Similar to sunscreen and personal protective respirator rating systems, higher protection factor values indicate lower exposures and thus increased protection. The *transmission factor* (also called the location factor or the building exposure ratio) is the inverse of the protection factor and is used during modeling calculations.



(Equation 1a)

$$Protection\ Factor = \frac{Unsheltered\ (Outdoor)\ Exposure}{Sheltered\ (Indoor) Exposure}$$

(Equation 1b)

$$Transmission\ Factor = \frac{1}{Protection\ Factor}$$

[14] In the nuclear power plant accident literature, some studies use the term protection factor to indicate other quantities.

For the purposes of a Regional Shelter Analysis, the unsheltered exposure is defined as the exposure present 1 m above an infinite, flat plane. For some health effect models, additional assumptions may be required, see the (*5. Hazard-Specific Health Effect Considerations*) section below. The unsheltered exposure can be determined either through direct measurement or calculated by an exposure model. We note that care should be taken in estimating the unsheltered exposure as individual outdoor exposures in a particular region can, and often do, vary for a variety of reasons. For example, the use of a respirator can reduce exposure to many inhalation hazards. Similarly, environmental features; including trees, hills, valleys, and even buildings; and non-homogenous environmental contamination are well known to affect outdoor exposures. The RSA method developed in this report can account for these variations in outdoor exposures by defining one or more outdoor locations with their corresponding protection factors and population distributions. Thus, the impact of local outdoor environment can readily be included in building protection calculations.

For readability, we use time-integrated exposure, i.e., time-integrated hazard air concentration, as the “exposure” metric of interest in this report. We note that for some assessments, alternative metrics may also be of interest. These alternative metrics include, but are not limited to, peak exposure over a short time period; dose (amount of material deposited on or in a person); and risk (probability of a specific health effect). Alternative metrics, their connection to the time-integrated exposure metric, and associated protection factor definitions appropriate for use in RSA, are discussed in the (*4.3.3. Health Effect Models*) section below.

3.2. Buildings and Inhalation Exposures

The inhalation exposure pathway occurs when individuals breathe hazardous airborne material. The inhalation pathway can dominate airborne exposures from (a) chronic air quality pollutants such as ozone and small particulates; (b) airborne chemical and biological warfare agents; (c) short-term (also called early phase, plume phase, or response phase) radiation exposures from many NPP accidents and RDD releases; and (d) naturally occurring airborne infectious particle dispersions.

Indoor individuals can be exposed to outdoor-origin particles and gases when these contaminants enter buildings through mechanical ventilation, e.g., heating, ventilation and air conditioning (HVAC) systems, natural ventilation (e.g., open windows), and/or infiltration (e.g., exterior wall cracks). Particles may also be transported into buildings via deposition on outdoor surfaces or fomites that are subsequently tracked, or otherwise transported, into the building and resuspended into the indoor air. These transport pathways are illustrated in the top panel of **Figure 1**. Once indoors, airborne particles can be removed from the indoor air through (a) air leaving the building through mechanical or natural ventilation and exfiltration, (b) active filtration within ventilation systems (if present); (c) deposition on indoor surfaces (which may resuspend); and (d) other processes, including radioactive decay, chemical reactions, stand-alone indoor air filtration systems, and the loss of infectivity of airborne microorganisms, among others. These loss terms are illustrated in the bottom panel of **Figure 1**.

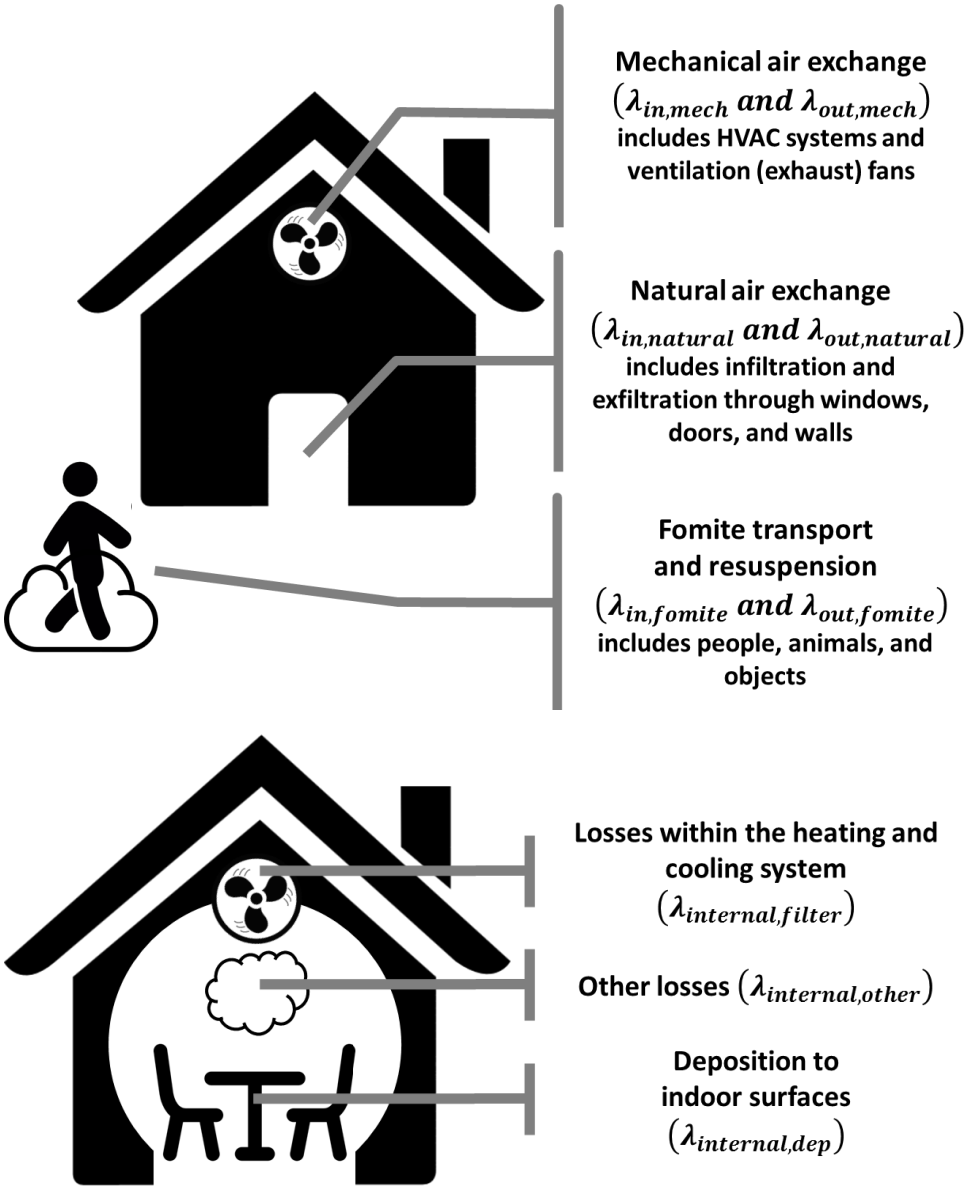


Figure 1. Illustrations of (top) mechanisms that airborne material can use to travel between the outdoor and indoor environments and (bottom) indoor loss mechanisms.

When outdoor gases and particles enter a given building, the single box model (**Equation 2**) can be used to describe the time evolution of indoor air concentrations, e.g., [228]–[231]. This study includes the commonly used assumption that the transport and loss terms, i.e., the λ parameters, are independent of both time and air concentration on the timescales of interest. **Equation 2** thus reduces to **Equation 3**.

(Equation 2)

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

(Equation 3)

$$C_{Indoor}(t) = \lambda_{in} \cdot \int_0^t C_{Outdoor}(\tau) \cdot e^{-(\lambda_{out} + \lambda_{internal})(t-\tau)} \, d\tau$$

where

t is time (h),

$C_{Indoor}(t)$ is the indoor hazard air concentration at time t (g m^{-3}),

$C_{Outdoor}(t)$ is the outdoor hazard air concentration at time t (g m^{-3}),[15]

λ_{in} is the rate at which outdoor material enters the building (h^{-1}),[16]

λ_{out} is the rate at which indoor material exits the building (h^{-1}), and

$\lambda_{internal}$ is the rate at which indoor material is lost within the building (h^{-1}).

[15] The outdoor hazard air concentration time series can be determined either by measurement or using an exposure model.

[16] This term includes both the rate at which air is exchanged between the outdoor and indoor environments as well as the losses that occur during the air exchange process, see [19] for more details.

For the common case in which the health effects due to toxic exposures depend upon the time-integrated air concentration of hazardous material, we derive **Equation 4** from **Equation 3** (using the convolution integral identity) to demonstrate that indoor inhalation exposures can be related to outdoor inhalation exposures by a linear scaling factor, which is the inverse of the building protection factor (i.e., a transmission factor), see **Equation 5**. Other cases are discussed in the (*4.3.3. Health Effect Models*) section.

(Equation 4)

$$Exposure_{Indoor} = \int_0^\infty C_{Indoor}(t)dt$$
$$= \left(\int_0^\infty \lambda_{in} \cdot e^{-(\lambda_{out}+\lambda_{internal})t}dt\right) \cdot \int_0^\infty C_{Outdoor}(t)dt$$
$$= \left(\frac{\lambda_{in}}{(\lambda_{out} + \lambda_{internal})}\right) \cdot Exposure_{Outdoor}$$

(Equation 5)

$$Building\ Protection\ Factor = \frac{Exposure_{Outdoor}}{Exposure_{Indoor}} = \frac{(\lambda_{out} + \lambda_{internal})}{\lambda_{in}}$$

where

$Exposure_{Indoor}$ is the indoor time-integrated hazard air concentration (g s m^{-3}), and

$Exposure_{Outdooor}$ is the outdoor time-integrated hazard air concentration (g s m^{-3}).

Figure 2 depicts the main features of inhalation pathway exposures in relation to building protection. Additional discussion is available in *Dillon and Sextro* [29]. Here, outdoor hazard air concentrations from a passing airborne plume (red dashed line) enter the building and the resulting indoor concentrations (both instantaneous and time-integrated) are plotted against time.[17] Two indoor scenarios are presented: one in which there is no indoor loss of airborne hazardous material (light blue line) and one in which significant losses take place (black line). In both cases, contaminated indoor air exfiltrates to the outside atmosphere. For illustration clarity, time and hazard concentrations are plotted on a linear scale in arbitrary units.

[17] For illustrative purposes, the outdoor plume shown in **Figure 2** is a "square wave" with a rectangular concentration time series. Real-world plumes can, and often do, possess more complicated concentration time series. **Equations 3** to **5** and the illustrative points discussed are also valid for more complicated outdoor plumes.

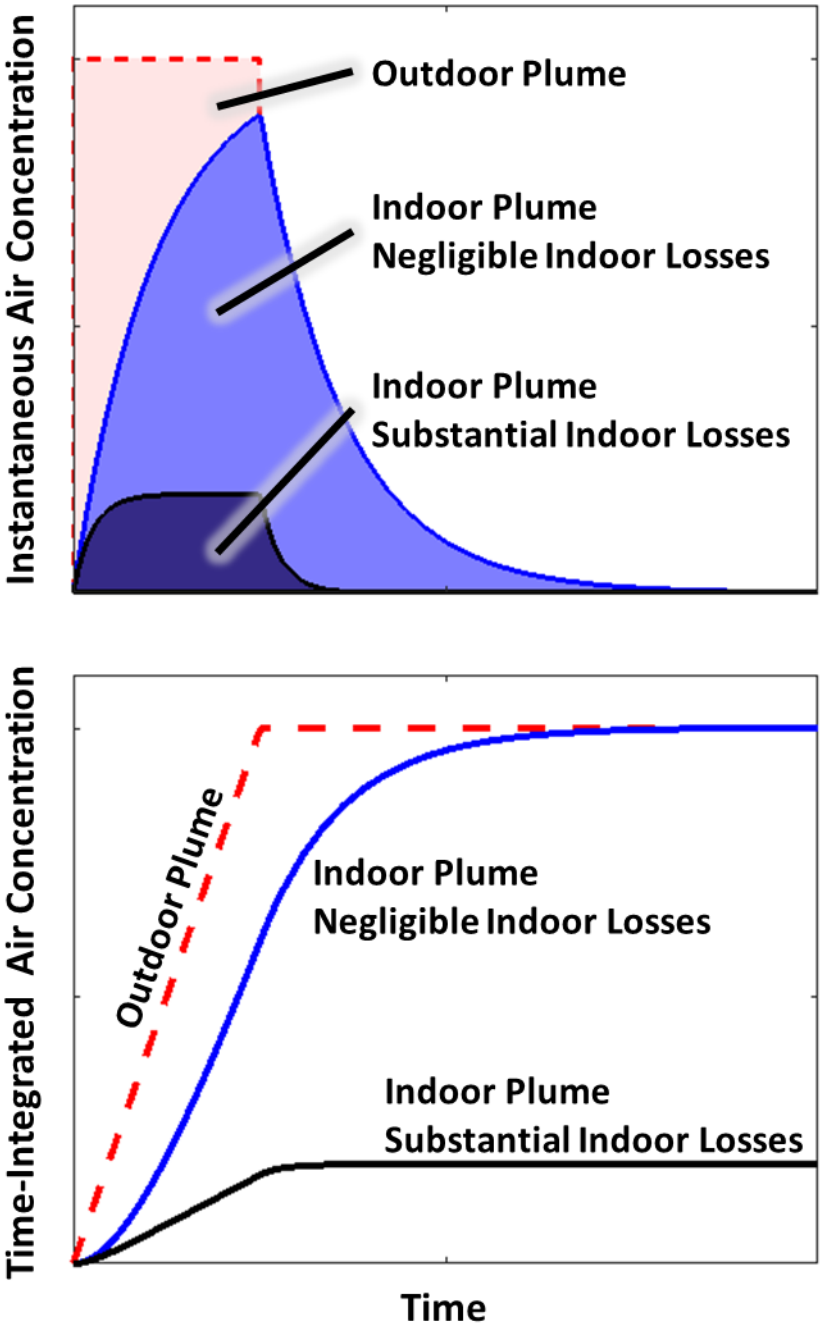


Figure 2. Illustration of inhalation building protection. The top panel shows the (instantaneous) air concentration time series of hazardous material for a passing outdoor plume (red dashed line), indoor plume without indoor losses (light blue line), and indoor plume with substantial indoor losses (black line). The bottom panel shows the corresponding exposures (time integrated air concentrations of hazardous material).

Equations 2 to 4 and **Figure 2** provide insight into key aspects of the inhalation pathway building protection. First, indoor hazard air concentrations resulting from outdoor exposures remain elevated after the outdoor plume has passed.[18] Indeed for some hazards such as ^{85}Kr, a radioactive noble gas (**Figure 2**, light blue line), there are no indoor losses (e.g., no deposition to indoor surfaces or mechanical filtration) and thus for sufficiently long exposures (time-integrated air concentration) there is no protection from inhalation hazards, i.e., the total inhalation exposure is the same indoors and outdoors. We note that the building protection against external radiation exposures remains and, for some hazards like ^{133}Xe, may significantly reduce the overall exposure. However, for airborne hazards, such as particulate matter, that are lost within the building (**Figure 2**, black line), there is passive building protection – with greater indoor losses corresponding to greater building protection.

[18] Building occupants who leave or increase the building ventilation rate after an outdoor hazardous plume has passed can reduce indoor concentrations and thus exposures. Also, when toxicity is sensitive to peak air concentrations rather than to the total time integrated indoor concentration, see [29], building protection remains, even if individuals do not exit or ventilate the building.

4. Regional Shelter Methodology

Regional Shelter Analysis method estimates *shelter quality* – defined as the (distribution of) building protection for a given region, time period, and population posture.[19] A *region* is defined as a geographic area in which the geographic distribution of building protection cannot be (or is not) resolved further. The scale or size of a region can vary with input(s) and/or application(s). Specific examples range from individual buildings, neighborhoods, and cities as well as much larger administrative regions (counties, states, countries, etc.). In the shelter quality database discussed later, each grid cell is a region. A *population posture* describes how people are distributed among and within various locations within a region. Population postures can change as people respond to a hazardous event and examples include unwarned scenarios, where people go about their normal day; shelter-in-place (often called minimally warned), where people shelter in the most protected portion of the nearest building; and neighborhood sheltering, where people go to the most protective building in the nearby area. A *time period* is defined as a specific time range during a day or day of the week with examples including weekday rush hour or weekend early morning hours. The population posture can vary with the time period, e.g., typically few people are in commercial buildings during the middle of the night.

[19] To enhance readability, the discussion here is restricted to population-weighted quantities. The RSA method can also use other importance weighting metrics including, but not limited to, area, building number, and monetary value. For example, area-weighted calculations can be used to assess the distribution of protection (populated or not) available in a given region.

4.1. Calculating Shelter Quality

The RSA method calculates regional shelter quality by (a) identifying the locations in which people are present; (b) characterizing, for each location: the (i) building protection factors, see (*3.1. Building Protection and Assessment Metrics*), and (ii) fraction of the regional population; and (c) combining the location specific protection factors and population fractions into a regional shelter quality estimate. A *location* is defined as a place within a region in which people are present. Like regions, the size of a location can vary depending on the application. Examples include a room in a building; an individual building; all residential buildings; or varying outdoor locations.

The details of the steps (a) and (b) vary by method implementation as several different types of (i) location definitions and (ii) associated protection factors and population fractions are available to develop a shelter quality database. A general discussion of these topics is provided in the (1) (*2.5. Building Characteristics, Populations, and Geographic Distributions*), (2) (*3. Building Protection Physics*), and (3) (*6.2. Practical Implementation and Practice Perspectives*) sections of this report. More specific discussion and examples are provided in the companion application report [19].

Calculation of shelter quality (step (c) above) is described as follows for a single region, population posture, and time period. This is illustrated in **Figure 3** using the example input dataset shown in **Table 1**.

First, the location protection factor cumulative probability distribution (black dashed line, **Figure 3**) is determined by (a) sorting the set of location-specific protection factors in order of decreasing value and (b) summing the corresponding population percents. **Table 2** illustrates this calculation using the example input dataset.

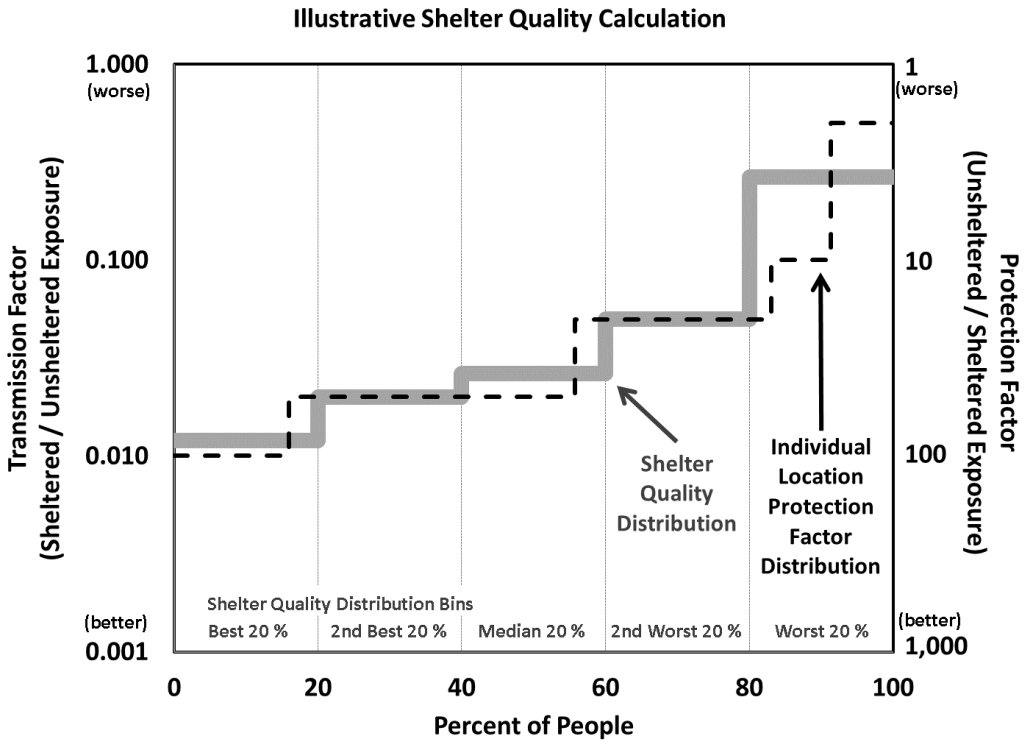


Figure 3. Illustrative shelter quality calculation for a single time, region, and population posture.

Second, five shelter quality probability bins were created in successive quintiles[20] and the shelter quality transmission factors (grey-shaded horizontal bars in **Figure 3**) were then determined by a population-weighted average of the location transmission factors in each shelter quality probability bin. **Table 3** illustrates this calculation using the example input dataset**.** In the case in which a sorted location probability spans more than one shelter quality probability bin, e.g., location 5 spans the best 20% and 2nd best 20% probability bins; the location is divided into sub-locations such that the resulting sub-location probabilities align with the shelter quality probability bin division(s). This case is denoted by the "a" and "b" notation in **Table 3** locations.

Third, the shelter quality protection factor for each probability bin was determined by inverting the corresponding shelter quality transmission factors (see **Equation 1b)**.

[20] Although in general the number and magnitude of the shelter quality probability bins can vary, five, equal shelter quality probability bins are used in this example for illustrative purposes and are also used in subsequent reports to demonstrate operational calculations. A small, consistent set of probability bins streamlines the operational use of the RSA method and facilities communication at different operational levels.

Table 1. Example input dataset

Location number	1	2	3	4	5	6	7	8
Protection factor	50	50	20	10	50	100	2	20
Population (percent)	22.1	5.4	13.5	8.2	12.3	16.0	8.7	13.8

Table 2. Example location protection factor cumulative probability distribution

Location number	6	5	1	2	8	3	4	7
Protection factor	100	50	50	50	20	20	10	2
Population (percent)	16.0	12.3	22.1	5.4	13.8	13.5	8.2	8.7
Start cumulative population (percent)	0.0	16.0	28.3	50.4	55.8	69.6	83.1	91.3
Stop cumulative population (percent)	16.0	28.3	50.4	55.8	69.6	83.1	91.3	100

Table 3. Example shelter quality transmission factor cumulative probability distribution

Location number	Location transmission factor (1 / protection factor)	Relative weight† (dimensionless)	Shelter quality transmission factor‡ (1 / protection factor)	Shelter quality probability bin name
6	0.01	0.80 (= 16/20)	0.012	best 20%
5a	0.02	0.20 (= 4/20)		
5b	0.02	0.42 (= 8.3/20)	0.020	2nd best 20%
1a	0.02	0.59 (= 11.7/20)		
1b	0.02	0.52 (= 10.4/20)	0.026	median 20%
2	0.02	0.27 (= 5.4/20)		
8a	0.05	0.21 (= 4.2/20)		
8b	0.05	0.48 (= 9.6/20)	0.050	2nd worst 20%
3a	0.05	0.52 (= 10.4/20)		
3b	0.05	0.16 (= 3.1/20)	0.27	worst 20%
4	0.10	0.41 (= 8.2/20)		
7	0.50	0.44 (= 8.7/20)		

† Calculated by dividing (a) the Table 2 location population percent (adjusted to align with the shelter quality probability bin) by (b) 20% (the probability associated for each shelter quality probability bin).

‡ Calculated by (a) multiplying (i) the location transmission factor by (ii) the relative weight and then (b) summing the resulting values associated with the locations within each shelter quality probability bin.

4.2. Shelter Quality Databases

Shelter quality estimates can be conveniently stored within a database, where each geographically distinct grid cell is a separate region, and later used to generate population-level risk analyses when combined with outdoor exposure estimates and health effect models. Visualizing the shelter quality database provides a graphical depiction (map) of the shelter quality for an area of interest (e.g., a city). This approach allows the shelter quality database to be derived from higher fidelity data sources, such as individual building data, where these higher fidelity data are available and lower fidelity data sources, such as the PAGER database, in the case where higher fidelity data are not available. *Dillon et al.* [203] and *Dillon et al.* [202] provide worked (hypothetical) examples that (a) use publicly available information about individual buildings to calculate shelter quality distributions for individual building and neighborhood-scale regions and, separately, (b) demonstrate how the higher fidelity HAZUS and lower fidelity PAGER databases can be combined into a single, multi-resolution shelter quality database.

The shelter quality database can have multiple data layers where each data layer has a specific spatial resolution and shelter quality probability bin values defined for each grid cell.[21] As a practical matter, a set of data layers that are self-consistent, but have different spatial resolutions enables computationally efficient exposure assessments by using the shelter quality layer resolution closest to the unsheltered exposure analysis

[21] (1) The grid cell resolution is not required to be constant in a given data layer. (2) While often the case, grid cells are not required to be square.

resolution, see also [202] and the (*6.2. Practical Implementation and Practical Perspectives*) section.

The method to generate lower spatial resolution shelter quality data layers, e.g., 10 km x 10 km grid cells, from higher spatial resolution shelter quality data layers, e.g., 1 km x 1 km grid cells, is described here.

First, the higher resolution grid cells that geographically overlap each lower resolution grid cell are identified, see **Figure 4**. The lower and higher resolution grid cells boundaries do not necessarily align and so in some cases a given higher resolution grid cell may only partially overlap, and thus only partially contribute to, a given lower resolution grid cell.

Second, **Equation 6** is used to calculate the population within the lower resolution grid cell. As an example, the lower resolution grid cell shown in **Figure 4** contains 20 people if there are 5 people in every higher resolution grid cell.

Third, the lower resolution grid cell shelter quality distribution is calculated for each time period and population posture using the algorithm described in the (*4.1. Calculating Shelter Quality*) section. For this calculation, the (a) input locations are the higher resolution grid cell probability bins, (b) input location protection factors are the protection factors associated with the higher resolution grid cell probability bins, and (c) input population is the fraction of

lower resolution grid cell population associated with each input location as determined by **Equation 7**.

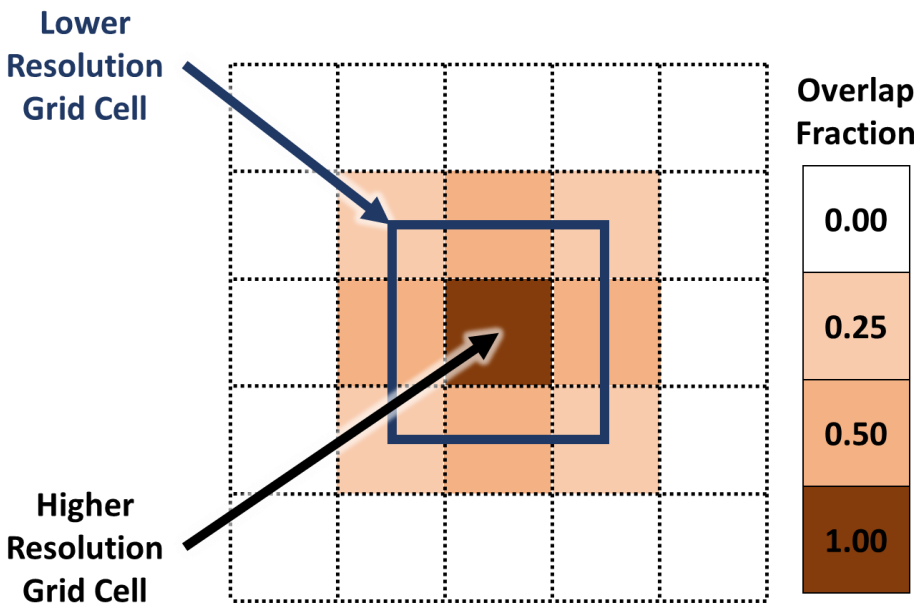


Figure 4. Illustration of higher resolution grid cells (outlined with dashed lines) overlapping a lower resolution grid cell (outlined with a solid blue line). In this illustration, the higher resolution grid cells can overlap the lower resolution grid cell fully, partially, or not at all.

(Equation 6)

$$Low\ Res\ Population_j = \sum_i \left(High\ Res\ Population_i \times Overlap\ Fraction_{i,j}\right)$$

(Equation 7)

$$Location\ Probability_{i,j,p} = \frac{High\ Res\ Population_i \times Overlap\ Fraction_{i,j} \times Probability\ Bin\ Value_p}{Low\ Res\ Population_j}$$

where

i is a high spatial resolution grid cell (dimensionless),

j is a low spatial resolution grid cell (dimensionless),

p is the high spatial resolution population bin (dimensionless),

$Low\ Res\ Population_j$ is the population for lower resolution grid cell j (people),

$High\ Res\ Population_i$ is the population for higher resolution grid cell i (people),

$Overlap\ Fraction_{i,j}$ is the fraction of higher resolution grid cell i area that overlaps the lower resolution grid cell j (dimensionless),

$Location\ Probability_{i,j,p}$ is the location probability for lower resolution grid cell j associated with the probability bin p from higher resolution grid cell i (dimensionless), and

$Probability\ Bin\ Value_p$ is the value of the probability bin p (dimensionless).

4.3. Population Impact Calculations

The Regional Shelter Analysis methodology can adjust existing model predictions of (a) unsheltered exposure and (b) health effects to estimate the impacts on sheltered individuals. For a given region, the general process occurs in the following four steps. First, the sheltered exposures for each probability bin are calculated by dividing the unsheltered exposure by the corresponding probability bin protection factor. Second, the fraction of affected individuals in each probability bin is determined from the sheltered exposure and the appropriate health effect model. Third, the fraction of affected individuals in the region is determined from the weighted average of the individual probability bin estimates. Finally, the total number of affected people is determined by multiplying the regional population by the affected fraction. For some RSA applications, certain parameter input details are hazard and/or exposure pathway specific and these are described in more detail in following subsections.

4.3.1. Population Impacts Due to Gaseous Inhalation Exposures

For gas inhalation exposures, where the physical form of the hazard is individual atoms or molecules floating freely in the air (which are approximately a nanometer or smaller in diameter); exposure estimates can be directly combined with RSA shelter quality estimates to calculate population impacts. These can be calculated using the following equations: [22] **Equation 8** calculates the sheltered exposure by dividing the unsheltered exposure by the RSA shelter quality estimates. **Equation 9** calculates the fraction of people impacted in a given region via a weighted average of the fraction of people

[22] These specific equations also apply to the special case of external gamma radiation exposures.

impacted in each probability bin, which in turn, is calculated using a health effect model (a model that relates exposure to one or more health outcome(s) of interest) and the sheltered exposures. **Equation 10** calculates the affected people in a given region by multiplying the fraction of people affected with the corresponding population estimate. **Equation 11** calculates the total number of affected people.

(Equation 8)

$$Sheltered\ Exposure_{r,p} = \frac{Unsheltered\ Exposure_r}{Shelter\ Quality_{r,p}}$$

(Equation 9)

$$Impact\ Fraction_r = \sum_{p \in probabilty\ bins} \frac{Health\ Effect\ Model\left(Sheltered\ Exposure_{r,p}\right)}{Probability\ Bin\ Value_p}$$

(Equation 10)

$$Regional\ Impacts_r = Impact\ Fraction_r \times Population_r$$

(Equation 11)

$$Total\ Number\ of\ Impacted\ People = \sum_{r \in regions} Regional\ Impacts_r$$

where

$Sheltered\ Exposure_{r,p}$ is the average (population weighted) exposure in region r and probability bin p (varies, possibilities include, but are not limited to g s m^{-3}, Gy, or Sv),

$Unsheltered\ Exposure_r$ is the unprotected exposure in region r (varies, possibilities include, but are not limited to g s m^{-3}, Gy, or Sv),

$Shelter\ Quality_{r,p}$ is the (population weighted) protection factor for probability bin p and region r (dimensionless),

$Impact\ Fraction_r$ is the fraction of people impacted in region r (dimensionless),

$Health\ Effect\ Model\ (Exposure)$ is the probability of a health effect for given exposure (dimensionless),

$Regional\ Impacts_r$ is the number of people impacted in region r (people),

$Population_r$ is the number of people in region r (people), and

$Total\ Number\ of\ Impacted\ People$ is the total number of people affected (people).

4.3.2. Population Impacts Due to Particulate Inhalation Exposures

For airborne particulate exposures, where the physical form of the hazard is a solid or liquid particle floating in the air (nominally greater than 10 nm in diameter); building protection is known to vary significantly with particle size and so the exposure estimates need to account for the particle size distribution of the airborne particulate cloud. In this report, we specify particle size using the aerodynamic diameter metric – which is defined as the diameter of an equivalent particle that settles in still air at the same rate as the particle in question but is spherical and has a density of 1 g cm^{-3}. The aerodynamic diameter metric was chosen because it is (a) widely used and (b) well describes the behavior of airborne particulate matter ≥ 0.1 µm. Historically, particles ≥ 0.1 µm have been of the highest concern with respect to inhalation hazards, although this may change due to recent research into ultrafine (nano) particle hazards, e.g., [232],

[233]. We note that other particle size metrics exist and may be suitable for certain applications, including relatively small, < 1 μm, particles.

Equations 12, 13, and 14 provide the general method to calculate impacts due to exposure to airborne particles. When the health effect model linking the exposure to the outcome of interest, e.g., disease, is independent of particle size, **Equations 12** and **14** can be replaced with **Equations 15** and **9**, respectively. This substitution allows for more efficient computations as it avoids numerically integrating the health effect model.

(Equation 12)

$$Sheltered\ Exposure_{r,p}(p_{size}) = \frac{Unsheltered\ Exposure_{r}(p_{size})}{Shelter\ Quality_{r,p}(p_{size})}$$

(Equation 13)

$$Health\ Effect\ Model_{r,p} = \int Health\ Effect\ Model\big(Sheltered\ Exposure_{r,p}(p_{size}), p_{size}\big) dp_{size}$$

(Equation 14)

$$Impact\ Fraction_{r} = \sum_{p \in probabilty\ bins} \frac{Health\ Effect\ Model_{r,p}}{Probabilty\ Bin\ Value_{p}}$$

(Equation 15)

$$Sheltered\ Exposure_{r,p} = \int Sheltered\ Exposure_{r,p}(p_{size}) dp_{size}$$

where

p_{size} is the particle aerodynamic diameter (m),

$Sheltered\ Exposure_{r,p}(p_{size})$ is the number of airborne particles of p_{size} diameter in the breathing volume (respiratory second volume) of an individual in region r and probability bin p (particles s m^{-3}),

$Unsheltered\ Exposure_{r}(p_{size})$ is the number of airborne particles of p_{size} diameter in the breathing volume (respiratory second volume) of an unsheltered individual in region r (particles s m^{-3}), and

$Shelter\ Quality_{r,p}(p_{size})$ is the p_{size} specific shelter quality in region r and probability bin p (protection factor).

As written, applying the above method to arbitrary particle size distributions requires knowledge of each region's shelter quality and unsheltered exposure as a function of particle size. It is more computationally efficient to calculate $Unsheltered\ Exposure_{r}(p_{size})$ and $Shelter\ Quality_{r,p}(p_{size})$ for each region of interest for a predefined set of particle sizes; e.g., 0.1, 0.3, 1, 3, and 10 μm; and then use interpolation to estimate results for particle sizes of interest. This approach can be further generalized with **Equation 16** to consider arbitrary release amounts and release particle size distributions from a set of $Normalized\ Unsheltered\ Exposure_{r}(p_{size})$ values.

(Equation 16)

$$Unsheltered\ Exposure_r(p_{size}) = Total\ Release\ Amount \times Release\ Probability(p_{size}) \times Normalized\ Unsheltered\ Exposure_r(p_{size})$$

where

$Total\ Release\ Amount$ is the total number of particles released into the atmosphere (dimensionless),

$Release\ Probability(p_{size})$ is the probability that a particle released has particle size p_{size} (dimensionless), and

$Normalized\ Unsheltered\ Exposure_r(p_{size})$ is the average (expectation value) number of airborne particles of p_{size} diameter in the breathing volume (respiratory second volume) of an unsheltered individual in region r assuming 1 particle was released (particles s m^{-3}).

4.3.3. Health Effect Models

Health effect modeling – mathematical modeling of the risk of a specific health outcome, e.g., disease, associated with a given hazardous exposure – is well advanced and for some hazards provides a useful basis to guide decisions. Accurate health effect models need detailed, substance-specific health effect dose response information based

on either toxicological or epidemiologic data or, ideally, on a combination of the two.[23, 24] The existing knowledge bases, many of which are discussed below, are in many respects extensive, however are primarily focused on the subset of highest priority hazards. So unfortunately, they are also quite limited with respect to the number of potential hazards and health outcomes that may be relevant. Therefore, current risk assessments typically use a wide variety of qualitative and quantitative health effect models and dose metrics based, in part, on the available dose-response information. For consistency in discussing different hazard types, we reserve the term dose to mean the quantity of hazard (a) deposited on, (b) deposited in, or (c) inhaled by a person unless otherwise noted. Mathematically, dose is often calculated by the multiplying the exposure by a scaling factor that accounts for the processes by which external hazards in the immediate vicinity of an individual are deposited on, deposited in, or inhaled by the individual. For inhalation hazards, **Equation 17** provides the scaling factor for hazards inhaled by an individual. Some health effect models require an additional scaling factor that accounts for the fraction of inhaled material that deposits in the lung or enters the bloodstream. We note that the chemical literature often uses the term

[23] In experimental toxicology, a material's dose-response relationship can be determined by administrating carefully measured exposures under controlled conditions. Epidemiology studies are based on relating the incidence of health effects to environmental exposure monitoring data. In both contexts, the dose absorbed by a host often can be measured via biomonitoring; however measurements of an actual target organ dose (i.e., the biologically effective dose that actually reaches the target organ causing a specific health effect) is typically limited to toxicology studies that use invasive procedures. Population level epidemiological models are described at the end of this section.

[24] Dose-response relationships can include a wide range of model assumptions and complexity. Furthermore, they can be based on data from a similarly broad assortment of hosts (receptors) and the air sampling measurement methods. Indeed such variety can be present even for the case of a single particle/hazard, e.g., [234]–[238].

dose to encompass many of the alternative "dose" metrics discussed later in this section.

(Equation 17)

$$Inhaled\ Dose = Time\ Integrated\ Hazard\ Air\ Concentration \cdot Breathing\ Rate$$

where

$Inhaled\ Dose$ is the amount of hazard inhaled into an individual's lung (g),

$Time\ Integrated\ Hazard\ Air\ Concentration$ is the time integrated concentration of the airborne hazardous material (g s m^{-3}), and

$Breathing\ Rate$ is the volume rate of air that an individual breathes ($m^3\ s^{-1}$).

In this section, we (a) review some of the more commonly used models and alternative "dose" metrics and (b) discuss the degree to which they are compatible with the current RSA methodology. Fundamentally, RSA compatibility is demonstrated when we can identify a protection factor equation that is equal to the ratio of the outdoor to indoor metric(s) of interest - allowing **Equations 8** or **12** to be used when calculating population level exposures and/or subsequent impacts. For cases in which the dose metric can be related to the time-integrated hazard air concentration, **Equation 5** is valid and the

health effect model is compatible with the RSA method as previously derived.[25] As will be shown in the (*5. Hazard-Specific Health Effect Considerations*) section, this is true for most radiological, chronic chemical, and biological hazard health effect models. For certain specific cases that require alternative "dose" metrics, including, but not limited to peak exposures, other protection factor equations are required and are discussed below.

We note that the input values needed to calculate the protection factor values are often building and hazard specific and so are determined during the implementation process. We note that particle size, chemical volitivity and reactivity, water solubility, and exposure timescales have the potential to affect both health effect outcomes and the protection factor values and so they may need to be explicitly considered. Health effect model parameters that do not affect the outdoor/indoor exposure ratio do not affect the RSA compatibility of a given health effect model and so do not need to be explicitly considered in the calculation of building protection factors (however these do remain important for health impact calculations). Examples of these latter parameters are body weight; microbiology of specific pathogens; and disease susceptibility due to age, gender, nutrition, and the pre-existing health status of an exposed individual(s). We caution that within a region, the building protection, which can vary by building type,

[25] **Equation 5** does not explicitly consider the effects of initially airborne material (gases or particles) depositing or sorbing onto indoor surfaces and becoming airborne once again through resuspension (particles) and desorption (gases) mechanisms – see [78] for a discussion of these processes. Broadly, these processes (a) reduce building (internal) losses and extend the exposure durations and so (b) require alternative building protection equations. **Supplemental Material S1** provides a protection factor equation for use when the deposition, resuspension, and surface loss processes are first-order.

may be correlated with demographic subgroupings, e.g., during a workday, children are at school while adults are in offices or residences.

4.3.3.1. Exposure Guideline Levels

For some hazards there exists an exposure level which, when a population is exposed to that level, the chance of adverse health effects is negligible (or at least tolerable).[26] As a consequence, hazard risk assessments often start by assessing which, if any, individuals or geographic regions are being exposed to conditions that exceed pre-established exposure guideline levels based on monitoring data or mathematical exposure models, e.g., [7], [14], [60], [243]–[246].[27] In general, exposure guideline levels are (a) intended to protect a specific population, e.g., healthy workers or sensitive individuals; (b) developed on the basis of toxicological and/or epidemiological models and/or data; (c) associated with a specific hazard and exposure duration; and (d) reported in units of dose and/or dose rate. Some inhalation guideline levels are referenced to the hazard air concentration to which individuals are exposed. Guideline levels can include other factors such as, but not limited to, an adjustment for (a) body mass, (b) activity level,

[26] These are often termed the No Observed Adverse Effect Level (NOAEL) or the Lowest Observed Adverse Effect Level (LOAEL). NOAEL methods cannot be applied to exposures where no minimum level of risk exists and can be study-design dependent. The Benchmark Dose (BMD) methodology was developed to address these limitations. The BMD methodology can be used to fit mathematical models to dose-response data. Once fit, the BMD method can estimate the concentration of a substance that, when inhaled, produces a predetermined change in the response rate of an adverse health effect relative to the background response rate, e.g., a 10% increase in health effect or disease incidence [239]–[242].

[27] We note that exposures exceeding an exposure guideline level do not necessarily result in adverse health effects – only that such effects are more probable or are not ruled out. Furthermore, the health effects being considered can vary by hazard, exposure duration, e.g., acute vs. chronic, and by guideline standards. Finally, some guideline standard levels also include the consideration of the potential economic impacts and technical feasibility of controlling adverse exposures. For these reasons, care should be taken when (a) comparing guideline levels and (b) using guidelines levels for applications other than for which they were designed.

and (c) the fraction of the total exposure time duration that a given individual is actually being exposed.

The RSA methodology is compatible with the use of exposure guidelines – although the specific details depend upon the underlying dose-response relationship. The RSA method is compatible with inhalation dose-response models (and exposure guidelines based on these models) in which the dose can be related to a time-integrated hazard air concentration - see the (*3.2. Building and Inhalation Exposures*) section. RSA compatibility with inhalation-based exposure guidelines in which the dose *cannot be* related to a time-integrated hazard air concentration is more complicated since being indoors changes the exposure timeseries relative to the outdoor plume. Notably, peak concentrations are attenuated, and the exposure durations increase.

When the building protection timescale is much shorter than the outdoor plume timescale,[28] the indoor and outdoor concentrations are in steady-state and the ratio of outdoor to indoor hazard air concentration is reasonably approximated by the value of the building protection factor value defined by **Equation 5.** The substantial indoor losses case in **Figure 2** illustrates this condition. Here, the RSA method can be used to scale the outdoor "exposure" to the corresponding indoor "exposure" and so help to determine if indoor exposures exceed the exposure guideline. For this application, "exposure" is

[28] (a) The building protection timescale is the time constant associated with the process of a building modifying the outdoor plume timeseries, i.e., $1/(\lambda_{out} + \lambda_{internal})$. The building protection timescale depends on building, environmental, and hazard properties and is typically minutes to hours [19]. (b) For this discussion, the plume timescale is equal to the exposure guideline duration.

defined at the highest time-averaged hazard air concentration – where the time averaging period is the exposure guideline duration.

When the building protection timescale is comparable to, or longer than, the plume (guideline) duration, extensions to the previously discussed RSA theory are required. The negligible indoor losses case in **Figure 2** illustrates this condition. While a general theory is not yet available, two important subcases provide practical utility and so are discussed in the following paragraphs.

First, **Supplemental Material S1** demonstrates that the peak (instantaneous) indoor concentration will not exceed the peak outdoor concentration divided by the building protection factor value as defined by **Equation 5**. Thus, the RSA method can be used to determine which indoor locations *will not exceed* an exposure guideline by calculating an upper bound on the indoor hazard air concentrations using **Equation 18a**.

Second, the RSA method can be used to determine some (but not necessarily all) of the locations that *will exceed* an exposure guideline whose level is based on the ten-Berge dose-response model.[29] In the ten-Berge model, the "dose" in the dose-response relationship is defined as the toxic load specified in **Equation 19**

[29] The following chemical exposure guidelines, which are commonly used in risk assessments, are based on the ten-Berge model (and/or follow Haber's Law): AEGL [247], TEEL [248], IDLH [249], PEL [250], [251], WEL [252], and RfC [253]. The ERPG guidelines do not require the use of the ten-Berge model, but recommends it when extrapolating to other exposure durations [254].

[255]. When the ten-Berge toxic load exponent (n) is equal to 1, the toxic load is equivalent to the standard RSA exposure definition, i.e., a time-integrated hazard air concentration (Haber's Law), and the standard RSA method can be used. When the toxic load exponent is greater than 1, the hazard toxicity is particularly sensitive to peak hazard air concentrations and a different building protection equation is required. **Supplemental Material S1** provides an alternative building protection factor equation for this important subcase (**Equation S1-11**) that scales the "dose" (toxic load) associated with an outdoor concentration held constant for a given duration (i.e., an exposure guideline level) to the corresponding indoor "dose" (toxic load). Thus, **Equation 18b** can be used with outdoor "exposure" estimates to identify locations in which indoor individuals could be exposed to "doses" (toxic loads) that exceed a given exposure guideline level "dose." For this application, "exposure" is again defined as the highest time-averaged hazard air concentration – where the time averaging period is the specified exposure guideline duration.

(Equation 18a)

$$Sheltered\ Peak\ Concentration_{r,p} \leq \frac{Unsheltered\ Peak\ Concentration_{r}}{Shelter\ Quality_{r,p}}$$

(Equation 18b)

$$Sheltered\ Toxic\ Load_{r,p} = \frac{Unsheltered\ Toxic\ Load_r}{Toxic\ Load\ Shelter\ Quality(n, exposure\ duration)_{r,p}}$$

(Equation 19)

$$Toxic\ Load = \int_0^{\infty} \left(Hazard\ Air\ Concentration(t)\right)^n dt$$

where

$Sheltered\ Peak\ Concentration_{r,p}$ is the peak (instantaneous) hazard air concentration to which a sheltered individual in region r and probability bin p is exposed (g m^{-3}),

$Unsheltered\ Peak\ Concentration_r$ is the peak (instantaneous) hazard air concentration to which an unsheltered individual in region r is exposed (g m^{-3}),

$Sheltered\ Toxic\ Load_{r,p}$ is the toxic load to which a sheltered individual in region r and probability bin p is exposed (g m^{-3}),

$Unsheltered\ Toxic\ Load_r$ is the toxic load to which an unsheltered individual in region r is exposed (g m^{-3}), and

$Toxic\ Load\ Shelter\ Quality(n, exposure\ duration)_{r,p}$ is the protection factor for region r and probability bin p as calculated by Equation S1 - 11 in **Supplemental**

Material S1 using the hazard specific toxic load n and the appropriate exposure guideline duration.

4.3.3.2. Dose-Response Relationships

The potential for adverse health effects cannot always be ruled out. This can occur either because the exposure is greater than the relevant exposure guideline level or the health effect, such as with many cancers, has no known minimum tolerable exposure. In such cases, the use of more detailed health effect models may be required. The most detailed health effect models relate a dose to a probability of a specified health effect (response). RSA compatibility with such dose-response models depends on the specific form of the dose-response relationship. We again note that there is a wide range of health effect models applicable to such circumstances and we focus here on only a few important common cases.

As previously mentioned, the current RSA method is compatible with all dose-response relationships where the dose metric can be related to a time-integrated airborne hazard exposure, e.g., **Equation 17**. A broad range of dose metrics can satisfy this condition and include administered (external), internal (absorbed), and target (tissue/organ) dose metrics. We note that the mathematical relationship between the dose metric and health effect can be arbitrary (non-linear) and a number of widely-used dose-response relationships satisfy this condition including (a) those that follow Haber's Law and (b) 10

of 11 common mathematical forms for dose-response relationships discussed in a World Health Organization critical review of chemical risk-assessment modeling [256].[30]

An important set of dose-response relationships includes the additional assumption that the health effect scales linearly and/or logarithmically with dose. This set is frequently used to assess, or bound, excess cancer risk due to low dose airborne exposures, e.g., [245], [257], as well to estimate health effect incidence rates [258] including the "Probit" model. **Equations 20a to 20d** show the generic dose-response relationships for these cases. These forms include consideration of a (a) background risk/incident rate (β_o) which reflects the health effect risk/incidence rate present in the absence of exposure to the hazard of interest and (b) background exposure (k) which reflects the degree to which individuals are exposed to the hazard of interest in the absence of an outdoor airborne plume of hazardous material. **Equations 21a to 21d** relate the indoor risk and/or incidence rate at indoor locations to the outdoor risk and/or incidence rate, respectively, due to exposure to a single, outdoor-origin airborne hazard. As building protection can vary by exposure pathway, particle size, and chemical form, mixtures of different chemicals and/or particle sizes require more complex shelter quality equations. For these cases, it may be more efficient to calculate the exposure to sheltered individuals for each pathway, hazard, and particle size of interest and then

[30] The "dose" in the other dose-response relationship discussed by WHO refers to concentration.

calculate the risk and/or incidence rate directly. This latter approach can also be used to model multi-hazard interactions, e.g., synergistic effects.

(Equation 20a - linear)

$$R = \beta_o + \beta_1 \cdot (Time\ Integrated\ Air\ Concentration - k)$$

(Equation 20b - log-linear)

$$\ln(R) = \beta_o + \beta_1 \cdot (Time\ Integrated\ Air\ Concentration - k)$$

(Equation 20c – linear-log)

$$R = \beta_o + \beta_1 \cdot ln(Time\ Integrated\ Air\ Concentration - k)$$

(Equation 20d - log-log)

$$\ln(R) = \beta_o + \beta_1 \cdot ln(Time\ Integrated\ Air\ Concentration - k)$$

(Equation 21a - linear)

$$R_{r,p} = \frac{R_r + \beta_o \cdot \left(Shelter\ Quality_{r,p} - 1\right) + \beta_1 \cdot k \cdot \left(1 - Shelter\ Quality_{r,p}\right)}{Shelter\ Quality_{r,p}}$$

(Equation 21b - log-linear)

$$ln(R_{r,p}) = \frac{ln(R_r) + \beta_o \cdot (Shelter\ Quality_{r,p} - 1) + \beta_1 \cdot k \cdot (1 - Shelter\ Quality_{r,p})}{Shelter\ Quality_{r,p}}$$

(Equation 21c - linear-log)

$$R_{r,p} = R_r - \beta_1 \cdot ln(Shelter\ Quality_{r,p}) \qquad (when\ k = 0)$$

(Equation 21d - log-log)

$$R_{r,p} = R_r \cdot Shelter\ Quality_{r,p}{}^{-\beta_1} \qquad (when\ k = 0)$$

where

R_r is the risk or incidence rate for a unsheltered individual in region r (varies),

$R_{r,p}$ is the risk or incidence rate for a sheltered individual in region r and probability bin p (varies)

$$\beta_o = \begin{cases} \text{background risk or incidence rate}, & \begin{matrix} linear\ model \\ linear - log\ model \end{matrix} \\ ln(\text{background risk or incidence rate}), & \begin{matrix} log - linear\ model \\ log - log\ model \end{matrix} \end{cases}$$

β_1 scales the time-integrated hazard air concentration, or ln(time-integrated hazard air concentration) to risk or incidence rate (varies), and

k is the background exposure level (g s m^{-3}).

As discussed in the (*4.3.3.1. Exposure Guideline Levels*) section and (*5. Hazard-Specific Health Effect Considerations*) section, acute chemical toxicity and some biological hazards can depend sensitively upon peak hazard air concentrations and so for these hazards the "dose" metric cannot be related to a time-integrated airborne hazard concentration. Useful operational solutions are provided in **Supplemental Material S1** for dose-response relationships that (a) depend solely on the peak hazard air concentration or (b) are adequately represented by (i) the ten-Berge dose-response model and (ii) a square wave outdoor hazard air concentration time-series, i.e., the hazard air concentration is zero until plume arrival, remains elevated at a constant value until a later time, and then is zero again.

Finally, by way of comparison, it should be remembered that population level dose-response relationships are often derived by first estimating outdoor ambient exposures and then tuning parameters in a dose-response relationship to best match the distribution of independently provided illness reports, e.g., [259]–[262].[31] In most cases, these relationships do not explicitly account for building protection effects or population postures. However, since regional building protection effects on health outcomes are in fact operative in these exposure scenarios and models, previously published population level dose-response relationships may not accurately estimate the hazard's true potency. Exposure risk to outdoor individuals may be underestimated as the bulk of the population is located indoors and buildings are known to significantly

[31] Similarly, the geographic distribution of exposures can be inferred from illness reports by using a known dose-response relationship, e.g., [263].

reduce exposures to outdoor-origin airborne hazards. It also follows that exposure risks to indoor individuals may be overestimated. Furthermore in the case of air pollutants, indoor individuals may also sometimes be affected by local, indoor, sources that are not reflected in the ambient (outdoor) exposure measurements. Thus not accounting for building protection and alternate exposure sources obscures opportunities to maximize dose-reduction strategies through sheltering and building protection enhancement, e.g., energy efficiency improvements that reduce indoor/outdoor air exchange rate, changes to building operation, and use of improved building air filters. Finally, applying such dose-response models to regions with a variety of different building properties, but not adjusting for building protection factor effects, introduces unnecessary, additional uncertainty and error into any analysis. We note that the RSA methodology, when coupled with shelter quality estimates for the original and target regions, provides a means to more accurately apply such dose-response relationships and might be usefully applied to enhance current health hazard surveillance systems.

5. Hazard-Specific Health Effect Considerations

This section (a) provides a limited review of the main classes of radiation, chemical, and biological hazards and (b) discusses the degree to which current health effect models are compatible with the RSA casualty calculation method presented here. We discuss, among other considerations, how appropriately chosen RSA protection factors (a) relate to current, hazard-specific methods for incorporating building protection into exposure and risk assessments and (b) can also capture the location-specific aspects of the exposure-to-dose scaling factor (where applicable).

5.1. Radiation Hazard Health Effects

5.1.1. Overview of Ionizing Radiation Injury Mechanisms and Modeling

Health effects due to ionizing radiation exposure are classified as either stochastic or tissue effects (the latter are also called deterministic or non-stochastic effects). Stochastic effects, which are of concern primarily at low radiation doses and/or dose rates, can result from injury to a single cell or small number of cells and the principal consequences are carcinogenic and/or heritable effects. Tissue effects, which occur at higher doses and dose rates, result from the collective injury of a substantial number of cells in the affected tissues. This collective injury can result, among other injuries, in eye cataracts, non-malignant skin damage (radiation burns), cell depletion in the bone marrow causing hematological deficiencies, and/or gonadal cell damage leading to fertility impairment. Stochastic or deterministic health effect models typically, although not always, use different types of radiation dose metrics (discussed below) – however both metrics are determined by a summing of the individual contributions from each

exposure pathway.[32] The likelihood of both stochastic or tissue health effects increases with radiation dose and decreases with radiation exposure duration.[33]

Although there is no strict time boundary to distinguish between radiation exposure time periods relevant to human health effects, these environmental exposures are commonly classified as acute or chronic when received in < 30 d and > 60 d, respectively (exposure periods between 30 to 60 d may be categorized differently depending on the specific study). The boundary between acute and chronic exposures is substantially longer than the timescales by which building structures prolong inhalation exposures and so the RSA methodology is compatible with the exposure timescales, and hence dose rates, used in current radiation health effect models.

Tissue health effect models typically use the absorbed dose to either an individual organ/tissue or to the whole body which is measured in Gy (SI unit) or rad [14], [202], [264]. Absorbed dose is the total amount of energy deposited (absorbed) per gram of matter, e.g., bone, tissue, air, over a specified time period.[34] Acute radiation syndrome (ARS) describes the combination of effects associated with tissue damage incurred

[32] Individuals can be exposed to ionizing radiation through a variety of pathways including external exposure and/or internal exposure through inhalation, ingestion, or direct contact, e.g., absorption through intact or broken skin.

[33] Shorter time period exposures are more hazardous as there is less time for the radiation damage to be repaired. For example, a 5 Gy to bone marrow dose would likely be lethal if received in 1 day while the same 5 Gy dose received evenly over 50 years would likely not result in any acute health effects.

[34] For human tissue, the relative effectiveness by which different radiation types, such as alpha particles, beta particles, and gamma rays, damage biological tissue can be considered. For this case, the adsorbed dose is reported in units of Gy-equivalents. This is related to, but distinct from, the equivalent dose concept discussed in the context of stochastic effects.

during an acute exposure(s) [14].[35] For lower doses, i.e., 1 Gy; ARS can present clinically in the first minutes to weeks after exposure with diarrhea, vomiting, fever and decreased number of blood cells due to damage to the most sensitive organs (bone-marrow, small-intestine wall, and lungs). High, acute, whole-body doses of radiation (> 8 Gy) are likely fatal (without medical attention) and exposed individuals may present within minutes of exposure with disorientation or coma. Below ~0.5 Gy, no acute tissue effects are expected.

Stochastic health effect models typically use either an equivalent (organ/tissue) dose and/or an effective (whole body) dose which are typically measured in Sv (SI unit) or rem – although a few models use absorbed dose [264]–[266]. The equivalent dose is estimated for individual organs by summing the contribution of each radiation exposure pathway and is weighted by the relative amount of damage caused by different types of radiation (radiation weighting factor). The effective dose is estimated by summing the individual equivalent doses for each organ/tissue as weighted by the sensitivity of the individual organ/tissue to radiation damage (tissue weighting factor). The US Environmental Protection Agency (US EPA) estimates general population lifetime cancer incidence risk to be ~10^{-4} per mSv [14]. Based on this dose-response relationship, the US EPA protective action guides, which are a form of exposure guideline level, recommend considering the relocation of the general population when the projected dose (which does not consider building protection) is above 20 mSv in the first year or 5 mSv in the

[35] External radiation burns may also occur, but are not considered part of the ARS.

second and subsequent years (corresponding to an increased lifetime cancer incidence risk of > 0.16% and 0.04% per year, respectively) [14].[36]

5.1.2. Dose Conversion Factors and Building Protection

Radiation Dose Conversion Factors (DCFs) are commonly used to scale air contamination levels to both adsorbed and equivalent/effective doses [2], [14], [265], [269]–[274]. DCFs vary with radiation type and energy (radionuclide) and, for inhalation exposures, can also vary with: (a) the physical and chemical form of the radioactive material[37] and (b) the timescale over which the health effect is being considered, e.g., likelihood of illness over a 10 yr period. The DCFs are based on a set of assumptions concerning the radiation source, environment, and the exposed individual. For the inhalation pathway, the air in the immediate vicinity of the individual is assumed to be uniformly contaminated (well-mixed). Finally, DCFs are referenced to the anatomy and breathing rate of the reference adult person and so estimated internal, e.g., organ, doses implicitly assume some shielding by the adult body. The use of "modification factors," which linearly scale the provided DCFs, is recommended when the source geometry, environment, and exposed population differ from these standard assumptions.

[36] This standard is comparable to the IAEA standard of 20 mSv per yr to transition from an emergency to an existing exposure situation [267] and lower than locations with naturally high levels of background radiation, e.g., [268].

[37] The physical and chemical form of the radioactive material determines (1) where the material deposits in the body, (2) where and how fast the deposited material migrates to other body tissues, and (3) how rapidly the material is removed from the body. See the related discussion in the (*5.2 Chemical and Air Quality Hazard Health Effects*) section.

For most use cases, the assumptions used in deriving the DCFs are consistent with the assumptions used in the RSA methodology. For example, the RSA location transmission (and protection) factors, which linearly scale the unsheltered dose, are functionally identical to the DCF modification factors used to adjust the standard DCFs to local conditions.[38] The references in this report, including but not limited to [18], [19], [275], provide improvements over the original modification factors. We note as a reminder that RSA shelter quality, which also has units of protection factor, also incorporates the distribution of population among different RSA locations.

[38] Factors analogous to RSA location protection factors can be used to scale health effects reference values from the reference man to other men as well as women and children, e.g., [265].

5.1.3. Additional Considerations

The building protection estimates may require additional adjustment(s) when assessing certain airborne radionuclides. First, some specific radionuclides have a half-life comparable to, or smaller than, the typical indoor-outdoor building air exchange rate of a few hours. If the progeny poses a significant hazard (relative to the parent radionuclide), then the building protection factor needs to be adjusted to account for this additional radiation exposure in a manner analogous to the derivation of the standard inhalation DCFs. Notable examples include ^{88}Kr and ^{138}Xe (with half-lives of 170 and 14 min, respectively) and their radioactive progeny ^{88}Rb and ^{138}Cs, respectively (with half-lives of 18 min and 33 min, respectively). We note that in these two cases, the physical form of the airborne hazard has changed (from a gas to a particle). Second if the radionuclide of interest deposits readily indoors and poses a significant external radiation hazard, then the effects of indoor surface contamination must also be considered.

5.2. Chemical and Air Quality Hazard Health Effects

Chemical inhalation exposure injury has historically been the subject of intensive toxicologic study. Data are available for a large number of chemical hazards and, when combined with the available medical and epidemiologic data, the overall scale of this field is sufficiently large that a comprehensive treatment of this subject is well beyond the scope of this section.[39] However, a review of key concepts relevant to chemical health effects is valuable in understanding the nature and range of commonly occurring chemical health effect possibilities and the degree to which commonly used models relating these health effects to environmental chemical exposures are compatible with the current RSA methodology.[40]

In this section, we provide a brief summary of (a) selected injury mechanisms and common health effects due to airborne toxic chemicals, e.g., inhalation exposures,[41] (b) some common health effects models, and (c) health effect exposure guidelines currently in use. Throughout we emphasize specific examples of chemical hazards identified

[39] See [124], [125], [276]–[278] for a fuller treatment from a toxicological, clinical and epidemiological perspective.

[40] This review is also relevant to emergency response and public health planning in assessing needed resources and effective medical treatment of inhalation injuries [80], [86], [279]. While current medical practice recommends a single, standardized emergency medical treatment protocol when the specific chemical hazard is unknown, e.g., [280]; medical professionals use symptoms to guide medical diagnosis and treatment decisions and these best-practices are starting to be incorporated into emergency medical care decision support software tools [281].

[41] This section considers airborne chemical exposures to both (a) toxic chemicals in either (i) gaseous or (ii) airborne liquid or solid particulate form, e.g., $PM_{2.5}$, PM_{10}, and (b) relatively chemically inert matter, i.e., inert gases and certain mineral dusts.

through prioritization efforts[42] as well as other inhalation hazards of known public health consequence, e.g., those relating to natural disasters such as weather events, geological processes, and large-scale fires.[43] Following this, theoretical and practical considerations are also discussed to assist the reader in applying the RSA method to other chemical health effect models. This discussion is also intended to assist in the use of epidemiologically based health effect models which relate the incidence of health effects to environmental exposure monitoring data.

5.2.1. Overview of Respiratory System Zones and Exposure Considerations

Conventionally, the respiratory system is divided into three anatomical-based zones: (a) the upper airways which include the mouth, nose and pharynx; (b) the trachea and bronchial airways that transmit air to the lungs; and (c) the deepest alveolar spaces of

[42] It is impractical to comprehensively address the complete chemical inventory due to the (a) the large number of chemicals currently in use, (b) the wide variety of possible exposure scenarios and potential health effects for any given chemical, and (c) the considerable level of effort required to develop a robust understanding of an even single chemical's toxicity. Consequently, chemical inhalation hazards are prioritized and formal risk assessments and guidelines are developed for those chemicals designated the greatest potential hazard (risk). While the details and results of the prioritization vary with each application, prioritization has, in general, been based upon the (a) assessed potential for human health and/or environmental toxicity, (b) volume in commerce, and/or (c) the potential inhalation risks to those who either (i) directly work with the chemicals and (ii) populations in neighboring or otherwise exposed communities. Important examples include the US National Research Council risk assessment process for developing acute exposure guideline levels [247], the North American chemical transport prioritization system [7], the NIOSH qualitative algorithm for prioritizing chemicals immediately dangerous to life and health [249], and the US EPA's list of priority (criteria) air pollutants [282]. There remain ongoing efforts to develop chemical prioritization lists and hazard risk algorithms for practical operational use in public health and emergency response planning, e.g., [108].

[43] (1) The intersection of natural disasters, e.g., hurricanes, tsunamis, earthquakes, etc., and chemical manufacturing, storage, transportation and distribution, and supply chain risks is a substantive concern [67]–[69], [283]. (2) Toxic volcanic gas emissions - CO_2, H_2S, SO_2, and the hydrogen halides (HF, HCl, and HBr) - occur regularly and cause significant morbidity and mortality on local and regional populations [71]–[73]. Also, ongoing lower level volcanic emissions cause air pollution-related health effects, i.e., "vog" [284]. (3) Non-industrial fires such as large-scale forest, grassland or urban wildfires can cause combustion product inhalation injuries and mortality on a community as well as a regional scale [74]–[77].

the lungs proper. The first two zones conduct air to and from the third (alveolar) zone - which is the site of rapid and effective gas exchange between lung air and the bloodstream, e.g., O_2, CO_2.

Inhalation exposure to toxic chemicals can produce characteristic injuries within each of the three respiratory system zones. Depending on the chemical and dose, these injuries may range from local irritation to fatal effects (see below). In addition, the deep lung alveolar spaces are a key portal of entry for inhaled hazards to access the bloodstream (circulatory system) and to subsequently distribute to organs throughout the body. In the lungs proper, chemical absorption is typically rapid and direct [44] – unlike ingestion exposures where stomach acid, intestinal enzyme systems, and a first-pass liver metabolism can degrade toxins before they reach the systemic bloodstream [277], [285], [286]. [45]

For toxic gases, injury to respiratory surfaces is in large part controlled by the chemical interactions between the toxin and the respiratory surfaces. Water soluble chemicals readily deposit on and readily react with respiratory surfaces. Examples include formaldehyde, sulfur dioxide, chlorine, and hydrochloric acid. These compounds

[44] For perspective, on average, human lungs have approximately 700 million alveolar sacs, with a net surface area of 70 m^2. Each alveolus is wrapped in a fine network of blood capillaries covering about 70% of its surface. The diffusion distance across the alveolar-capillary membrane space is extremely small (0.1 to 0.5 µm) and it takes only 3 to 4 seconds for blood to transit the entire lung capillary network. Hence, solute passage across the alveolar-capillary membrane and into the lung blood vessel system is equivalent to an intra-arterial injection of potentially hazardous material at the source of the systemic circulation. See [285], [286] for more information.

[45] The deposition of inhaled chemicals on the upper airway mucosa followed by swallowing and ingestion may also result in systemic exposures. This may be important in some settings, but this is beyond the scope of the current discussion.

commonly produce injuries in the upper two respiratory system zones [287]. The specific injuries depend to some degree on the compound, but include (a) direct mucous membrane irritation or injury and (b) narrowed airways due to tissue swelling or injury which can be associated with compromised breathing, and (c) fatal obstruction of the airways [279]. At lower concentrations, irritant effects and airway defense mechanisms, such as coughing, can prevent inhalation of these gases deeper into the lungs. On the other hand, high concentration exposures can result in these gases penetrating into the deep lung - resulting in alveolar space toxicity including chemical pneumonitis, pulmonary edema (excess fluid filling the lungs) and, in severe cases, fatal Acute Respiratory Distress Syndrome [80], [279], [288], [289].

Less water soluble chemicals – such as phosgene and oxides of nitrogen – typically cause less injury in the upper two respiratory system zones and so may have less significant warning properties. Therefore these chemicals more readily penetrate to, and subsequently injure, the deep alveolar spaces. This penetration also increases the potential not only for serious alveolar injury and interference with O_2-CO_2 gas exchange, but also for the systemic absorption of these chemicals into the blood. For these reasons, less water soluble toxic chemicals are often associated with significant morbidity and mortality [80], [86], [279].

For chemicals that pose a systemic absorption risk, the process by which the compounds are (a) absorbed, (b) distribute and reside within the body, and (c) are ultimately removed directly affect both the (i) speed and degree to which individuals are exposed

and (ii) subsequent health effects. Since gas exchange is rapid between alveolar air and the bloodstream, the rate at which compounds are absorbed within the body depends on (a) compound solubility and its prior concentration in the blood, (b) air and blood flow parameters, and (c) the body's removal processes [125], [277], [290], [291]. Water soluble and water insoluble compounds associate, and hence are transported, in different blood compartments. Water soluble (hydrophilic) compounds, such as alcohols, readily dissolve within the plasma compartment. Water insoluble (lipophilic) compounds, such as benzene, associate with the red or white blood cell membranes and/or circulating proteins, e.g., albumin. Flow-dependent parameters, including (a) breathing volumes and rates and (b) the volume of lung blood flow, control the rate at which contaminated air and blood is refreshed at the alveolar level. Absorbed toxicants may be removed from the bloodstream via (a) uptake in target body organs or tissues or (b) liver metabolic degradation, urinary excretion, and/or exhalation. Note that water insoluble compounds generally take longer than water soluble compounds to reach a steady state concentration (dynamic equilibrium) in lung air, the bloodstream, and in target organs.

When inhalation exposure ceases, the body burden starts to decrease. Material dissolved in the bloodstream rapidly passes back into the alveolar air and is exhaled. At longer timescales, compounds bound within body tissues and target organs reenter the bloodstream and are subsequently removed. However, when compounds are tightly bound to target organs and/or retained in the body's fat stores (which have minimal

blood circulation), this process can proceed for years [290], [291]. As blood levels remain elevated during this process, other body tissues and organs are subject to long-term exposures and so this process can result in chronic disease, e.g., the bone-lead reservoir [292]. In other cases, such as cadmium exposure due to cigarette smoke exposure, the compound is so tightly bound to the target organ tissues that blood concentrations do not correlate with the body burden or long-term health risks [293]–[295].

For airborne particulate inhalation exposures, the probability that an airborne particle can enter, and subsequently deposit within, a respiratory zone strongly depends on the particle size (aerodynamic diameter). These probabilities are commonly grouped into three independent sets (one for each respiratory zone) [106], [296]. The "inhalable fraction" assesses the probability that a particle will enter the mouth, nose, or pharynx. The "thoracic fraction" assesses the probability that a particle will enter the tracheal-bronchial airways region. The "respirable fraction" assesses the probability that a particle will enter the deep alveolar region. The most probable (> 50%) particle sizes that deposit in each zone are $p_{size} \lesssim 100$ µm, $p_{size} \lesssim 10$ µm, and $p_{size} \lesssim 4$ µm, respectively. For context, the current standard US ambient atmospheric particulate measurements broadly map to the "thoracic fraction" (PM_{10} coarse particles; < 10 µm) and the "respirable fraction" ($PM_{2.5}$ fine particles; < 2.5 µm) respectively [106]. Particle sizes that lie outside these ranges have a lower, but non-zero, probability of entering and depositing within each zone and so can be important when assessing inhalation

exposures to high concentrations of particulates. For this reason, particulate exposure assessments inherently require consideration of a wide range of potential particle sizes [297]. For example, the internationally harmonized CEN/ISO/ACGIH particle measurement (sampling) criteria for thoracic and respirable fractions explicitly account for particle sizes up to 10 and 25 µm, respectively [298]–[300].[46] The distributions of atmospheric aerosol particulates and their health effect mechanisms have recently been reviewed [301], [302].

5.2.2. Illustrative Acute and Chronic Chemical Health Effects

Tables 4a and 4b provide examples that illustrate the wide range of acute and chronic adverse human health effects that toxic chemicals can cause in each of the three respiratory system zones [125], [277], [288], [289]. These tables are not intended as a comprehensive listing and, for example, do not include many important human disease examples. Further, many other chemicals are classified as toxic inhalation hazards on the basis of animal toxicology studies where human data are incomplete or unavailable, e.g., [7], [303], [304]. Acute health effects here are defined here as those occurring seconds to hours after exposure while chronic health effects are those developing months to years after exposure. For readability, we do not discuss time periods that lie between acute and chronic effect timescales (these are often called sub-chronic effects).

[46] Ultrafine particulates <0.1 µm are potentially more hazardous than larger-sized particles [232], [233]. This is a developing research area and has yet to produce risk assessment guidelines.

Table 4a. Illustrative Acute Health Effects Due to Inhalation Exposure to Chemical and Particulate Hazards

Respiratory system zone	Acute health effect	Example chemical/particulate
Upper airway	Respiratory mucosal irritation, Rhinitis, Pharyngitis, Laryngitis	Acrolein, ammonia, chlorine, chromium fume, formaldehyde hydrogen chloride, hydrogen fluoride, methyl bromide, nitric acid, sulfur dioxide
	Laryngeal edema, Fatal airway obstruction	Inhalation burn injuries
Tracheal-Bronchial airways	Tracheitis	Hydrofluoric acid, sulfur mustard, combustion products, inhalation injury/burns
	Acute bronchitis, Bronchiolitis	Acrolein, anhydrous ammonia, chlorine, hydrogen chloride, oxides of nitrogen, ozone, sulfur dioxide
	Reactive Airways Disease (RADS)	Chorine, toluene diisocyanate, oxides of nitrogen
Deep lung alveolar spaces – local injury	Chemical pneumonitis (alveolitis)	Chlorine, phosgene, petroleum distillates, pesticides, smoke inhalation
	Pulmonary edema	Ammonia, phosgene, nitrogen dioxide, smoke inhalation
	Acute Respiratory Distress Syndrome (ARDS)	Chlorine, hydrochloric acid, cadmium fume, nitric acid
Deep lung alveolar spaces – systemic absorption	Chemical asphyxiation	Carbon monoxide, cyanide, hydrogen sulfide, acrylonitrile
	Cholinergic neurological syndrome	Organophosphate pesticides
	Metal fume fever, Polymer fume fever	Chrome, nickel, copper and manganese fumes; fluorocarbon polymer decomposition products

Table 4b. Illustrative Chronic Health Effects Due to Inhalation Exposure to Chemical and Particulate Hazards

Respiratory system zone	Chronic health effect	Example chemical/particulate
Upper airway	Allergic and non allergic rhinitis	Isocyanates, glutaraldehyde, anhydrides, solder/colophony, resins and glues, metal salts, persulfates, aldehydes
	Nasal septal ulceration, Perforation (corrosive rhinitis)	Hexavalent chromium (VI) fumes
	Nasopharyngeal cancer	Formaldehyde, production of isopropyl alcohol, nickel
Tracheal-Bronchial airways	Asthma	Isocyanates, epoxy resins, metals (nickel, platinum, chromium VI), ethylenediamine, gluteraldehyde, trimellitic anhydride
	Tracheal stricture	Combustion products, inhalation injury/burns
	Chronic Obstructive Pulmonary Disease (COPD)	Cadmium, mineral dust (coal, silica), welding fumes
	Bronchiectasis	High dose ammonia
	Bronchiogenic lung cancers	Crystalline silica, asbestos, diesel exhaust, metals (As, Be, Cd, Cr (VI), Ni), polycyclic aromatic hydrocarbons (PAHs), air pollution, environmental tobacco smoke
Deep lung alveolar spaces – local injury	Hypersensitivity pneumonitis (Extrinsic Allergic Alveolitis)	Toluene diisocyanate and diphenylmethane diisocyanate, insecticides, trimetallic anhydride, epoxy resins
	Chronic restrictive interstitial lung disease	Crystalline silica, asbestos
	Lung adenocarcinoma	Environmental tobacco smoke exposure
	Lung pleura – mesothelioma	Asbestos, erionite
Deep lung alveolar spaces – systemic absorption	Neurological disease	Lead, mercury, manganese (Parkinson's Disease), carbon monoxide, carbon disulfide
	Heart disease	Air pollution ($PM_{2.5}$)
	Kidney disease	Lead, high concentration mercury, cadmium fume, crystalline silica
	Hematologic: aplastic anemia (bone marrow toxicity); hemolytic anemia	Benzene, arsine

Tables 4a and **4b** also illustrate several important features commonly seen in inhalation exposure health effects. First, a single chemical exposure may cause multiple health effects in a single organ – including both acute and chronic effects. For example, formaldehyde causes acute upper respiratory irritant syndromes as well as nasopharyngeal cancers, whereas inhaled crystalline silica and asbestos can cause both lung scarring (interstitial fibrosis) and lung cancer. Similarly, inhaled chromium (VI) can cause nasal ulcerations, nasal septum perforation, and asthma, as well as lung cancers. Second, a single chemical or particulate may cause health effects in multiple organ systems. Examples include inhaled lead, which causes neurological and chronic kidney disease, and cadmium and crystalline silica, which both cause kidney and lung disease. Third, with increasingly high doses there is an increasing likelihood that multiple lung zones will be affected and also that systemic health effects will occur. For example, ammonia can cause acute direct injury to the upper or the tracheal-bronchial airways with rapid (near immediate) health effect onset times. However with high dose exposures, ammonia inhalation can also cause alveolar-level pulmonary edema [305].

5.2.2.1. Acute Health Effects

Acute health effects can occur in two ways. First, acute inhalation exposures can cause direct injury to the respiratory system. Second, inhaled chemicals can traverse the alveolar-capillary membranes, enter the main arterial systemic circulation, and cause acute health effects in target organs other than the lungs or produce a more widespread "systemic" illness response. **Table 4a** presents examples of both these cases, which are discussed in more detail here.

Direct injury to the respiratory system is often a result of exposure to chemicals in the irritant and vesicant chemical classes [80]. Health effects often occur more quickly with exposure to irritant class chemicals than with vesicant class chemicals. For both classes, injuries to the upper two lung zones can rapidly result in inflammation (chemically induced pharyngitis, rhinitis, laryngitis, tracheitis or bronchitis) [279], [306]–[308]. Reactive Airways Disease (RADS), an acute onset asthma-like syndrome resulting from a single exposure incident that persists for three or more months, may also occur. At higher concentrations, many respiratory tract irritant exposures, such as ammonia, hydrofluoric acid, and chlorine, are well demonstrated to cause chemical burns, mucosal inflammation and swelling (edema) and even fatal upper airways obstruction. In the most severe injuries, tissue damage may not be reversible, resulting in chronic illness and disability, see also the (*5.2.2.2. Chronic and Long Lasting Health Effects*) section [80], [86], [279], [288], [289].

Acute inhalation injuries in the deep lung are due to injury to the thin, delicate alveolar-capillary membrane units. Direct chemical injury to these tissues and injury-related tissue inflammatory responses result in toxic pneumonitis (chemical pneumonia). Pulmonary edema can also occur. These two conditions are serious as they may compromise the primary lung function (O_2-CO_2 gas exchange), and indeed pulmonary edema that evolves within four hours of inhalation exposure is associated with high mortality rates [304]. Acute Respiratory Distress Syndrome (ARDS), a more serious condition which also carries significantly high mortality rates, is due to widespread

necrosis and shedding of the thin alveolar-capillary membranes which compromises lung airspace capacity [80], [86], [279].

Systemically absorbed chemicals can cause acute illness. Examples include metal and polymer fume fever, a systemic illness caused by chemical activation of innate immunity inflammatory mediators. Symptoms include chills, fever, cough, malaise and muscle aching with onset a few hours following exposure to metal or polymer fumes. The syndrome typically resolves with withdrawal from exposure [309], [310]. Absorbed chemicals can also target key physiological systems, causing acute illness by reducing or blocking their functioning [80]. These will have symptoms associated with the affected system(s). For example, asphyxiation occurs when chemical exposure interferes with respiration. This interference can occur through a variety of mechanisms including interfering with (a) the hemoglobin protein system in red blood cells that transports oxygen from the lungs to individual cells in the body or (b) body's cellular level oxygen based energy production system (cellular respiration) or (c) suppression of central nervous system respiratory drive mechanisms. As one example, inhaled carbon monoxide is systemically absorbed and binds to hemoglobin, forming carboxyhemoglobin, with an affinity 200 times stronger than oxygen.[47] Thus carbon monoxide exposures cause decreased oxygen-carrying capacity and tissue hypoxia. Headaches, dizziness, nausea, fatigue, and impaired manual dexterity occur when

[47] Indoor epidemics of carbon monoxide poisoning can occur after storms and other natural disasters that cause electrical service disruptions. Two main carbon monoxide indoor exposure sources in this setting are improperly vented gasoline-powered electrical generators and cooking or heating with charcoal briquettes. [311]–[313].

carboxyhemoglobin saturates 15 to 30% of the hemoglobin oxygen binding sites. Fatal loss of consciousness and cerebral ischemia are associated with blood carboxyhemoglobin saturation levels of 30 to 70% [314]. Other chemical asphyxiates can have different, physiologically specific mechanisms of action.[48] Sodium cyanide and hydrogen sulfide both prevent cellular-level utilization of oxygen throughout the body by inhibiting the key enzyme cytochrome oxidase [80].[49]

Acute systemic inhalation hazards may affect other aspects of body metabolism such as maintaining serum electrolyte levels and proper body acid-base status, which are both essential for the body's PH-dependent biochemical systems to function. Examples include hydrofluoric acid – which releases fluorine ions which bind calcium and magnesium causing fatal hypocalcemia [278].[50] Toluene and cyanide both cause systemic metabolic acidosis (low arterial blood PH) – which in the case of toluene is associated with serum low potassium levels [80], [319].

[48] While not systematically absorbed, inert gases such as nitrogen can physically displace atmospheric oxygen and, when an oxygen deficient atmosphere occurs, can cause asphyxiation in just a few breaths. Mass asphyxiation casualties have occurred after carbon dioxide gas releases from "dormant" volcano crater lakes, e.g., the 1,800 deaths in the 1986 Lake Nyos catastrophe [315], [316]. More generally, asphyxiation deaths from dispersion of volcanic gases during eruptions can account for a majority of casualties, for example the 1980 Mount St Helens USA event [72].

[49] In the US, there is continuing risk for hydrogen sulfide related occupational fatalities not only for workers, but also for their rescuers [317]. The potential hazards of cellular-level asphyxiates on a population level is illustrated by the 2003 hydrogen sulfide gas release from a natural gas well blowout in Chongqing, China [318]. Hydrogen sulfide gas was dispersed to surrounding communities over a 25 mi^2 area with 243 persons killed, 4,000 hospitalized, and 60,000 evacuated.

[50] Hydrofluoric acid is highly water-soluble and fatal hypocalcemia may also occur through skin absorption.

Another important example of acute systemic inhalation toxicity resulting in multiple health effects is organophosphate pesticide induced "cholinergic neurological syndrome." Levels of neurotransmitters in the nervous system are regulated by a balanced system of controls on their synthesis and the enzyme systems that degrade them [80]. In acute organophosphate pesticide inhalations, inhibition of the degrading enzyme acetyl-cholinesterase leads to a sustained, increasing levels of the neurotransmitter acetylcholine and, potentially, a fatal "cholinergic crisis." Symptoms include profuse exocrine secretions (tearing, sweating, salivation, rhinorrhea, and bronchorrhea), impaired vision, headache, nausea, vomiting, diarrhea and incontinence, as well as muscle weakness, paralysis, seizures and coma. Respiratory failure (and death) can result from combined bronchial secretions and constriction, respiratory muscle weakness and a decreased central nervous system respiratory drive [80].

5.2.2.2. Chronic and Long Lasting Health Effects

Chronic and/or long-lasting health effects can occur in two ways. First, acute inhalation exposures can cause tissue damage so severe and disabling that the health effects are permanent. Second, chronic lower concentration inhalation exposures over time may result in chronic tissue injuries, which later manifest as chronic disease(s), either in the respiratory system or elsewhere in the body. **Table 4b** presents examples of both cases, which are discussed in more detail here.

Long-lasting, disabling complications can follow acute inhalation injuries. For example, smoke inhalation can result in tracheal narrowing (stricture), which is not always

amenable to reconstructive surgery. Similarly high concentration ammonia inhalation can cause chronic bronchiectasis - a permanent, pathological dilatation of the bronchi which can result in chronic cough. Bronchiectasis predisposes individuals to recurrent bronchial infections which, if untreated, causes a disabling decline in lung function [305], [320]. Furthermore, high dose carbon monoxide inhalation can result in neurological impairment due to cerebral demyelination. In non-fatal carbon monoxide inhalation exposures, withdrawal from exposure or treatment may initially resolve acute symptoms, however delayed neurologic complications may occur 2 to 40 days afterwards and include lethargy, behavior changes, memory loss, and Parkinson's Disease like symptoms. These conditions become permanent in a quarter of the cases [314].

For chronic chemical inhalation exposures, the respiratory system is often the initial target organ and chronic respiratory diseases resulting from chemical inhalation exposures occur in all three respiratory system zones. Important examples include (a) local upper respiratory syndromes such as chronic rhinitis from isocyanates, glutaraldehyde, anhydrides, solder/colophony, resins and glues, metal salts, persulfates, and aldehydes [321]; (b) a variety of bronchial-level diseases, such as asthma, from chemical exposures similar to those that cause chronic rhinitis, as well as ethylenediamine, and trimellitic anhydride; chronic obstructive pulmonary disease (COPD) including chronic bronchitis and emphysema from cadmium fumes, mineral

dusts such as coal and silica, and welding fumes [287]–[289];[51] (c) and alveolar-level or "intrinsic lung" disease which includes interstitial (fibrotic, scarring) lung disease from crystalline silica and asbestos [288], [289]; as well as hypersensitivity pneumonitis due to small-molecular-weight chemical compounds such as toluene diisocyanate and diphenylmethane diisocyanate, trimetallic anhydride, insecticides, and epoxy resins [287]–[289], [323]. Furthermore, chronic chemical inhalation exposures are proven causes of a wide variety of respiratory cancers involving the upper airways (e.g., formaldehyde and nickel compounds cause nasopharyngeal cancer; strong inorganic acids and asbestos cause laryngeal cancer); and a variety of inhalation exposures cause cancers in the bronchial and deep lung regions (e.g., metals including beryllium, cadmium, chromium VI, nickel compounds; diesel engine exhaust; outdoor air pollution, asbestos) [124], [324]–[326].

Even chemically inert and physically indigestible materials, such as asbestos and crystalline silica, can cause health effects when chronically inhaled. These particles, which primarily deposit locally in the deep lung spaces, are secondarily distributed via the regional lymph node system – with much smaller quantities being absorbed into the bloodstream. In the lung proper and in the local regional lymphatic system, white blood cells (tissue macrophages) attempt to digest these materials, releasing oxidative radicals, enzymes, and inflammatory mediators. This ongoing process causes chronic

[51] Approximately 3 billion people cook and heat their homes using solid fuels in open fires and rudimentary stoves resulting in household air pollution due to indoor combustion of solid fuel. This is highly associated with both the chronic bronchitis and emphysema phenotypes of COPD as well as a unique form of COPD (bronchial anthracofibrosis) [322].

lung damage, specifically tissue scarring (pulmonary fibrosis) and increased cancer risk [287], [325], [327]. Furthermore, systemically absorbed crystalline silica can be found in a variety of body organs and causes chronic kidney and systemic autoimmune diseases [328]–[330].

A variety of inhaled chemicals can be directly absorbed and cause chronic health effects in non-respiratory target organs and/or systemic responses. These chemicals are adsorbed into the bloodstream either (a) at the alveolar level or (b) via inhalation and deposition in the upper airway with subsequent direct absorption or swallowing/ingestion. A number of inhaled hazards cause chronic kidney disease, particularly including metals such as lead, cadmium and high dose mercury exposures [288], [289]. Chemicals, such as benzene, cause insufficient red blood cell production (aplastic anemia) due to bone marrow injury whereas other chemicals, such as arsine, directly destroy red blood cells already in the blood (hemolytic anemia) [277], [278], [331]. Short-term exposure to small particle ($PM_{2.5}$) outdoor air pollution causes increased cardiovascular mortality, while long term $PM_{2.5}$ exposure is demonstrated to cause atherosclerotic heart disease [332]–[334]. [52] Finally, central nervous system

[52] The primary $PM_{2.5}$ toxic mechanisms are thought to be (a) induction of a systemic inflammatory response, (b) oxidative stress (a condition in which high levels of free radicals or reactive oxygen/nitrogen species are present – these species are capable of lipid/protein/deoxyribonucleic acid [DNA] oxidation), and (c) the initiation of systemic proinflammatory cascades [124], [129], [232], [333], [335].

toxicity is well known for some chemicals including mercury, carbon disulfide, and manganese (the latter causes a chronic Parkinson's disease syndrome) [336].[53]

5.2.3. Chemical Exposure Guideline Levels

Several different types of chemical exposure guideline levels exist. **Figure 5**, taken from a US EPA summary document, illustrates the wide range of chemical exposure guideline level concentrations, durations, and target populations currently in use using chlorine as an exemplar chemical [339].

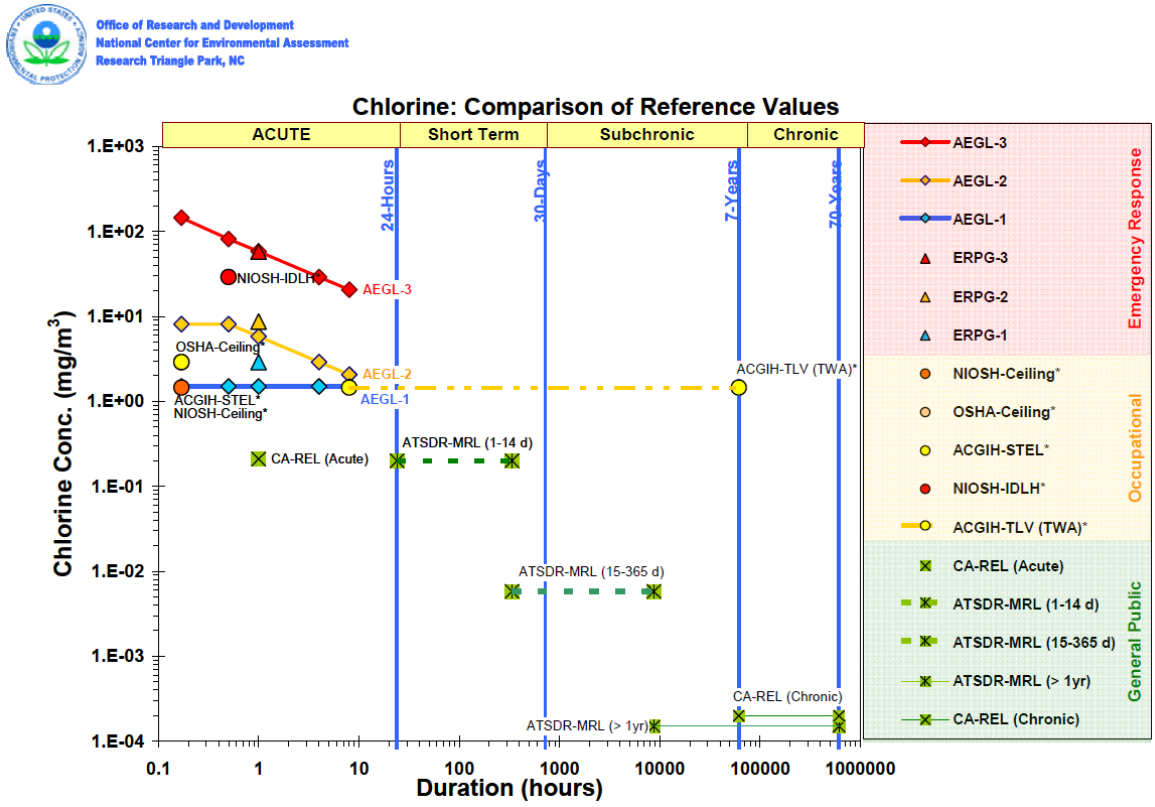


Figure 5. US EPA provided comparison of exposure guideline level values for inhalation exposure to chlorine [339]. In this figure, "*" indicates an occupational value in which expert judgment is needed prior to applying these values to the general public.

[53] Perhaps the most notable example is the use of the gasoline additive tetraethyl lead in the 1950s to 1970s that significantly contributed to air pollution and caused wide-spread US population-level lead inhalation exposure. US blood lead levels were substantially higher during these periods than was subsequently determined to be safe for children's cognitive development [337], [338].

In the context of chemical emergencies – a short-term, once in a lifetime exposure to a toxic chemical, exposure guideline levels are called Protective Action Criteria (PAC). PACs are commonly used in conjunction with exposure models and/or monitoring data to assess when and where populations are at risk for developing acute adverse health effects. Identified populations and regions can then be targeted by emergency planners and responders for additional protective actions, e.g., sheltering, evacuation, decontamination, or respiratory protection [7]. There are three major sets of emergency response guideline levels: Acute Exposure Guideline Levels (AEGLs), Emergency Response Planning Guidelines (EPRGs), and Temporary Emergency Exposure Limits (TEELs) [247], [248], [254], [340], [341]. Each exposure guideline level has a differing scope, degree of development rigor, exposure duration coverage, and target population. The current US policy for emergency response health risk evaluation uses all three sets in an integrated, hierarchical fashion, e.g., [341], [342]. In all three sets, the exposure guideline levels are defined as an exposure to a time weighted average (TWA) chemical air concentration for a given exposure duration (which ranges from 10 min to 8 h).

In the context of occupational exposures – workplace inhalation exposures to toxic chemicals and particulates, exposure guideline levels are called Occupational Exposure Levels (OEL). The history of and development process for OELs has been recently reviewed [343]. OELs are in routine use by Industrial Hygienists to identify and control potential workplace hazards. OELs typically are designed to apply to healthy, working adults and so may not be appropriate for other persons. Some OEL types apply only to

brief exposure time periods and include the (a) Short-Term Exposure Limits (STEL) which are TWA chemical air concentrations not to be exceeded during any 15-min period and (b) Immediately Dangerous to Life or Health (IDLH) or ceiling levels which are typically concentrations not to be exceeded at any time. Other OEL types are designed to control long-term exposures with the general intent to define airborne chemical concentrations to which nearly all workers can be repeatedly exposed over a working lifetime without experiencing adverse health effects. The long-term OEL exposure durations are specified as TWA chemical air concentrations over a work period, e.g., 8 h per day, 40 h per week. Examples of short and long term exposure duration OELs include ACGIH Threshold Limit Values (TLVs®) [298], NIOSH Recommended Exposure Limits (RELs) and IDLH [249], [344], AIHA Workplace Environmental Exposure Levels (WEELs®) [254], OSHA and State of California CAL/OSHA Permissible Exposure Limits (PELs) [250], [251], UK Workplace Exposure Limits (WELs) [252], as well as other international standards, e.g., [345].

In the context of ambient air pollution – short and long-term exposures to harmful chemicals present in ordinary air, exposure guideline levels are called air pollution (or sometimes air quality) standards. Air pollution standards are commonly used in conjunction with air quality models and/or monitoring data to (a) identify when and where ambient outdoor air is hazardous and (b) guide actions to reduce hazardous air pollutants and minimize hazardous air exposures. Air pollution standards have been developed by many different states, nations, and international organizations including, but not limited to, the US, the European Union, and the World Health Organization

[282], [346]–[348]. A small number of pollutants, e.g., SO_2, NO_2, $PM_{2.5}$, PM_{10}, and O_3, have been identified as a particular concern and are often called criteria pollutants. Some organizations also consider additional chemicals, such as CO, to be criteria pollutants. Other metrics used for public health warnings, such as the Air Quality Index, summarize the net hazard of criteria pollutants and are in widespread use [152], [154], [155]. The details of the criteria air pollution standard specification depends on the chemical, organization, and target being protected. However, these standards are typically defined as a TWA concentration, with an averaging period ranging from 1 h to 1 y, that should not to be exceeded more than a specified number of times over a defined time period. For non-criteria air pollutants, some organizations have developed additional standards for use in chemical risk assessments. Notable examples include the US Environmental Protection Agency Reference Concentration (RfC) [253], [349]; the US Agency of Toxic Substances and Disease Registry Minimal Risk Levels [350], [351] and references within; and the State of California Reference Exposure Levels [245], [352] which are specified as chemical air concentration(s) to which individuals can be continuously exposed over a standard-specific period (ranging from 1 d to a lifetime) and not develop adverse, non-cancer health effects.

5.2.4. Modeling Approaches that Incorporate Building Protection

The original, and still the most common, subclass of chemical dose-response relationships is developed by correlating ambient (outdoor) atmospheric chemical (and particulate) concentrations with observed health effects (termed population level dose-

response relationships).[54] These models do not explicitly account for building protection effects, see discussion in the (*4.3.3.2. Dose-Response Relationships*) section. Modern examples include the health effect relationships built into the World Health Organization AirQ+ software program which relates routine monitoring ambient $PM_{2.5}$, PM_{10}, NO_2, and O_3 concentrations to acute and chronic health effect outcomes such as hospital admissions, mortality categories and respiratory disease incidence [259]–[261].

Within the context of air pollution research studies, the effects of building protection has been explicitly incorporated in exposure model risk assessments through the use of microenvironments. For the purposes of this discussion, a microenvironment is a (potentially) populated location in which the hazard concentration is spatially uniform and temporally constant for a given exposure duration [354]. Scaling factors – often called “infiltration factors” or, less commonly, “exposure factors,” “air decontamination factors,” and “penetration factors”[55] – are multiplied to outdoor-origin pollution concentrations to estimate the corresponding indoor contamination of outdoor origin. These scaling factors can be derived from either theoretical analyses or from experimental data [136], [138], [145], [146], [150], [355]–[357]. Microenvironments are closely related to RSA locations; however, the RSA location does not share the microenvironment limitation that concentrations are constant for a given exposure duration. In addition, while the linear scaling factors are analogous to RSA protection (or

[54] Epidemiologic exposure assessment models and methods utilized in air pollution research studies have recently been reviewed [353].

[55] The term “penetration factor” is also commonly used to refer to the fraction of outdoor-origin material that passes through the building exterior and so enters the indoor airspace.

transmission) factors for the microenvironment building types; RSA shelter quality, which also has units of protection factor, incorporates the distribution of population among different RSA locations (microenvironments). We note that care should be taken when comparing the reported ratio of indoor and outdoor concentrations to protection factors as some common air pollutants, including $PM_{2.5}$, are known to have significant local (indoor) sources and so indoor pollutant concentrations can, and often do, exceed outdoor concentrations [136], [138], [357].This caveat is applicable primarily to a select set of ambient air pollution study chemicals and particles and is not applicable to hazardous chemical release scenarios.

Several software packages exist that use microenvironments for air quality exposure and risk assessments. One notable set of software tools was developed by the US Environmental Protection Agency and includes the related TRIM.Expo/APEX, SHEDS, and HAPEM programs [358], [359]. These software packages have been used in a variety of airborne hazard research studies, including $PM_{2.5}$ and benzene [22], [360], as well as the National US Air Toxics Assessment (NATA), which analyzes US population-level health effects due to exposure to more than 100 toxic airborne chemicals [147], [148]. Broadly, these software packages assess the distribution of population level, e.g., census tract, metropolitan area, state, and national, inhalation exposures (and doses) by combining (a) the amount of time spent in each microenvironment (based on statistical studies of population behavior) with (b) estimated location (microenvironment) contamination. The latter is estimated by combining regional contamination levels, determined from (a)

fixed-site ambient air quality monitor data or (b) regional air quality models, with estimated building penetration (protection) factors for the populated microenvironments. We note that any given assessment typically uses a relatively small number of microenvironments, e.g., the NATA uses 18 microenvironments. Notable, recent research has provided estimates of individual building (microenvironment) protection for approximately 11.5 million UK residences, theoretically allowing for a higher degree of spatial resolution [145], [146].

5.3. Biological Hazard Health Effects

Bioaerosol[56] hazards are a significant cause of morbidity and mortality. We provide here a brief literature review of selected known bioaerosol hazards and their health effects relevant to population-level inhalation hazards. This review includes both the population-level airborne infectious microbial disease transmission and key literature for pathogenic, but non-infectious bioaerosol dispersions.[57] We note that much of this section falls under, and draws from, the well-established scientific discipline of aerobiology, e.g., [361]–[363].

5.3.1. Common Bioaerosols and Their Health Effects

Bioaerosols are particulates that can contain a wide range of biological materials, are normally ubiquitous in the indoor and outdoor atmosphere, and constitute a significant fraction of total atmospheric particulate matter [190], [364], [365]. With respect to the RSA methodology, there are two major classes of bioaerosol inhalation hazards: (a) intact, viable microorganisms such as viruses, bacteria and fungi that cause infectious disease and (b) inactive (dead) microorganisms; non-infectious microbial, plant, or animal subcomponent fragments; microbial cell contents, e.g., proteins, enzymes, toxins, metabolites, excreta; and plant pollen [364]. Non-infectious inhaled bioaerosols may cause significant adverse health effects either via direct toxic action or on an immunologic basis.

[56] We define bioaerosols as airborne particulate matter that contains biological-origin material.
[57] While this section focuses on the airborne particle inhalation pathway, microorganisms are opportunistic and in real-world disease outbreaks, a single agent may employ multiple routes of disease transmission, e.g., direct contact, fomites, ingestion, airborne transmission, etc. .

Bioaerosol particles have a wide range of aerodynamic diameters ranging from 10s to 100s of nanometers (e.g., viruses) to 100s of micrometers (e.g., some bacterial bioaerosols).[58] Bioaerosols are known to travel in the outdoor atmosphere over distances ranging from tens of meters to 100s of kilometers – with longer distances termed Long Distance Dispersions (LDD) [363], [364]. As such, bioaerosols are of potential relevance to disease outbreak and public health surveillance planning for both emerging and re-emerging diseases, background disease risk assessments, as well as veterinary and agricultural biosafety, e.g., [201].[59,60]

There are numerous examples in the human and veterinary public health literature of infectious diseases transmissible via the respiratory route [167], [175], [372]–[375]. Particularly relevant for RSA modeling, there are also cases in which infectious aerosols have had a significant population-level health and economic consequences resulting from medium and long-range (> 1 km) outdoor airborne transmission. Examples include the bacterial pathogens *Legionella pneumophilia* [192]–[195], [376]–[378], *Coxiella burnetti* [196]–[200], [379], and Methicillin-resistant *Staphylococcus aureus* [380]–[382]; the fungal pathogens *Histoplasma capsulatum* [168]–[170], [383]–[386], *Coccidioides immitis* [387]–[390], and *Aspergillus fumigatus* [167], [174], [191]; and viral pathogens

[58] An additional paper [19] focuses on particles sizes most of concern for human inhalation exposures, 0.1 to 10 µm aerodynamic diameter.

[59] Indoor origin bioaerols can be ventilated to the outside atmosphere and subsequently transported downwind. It is straightforward to show that the building transmission factors discussed here are often similar in scale to the fraction of indoor emissions that are released to the greater atmosphere.

[60] LDD bioaerosol dispersions are relevant to plant biology and biosafety, e.g., LDD aerosol transport of seeds and plant pathogens [366]–[370]. As emphasized in literature reviews, these scientific fields share methodological features with the human and veterinary medicine fields discussed in this report, e.g., [371].

including Foot and Mouth Disease virus [391]–[396], Newcastle virus [397]–[399], and highly pathogenic Avian Influenza (Influenza H5N1 virus) [400]–[402].[61] There is also the potential for medium range atmospheric dispersal of multiple potentially pathogenic microorganisms from environmental composting facilities and in livestock production [405], [406].

There are also numerous examples of known non-infectious bioaerosol inhalation hazards. Pollen allergy (Type I IgE-Mediated Hypersensitivity) is a clear exemplar of a significant outdoor to indoor transmitted inhalation hazard [407]. Other bioaerosols that are recognized inhalation hazards in industrial, agricultural or indoor settings include organic dusts (e.g., cotton, flour, and grain), mold and mold fragments, inactive (dead) bacteria, and toxins (e.g., mycotoxins, enotoxin, Beta Gucans, and Subtilisin enzyme). Collectively, these examples illustrate the variety of disease syndromes that can result from inhalation of non-infectious bioaerosols including, but not limited to, asthma, Organic Dust Toxic Syndrome, Hypersensitivity Pneumonitis, and chronic lung disease (Byssinosis, Allergic Bronchopulmonary Aspergillosis, etc.) [323], [408]–[410].

A single bioaerosol type may cause multiple, and categorically different, types of health effects. In fact, a disease spectrum is normal for many, if not most, bioaerosols. This spectrum may include conventional infectious diseases, purely immunologically based

[61] Influenza H5N1, has known veterinary animal to animal airborne transmission and probable LDD airborne dispersion [400]–[402]. The influenza H5N1 virus is under surveillance for human epidemic potential and hundreds of human fatalities from direct animal exposure are documented. However to date, there is limited human to human transmission documented [403], [404].

syndromes, toxic effects, classic allergic diseases, as well as other outcomes. For example, airborne exposure to *Aspergillus* fungi species and *Coxiella burnetti* bacteria can result in a particularly wide spectrum of diseases and health effects ranging from acute infection to allergy to disabling or even fatal chronic illnesses [174], [408], [411], [412]. Pontiac Fever is a *Legionella* related disorder with fever, headache, cough, myalgias, and/or GI symptoms and is clinically distinct from *Legionella* pneumonia. While *Legionella* strain variation has been hypothesized as a causal factor, an increasing number of reports indicate that Pontiac Fever may result from inhalation of inactive (dead) *Legionella* bacteria [378].

5.3.2. Bioaerosol Health Effect Models

Dose-response relationships have currently been estimated for a limited number of bioaerosols.[62] These bioaerosols, such as *Coxiella*, *Legionella*, and B. *anthracis* [414]–[418], primarily cause infectious diseases of public health significance and can cause wide-area population exposures resulting from LDD dispersions. Many of these published dose-response relationships are compatible with RSA methodology. First, many infectious and non-infectious dose-response relationships define dose as the total amount (expectation value) of inhaled biological material [234] which can be directly related to a RSA exposure by **Equation 17**. Second, infectious disease dose-response relationships are often based on the "independent risk" assumption (also termed "independent action" assumption). This is an assumption that the probability of any one

[62] In contrast, dose-response relationships are routinely employed to assess waterborne exposures and food safety risks, e.g. [234], [413].

infectious unit, e.g., microorganism, causing disease upon inhalation is independent of the total number or timing of infectious units inhaled, i.e., each infectious unit acts independently. As a consequence, only the dose (the total number of infectious units) is required to estimate a probability of host response (health effect).

Some important biological dose-response relationships are based on peak exposures or limited duration bioaerosol exposure concentrations rather than time-integrated bioaerosol concentrations. A classic example is environmental allergy to pollen where an initial exposure to a high peak concentration is known to increase risk of developing Type I hypersensitivity and subsequent allergic disease. While withdrawal from pollen exposure typically resolves the disease symptoms, once an individual is sensitized re-exposure at much lower concentrations may be sufficient to cause renewed symptoms. Depending on the time-scale of the initial sensitizing exposure, building protection factors suitable for peak concentration exposures may be need to be applied in RSA modeling of this type of inhalation exposure-health effect relationship (see the more general discussion in the (*4.3.3. Health Effect Models*) section).

For selected noninfectious bioaerosols, hazard-specific “benchmark” exposure guideline levels exist to ensure worker safety. Similar to chemical inhalation hazards, these benchmark guidelines can be directly incorporated into RSA risk assessments. General RSA compatibility relevant to these examples has already been discussed in the (*4.3.3.1. Exposure Guideline Levels*) section and the OELs types of interest have been previously discussed in the (*5.2. Chemical and Air Quality Hazard Health Effects*) section. For

context, specific examples of non-infectious bioaerosol OELs include Subtilisin enzyme (a protease from *Bacillus subtilis*): 60 ng m^{-3} (total dust, STEL); Grain Dust: 4 mg m^{-3} (of total dust); Raw Cotton Dust: 0.2 mg m^{-3} (<15 mm particles); and Endotoxin: 90 endotoxin units m^{-3} [250], [409], [410]. In a related note, toxicologic human challenge and epidemiological studies suggest a lowest effect level (LOAEL) of 10^5 spores m^{-3} of air across a diverse set of fungal species [419].

5.3.3. Additional Considerations

Some bioaerosol dose-response relationships do not rely upon the independent risk assumption. These models are typically more research, rather than operationally, oriented and, for example, may explore detailed features of a host receptor immune responses; the physical removal or destruction of particles deposited within the respiratory system; or bacterial cooperation/synergy during the host infection process [234], [420]–[422]. For these types of models, compatibility with the current RSA method is determined by the relative timescales of the (a) relevant health effect exposure[63] and (b) building protection timescale, see the (*4.3.3. Health Effect Models*) section for more details.

Significant indoor exposures may occur after the outdoor plume has passed – such as when individuals enter a building with elevated bioaerosol concentrations.[64] While this is also a concern for radiological and chemical hazards, it is particularly relevant for

[63] This is distinct from incubation period considerations, e.g., the time between the receipt of dose and first established infection and the onset of initial clinical symptoms.

[64] Such scenarios can occur when (a) the outdoor plume has passed but indoor concentrations remain elevated as well as due to (b) resuspension of initially deposited bioaerosols.

highly virulent infectious disease hazards where an individual inhaling a small number of bioaerosol particles has a high probability of developing disease. For example, the inhalation of 1 to 10 *Coxiella burnetti* bacteria particles is estimated to result in infection in 50% of exposed people [414], [418].

6. Discussion

Buildings can provide significant protection to their occupants – in some cases reducing acute and chronic exposures by orders of magnitude relative to exposures received by individuals outside. An international, multi-decadal research effort has advanced the scientific knowledge of building protection physics. However an operationally efficient method suitable for assessing US regional-level protection, as opposed to individual building-level protection, has not been previously available.

While sheltering is a well-recognized protective action, no general-purpose decision support tool currently exists to assist decision makers in emergency situations. This technical gap poses a challenge to both risk assessments in general, and emergency response planning in particular, as it inhibits the more nuanced use of sheltering including optimizing assessments by region, time period, and/or hazard as well as the development and use of more advanced shelter-evacuate strategies. The Regional Shelter Analysis methodology presented here attempts to address this need by extending prior research to provide a practical method that accounts for the protection that buildings provide their occupants against external hazards on a regional scale. Applications are specifically discussed in a companion report [19].

The Regional Shelter Analysis method presented here provides practical operational impact calculation capabilities for a variety of different types of exposures. In a given region, significant localized differences in exposures and health risks can exist and can be modeled using RSA shelter quality values. A separate shelter quality value is defined

for each distinct group of people in the built environment (i.e., modeling multiple probability bins).[65] The RSA method also allows for more accurate consequence assessments for hazards whose health effects do not vary linearly with exposure or population demographics, such as acute radiation exposure and many biological hazards (see the above (*4.3.3. Health Effect Models*) section). **Figure 6** illustrates the value of assessing regional variability in risk analyses using a hypothetical example in which almost all injuries (impacts) are predicted to occur in the "worst" protected 20% of the population while the "typical" (median exposure) individual is not injured. In this case, a global population assessment, i.e., a risk estimation that relies on calculating an "average" regional population-level protection factor, would not capture the fact that 20% of the regional population were injured, since the overall median population exposure is low. We note that the overall accuracy of the RSA method will depend, in part, upon the degree to which the probability bin specification accurately resolves the underlying shelter quality distribution.

[65] We note that uncertainty can be treated (a) analytically (error propagation) or (b) statistically using Monte Carlo methods or by adding an additional uncertainty axis analogous to the variability axis (i.e., shelter quality distribution) discussed in this report.

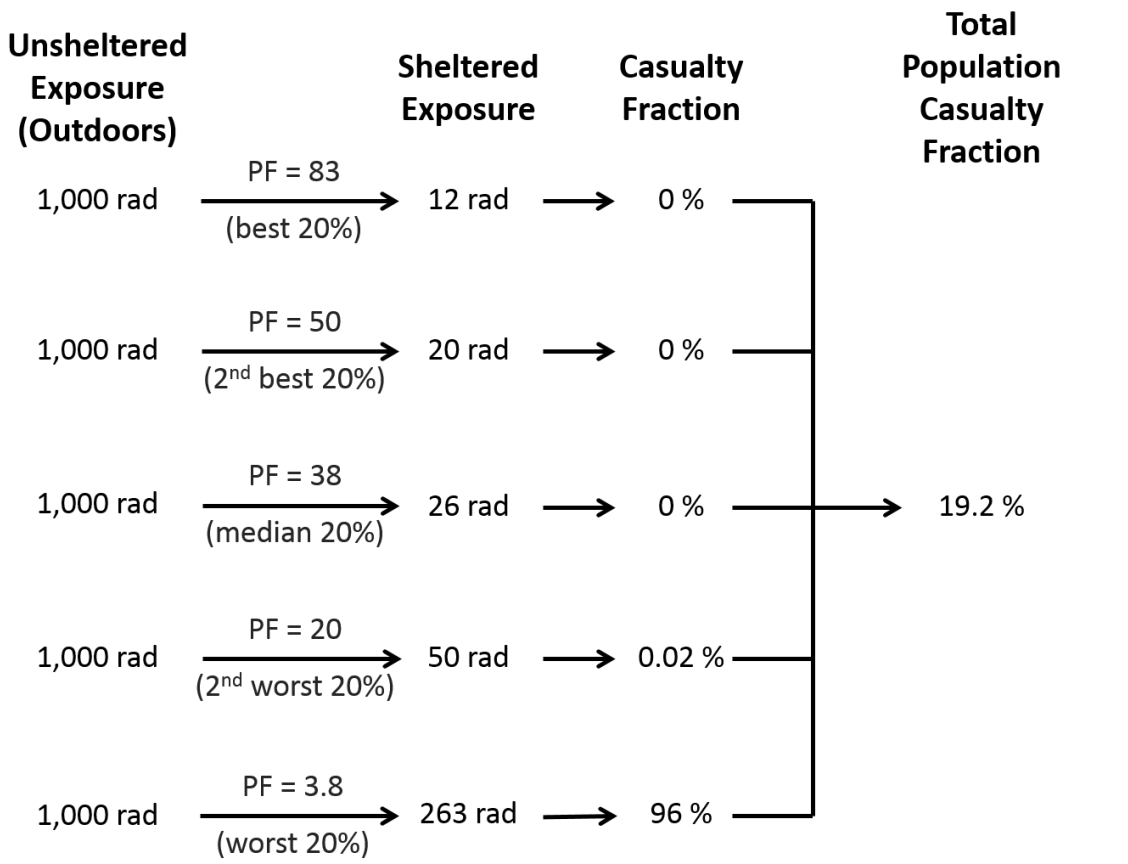


Figure 6. Illustrative casualty (impact) calculation. PF = protection factor

A more comprehensive RSA model could facilitate broader operational efforts to manage hazardous exposures. For example, the RSA method is intended to further the all hazards emergency response initiative by developing a consistent framework for considering how buildings affect both the external radiation and inhalation exposure pathways [20], [21]. Furthermore, an RSA model can inform more general public health planning efforts to maximize the benefits provided by the built environment by assessing the impact of proposed government policies on building protection (through updated building code standards) and population postures (through updated zoning ordinances and transportation infrastructure planning), e.g., [423]–[425] and references

therein. We note also RSA's potential ability to be adapted to provide exposure assessments for specific demographic subgroups including, but not limited to, economically and socially vulnerable populations [425], [426]. In performing such targeted assessments, consideration should be given to the degree to which the subpopulation of interest may be distributed within the built environment, i.e. whether it differs from the overall population. For example, from a building air infiltration perspective it is well known that low-income US houses are often "leakier" than higher income houses [427].

6.1. Limitations

The Regional Shelter Analysis method relies on a small set of technical assumptions which, while reasonable, deserve mention and comment. First, the RSA methodology, as described in this report, implicitly assumes that the location protection factors do not vary with time. Theoretical extensions to the current method are required when considering the effects of (a) certain types of building contamination;[66] (b) changing building properties, e.g., changing HVAC operating conditions; and (c) certain changes in the distribution of the hazard in the outdoor environment, e.g., nuclear fallout washing off of a roof in a rainstorm. Second, this report has focused on the airborne inhalational exposure pathways. A comprehensive exposure assessment should include consideration of other exposure pathways and hazards related to the built environment. These other considerations include, but are not limited to, (a) other nuclear explosion effects, e.g., prompt radiation, blast, thermal effects and (b) injuries due to building damage, e.g., building collapse and glass breakage. For some hazards, including, but not limited to many infectious diseases; other exposure pathways, such as the ingestion of contaminated food and fomite/vector transmission, can in specific instances significantly contribute to, if not dominate, the overall exposure, see [2], [205], [431], and references therein. Third, the air infiltration RSA theory developed here generally assumes that the time-integrated air concentration is the relevant exposure metric. For many airborne chemicals acute toxicity depends sensitively upon the peak

[66] Examples include (1) radionuclides, such as ^{88}Kr and ^{138}Xe, that (i) have a half-life comparable to indoor-outdoor building air exchange rates and (ii) whose radioactive progeny poses a significant hazard (this case is discussed in section *(5.1.3. Additional Considerations)* above) and (2) volatile chemical species such as ammonia and some organic chemicals [428]–[430].

concentrations. Theory is developed here to account for this, however additional theory needs to be developed prior to using the RSA methodology for a variety of other arbitrary outdoor plumes and chemical health effect models.[67] Fourth, the current report focuses on human health impacts. We note that social and economic disruptions are also major concerns in emergency planning [423]. Fifth, we are unaware of any studies that provide broadly applicable estimates of the distribution of people within buildings (limited information exists for some building types).

Finally, the RSA method presented in this report applies to stationary population exposures and risk assessments. Many of the more complex population responses, including some combined shelter and evacuation strategies currently in use, require consideration of dynamic (mobile) populations. Dynamic population considerations may either decrease hazardous exposures, e.g., individuals with poor shelter may move to higher quality shelters, or increase hazardous exposures, e.g., individuals with good shelter may temporarily go outside (where they may be less protected) to assist in rescue operations or obtain food and medical assistance [432]. While the RSA method is compatible with existing tools that consider dynamic populations, e.g., [433]; these tools are computationally intensive and/or require significant analyst time and skill. As such, use of these tools is typically restricted to advanced assessments or work within a specific research context, e.g., [22], [147], [360], [434], [435]. Extensions to the RSA methodology (or other methodologies) that provide a more operationally practical

[67] **Supplemental Material S1** derives building protection factors suitable for use in (a) determining peak indoor concentrations and (b) identifying individuals that may require emergency protective actions.

solution in this regard would be of significant benefit. We note that such an effort should include an understanding of government policy, warning dissemination and compliance, and human behavior, e.g., [48], [436]–[440], as government emergency communications and actions have the potential to significantly influence population locations (and hence shelter quality) via evacuation, relocation, sheltering as well as in a preventive sense by zoning and building code planning, e.g., [423]–[425] and references therein.

6.2. Practical Implementation and Practice Perspectives

As with all methods, the practical utility of RSA depends upon how the method is implemented and used. Here we provide some thoughts based on our experiences implementing the RSA for various hazards on (a) spatial scales ranging from individual buildings to world-wide datasets and (b) in a variety of software platforms ranging from stand-alone systems to components within a larger assessment system.

The appropriate choice of RSA resolution depends upon the particular application and available input datasets. For simple analyses, the RSA spatial, temporal, and shelter quality bin resolution may be determined mainly by the availability of the underlying building and population datasets. As previously discussed in (*2.5. Building Characteristics, Populations, and Geographic Distributions*) section, these datasets can range from detailed information about individual buildings to broad county-level estimates. For more advanced analyses, a variety of datasets may be used simultaneously and so the appropriate choice becomes less clear. Furthermore for some problems, effective risk management may require a response coordinated across a wide range of decision makers at different levels, such as a country president, state governor, county supervisor, city mayor, precinct captain, and neighborhood-level emergency responders. For these cases, RSA estimates need to be self-consistent across multiple regions of control/interest, i.e., a common operating picture, so that decisions and resource allocations are well aligned. These requirements can be met with a set of self-consistent, hierarchal (and potentially overlapping) RSA databases, similar to those as described in (*4.2. Shelter Quality Databases*) section above. We note that this type of

implementation provides exposure estimates (and the underlying data) in a manner that is sufficiently precise, but not overly precise as to overwhelm each analyst and/or decision maker with unnecessary amounts of data – even if ultimately the underlying input data used for the RSA is detailed and high-resolution.

7. Conclusion

Buildings can protect their occupants from outdoor hazards during normal operations. Sheltering, a widely recognized protective action, can increase this protection. However, despite a long-term, on-going, international research effort; the details and extent of building protection have remained incompletely understood and not incorporated into practical tools for use on a regional level. Furthermore, building protection is not routinely incorporated into modern regional exposure, risk, and casualty assessments. In such cases, population exposures may be overestimated, potentially leading to both miscommunication as to the risk extent and misallocation of resources away from those most at risk in both the management of emergencies and chronic public health issues assessments. Similarly, population level dose-response relationships, often derived by estimating ambient (outdoor) exposures and then tuning dose-response relationship parameters to best match the distribution of illness reports, may underestimate an exposure hazard's true potency.

The Regional Shelter Analysis (RSA) method developed here accounts for the distribution of building protection (both within and among buildings), the population posture (how people are distributed among and within buildings) and temporal considerations (e.g., night vs. workday). The RSA method is scalable from the level of individual building to local (neighborhood) and larger (country) scale estimates and is compatible with existing building and population databases as well as most current exposure and injury assessment tools.

This report develops the general methodology and places the RSA method in context of prior work and current initiatives. The planned follow-on reports discuss the specific implementations for inhalation and external radiation exposure pathways and include exposure pathway specific discussion of key scientific gaps and the degree to which current building descriptions (taxonomies) describe the relevant building properties of interest. More generally, we note that while building characterization and occupancy is an active area of research in numerous fields; we are unaware of any studies that provide broadly applicable estimates of the distribution of people within buildings. Finally, we note that multiple RSA implementations may need to be created to support different sets of operational and/or scientific assessment requirements. These requirements include accuracy; resolution at multiple spatial and temporal scales; computational efficiency; compatibility with existing exposure and health effect models and measurements; all-hazards emergency response planning and messaging; and clear, timely, simultaneous results provided to different operational domains as needed to coordinate and support decision making by officials and staff.

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9. Attestations

Ethics statement
No humans or animals were used this in work

Data accessibility
No primary data were used in this analysis. The referenced supplemental material has been provided.

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 study concept and design, including method and theory development, discussion, historical perspectives, building protection physics, and discussion. MBD, with valuable help from Steve Homann, also developed the radiation health effect section (i.e., Steve Homann was a co-author on the radiation health effect section).

Charles Dillon (CFD) was responsible for medical and epidemiologic content and development of the chemical and air quality and bioaerosol health effects section content not related to mathematical modeling. He also contributed to the historical perspectives and radiation health effects sections.

MBD and CFD both participated in literature searches, manuscript drafting, and revision through its many versions.

All authors give approval for publication.

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Supplemental Material S1:
Additional Building Protection Factor Equations

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This self-contained supplemental material derives additional building protection factor equations for use when (a) the health-effect of interest is particularly sensitive to the peak airborne hazard concentrations or (b) when a significant portion of the airborne hazard deposits (sorbs) on indoor surfaces and later becomes airborne, e.g., desorbs, evaporates, or resuspends. As in the main text [S1], we assume that indoor airborne hazard concentrations are readily and evenly mixed within a given building, i.e., a single box model. To enhance readability, some text and figures are duplicated from [S1].

For the case in which the health effect is particularly sensitive to peak concentrations, we develop two types of building protection factor equations that, when combined with outdoor exposure estimates, provide (1) an upper bound on the peak indoor airborne hazard concentrations and (2) are suitable to assess the acute inhalation toxicity of many chemical hazards. For the acute chemical toxicity case, we extend an analysis first described by *Haastrup* [S2] and assume (i) the toxicity is described by the ten-Berge model [S3], and (ii) the outdoor airborne hazard concentrations are constant during a specified time period and zero otherwise (a square wave).

For the case in which the hazard first deposits indoors and then resuspends, we develop a building protection factor equation appropriate for conditions in which the hazard decays on, and resuspends from, indoor surfaces with first order physics.

Hazard Toxicity is Particularly Sensitive to Peak Concentrations

When outdoor gases and aerosols penetrate a given building and indoor airborne hazard concentrations are readily and evenly mixed within it, the single box model (**Equation S1 - 1**) describes the time evolution of indoor airborne hazard concentrations [S4]. If the transport and loss terms, i.e., the λ parameters, are independent of both time and airborne hazard concentration, then **Equation S1 - 1** reduces to **Equation S1 - 2**.

(Equation S1 - 1)

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

(Equation S1 - 2)

$$C_{Indoor}(t) = \lambda_{in} \cdot \int_0^t C_{Outdoor}(\tau) \cdot e^{-(\lambda_{out} + \lambda_{internal})(t-\tau)} \, d\tau$$

where

t is time (h),

$C_{Indoor}(t)$ is the indoor airborne hazard concentration at time t (g m^{-3}),

$C_{Outdoor}(t)$ is the outdoor airborne hazard concentration at time t (g m^{-3}),

λ_{in} is the rate at which the outdoor airborne hazard enters the building (h^{-1}),

λ_{out} is the rate at which the indoor airborne hazard exits the building (h^{-1}), and

$\lambda_{internal}$ is the rate at which indoor material is lost within the building (h^{-1}).

Here we consider the case in which the outdoor airborne hazard concentration time series is a *square wave* – namely absent prior to time t_1; remains elevated at a constant value (C_{Plume}) until time t_2, and then absent again, see **Equation S1 - 3**. With this additional assumption, **Equation S1 - 2** can be simplified to **Equation S1 - 4**. **Figure S1 - 1** illustrates the resulting time series of outdoor and indoor airborne hazard concentrations.

(Equation S1 - 3)

$$C_{Outdoor}(t) = \begin{cases} 0\,, & t < t_1 \\ C_{Plume}\,, & t_1 \le t \le t_2 \\ 0\,, & t > t_2 \end{cases}$$

(Equation S1 - 4)

$$C_{Indoor}(t) = \begin{cases} 0\,, & t < t_1 \\ \dfrac{\lambda_{in}}{(\lambda_{out} + \lambda_{internal})} \cdot C_{Plume} \cdot \left(1 - e^{-(\lambda_{out} + \lambda_{internal}) \cdot (t - t_1)}\right), & t_1 \le t \le t_2 \\ C_{Indoor}(t_2) \cdot e^{-(\lambda_{out} + \lambda_{internal}) \cdot (t - t_2)}\,, & t > t_2 \end{cases}$$

where

C_{Plume} is the non-zero outdoor airborne hazard concentration (g m^{-3}).

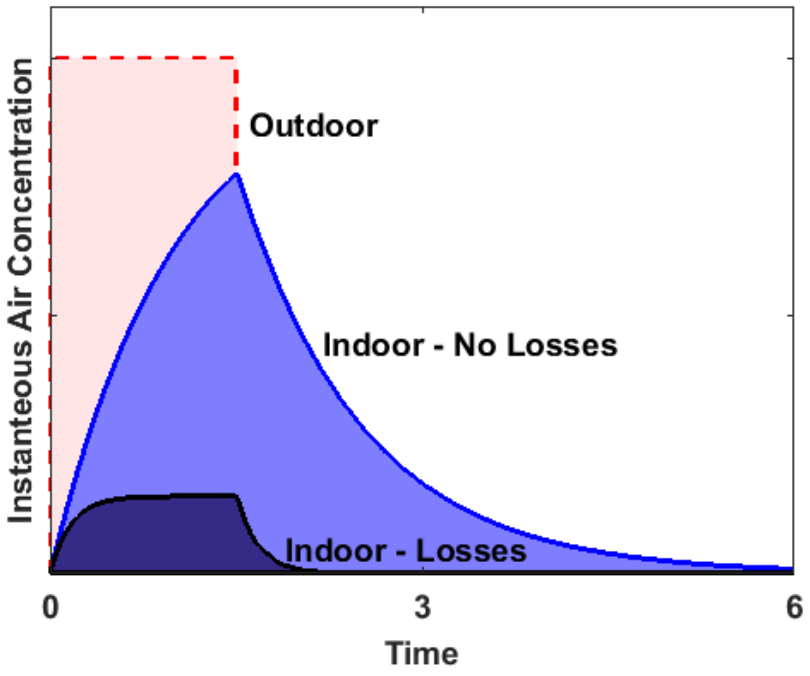

Figure S1 - 1 – Illustration of building protection showing the (instantaneous) airborne hazard concentration time series for an outdoor plume ($C_{Outdoor}$; red dashed line); the resulting indoor plume without indoor losses (C_{Indoor} with $\lambda_{internal} = 0$; light blue line); and the resulting indoor plume with indoor losses (C_{Indoor} with $\lambda_{internal} > 0$; black line).

Theorem 1

The peak indoor air concentration of outdoor origin material will not exceed the peak outdoor airborne hazard concentration divided by the building protection factor value of $\frac{(\lambda_{out}+\lambda_{internal})}{\lambda_{in}}$.

Proof 1

Step 1.1 – When the outdoor airborne hazard concentration time series is a single square wave

Let $C_{Peak\ Outdoor}$ be the outdoor airborne hazard concentration associated with the square wave. Then **Equation S1 - 4** implies **Equation S1 - 5** as the λ parameters and time t are greater than or equal to zero.

(Equation S1 - 5)

$$C_{Peak\ Indoor} \leq \frac{\lambda_{in}}{(\lambda_{out} + \lambda_{internal})} \cdot C_{Peak\ Outdoor}$$

Step 1.2 – More complex outdoor airborne hazard concentration time-series

If we discretize, without loss of generality, an arbitrary time series of the outdoor airborne hazard concentration, then **Equation S1 - 6** represents the time series of the corresponding indoor airborne hazard concentration. Here we assume, without loss of generality, that $t_{2,i_t} = t$.

(Equation S1 - 6)

$$C_{Indoor}(t) = \frac{\lambda_{in}}{(\lambda_{out} + \lambda_{internal})} \cdot \sum_{i=1}^{i_t} \left(\begin{array}{c} C_i \\ \cdot \left(1 - e^{-(\lambda_{out}+\lambda_{internal})\cdot(t_{2,i}-t_{1,i})}\right) \\ \cdot e^{-(\lambda_{out}+\lambda_{internal})\cdot(t-t_{2,i})} \end{array} \right)$$

where

i is an integer corresponding to distinct, sequential time periods (dimensionless),

i_t is the integer corresponding to the time period that ends at time t (dimensionless),

C_i is the outdoor airborne hazard concentration for time period i – which is assumed to be constant (g m^{-3}),

$t_{1,i}$ is the start time of time period i (h), and

$t_{2,i}$ is the end time of time period i (h).

We assign, without loss of generality, $C_{Peak\ Outdoor}$, to be the highest (largest value) outdoor airborne hazard concentration and note that $t_{2,i} = t_{1,i+1}$. This results in **Equation S1 - 7** – which is identical to the single square wave case (note again that $t_{2,i_t} = t$).

(Equation S1 - 7a)

$$C_{Indoor}(t) \leq \frac{\lambda_{in}}{(\lambda_{out} + \lambda_{internal})} \cdot C_{Peak\ Outdoor} \cdot \left(1 - e^{-(\lambda_{out} + \lambda_{internal}) \cdot (t_{2,i_t} - t_{1,1})}\right)$$

(Equation S1 - 7b)

$$C_{Indoor}(t) \leq \frac{\lambda_{in}}{(\lambda_{out} + \lambda_{internal})} \cdot C_{Peak\ Outdoor}$$

Theorem 2

When the outdoor airborne hazard concentration time series is a square wave, the indoor toxic load is equal to the outdoor toxic load divided by a scalar value, i.e., a building protection factor, which does not depend on the value of the outdoor airborne hazard concentration.

Proof 2

For some acute chemical exposures, toxicity can be related to the toxic load as calculated by the ten-Berge model [S3], **Equation S1 - 8**. For many chemicals, peak concentrations are very important for acute toxicity and the toxic load exponent (n) is greater than 1, e.g., n = 2.75 for chlorine gas [S5]. For context, the toxic load is a time-integrated airborne hazard concentration when the toxic load exponent (n) is equal to 1.

(Equation S1 - 8)

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

where

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

n is toxic load exponent (dimensionless).

Thus if the time-series of the airborne hazard concentration can be approximated as a single square wave:

(Equation S1 - 9)

$$Exposure_{Outdoor} = \int_0^\infty C_{Outdoor}(t)^n dt = {C_{Plume}}^n \cdot (t_2 - t_1)$$

(Equation S1 - 10)

$$Exposure_{Indoor} = \int_0^{t_2} C_{Indoor}(t)^n dt + \int_{t_2}^\infty C_{Indoor}(t)^n dt$$

$$= \left(\frac{\lambda_{in}}{(\lambda_{out} + \lambda_{internal})}\right)^n \cdot {C_{Plume}}^n \cdot \int_{t_1}^{t_2} \left(1 - e^{-(\lambda_{out} + \lambda_{internal})t}\right)^n dt$$

$$+ \left(\frac{\lambda_{in}}{(\lambda_{out} + \lambda_{internal})}\right)^{n} \cdot {C_{Plume}}^{n} \cdot \left(1 - e^{-(\lambda_{out} + \lambda_{internal})(t_2 - t_1)}\right)^{n} \cdot \frac{1}{n\,(\lambda_{out} + \lambda_{internal})}$$

Given the definition of building protection, i.e., outdoor exposure / indoor exposure:

(Equation S1 - 11)

$$Building\ Protection\ Factor$$

$$= \frac{Exposure_{Outdoor}}{Exposure_{Indoor}}$$

$$= \left(\frac{(\lambda_{out} + \lambda_{internal})}{\lambda_{in}}\right)^{n} \frac{(t_2 - t_1)}{\int_{t_1}^{t_2}(1 - e^{-(\lambda_{out} + \lambda_{internal})t})^{n} dt + \frac{(1 - e^{-(\lambda_{out} + \lambda_{internal})(t_2 - t_1)})^{n}}{n\,(\lambda_{out} + \lambda_{internal})}}$$

We note that the building protection factor exposure does not depend on C_{Plume}, the outdoor airborne hazard concentration.

Hazard Deposits and Resuspends Indoors

Theorem 3

For the case in which the airborne hazard deposits on, and later resuspends from, indoor surfaces with first order physics; the time-integrated indoor air concentrations of outdoor origin material is equal to time-integrated outdoor airborne hazard concentration divided by the building protection factor of $\frac{(\lambda_{out}+\lambda_{others}+\lambda_{dep}(1-Resuspension\ Efficiency))}{\lambda_{in}}$.

Proof 3

Step 3.1 – Problem Setup

The total indoor exposure to airborne material is the sum of indoor exposure to material that has been deposited and resuspended i times (i can equal zero indicating that no deposition/resuspension has occurred).

(Equation S1 - 12)

$$\int_0^\infty C_{Indoor}(t)dt = \sum_{i=0}^{\infty}\int_0^\infty C_{Indoor,Resuspension\ Case\ i}(t)dt$$

where

i is the number of times the airborne hazard has been deposited and resuspended indoors (dimensionless) and

$C_{Indoor,Resuspension\ Case\ i}(t)$ is the time-dependent indoor air hazard concentration that has been deposited to, and resuspended from, indoor surfaces i times (g m^{-3}).

Step 3.2 – No Resuspension Case (i = 0)

As derived in the main text,

(Equation S1 - 13)

$$\int_0^\infty C_{Indoor,Resuspension\ Case\ 0}(t)dt = \left(\frac{\lambda_{in}}{\lambda_{out}+\lambda_{internal}}\right)\cdot\int_0^\infty C_{Outdoor}(t)dt$$

Step 3.3 – Resuspension Cases (i > 0)

Mathematically, the introduction of material that has been deposited and resuspended i times in indoor air is functionally identical to the infiltration of an outdoor-origin material shown in Step 3.2. Therefore **Equation S1 - 13** can be modified to account for exposures to deposited/resuspended material:

(Equation S1 - 14)

$$\int_0^\infty C_{Indoor,Resuspension\ Case\ i}(t)dt = \left(\frac{1}{\lambda_{out} + \lambda_{internal}}\right) \cdot \left(\frac{Resuspended\ Material_{Resuspension\ Case\ i}}{Volume_{Building}}\right)$$

where

$Resuspended\ Material_{Resuspension\ Case\ i}$ is total amount of material deposited and resuspended i times into the air (g), and

$Volume_{Building}$ is the volume of the indoor space (m^3).

(Equation S1 - 15)

$$Resuspended\ Material_{Resuspension\ Case\ i} = \sum_{a \in all\ surfaces} \left(\begin{matrix} Area_{Surface\ a} \cdot \lambda_{resup,Surface\ a} \\ \cdot \int_0^\infty C_{Surface\ a,Resuspension\ Case\ i}(t)\partial t \end{matrix} \right)$$

where

a is a specific indoor surface from which material can deposit and resuspend (dimensionless),

$Area_{Surface\ a}$ is the area of surface *a* (m^2),

$\lambda_{resup,Surface\ a}$ is the rate at which material deposited on the surface *a* is resuspended (h^{-1}), and

$C_{Surface\ a,Resuspension\ Case\ i}(t)$ is contamination of surface *a* at time *t* due to material that has deposited *i* times ($g\ m^{-2}$).

If there is no initial surface contamination, i.e., $C_{Surface\ a,Resuspension\ Case\ i}(t=0)=0$ for all indoor surfaces:

(Equation S1 - 16a)

$$\frac{\partial C_{Surface\ a,Resuspension\ Case\ i}(t)}{\partial t} = \left(\frac{\lambda_{dep}\ \cdot\ F_a\ \cdot\ Volume_{Building}}{Area_{Surface\ a}}\right)\ \cdot\ C_{Indoor,Resuspension\ Case\ i-1}(t) - \left(\lambda_{decay,Surface\ a}+\ \lambda_{resup,Surface\ a}\right)\ \cdot\ C_{Surface\ a,Resuspension\ Case\ i}(t)$$

(Equation S1 - 16b)

$$\int_0^{\infty} C_{Surface\ a,Resuspension\ Case\ i}(t)\partial t = \frac{\left(\frac{\lambda_{dep}\ \cdot\ F_a\ \cdot\ Volume_{Building}}{Area_{Surface\ a}}\right)}{\left(\lambda_{decay,Surface\ a}+\ \lambda_{resup,Surface\ a}\right)}\ \cdot\ \int_0^{\infty} C_{Indoor,Resuspension\ Case\ i-1}(t)\partial t$$

where

λ_{dep} is the overall rate at which airborne material deposits on all indoor surfaces (h^{-1}),

F_a is the fraction of the overall deposition that occurs on surface *a* (dimensionless), and

$\lambda_{decay,Surface\ a}$ is the rate at which material deposited on surface *a* is lost and so is unavailable for resuspension (h^{-1}).

Combining **Equations S1 - 15** and **S1 - 16b** yields:

(Equation S1 - 17a)

$$Resuspended\ Material_{Resuspension\ Case\ i} = \left(\lambda_{dep} \cdot Volume_{Building}\right) \cdot Resuspension\ Efficiency \cdot \int_0^\infty C_{Indoor,Resuspension\ Case\ i-1}(t)\partial t$$

(Equation S1 - 17b)

$$Resuspension\ Efficiency = \sum\nolimits_{a\ \in all\ surfaces} F_a \cdot \left(\frac{\lambda_{resup,Surface\ a}}{\left(\lambda_{decay,Surface\ a} + \lambda_{resup,Surface\ a}\right)}\right)$$

where

$Resuspension\ Efficiency$ is the fraction of deposited material that subsequently resuspends at least once (dimensionless)

Combining **Equations S1 - 14** and **S1 - 17a** yields:

(Equation S1 - 18a)

$$\int_0^\infty C_{Indoor,Resuspension\ Case\ i}(t)dt = \frac{\lambda_{dep} \cdot Resuspension\ Efficiency}{\left(\lambda_{out} + \lambda_{others} + \lambda_{dep}\right)} \cdot \int_0^\infty C_{Indoor,Resuspension\ Case\ i-1}(t)\partial t$$

(Equation S1 - 18b)

$$\lambda_{internal} = \lambda_{others} + \lambda_{dep}$$

where

λ_{others} is the overall rate of all non-deposition indoor loss processes for airborne material (h^{-1}).

Step 3.4 – Combining the No Resuspension and Resuspension Cases

Combining **Equations S1 - 12, S1 - 13, S1 - 18a,** and **S1 - 18b** and using the infinite power series identity:

(Equation S1 - 19)

$$\int_0^\infty C_{Indoor}(t)dt = \sum_{i=0}^{\infty}\int_0^\infty C_{Indoor,Resuspension\ Case\ i}(t)dt$$

$$= \left(\frac{\lambda_{in}}{\lambda_{out} + \lambda_{others} + \lambda_{dep}}\right) \cdot \sum_{i=0}^{\infty}\left(\frac{\lambda_{dep} \cdot Resuspension\ Efficiency}{(\lambda_{out} + \lambda_{others} + \lambda_{dep})}\right)^i \cdot \int_0^\infty C_{Outdoor}(t)dt$$

$$= \left(\frac{\lambda_{in}}{\lambda_{out} + \lambda_{others} + \lambda_{dep}(1 - Resuspension\ Efficiency)}\right) \cdot \int_0^\infty C_{Outdoor}(t)dt$$

Thus,

(Equation S1 - 20)

$$Building\ Protection\ Factor = \frac{Exposure_{Outdoor}}{Exposure_{Indoor}} = \frac{\int_0^\infty C_{Outdoor}(t)dt}{\int_0^\infty C_{Indoor}(t)dt}$$

$$= \left(\frac{\lambda_{out} + \lambda_{others} + \lambda_{dep}(1 - Resuspension\ Efficiency)}{\lambda_{in}}\right)$$

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