Status of Guidance and Scientific Knowledge on Using Heating, Ventilation, and Air Conditioning (HVAC) Systems for Protection During Radiological / Nuclear Emergencies

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The “Status of Guidance and Scientific Knowledge on Using Heating, Ventilation, and Air Conditioning (HVAC) Systems for Protection During Radiological and Nuclear Emergencies” was prepared by staff from the Department of Homeland Security’s Science & Technology Directorate (DHS S&T) National Urban Security Technology Laboratory and the U.S. Nuclear Regulatory Commission (NRC).

This document contains two separate reports. The report, *A Literature Review of Heating, Ventilation, and Air Conditioning Strategies following Radiological/Nuclear Incidents*, was developed by Lawrence Berkeley National Laboratory (LBNL) for the U.S. Department of Homeland Security (DHS) Science and Technology Directorate (S&T) under contract 70RSAT23KPM000015. The report, *Literature Review: Use of Heating, Ventilation, and Air Conditioning Systems for Controlling Airborne Contamination*, was developed by the NRC. The Foreward to this document is jointly authored by DHS S&T and NRC .

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FOREWORD

This report contains two separate review papers from DHS Science & Technology Directorate (DHS S&T) and the U.S. Nuclear Regulatory Commission (NRC), respectively. Both reviews examine the status of current guidance and scientific knowledge on how to use heating, ventilation, and air conditioning (HVAC) systems for protection during a radiological or nuclear emergency.

Buildings are essential in protecting occupants and reducing exposures to radionuclides released during a radiological incident, as could result from a radiological dispersal device, nuclear power plant accident, or nuclear device detonation. A building's protection factor depends on many factors including the physical nature of the hazard, building type and materials, and the type and operation of HVAC systems. A building's ventilation system can have a significant impact on the safety and health of occupants while sheltering-in-place; however, there are many unknowns regarding the best way to control exposure to airborne contaminants during and after radiological emergencies. A better understanding of the use of HVAC systems to control airborne contaminants could enhance implementation of strategies for sheltering-in-place during radiological incidents to ensure public health and safety.

The National Urban Security Technology Laboratory's (NUSTL) Radiological and Nuclear Response and Recovery (RNRR) Research and Development (R&D) program at DHS S&T funded Lawrence Berkeley National Laboratory (LBNL) to conduct a literature review that documents the current state of scientific knowledge about building protection from radiological hazards and the role of HVAC systems; summarize the public action guidance promoted on Federal, state, and local agency websites; and identify areas where further research is recommended.

The U.S. Nuclear Regulatory Commission (NRC) conducted a similar literature review on HVAC effectiveness for reducing indoor air concentrations of outdoor contaminants to assess the extent to which HVAC systems could be applied to enhance sheltering-in-place strategies in response to nuclear power plant accidents.

The findings from the LBNL and NRC literature reviews were similar; therefore, the two reports were combined into *Status of Guidance and Scientific Knowledge on Using Heating, Ventilation, and Air Conditioning (HVAC) Systems for Protection During Radiological / Nuclear Emergencies* to make it easier for readers to access and use the information.

Introduction to the LBNL Report: HVAC Strategies Following Radiological/Nuclear Incidents (2024)

LBNL conducted a literature search, which included analysis of approximately 300 publications from 2016 to 2023, to investigate how building ventilation can be used to protect occupants during and after a radiological or nuclear emergency. Guidance on effective manipulation of HVAC systems following an incident was primarily established in documentation from the early 2000s and does not appear to have been substantially

updated since its initial publication. Additionally, wildfires and the COVID-19 pandemic have sparked numerous studies on how airborne particles infiltrate and spread throughout a building, and how particle concentration can be affected by building pressurization, filtration, directional airflow, and HVAC configurations. In general, findings from this report highlight the need to better understand the particle size distribution for different scenarios, how to leverage the latest advancements in building ventilation systems, and the need to incorporate research from the biological aerosol exposure community. This report also looked at changes to the HVAC technology landscape, which may affect the range of protective actions available to first responders and the public. One notable finding is the recent broad public adoption of portable air cleaners during the COVID-19 pandemic, which may offer novel risk-mitigation options for residential buildings and older single-family homes. Conclusions are discussed in greater detail in the LBNL report.

Introduction to the NRC Report: Use of HVAC Systems for Controlling Airborne Contaminants (2024)

The NRC review focused on published research that could be relevant to nuclear power plant accidents. The report included a focused review of 11 studies dating back to 2001 on the topic of HVAC use while sheltering, accompanied by a broader, more exhaustive review of studies related to HVAC use to control indoor air quality and reduce contaminant concentrations. The report highlighted that modern HVAC systems with high efficiency filtration systems may decrease airborne concentrations for particle sizes comparable to radiological incidents. These findings suggest that it would be feasible to develop more nuanced guidance for use of HVAC systems while sheltering-in-place.

Common Findings of Both Reports:

Results of the LBNL and NRC literature reviews were similar, providing some validation for both studies, which were conducted independently. A synthesis of some common findings from both reports include:

1. More detailed and specific guidance is needed for use of HVAC systems during radiation emergencies since there may not be a one-size-fits-all approach. Knowledge of HVAC air exchange rates is necessary for making effective recommendations. Additionally, nuanced revision to guidance is needed that takes into consideration factors that impact HVAC effectiveness, such as filtration efficiency, indoor and outdoor pressure differential, building composition and materials, particle size(s), air exchange rates, flow rates, and timing. From a policy perspective, this guidance should incorporate human factors considerations to ensure guidance is easy to implement in the event of an actual emergency, especially if newer guidance contradicts longstanding traditional guidance.

2. Both studies highlighted "timing" as a critical factor to consider. Shutting down ventilation systems can be beneficial, but improper timing can reduce efficacy of protection from radiation exposure and may also amplify other risks to occupants (e.g., prolonged exposure to extreme heat or cold). For example, shutting down HVAC

during the early moments of an incident may reduce the amount of radioactive particles infiltrating into a building. But after the airborne plume passes, resuming HVAC operation can help to reduce the concentration of suspended particles from the air inside. Emergency managers may benefit from a decision-making tool to aid in protective action guidance based on real-time information during an incident.

3. Additional experiments or modeling may help to elucidate ventilation best practices specific to a variety of radiological scenarios, since the particle sizes, timing of the plume, and other factors depend on the type of incident. This research will be needed to inform guidance updates and decision-making tools.

4. Much of the underlying research and ventilation guidance has been generalized for all chemical, biological, radiological, and nuclear threats and radiological-specific guidance has not been updated in approximately 20 years. Incorporating the latest scientific findings from studies sparked by COVID-19 and recent wildfires into building ventilation guidance would provide responders, building managers, decision-makers, and the public with evidence-based information needed to effectively manipulate HVAC systems before, during, and after a radiological incident.

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A Literature Review of Heating, Ventilation and Air Conditioning (HVAC) Strategies Following Radiological/Nuclear Incidents

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Executive Summary

This report analyzes the open literature, current guidance, federal reports and emerging technologies regarding the use of HVAC systems to protect building occupants from outdoor radiological or nuclear releases. Buildings can play a key role in protecting building occupants from outdoor airborne hazards. Despite significant advancements in HVAC technology and an increased understanding of aerosol behavior, prevailing federal guidance – to go inside, seal doors and windows, and turn off fans – has remained largely unchanged since the early 2000s. Most protective action guidance is generalized and lacks specific recommendations tailored to different radiological scenarios. Traditional advice to turn off ventilation systems and seal doors and windows may conflict with recent infectious disease mitigation guidance, highlighting the need for a nuanced and context-specific review of relevant guidance. This literature review and analysis seeks to summarize the current state of scientific knowledge of building protection and the role of HVAC systems in reducing indoor exposures to radionuclides released in an outdoor radiological incident, and to identify areas that require further research and guidance.

Key findings include:

1. There has been a decline in new research on building protection from radiological and nuclear particles, due to shifting research priorities towards bioaerosols.
2. Current literature does not contradict existing guidance but suggests a need for more detailed recommendations for different threat scenarios.
3. Insights from recent research on transport of bioaerosols and wildfire smoke studies could enhance strategies for reducing indoor exposure to radioactive particles.
4. Recent recommendations to increase fresh air ventilation rates might not suit residential settings during radiological incidents. An analysis is needed to evaluate the effectiveness of building hardening, local filtration, and forced positive pressure HVAC flow, especially in older homes with higher leakage pathways.
5. The rapid adoption of portable air cleaners could significantly mitigate risks from radiological particles, particularly in older homes with higher leakage.
6. Increased understanding of particle size distribution for different radiological scenarios is crucial for updated guidelines.

Abstract

An accidental or deliberate release of airborne radiological or nuclear material can expose the general population to hazardous particles and gas. Emergency preparedness and prompt response can minimize adverse health outcomes. Sheltering-in-place is a common protective action that temporarily uses a building's envelope to protect occupants from an outdoor hazardous atmosphere. Guidance on effectively manipulating building operations during an emergency – such as closing windows and doors and/or manipulating furnace systems or HVAC (heating, ventilation and air conditioning) systems – was established in the early 2000s and is generalized for all chemical, biological, radiological, and nuclear (CBRN) threats. Over the past two decades, advancements in modern HVAC systems and research on plume modeling, indoor particle dispersion, infiltration, and high-efficiency filtration have transformed building science and indoor airflow management. The COVID-19 pandemic has also changed the way building managers operate HVAC systems and spurred research into airborne particle behavior within buildings. This literature review assesses the current state of science and prevailing guidance on manipulating building ventilation (or HVAC system, if available) during radiological or nuclear incidents involving a radiological dispersal device (RDD), a nuclear power plant accident (NPP), an improvised nuclear device (IND), or a nuclear detonation (ND). This analysis aims to summarize the current guidance, best practices, tools and training materials from federal, state, and local sources that are available to assist first responders, emergency planning organizations, building owners and the public and to identify knowledge gaps and areas where further research is needed.

Introduction

On average, people spend 85% to 90% of their time indoors, with 69% of that time spent in residential buildings (Klepeis et al., 2001). Buildings can play a key role in protecting occupants from outdoor airborne hazards. The extent of that protection depends on a number of factors, including the physical nature of the hazard (e.g., particle or gas phase), the building type (e.g., residential, commercial, etc.) and the operational characteristics of the building, whether or not the building contains a heating, ventilation, and air conditioning (HVAC) system. Most residential buildings use some combination of forced air furnaces, window units, fans, or room-sized space conditioners and do not have a centrally operated HVAC system, whereas most commercial buildings do. Buildings' protective role can be important for large portions of a local population. The effective operation of a building's ventilation system can significantly impact occupant safety and well-being during the release of an outdoor hazardous material.

In most situations, buildings provide passive protection: that is, protective measures result from ordinary or typical building operations, and not occupant responses. The results of several passive protection scenarios for residential buildings are presented in Appendix A, illustrating the range in protective results. These results also illustrate the dependence of building protection on the particle size distribution of the outdoor hazard; the quality of the filters used in the furnace or HVAC system; and the penetration fraction and infiltration rate (i.e., the uncontrolled leakage of outdoor air into the building through cracks or gaps in the building envelope). Other important parameters include exfiltration (the opposite of infiltration); deposition on indoor surfaces (where large particles are removed by settling on surfaces); and the air exchange rate (AER – or ACH, air changes per hour – is the volume of air removed and replaced in a room or building space). Note that all three processes – filtration, penetration, and deposition – are particle-size dependent.

Active protection strategies, on the other hand, involve actions taken by building managers or occupants in response to external information about a threat or event. These responses can include shelter-in-place (SIP) actions such as moving occupants to pre-established "safe spaces" where infiltration rates are reduced, filtration rates are increased, occupant entry/exit is reduced, etc. There can also be building-wide responses, such as changing the operation of an HVAC system in a commercial building to significantly reduce or eliminate entry of outdoor air and instead increase air recirculation as a means of providing additional filtration of particles. It is possible to increase positive pressure in the building, but most residential systems are not designed for this purpose due to the implications for energy. Similarly, forced-air heating and cooling systems in residential buildings could be run continuously to provide additional filtration removal. Building protection, in its simplest form, is the ratio of the rate at which outdoor hazardous contaminants enter the building to the rate at which they are removed. (See Appendix A for more details.)

Outdoor airborne radionuclides can result from four main source scenarios: detonation of an improvised nuclear device (IND), nuclear detonation (ND), radiological dispersion device (RDD), or a catastrophic accident at a light water nuclear power plant (NPP). While all four sources produce airborne radioactivity, the magnitude, dispersion rate, and timing between release and "cloud arrival," among other factors, will affect the efficacy of building protection – especially if there is time to implement a shelter-in-place (SIP) response.

Of the four scenarios, an ND or an IND (typically assumed to be low-yield) will produce the largest blast zone and a plume of both radioactive noble gases and particles with a large distribution in particle size that can disperse downwind for many miles. In these two scenarios, appropriate protective actions and HVAC guidance will vary depending on each damage zone. (This review focuses on HVAC protective actions appropriate for areas far from the blast zone where buildings, windows, and doors are still intact.) In contrast, a radiological dispersion device (RDD) uses conventional explosives to aerosolize and disperse either a solid or a liquid solution containing radioactive materials. The fourth scenario, an accident at a nuclear power plant (NPP), will produce a release of primarily radioactive noble gases and inhalable radioactive particles. The NPP scenario is the only one where the location of the source is known and where there will likely be time to warn the public and implement protective actions (i.e., evacuation or shelter-in-place). In all cases, knowing when and where a release might occur are critical. Response measures that might be helpful if implemented before a release are not likely in the event of an RDD or ND/IND, although for some ND scenarios involving a ballistic missile there may be sufficient time (e.g., roughly 15-30 minutes) to inform the public and responders to go inside prior to detonation. Additionally, for people farther away from an ND, fallout may not arrive in their area for some time (FEMA, 2022).

Because particle size is a key determinant of building protection, it is important to better understand the particle size distribution produced in deliberate (ND, IND, RDD) or accidental (NPP) releases. RDDs have been the topic of several recent papers and presentations (Potter, 2021) focusing on the radionuclides of most concern and the size distributions produced by an RDD. Several papers were published in a special issue of *Health Physics* in 2016 describing a series of experiments conducted by Defense Research and Development Canada. In these simulations, La-140 oxide was used as an RDD simulant (Green et al., 2016) and produced particles distributed between 1 and 200 microns. Two other papers (Brambilla et al., 2023); (Di Lemma et al., 2016) also discuss particle sizes produced from RDDs and find significant mass in the inhalable size range (<1 to ~10 µm), which is the same size range of importance for transport into buildings.

Three studies (Lin et al., 2015); (Hirose, 2020); (Katata et al., 2015) report size distributions of radionuclides released from the Fukushima NPP accident. There is a wide range of particle sizes, but again, significant mass in the inhalable size range.

It is worth noting that in the aftermath of an event that disperses airborne radionuclides, buildings also provide protection or shielding from the external gamma radiation produced by some of these materials, either during passage of the radioactive cloud ("skyshine") or from materials deposited on external building surfaces or on the surrounding landscape ("groundshine") (Dillon & Homann, 2016). However, this topic is beyond the scope of the present work.

Over the past two decades, the science and strategies guiding the management of air quality of indoor environments has grown. This is partly due to increased scientific interest and public health concern over improved indoor air quality (Baeza_Romero et al., 2022), but also due to two key episodes that stimulated interest in understanding how to better protect building occupants from outdoor airborne hazardous materials: first, the events and threats in the aftermath of 9-11-2001, including the release of anthrax in the Hart Senate Office Building in Washington, DC; and second, the recent SARS-CoV2 (COVID-19) pandemic.

The COVID-19 pandemic sparked a considerable number of studies on how airborne particles move throughout a building, and how to mitigate particle concentrations using building pressurization, directional airflow, and HVAC configurations. It is unclear how these new HVAC operating strategies impact current guidance and practices in the event of a radiological release, which makes it essential to develop a comprehensive understanding of the strategies available for mitigating exposures to airborne radiological hazards.

Federal protective action guidance (United States Environmental Protection Agency, 2017) for radiation exposure has existed for decades and was initially established in 1992 as guidance for public officials in response to an accident at a nuclear power plant. In 2008, the guide was expanded to include RDDs and INDs. (In 2010, a separate guide was published covering NDs.) The guidance covers three phases of a scenario (early, mid, and late). Building ventilation is included in the early phase guidance and is generalized for all radiological and nuclear threats (i.e., RDDs, NPPs, and INDs). While regular updates to the guide occurred in 2013 and 2017, minimal changes have been made to its shelter-in-place guidance, which is based on research from the early 2000s (Mead & Gressel, 2002).

This literature review and analysis seeks to summarize the current state of scientific knowledge of building protection and the role of HVAC systems in reducing indoor exposures to radionuclides released during an outdoor radiological incident, and also to identify areas that require further research and guidance. Our review aims to be as through as possible and includes not only scientific peer-reviewed journals (focusing on recent studies from 2016 to 2023) but also government reports; protective action guides; website guidance for building managers, emergency personnel, and the general public; and interactive, web-based tools for optimizing building ventilation.

Goals

1. Create a list of peer-reviewed references with summaries of recommendations and conclusions.
2. Collect and summarize website guidance from federal and state levels, non-governmental organizations, and industry.
3. Review state and federal protective action recommendations and guidance available to first responders, emergency managers, and building managers. Is there adequate pre-incident guidance tailored to the hazard?
4. Confirm whether recent research supports prevailing protective action guidance.
5. Conduct an initial assessment to gauge whether recommendations for a chemical or biological release are applicable to a radiological or nuclear scenario.
6. Determine if and how the radiological response and recovery community can apply lessons learned from the pandemic response and leverage recent research.

Methods

This review is based on a collection of peer-reviewed published literature gleaned from the following five databases and search engines:

1. The Web of Science Core Collection™ (WoS)
2. SCOPUS
3. Google Scholar
4. Office of Scientific and Technical Information (OSTI)
5. PubMed

The Web of Science Core Collection™, managed by Clarivate Analytics, includes 13,000 journals in their databases (the Science Citation Index Expanded™, Social Sciences Citation Index™, Arts & Humanities Citation Index™, and Emerging Sources Citation Index™). Many building science, environmental, radiation, and atmospheric journals are included. Only journals with high scientific impact are included in the WoS database, making it more selective than the other databases used in this review.

SCOPUS is the largest abstract and citation database of peer-reviewed literature, scientific journals, books, and conference proceedings. Managed by Elsevier, the database includes over 22,000 journals (27% in physical sciences) as well as citation analysis. This database provided the most relevant citations for this review.

Google Scholar has very broad coverage including journals, non-English language publications, articles, theses, books, abstracts, and court opinions from academic publishers, professional societies, online repositories, universities, and other web sites. Their database is not disclosed, and results are often too broad. The search engine often returned too many hits and was too permissive, even when restrictive qualifiers were added to search terms.

OSTI is an open federal repository of scientific reports managed by the Department of Energy's Office of Science. The database encompasses 75 years' worth of federally funded research reports and contains over 3 million records.

The PubMed database, administered by the National Institute of Health, contains primarily peer-reviewed scientific literature in the medical and life science fields. It includes over 36 million citations including biomedical literature from MEDLINE, as well as books.

The database search strategy (Figure 1) involves four steps that were repeated for each search term string and in each database. This strategy ensured a thorough review of all five databases.

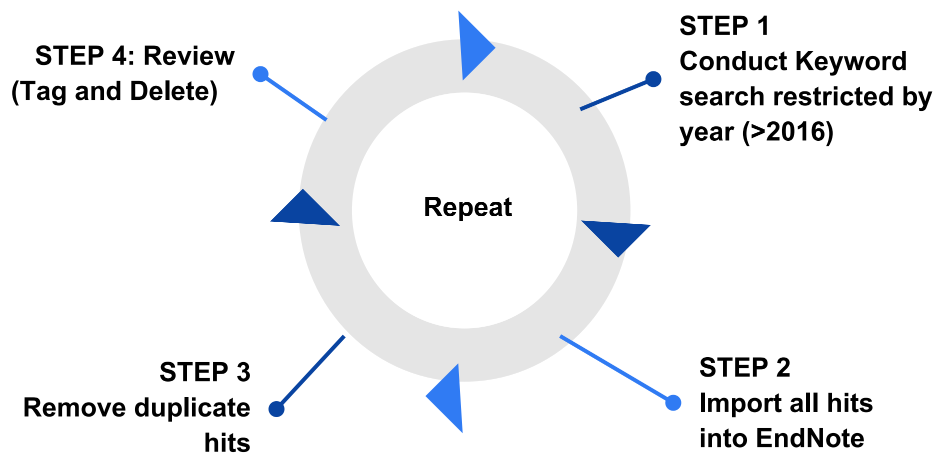

Figure 1. Schematic of search process.

The primary keyword search was completed using several combinations of keywords (Table 1) such as HVAC, building ventilation, radiological, nuclear, airborne hazard, guidance, best practice, first responders, emergency response, protecting building occupants, and CBRN (chemical, biological, radiological, or nuclear). (Note that CBRNe is not included, since explosives are outside the scope of this review.) These keywords were entered into the title, abstract, and keyword sections of each search engine, with year of publication restricted to 2016 or later. An example of the number of hits generated by each search engine (Table 1) exemplifies the differences among search engines. Restricting terms (e.g., "thermal," "energy," etc.) were often used to refine and narrow search results.

Table 1. Comparison of "hits" generated by each search engine used in the literature search.

Search Term	Web of Science	Scopus	OSTI	Google Scholar
TITLE-ABS-KEY (hvac AND radiological OR nuclear) AND PUBYEAR > 2016	0	35	11	>10k
TITLE-ABS-KEY ("best practice" AND "hvac") AND PUBYEAR > 2016	51	41	>10k	>10k

TITLE-ABS-KEY (protect* AND buildings AND airborne AND hazards) AND PUBYEAR > 2016	9	15	>20k	>32k
TITLE-ABS-KEY (fallout AND radiation AND building)	23	101	>24k	>15k

All hits were imported into the reference management software EndNote 21™, which easily identified and removed duplicate hits. Once imported into the library, the review process began. Titles and abstracts were read, and irrelevant publications removed. Articles were sorted into the eight subject categories shown in Table 2.

Table 2: List of subject categories.

Category	Subject
Guidance	Ventilation Guidance During an Outdoor Release
COVID	COVID-19 and Building Ventilation
Mitigation	Manipulating HVAC Systems to Reduce Exposure
Protection	Strategies to Shield Building Occupants
CBRN	Chemical, Biological, Radiological, and Nuclear Release
Emergency Response	Protective Actions and Lessons Learned
Fire	HVAC Strategies to Reduce Particulate Intake During a Wildfire Event
HVAC Technology	Current and Emerging HVAC Systems Technology

During this review key references, impactful research, and leading authors in respective fields were identified and highlighted in the database. From these key references, citations were used to discover other impactful research articles that were added to the library. This aspect of the search expanded the library to include impactful articles dating back to the year 2000.

Table 3: List of keyword search terms.

1. TITLE-ABS-KEY (”best practice” AND ”hvac”) AND PUBYEAR > 2016
2. TITLE-ABS-KEY (protect* AND buildings AND airborne AND hazards) AND PUBYEAR > 2016
3. TITLE-ABS-KEY (fallout AND radiation AND building) AND PUBYEAR > 2016
4. TITLE-ABS-KEY (”HVAC systems” OR ”building ventilation”) AND TITLE-ABS-KEY (”Guidance” OR ”Best practice” OR ”emergency” OR ”first respon*”) AND PUBYEAR > 2016
5. TITLE-ABS-KEY (“HVAC system*” OR “build* ventilation”) AND TITLE-ABS-KEY (“Guidance” OR “Best practice” OR “resilience”) AND TITLE-ABS-KEY (“nuclear” OR “chem*” OR “rad*”) PUBYEAR > 2016
6. TITLE-ABS-KEY (”Build*” AND ”ventilation” AND ”guidance”) AND TITLE-ABS-KEY (”Guidance” OR ”safety” OR ”nuclear” OR ”mitigation”) AND NOT (”Thermal”) PUBYEAR > 2016
7. TITLE-ABS-KEY (“Building ventilation” AND “best practices”)
8. TITLE-ABS-KEY(“Building”) AND (TITLE-ABS-KEY (“ventilation” OR “HVAC”)) AND (TITLE-ABS-KEY(“nuclear” OR “Radi*”)
9. TITLE-ABS-KEY (“Building”) TITLE-ABS-KEY (“ventilation” OR “HVAC”) TITLE-ABS-KEY (“nuclear” OR “Radiological” OR “Radiation”) AND NOT (“thermal”) PUBYEAR > 2016
10. TITLE-ABS-KEY (“Building ventilation” OR hvac) AND TITLE-ABS-KEY (“best practice” OR “guidance” OR “mitigation”) AND NOT (“thermal” OR “efficiency”) PUBYEAR > 2016
11. TITLE-ABS-KEY (hvac AND radiological OR nuclear) AND PUBYEAR > 2016 AND PUBYEAR > 2016
12. Search: (((Building[Title/Abstract]) AND (Protection[Title/Abstract])) AND (nuclear[Title/Abstract])) Filters: from 2010 – 2023

13. (HVAC[Title/Abstract]) AND (Nuclear[Title/Abstract])
14. ((Building ventilation) AND (Nuclear)) OR (Radiological)
15. Search: ((Building HVAC) AND (Nuclear))
16. HVAC System[Title/Abstract] AND (2016:2023[pdat])
17. TITLE-ABS-KEY (building AND protection AND radiological AND dispersal AND device)
18. TITLE-ABS-KEY (emergency AND response AND building AND hvac) AND PUBYEAR > 2016 AND PUBYEAR < 2024
19. TITLE-ABS-KEY (emergency AND response AND building AND hvac AND nuclear incident)
20. TITLE-ABS-KEY (nuclear AND incident AND public AND safety) AND PUBYEAR > 2016 AND PUBYEAR < 2024
21. TITLE-ABS-KEY (cbrn AND (building OR best AND practices OR protection OR guidelines))
22. TITLE-ABS-KEY (chemical AND biological AND radiological AND nuclear AND (building AND ventilation))

Results

This reference collection investigates how building ventilation control (or HVAC system operation) can be used to protect building occupants by mitigating or reducing the entry of outdoor airborne hazards into the interior of a building, focusing on radiological and nuclear hazards. We identified 293 peer-reviewed journal articles, open federal reports, and technical notes, of which 216 were collected using a formal structured literature search and publication dates from 2016 to July 2023. The journal articles included in this analysis are distributed among eight subject categories, as shown in Figure 2. The largest fraction of research articles (25%) investigated the use of HVAC systems to control the spread of infectious diseases. These are recent publications (2020 to July 2023), demonstrating the tremendous growth in research on the transmission of infectious diseases a result of the COVID-19 pandemic. The emergency response category is second-largest, representing 19% of library contents. In comparison, this category has a much wider range of publication dates (2016 to July 2023).

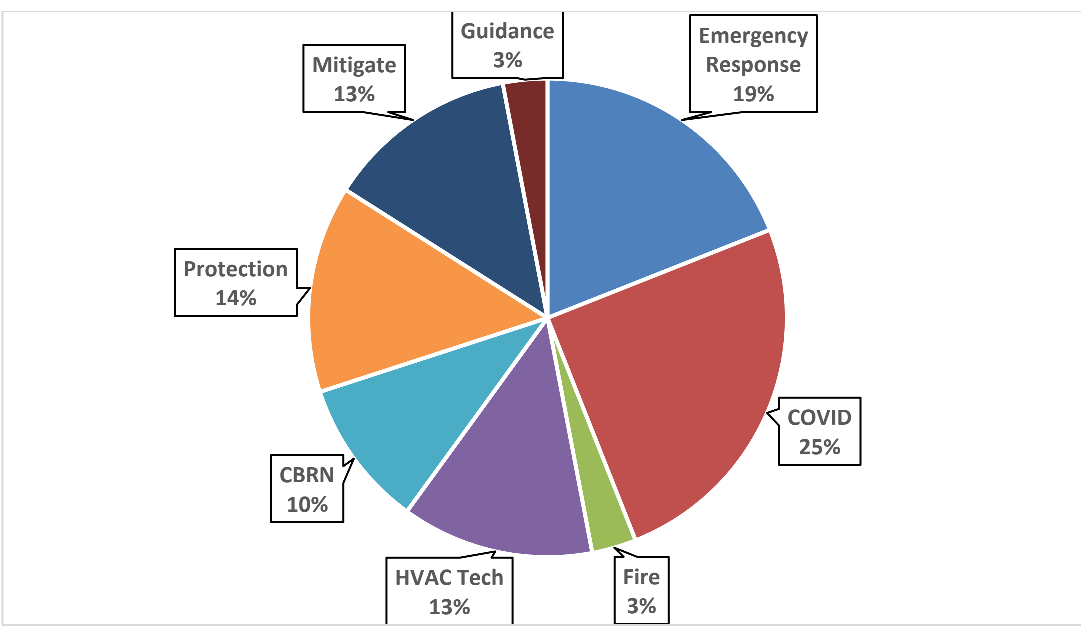

Figure 2. Distribution of references (2016–July 2023) by subject.

An analysis of the references by year shows the growth in the field of HVAC systems and building protection from an airborne hazard (Figure 3). Starting in 2020, a significant fraction of research focused on using HVAC systems to control the spread of infectious diseases.

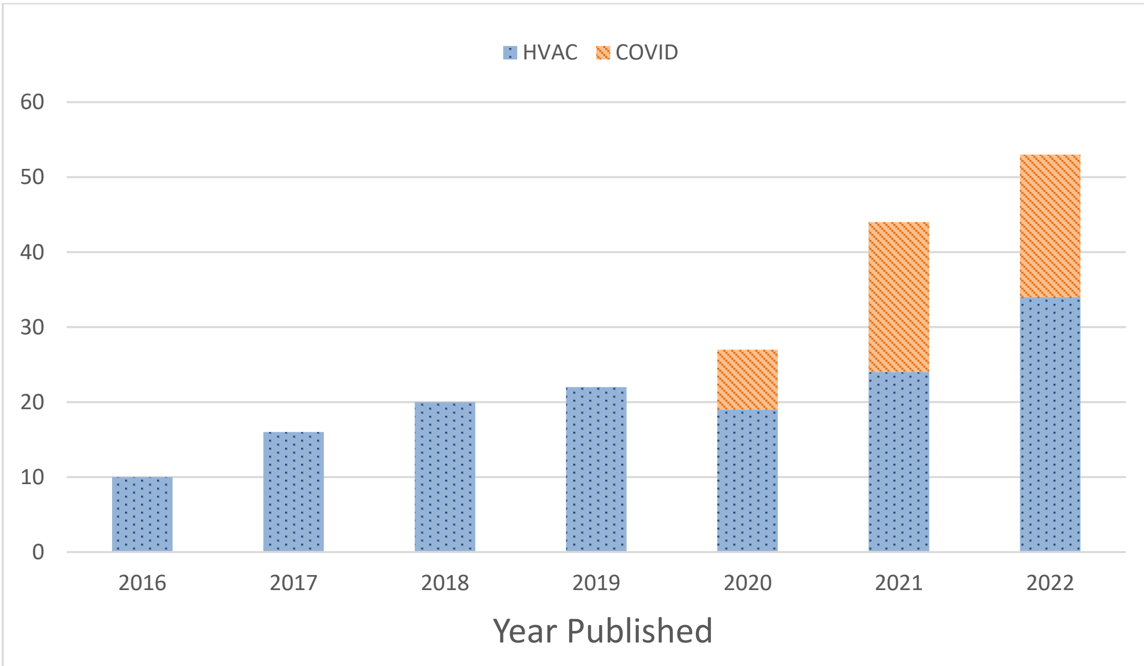

Figure 3. References by publication year and share focused on COVID.

Certain references stood out as being particularly impactful due to the sheer number of times they were cited. These key references were subject to a more in-depth analysis.

Literature Analysis

<u>Ventilation Guidance During an Outdoor Release (Guidance Category)</u>

References in the ventilation guidance category contained the key words: best practice, guidance, HVAC system or ventilation, but not COVID. All are relatively recent, with publishing dates of 2018 to present. There are only 11 relevant references in this category. Of these, eight were related to efficiency, comfort, moisture, or IAQ, and thus were not particularly applicable to radiological of nuclear release. Two key references explored using building pressurization to protect building occupants from an outdoor hazardous release (Cooper, 2018; Mamoun & Alyafi, 2020). Cooper (2018) presents an HVAC model to reduce infiltration of an outdoor hazardous material by using building pressurization and improved filtration. Two key parameters are effective filtration of the outdoor pollutant and a sufficiently tight building envelope to allow the pressurization.

> *"This is achieved by using forced inflow of well-filtered outside air to pressurize the building to the extent that all outside infiltration through the inherently leaky building envelope is constantly eliminated."*

The Mamoun & Alyafi (2020) study, "HVAC Design in Extreme Defensive Conditions: Temporary Refuges and Shelters," presents HVAC system design strategies for protection of indoor spaces in response to a disaster. Filtration, infiltration, exhaust design, cooling and HVAC zoning were important parameters used to create a safe space for up to three days. The authors note that there is a lack of guidance in operating HVAC systems in a defensive condition. This literature search uncovered many other articles on the topic of ventilation guidelines, but these focused on infectious diseases and are consequently listed in the COVID and Building Ventilation category.

COVID and Building Ventilation (COVID Category)

This was the largest category in the library, with 54 references published since 2020. Reports from the research community focused largely on designing HVAC systems for the purpose of reducing the transmission of infectious disease and aerosol removal. In general, these works focused on the mitigation of indoor sources and not the infiltration of outdoor sources of hazardous materials. Unsurprisingly, this research is largely about HVAC systems that change how buildings are ventilated and occupied. Research in the past three years has resulted in new guidance suggestions for building operations that include higher rates of outdoor air, as recommended by the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE), details of which are published in ASHRAE Standard 241: Control of Infectious Aerosols (ASHRAE, 2023). These new practices could have implications for how to protect occupants from an outdoor airborne hazard.

Multiple papers in this category offer HVAC system best practices and guidelines to reduce the spread of infectious diseases in a building. Papers generally were divided between guidance and mitigation. ASHRAE published articles with guidelines for operating a building during the pandemic and re-occupying a building after a shutdown (Mccarthy & Coghlan, 2021; Schoen, 2020; Schoen, 2022). Several papers discuss guidelines and emphasize an increased outdoor air ventilation rate and lower occupancy to reduce indoor disease transmission (Faulkner et al., 2022; Fleming et al., 2023; Guo et al., 2021), as summarized below. (Note that we often use the term "ventilation rate," but some documents refer to air exchange rate, fresh air ventilation rate, effective leakage area, or CFM per person; no "gold standard" has been adopted by the community as of yet.)

- Fleming (2023): This review targeted a range of evidence from recommendations, best practices, codes and regulations and peer-reviewed publications and evaluated how they cumulatively evolved over time.
- Guo (2021): Most terms and suggestions in these guidelines are consistent with each other, although there are some conflicting details, reflecting the underlying uncertainty surrounding the transmission mechanism and characteristics of COVID-19 in buildings. All guidelines emphasize the importance of ventilation, but the specific ventilation rate that can eliminate the risk of transmission of airborne particulate matter has not been established.
- Faulkner (2022): Filtration, dilution, and energy use. This paper develops a temporal simulation capability that is used to investigate the indoor virus concentration and operational cost of an HVAC system for two mitigation strategies: (1) supplying 100% outdoor air into the building, and (2) using different HVAC filters, including MERV10 (i.e., Minimum Efficiency Reporting Values; see Appendix A for further discussion), MERV13, and HEPA filters.

Mitigation strategies all focused on particles, improved high efficiency filtration, minimizing leaks, and minimizing air recirculation (Armenta et al., 2021; Morawska et al., 2020; Nafchi et al., 2021; Szalanski et al., 2023). A key reference (Dillon & Sextro, 2020) showed that exposure could be reduced by increasing the MERV rating of furnaces or HVAC filters:

> *"Our analysis suggests that, for most building types studied, upgrades to the filters currently used in furnaces or HVAC systems may reduce airborne particle exposures. Of the building types studied, apartments are predicted to benefit most, with greater than a factor of 2 improvement (≥50% reduction in exposures) for 1 µm particle exposures when using MERV 7 to 12 rated filters. Non-residential buildings were notably less responsive to improved filtration."*

Two other articles in the COVID category describe lessons learned from the pandemic and their application to a radiological release (Maiello, 2022; Martell et al., 2022). Both focus on emergency preparedness, risk communication, and social and economic impacts. Guidelines for protective actions were not discussed.

Strategies to Shield Building Occupants (Protection Category)

There are two meanings of the term "building protection" in the context of radiological or nuclear incidents. The first and by far most common in the literature refers to the shielding provided to building occupants from exposures to external gamma radiation from outdoor radionuclides. This radiation exposure is from both airborne radionuclides contained in the passing plume from a nuclear explosion (ND or IND), a radioactive dispersion device (RDD), or a nuclear power plant accident (NPP) as well as from radionuclides deposited on the ground, external building surfaces, or other outdoor surfaces (e.g., vegetation, etc.). Although this was the subject of early civil defense analysis and guidance, there has been considerable recent work in this area, including several papers from Dillon and colleagues at LLNL (Dillon et al., 2021; Dillon, 2014, 2019; Dillon & Homann, 2016; Dillon et al., 2016; Dillon, Schwefler, et al., 2022), and studies elsewhere (Bouville et al., 2022; Dickson & Hamby, 2016; Ghita, 2018). Most of these papers focus on the radiation shielding (attenuation) afforded by various common construction materials, building types, and occupant locations within buildings. SIP remains an effective passive strategy to reduce exposure to occupants, and some research shows the potential use of an HVAC system to extend the building's protection (Smith, 2021). None of these papers discusses potential conflicts between optimal shielding from external radiation and sheltering to reduce exposures to airborne radionuclides transported indoors.

The second meaning of "building protection" refers to reducing exposure to airborne radionuclides that enter the building from outdoors. With the exception of noble gas radionuclides (e.g., Kr-85, Xe-133) and iodine vapor, radionuclides produced by IND, RDD, or NPP accidents are particles or attach to them, so studies of outdoor/indoor particle concentration reductions are directly relevant. A number of papers have examined these effects, both experimentally and via modeling, with a focus on the components of this process (i.e., infiltration/ventilation deposition and filtration; see further discussion in Appendix A). A key finding from building protection studies is the importance of particle size, as all particle removal/loss terms (e.g., penetration factor, deposition loss rate to indoor surfaces, and filtration efficiency), with the exception of ventilation, are particle size dependent.

Two recent papers used indoor and outdoor radionuclide measurements near the Fukushima nuclear power plant accident to estimate the building protection factor for nearby buildings. While a large number of outdoor airborne radionuclide measurements were performed after the accident, (Ishikawa et al., 2014) made simultaneous filter sample measurements indoors and outdoors at their laboratory building, starting within a few days of the accident. Based on measurements of I-131 (adhered to particles), Cs-134, and Cs-137, they estimated a building protection factor of ~0.4 to 0.6. (Tan et al., 2015) used the data from Ishikawa along with estimates of building parameters and particle properties to extend protection factor estimates to a variety of dwelling types.

Modeling studies, most using empirically based values or value ranges for key parameters (e.g., penetration, deposition, and filtration) have explored the relationships between these parameters, particle sizes, and overall building protection efficacy. (Singh et al., 2022) modeled both the external radiation shielding effects of three hypothetical houses (patterned after houses in India) and the reduction in indoor radioactive particle concentrations in the houses. This is the only recent paper to have evaluated both shielding for external radiation and reductions in the indoor inhalation dose. The paper did not compute effective doses, only relative effects, so there was no direct comparison of the exposures and doses from the two sources of radiation.

Dillon and colleagues modelled outdoor and indoor inhalation exposures across a range of building types, operating characteristics, and particle sizes (Dillon & Dillon, 2019; Dillon, 2019) (Dillon, Schwefler, et al., 2022). The smallest protection factors (i.e., the best protection levels) were obtained for single family homes and small apartment buildings. Particle size had the largest overall influence on protection factors: deposition loss rates and filter efficiency both increase significantly with increasing particle size. The authors describe a methodology for estimating the protection factor of a building against the inhalation of an outdoor aerosol, and argue that traditional building ventilation systems are often inadequate for protecting occupants against aerosols, as buildings are not designed to filter out inhalable particle sizes. The protective factor of a building is most linked to the likely particle size (i.e. protection factors were high with large particle sizes), while building type (e.g, residential, commercial, industrial) played a lesser role. The authors investigated six building types from residential to a retail store and found that in all cases, fine and ultra-fine particles had high penetration rates. (We note here that “penetration rate” is used to explain the amount that flowed through an opening, rather than though the ventilation system.) The authors discuss several strategies for mitigating risks of outdoor-origin aerosols in buildings, including:

- Increasing outdoor air ventilation rates to attempt to dilute the concentration of aerosols in the indoor air, thereby reducing the risk of exposure.
- Using air filtration with high-efficiency particulate air (HEPA) filters and other advanced filtration systems to capture a wide range of particle sizes, including those found in outdoor-origin aerosols.
- Implementing air cleaning technologies such as ultraviolet germicidal irradiation (UVGI) and photocatalytic oxidation (PCO) to biologically inactivate or chemically remove harmful particles from indoor air.

The authors note that these strategies must be implemented carefully to avoid unintended consequences including increased energy use or negative impacts on indoor air quality.

While sheltering in place is a common protective action, the quality of the shelter varies significantly among U.S. buildings (e.g., commercial vs residential, mechanically ventilated vs. naturally ventilated). Several papers by Dillon describe the sheltering from external sources (Dillon & Homann, 2016; Dillon, Schwefler, et al., 2022; Dillon et al., 2019).

Another approach to improving building protection is to reduce the effects of infiltration, which is driven by the size of leaks and the pressure differential across the building shell. (Cooper, 2018) has modeled the effects of building pressurization as a means of reducing or eliminating infiltration and has suggested a detailed monitoring and control algorithm that could be used with a mechanical HVAC system. This approach relies heavily on having a distributed network of pressure sensors for pressure control and a high efficiency filtration system with which to supply the filtered outdoor air for the pressurization. The paper does not explore the maintenance requirements for ensuring the filtration system does not fail.

A key reference titled "A tool for determining sheltering efficiency of mechanically ventilated buildings against outdoor hazardous agents" (Kulmala et al., 2016) developed a model to explore HVAC system parameters. The two main parameters explored are infiltration and supply air delivery rates. Improving the filtration efficiency of the supply air was key to increasing the protection factor of the building through reduced penetration through openings:

> *"To shelter against sudden contamination events, the current recommendations are to go in, stay indoors, close windows and doors and shut ventilation off. While this is an effective way to protect people from short-term releases of hazardous materials, during long-lasting releases it may be more beneficial to run the ventilation continuously to minimize occupant exposure, provided that the supply air filter is effective against the threat agent in question. The sheltering efficiency against airborne radionuclides can be improved by enhancing the filtration efficiency against submicron particles."*

Estimating exposure and dose to the public was a main topic in the Protection category, and many of the papers focused on protection of first responders. Estimating exposure and dose when outside or sheltering in place is important information for emergency responders (Biancotto et al., 2021; Bouville et al., 2022; Dillon et al., 2021). We note that acceptable exposure and consequence limits are different for the public, a worker, and a responder.

Lastly, one reference investigated the impact of a nuclear detonation on indoor occupants (Kokkinakis & Drikakis, 2023). This study focused on the force of the blast wave, the pressure generated, and the location of occupants in a building.

Manipulating HVAC Systems to Reduce Exposure (Mitigation Category)

One important method of improving building protection is to increase the efficiency of particle filtration. (Dillon & Sextro, 2020) modeled the effects of improved filters across a range of building types and particle sizes. Apartment buildings, schools, and retail stores showed the greatest improvement in building protection with increasing filtration efficiency, especially for particle sizes around 1 µm in diameter. (Rawat & Kumar, 2023) evaluated improved filtration strategies, including the use of stand-alone air cleaners, for reducing airborne particle concentrations in schools.

This category explores the relationship between ventilation system performance and indoor air quality. The category is predominantly focused on filtration and infiltration, with the remaining papers focused on controlling an indoor source. Only one reference specifically studied building ventilation system parameters during a radiological or nuclear release. Kulmala (2020) investigated the effect of installing a high efficiency electrostatic filtration system. The system was very effective in reducing particle exposure to occupants, but the effect was reduced by leakage in the building envelope. The infiltration rate was driving the exposure risk to occupants:

> *“Despite the high improvement in the supply air filtration efficiency the indoor concentrations decreased only modestly which is likely due to the leaky construction of the building, demonstrating the detrimental effect of air infiltration on the protection provided by buildings against outdoor airborne hazards”*

Almost half of references in this category focused on filtration in residential homes, with an emphasis on fine and ultra-fine particles (Fazli et al., 2019; Singer et al., 2017). (Wu et al., 2022) evaluated filter performance in a lab test system for several filter types and ratings for a range of particle sizes. One paper evaluated the effectiveness and lifetime of HEPA filters for commercial and laboratory buildings only and found that the lifetime of the filters exceeds 10 years (Barnett et al., 2022). Outdoor hazardous materials can also enter a building through infiltration (Howieson et al., 2014; Mckeen & Liao, 2022). Infiltration remained a main topic of research, and new tools and techniques for measuring infiltration rates were published in 2020 (Kulmala et al., 2020). We note that the proper usage and fitting of the filters remain an important issue.

<u>Chemical, Biological, Radiological, and Nuclear Releases (CBRN Category)</u>

Among 23 references in this category, two specifically address building ventilation during a chemical release. In “Building Ventilation Strategies to Protect the Public During Health Emergencies” (Stewart-Evans, 2014), the author highlights minimizing building ventilation, such as shutting off fresh air ventilation and other “sheltering” actions before the plume reaches the area. However, we note that delays in communication or in minimizing ventilation before the outdoor hazard arrives complicates the feasibility of this consideration. The article also notes that further research in filtration is needed. The second reference (Thompson & Bank, 2020) used a computer model to investigate the impacts of several building parameters, including outside air intake and filtration, on occupant safety in the event of a bioterrorist attack. In particular, they noted that upgrading to a MERV10 to 13 provided optimum removal rates of a bio-agent.

The remaining references cover a variety of topics. One examines particle deposition and resuspension (Dols & Persily, 2015), several focus on estimating exposure that could result in inhalation dose to building occupants (Castellini et al., 2023; Liu et al., 2020), and another outlines considerations for conducting a shelter in place risk assessment (Gai et al., 2020). The remaining topics are cyber security

(Elnour et al., 2021), emergency preparedness (Alpert & Grossman, 2023; Kaszeta, 2022; Regal et al., 2022) and prevention (Blatny, 2022; Carbonelli et al., 2021; Sharma et al., 2019).

Protective Actions and Lessons Learned (Emergency Response Category)

With 46 references, this is the second-largest category after the COVID analysis category. References cover emergency preparedness, lessons learned from the Fukushima accident, risk analysis, disaster recovery and guides for facility managers in the event of a nuclear or radiological release (Case et al., 2018; NUSTL, 2017). Risk analysis and research on emergency response guidelines for three types of releases are covered: nuclear power plants, especially lessons learned from the Fukushima accident, (Ayoub et al., 2022; Callen-Kovtunova & Homma, 2022; Kyne, 2015), nuclear detonations (Buddemeier & Suski, 2015), and RDDs (Cavalieri d'Oro & Malizia, 2023; Nasstrom et al., 2017; NUSTL, 2017; Ropeik, 2018). Research in this area focuses on guidance and training for emergency responders and building managers covering the initial phase of the incident and recovery efforts (Case et al., 2018; Gustin, 2020; Lavin et al., 2022; NUSTL, 2017; Rojas-Palma et al., 2020). Absent are specific guidelines for operation of building HVAC systems during or after a nuclear event.

Building HVAC Strategies to Reduce Particle Intake During a Wildfire Event (Fire Category)

Wildfire smoke can travel great distances and pose a significant inhalable hazard to large population centers. Recent research in various mitigation strategies could be applied to other outdoor hazards, such as a release from a NPP, where fine to ultrafine particles (i.e., below one micrometer in diameter) are produced. While most radiological releases last a relatively short period of time, wildfire smoke events can last for days, even weeks. Although there are only 10 references in this category, the main topics of research are similar to those found in other categories. Research primarily focuses on fine particles and explores the use of filtration and infiltration reduction measures to protect occupants. Three references, all from 2021, showed that the use of a personal air cleaner along with HVAC filtration and reduction of infiltration in residential buildings significantly reduced indoor levels of wildfire smoke (Davison et al., 2021; Rajagopalan & Goodman, 2021; Tran et al., 2021). All three studies note that even in airtight homes, indoor concentrations of outdoor pollutants will increase over time, especially since wildfire events last for days. Research found it was essential to implement particle filtration systems such as personal air cleaners or high filtration HVAC systems to reduce indoor exposures. A cost benefit analysis (Shum & Zhong, 2022) recommended that residential ventilation systems should increase the filters from MERV6 to MERV11 or MERV13 during wildfires and use a higher recirculation ratio during peak exposure times.

Current and Emerging HVAC Systems Technology (HVAC Technology Category)

Over the past 10 years, there have been advancements in HVAC technology for both residential and commercial buildings. The ventilation system controls a variety of parameters including thermal comfort, humidity control, energy efficiency, air distribution, indoor air quality, and pollutant removal (Absar Alam et al., 2023; Cao et al., 2014). In recent years, new technology on control systems (Ceccolini & Sangi, 2022) and pollutant removal have penetrated the market in residential homes. There are a wide variety of residential ventilation systems in place from natural ventilation systems (Chen et al., 2019), portable window AC units, ductless HVAC systems, to multi-zone HVAC systems with high efficiency filters. Improvements in filtration systems in particular are now common in residential buildings (Liu et al., 2017). ASHRAE recommends MERV8 filters for single-family residential buildings.

The recent popularity in portable air cleaners has contributed to significant market growth for these types of products. According to Consumer Reports, one in four homes have purchased an air cleaner (Santanachote, 2019). Commercially available units have been shown to effectively reduce particle concentrations in residential settings (Cox et al., 2018). The time occupants spend in rooms with portable air cleaners is not presently known, to our knowledge.

Sensor-driven control systems are common in commercial buildings (Granderson et al., 2018). These include demand control (based on CO_2 sensors), occupancy control, or movement-activated control systems. Ventilation control can also receive feedback from air quality sensors or weather forecasts (Cheng & Lee, 2019). Research has expanded on how to capitalize on the Internet of Things (IoT) and use this new connectivity to enhance energy efficiency without compromising indoor air quality. These "smart" building features (Guetter & Luntovskyy, 2023) have reached the residential market. Newer homes are built with IoT-connected sensors and ventilation control systems, allowing homeowners to manage ventilation systems through a smartphone app and enable remote control of ventilation features – even opening and closing windows if they are not home (Kumar et al., 2016; Liu et al., 2022). Artificial intelligence and machine learning are also being applied to advanced HVAC control systems (Ren & Cao, 2020; Ren et al., 2023; Tien et al., 2022).

Website Analysis

Our literature review extended beyond the scientific literature to resource materials that are widely available to the public. These materials include websites, white papers, infographics, videos, and other tools designed to help first responders, homeowners, building managers, and critical infrastructure operators respond after an airborne release. While the search focused on guidance for adjusting HVAC systems after a radiological release, we also captured generalized information and protective action guides referring to any CBRN incident. Nuclear scenarios included in the search were radiological dispersive device (RDD), nuclear power plant emergency (NPP), and nuclear detonation (ND). We primarily surveyed federal, NGO, and state websites. Appendix B (Websites and Resources for HVAC Guidance During an Emergency) contains a full listing of websites and resources, along with brief bullet point summaries. Table 4 (below) lists website sources divided into three main categories for quick reference.

Table 4. Federal, NGO and state websites surveyed for emergency guidance.

Federal	NGO	State
•DHS (Ready.gov) •CDC •FEMA •EPA •NIOSH •NIST •HHS •DOD •NRC •OSHA •REMMS (Dept. of Education) •FDA •CIA •LBNL •LLNL •NIEHS •Fed Register	•NIBS •ASHRAE •CHS •NASEM •AIA •ICRP •IFMA •Red cross •IAEA •NARR •PGE •CRCPD •NRT •NCRP •AIVC	•CN •MN •CA •NY •AL

Overall, the prevailing recommendation is to shelter-in-place and reduce infiltration either by closing doors, windows, and/or vents or by adding active sealing with tape and plastic sheeting. Shelter-in-place is based on research conducted in the 1980s and 1990s and is well established as a protective action (NICS, 2001). Sealing guidance is also based on research that was conducted in the 2000s on both residential and commercial buildings (Environmental Protection Agency, 2009; Sorensen, 2002). In these two references, plastic sheeting and duct tape were tested for infiltration rates. Both references found that sealing effectively reduced infiltration rates, but noted that the time required for implementation could vary from two minutes to almost 40 minutes. A delay in quickly sealing a room could result in higher exposures due to the timing of mass entering but not exiting the building (Jetter & Whitfield, 2005). Key components for creating a safe shelter include having enough time to warn the public, quick implementation before the outdoor plume reaches the shelter, and releasing the shelter after a few hours. Effective sealing could eventually create increased levels of CO_2 and reduced amounts of O_2, and should only be put in place for a few hours. Finally, we note that most of this research was conducted with a chemical or gas release, and not a radiological particle.

The prevailing website guidance is also generalized for all nuclear scenarios, even though timing and particle size of the hazard released varies. We found sealing guidance in particular to be varied and inconsistent among websites we reviewed. Some advised duct tape only and no plastic, others recommended using tape and plastic, still others suggested wax paper, aluminum foil, or wet towels. Another issue was that guidance was generalized for any outdoor hazardous release (either chemical or radiological) and not specific for the different hazard that each scenario presents. Another variable in the guidance was the timing. In the event of an ND or RDD, the public would likely have little to minimal time to implement an extensive sealing of a safe room. If the building infiltration rates are high – such as more than two air changes per hour, as can occur in an older home – the outdoor hazard may enter the safe room before sealing is completed. Lastly, there was often no guidance on when to leave the safe shelter, and some guidance said to shelter for 24 hours without distinguishing between a nuclear detonation or an RDD event. This could result in adverse health outcomes for vulnerable populations in climate zones that experience extreme heat or cold.

Federal Websites

Federal websites offer guidance for different types of emergencies including radiological incidents, chemical releases, and wildfires, among others. They are user-friendly, well structured, and provide valuable resources for individuals and communities to prepare for and respond to various emergency situations. Guidance was clear and easy to follow, but sometimes generalized for any type of outdoor release. The overall message is to shelter in place with doors and windows closed (Figure 4).

Figure 4. DHS radiation safety infographic. (Source: ready.gov/radiation.)

We identified 17 different federal agencies posting videos, advice, info sheets, and guidance, whether generalized for hazardous materials or specific to nuclear/radiological outdoor releases. The protective action guidance from the top four agencies (DHS Ready.gov, CDC, FEMA, and EPA) is intended for the general public and residential buildings. These websites are summarized in more detail below. Federal guidance for first responders and building managers is also found at FEMA, NIST, NIOSH, NUSTL, OSHA, and NIEHS websites. NIOSH publishes detailed protective action guidance for public commercial buildings (rather than residential buildings) for emergency responders and technical staff. The federal government's two in-depth guides are both more than two decades old: *Guidance for Protecting Building Environments from Airborne Chemical, Biological, or Radiological Attacks* (2002) and *NIOSH Guidance for Filtration and Air Cleaning Systems to Protect Building Environments for Airborne Chemical, Biological, or Radiological Attacks* (2003).

Department of Homeland Security (DHS)

The Ready.gov website, hosted by DHS, is a comprehensive resource for emergency preparedness. We found six resources that give HVAC guidance for an outdoor hazardous material release (Table 5). All advocate sheltering in place with doors, windows, and vents closed and fans turned off.

Table 5. List of Ready.gov websites with HVAC guidance for emergency response.

1. https://www.ready.gov/radiation (2023)
2. https://www.ready.gov/radiological-dispersion-device-old (2022)
3. https://www.ready.gov/faq/sealing-your-shelter-place-advance (2019)
4. https://www.ready.gov/shelter (2022)
5. https://www.ready.gov/hazmat (2023)
6. https://www.ready.gov/wildfires (2022)

The first website in the table (https://www.ready.gov/radiation), offers protective guidance in the event of a nuclear detonation:

> *"If possible, turn off fans, air conditioners, and forced-air heating units that bring air in from the outside. Close windows and doors. Close fireplace dampers"*

The guidance includes an infographic (Figure 5) and is aimed at a general audience and applicable to any building type. This website offers more detail as the reader continues scrolling down, with specific guidance for the different phases and timing of a detonation.

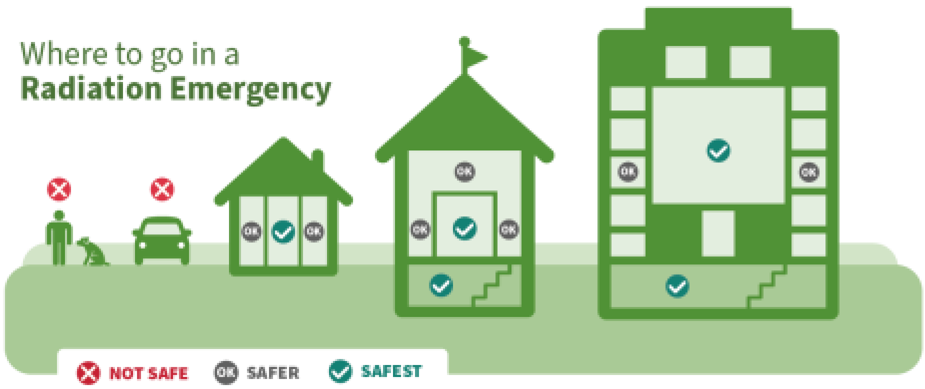

Figure 5. DHS "Where to go in a Radiation Emergency" infographic. (Source: ready.gov/radiation.)

In four of the six websites listed in Table 5, emergency guidance for the public includes instructions to seal doors and windows of their safe room with plastic sheeting and duct tape. For example, the second website recommends in case of an RDD event to:

> *"Seal windows and external doors that do not fit snugly with duct tape to reduce infiltration of radioactive particles. Plastic sheeting will not provide shielding from radioactivity nor from blast effects of a nearby explosion."*

Website three gives advice on preparing a safe shelter ahead of time by including sealing material in an emergency kit:

> *"DHS recommends that you precut plastic sheeting for any windows, doors, vents or openings and label them appropriately. The plastic should then be stored with duct tape and scissors in the designated shelter-in-place room so that it can be quickly accessed and installed. DHS does not recommend that you install the plastic sheeting in advance. You can, however, make sure that any areas that can be permanently sealed such as where pipes come out of the wall or where trim meets the floor and walls, are properly caulked. This will also help reduce heating and cooling costs so is good idea overall. "*

The fifth website contains guidance in case of an outdoor hazardous material release, including explosives, flammable and combustible substances, poisons, and radioactive materials. It instructs the public to seal gaps with wet towels, plastic sheeting, and duct tape, as well as wax paper or aluminum foil:

If told to stay indoors:

- Bring pets inside.
- Seek shelter in an internal room. Close and lock all exterior doors and windows. Close vents, fireplace dampers and as many interior doors as possible. Seal the room with duct tape and plastic sheeting.
- Turn off air conditioners and ventilation systems, or set ventilation systems to 100 percent recirculation so that no outside air is drawn into the building.
- Seal gaps under and around the following areas with wet towels, plastic sheeting, duct tape, wax paper or aluminum foil:
  - Doorways and windows
  - Air conditioning units
  - Bathroom and kitchen exhaust fans
  - Stove and dryer vents with duct tape and plastic sheeting
- Take shallow breaths through a cloth or a towel if gas or vapors could have entered the building.
- Avoid eating or drinking any food or water that may be contaminated.

Figure 6. Information from Ready.gov (source: https://www.ready.gov/hazmat)

The final website on the list focuses on wildfires as a significant source of outdoor particles. General guidance is to evacuate, but if smoky conditions exist in your area, the website advises the public to stay indoors, close a room from outside air, use a portable air cleaner, set your air conditioning system to recirculate, and use a high efficiency filter.

The Centers for Disease Control (CDC)

CDC hosts multiple websites containing infographics, tools, and videos with protective guidance for the public on how to respond in a radiation emergency. (See Appendix B for a full list of websites and resources.) The general message is to “get inside, stay inside, stay tuned” (Figure 7). Guidance regarding building ventilation is: “If possible, turn off fans, air conditioners, and forced-air heating units that bring air in from the outside. Close fireplace dampers.” CDC’s SIP guidance covers several different building types, from single-family residences to commercial buildings. The CDC offers guidance for three types of nuclear incidents and does a clear job of defining each type of radiation emergency. The guidance for all three scenarios is identical: to shelter in place with doors and windows closed.

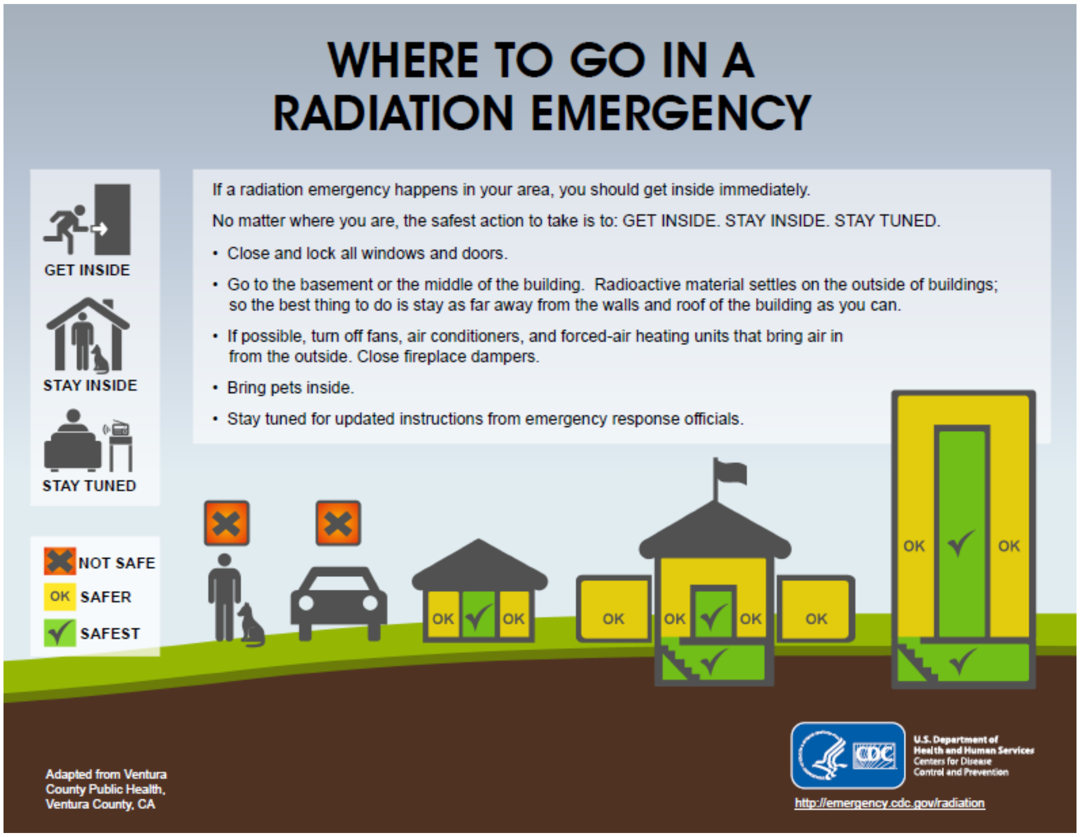

Figure 7. **CDC "Where to Go in a Radiation Emergency" infographic. (Source: cdc.gov/nceh/radiation/emergencies/getinside.htm.)**

Wildfire smoke is an outdoor hazardous material that has become more prevalent in recent years and has affected air quality for many homes. CDCs "Stay Safe During a Wildfire" website (https://www.cdc.gov/disasters/wildfires/duringfire.html) recommends staying inside, closing doors and windows, using the HVAC system in recirculation mode with a high efficiency filter installed, and using a portable air cleaner.

Federal Emergency Management Agency (FEMA)

FEMA, managed by DHS, provides many protective action guides addressing different types of emergencies (see Appendix B). Detailed advice covers chemical hazards, nuclear detonations, and natural disasters (Figure 8). There are specific action plans for nuclear detonations, but not for NPPs or RDDs. In the event of a nuclear detonation (or IND) the prevailing guidance is: "Close windows and doors. If possible, turn off units that bring in air from the outside." The guidance suggests that the public will likely have a 10- to 15-minute warning before fallout occurs. The guidance also recommends to SIP for 24 hours. The FEMA website tailors advice to different building types including mobile homes, condominiums, and multi-story buildings.

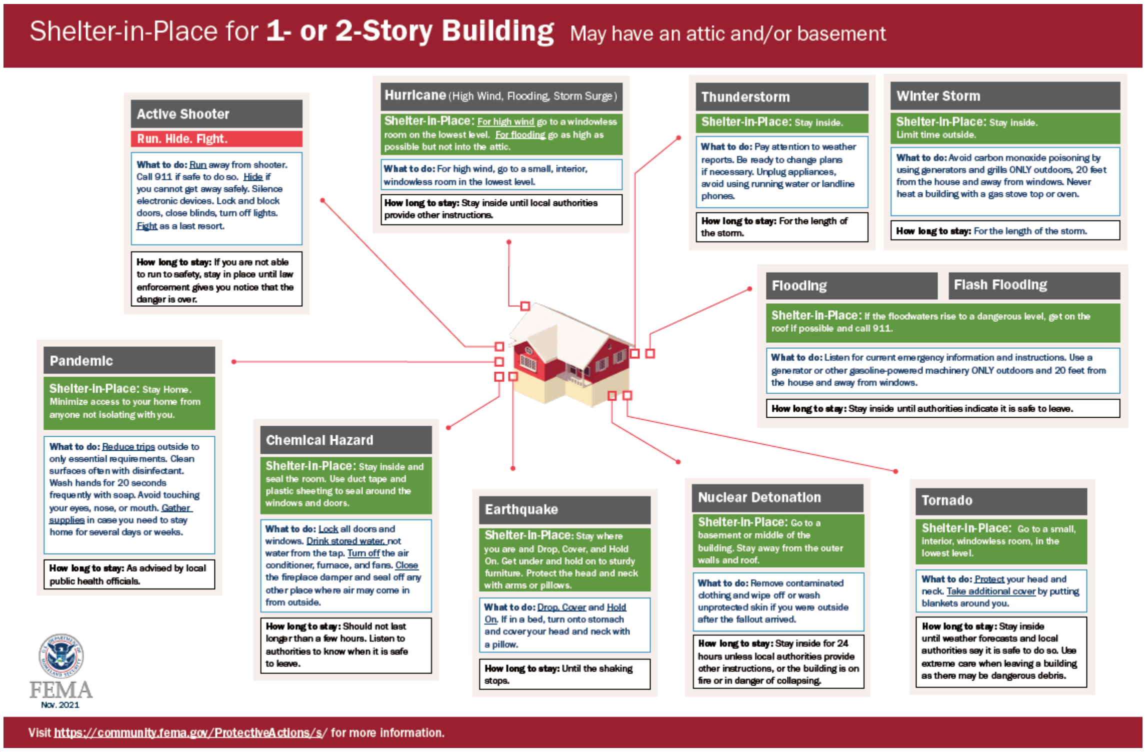

Figure 8. FEMA "Shelter-in-Place" infographic. (Source: fema.gov/emergency-managers/national-preparedness/plan/evacuation-shelter-in-place.)

FEMA offers advice in the event of a chemical release and recommends turning off all fans and air conditioners and then using duct tape to seal windows, doors, and vents. Unlike the nuclear guidance, this SIP is recommended for only a few hours.

The Environmental Protection Agency (EPA)

The EPA offers Protective Action Guides (PAGs), resources, and infographics across six different websites (see Appendix B). There is guidance for the general public as well as guidance for first responders and public officials. For the public, guidance includes shelter-in-place instructions but not specific HVAC recommendations (Figure 9). EPA's guidance is generalized for any radiation emergency including NPPs, RDD, transportation accidents, or nuclear detonation. The public is also instructed to shelter for 24 hours.

Figure 9. EPA "Guidance in the Event of a Radiation Emergency" infographic. (Source: epa.gov/radtown/radiation-emergencies-and-preparedness.)

EPA also offers a manual of *Protective Action Guides and Planning Guidance for Radiological Incidents* (United States Envirnomental Protection Agency, 2017), which contains guidance for first responders to plan for radiation emergencies. The guide applies to all types of radiological incidents and includes detailed information on the timing of protective actions, dose criteria, reducing first responder exposures, guidance for re-entry to affected areas, protecting food and water sources, etc. There is no detailed HVAC guidance for buildings, but there is information on the protective factor of buildings from fallout radiation. The two protective action choices for the public are evacuation and shelter-in-place.

EPA's website on Wildfires and Indoor Air Quality (epa.gov/indoor-air-quality-iaq/wildfires-and-indoor-air-quality-iaq) offers detailed HVAC guidance on how one might create a clean room, for example, in the event of a wildfire. The public can find information on how to use an HVAC system to reduce particulate matter when outside air contains unhealthy smoke levels. Recommendations include closing doors, windows, and vents, installing a high filtration filter (i.e., MERV 13 or higher), running the HVAC system in recirculation mode, and using a portable air cleaner (Figure 10).

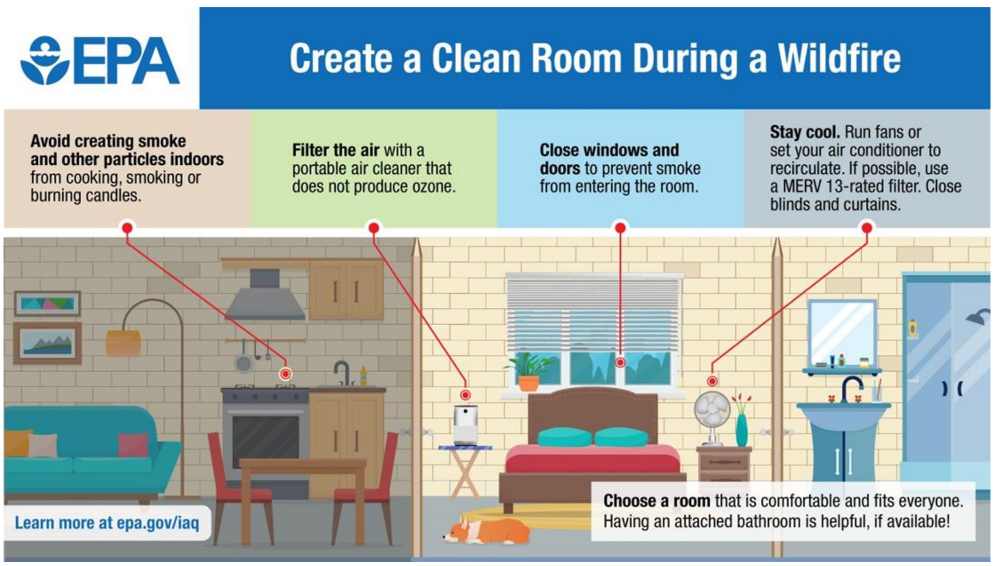

Figure 10. EPA "Create a Clean Room During a Wildfire" infographic. (Source: epa.gov/indoor-air-quality-iaq/create-clean-room-protect-indoor-air-quality-during-wildfire.)

NGO Websites

Table 5 lists non-governmental organizations that publish protective actions in the event of a nuclear or radiological incident, and Appendix B contains a full list of sources and website links. Some NGOs, such as the Red Cross, refer the reader to federal websites such as Ready.gov or the CDC. Others, including the International Atomic Energy Agency, offer guidance that is outdated or does not address HVAC building systems. Some NGOs, however – namely the American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE), the National Institute of Building Science, and Johns Hopkins Center for Health Security – offer more detailed HVAC emergency preparedness guidance that is suitable for a professional or building manager.

The leading NGO for building ventilation is ASHRAE, a non-profit group that specializes in the science of building ventilation systems and publishes standards on building operation and ventilation primarily for building managers and professionals. ASHRAE recently published updated building operation guidelines (ASHRAE Standard 241, *Control of Infectious Aerosols,* 7/2023), which are designed to reduce the spread of infectious disease through high efficiency filtration (using MERV rated HVAC filters) and increased flow of outside air.

The National Institute of Building Science (NIBS) publishes guidance for building managers and engineers to prepare before a CBRN emergency. Preparedness actions include tightening the building envelope, providing enhanced filtration, and ensuring the physical security of the HVAC system components (Whole Building Design Guide, 2017).

The John Hopkins Center for Health Security publishes HVAC guidance designed to protect building occupants from an indoor biological airborne hazard. Guidelines advocate for building pressurization, enhanced filtration, and reducing infiltration to reduce occupant exposure and clean the air. This guidance, published in 2008, has not been updated (https://centerforhealthsecurity.org/our-work/research-projects/completed-projects/protecting-building-occupants).

Working Group on Reduction of Exposure to Infectious Agents during a Covert Bioterrorism Attack

1. Minimize filter bypass: Seal, caulk, and gasket everything (filter cartridge, retainer bank, tracking, etc.) to minimize filter bypass.
2. Commission: Commission buildings during design and construction, and re-commission routinely to ensure that ventilation systems are operating in line with design intent.
3. Enhance filtration efficiency: Increase air filtration to the maximum economically justifiable MERV level to improve the removal of particulate matter from the air.
4. Maintain filter systems: Conduct regular inspections and maintain filter systems correctly to ensure that the HVAC system functions properly.
5. Train staff: Ensure that maintenance staff has the appropriate training to operate and maintain the HVAC system.
6. Tighten the envelope: When economically feasible, tighten the building envelope to reduce the infiltration rate.
7. Pressurize: When economically feasible, pressurize the building to reduce infiltration rate.

State and City Websites

Most state and city websites refer the reader to Federal websites such as Ready.gov and advise the public to follow the traditional SIP with or without sealing guidance. A few examples are included in the appendix. For example, Connecticut's Department of Public Health sites the Ready.gov website, and recommends homeowners to SIP in case of any chemical, nuclear or radiological emergency and includes detailed instructions for sealing windows and doors closed. The website advised the public to shelter in place for 2 to 3 hours (See Figure 10). Note that no distinction is made between a chemical and nuclear emergency.

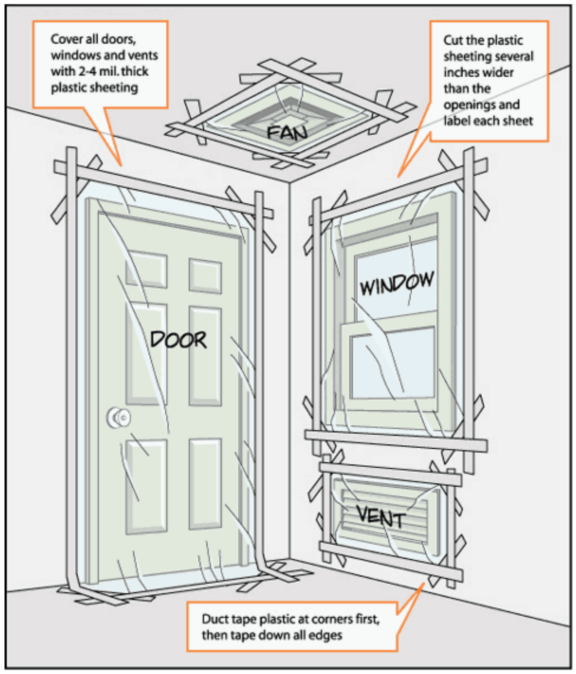

Figure 11. State of Connecticut sealing guidance infographic. (Source: portal.ct.gov/DPH/Public-Health-Preparedness/Main-Page/Nuclear-and-Radiological-Emergencies.)

The State of Minnesota's Emergency Preparedness website also advises sealing guidance, but the protective action is specific to an RDD event. The sealing guidance recommends using wet towels, plastic, wax paper, aluminum wrap, or duct tape to seal gaps (https://www.health.state.mn.us/communities/ep/ltc/annexo.html).

Web-based Tools

Lastly, we compiled a list of web-based software programs that compute or analyze building ventilation rates and show users how changes in ventilation systems affect the building's ventilation rate. Table 6 lists seven web-based tools, all of which were created by federal agencies; three of seven tools specifically target the reduction of viral particles. Only one tool, CONTAM, was designed to model the transport of an outdoor pollutant. We could not find a web-based tool made specifically for a radiological or nuclear event that homeowners could use to gain insight on interventions to improve occupant protection.

Table 6: List of web-based tools for building ventilation analysis.

Institution	Website	Audience	Description
CDC	Improving Ventilation in your Home	Homeowners	Use tool to learn how to reduce viral particles by increasing fresh air.
CDC	Interactive School Ventilation Tool	Building managers, school administrators	Use ventilation system to reduce viral particles in the air.
LBNL	Secure Building Tool	Scientists, building managers	Early screening and background documents produced shortly after 9/11.
LLNL	National Atmospheric Release Advisory Center	Scientists, emergency responders	Models for atmospheric plume predictions but no ventilation guidance.
NIST	Quick Indoor CO2 Tool	Building professional or manager	Estimates ventilation rates based on CO_2 levels in commercial buildings.
NIST	Virus Particle Exposure Tool (ViPER)	Homeowners	A single-zone indoor air quality and ventilation analysis tool designed to estimate virus particle exposure for single-family residences.
NIST	CONTAM	Scientists	A multi-zone indoor air quality and ventilation analysis software designed to determine transport and contaminant concentrations of pollutants.

Discussion

We have reviewed the open literature, past and current guidance, and emerging technologies, as well as tools and recent analysis concerning protective actions using buildings to protect occupants from an outdoor radiological or nuclear release. Broadly, the prevailing federal guidance – to go inside, seal doors and windows, and turn off fans – has remain largely unchanged since the early 2000s. Existing guidance lacks specific recommendations tailored to outdoor vs. indoor threats. The traditional advice to turn off ventilation systems and seal doors and windows can conflict with recent research on reducing the spread of an infectious disease outdoors. This highlights the need for nuanced and context-specific guidance. Additionally, while past research on radiation and nuclear threats remains accurate, it has yet to incorporate the latest advancements in building ventilation systems or capitalized on research from the biological aerosol exposure community.

We highlight broad observations that are discussed in greater detail in earlier sections:

1. We have seen a large decline in new research related to building protection from exposure to radiological and nuclear particles. This does not imply that current guidance is outdated, but rather it suggests that routine updating of existing knowledge products has not occurred, perhaps due to other recent priorities (e.g., bioaerosol threats). We recommend a proactive approach to regularly updating federal guidelines. In part, this document lists research that should be reviewed and incorporated into ventilation guidance and standards by organizations such as CDC and ASHRAE.

2. Our review of recent literature does not reveal new knowledge that conflicts with past guidance recommendations. An important consideration here is identifying recommendations based on the location of the source. Given our current understanding of particle behavior (whether radioactive or not), the physics of particle transport into and within buildings remains unchanged. We do note that accumulation of particles on building filters is of possible relevance to the greater use of high-efficiency filters. Notably, we have noted that the opposite action (i.e., increasing filtered air using the HVAC or portable air cleaner) can have benefits, so future guidance can shed valuable light by parsing out recommendations for more uniquely defined threat scenarios. How to promulgate this option is not clear.
3. New learning and guidance related to protections against the inhalation of biological particles and smoke from wildfires could have important benefits to reducing indoor exposure and risks to radioactive particles. It is possible that a building response mode could be identified that applies to a range of outdoor threats. For example, does building hardening apply to all types of outdoor hazardous releases? The next step of this research should explore these considerations.
4. Both ASHRAE's and the CDC's recent recommendations to increase fresh air ventilation amounts/rates are far-reaching and ambitious, but they may not apply to most residences. These recommendations are for overall improved indoor air quality; for radiological incidents, we often face concerns about an outdoor radiological release and residents' safety. Therefore, these guidelines could be counter-productive, as outdoor sources are likely best combatted through hardening and/or filtering. Similarly, these guidelines often focus on benefits to commercial buildings and their applicability to residences, in particular single-family houses, are not considered in sufficient detail. Research indicates that older homes have many leakage pathways that can lead to unfiltered outdoor air getting into houses. This is previously known, but the benefits of building hardening have not been explored in much detail. A modeling analysis should be considered to assess the feasibility and benefits of hardening, local filtration from typical HVAC units in houses, and forced positive pressure HVAC flow to reduce outdoor flow through leakages. This analysis should also consider guidance where residences are unable to operate HVAC systems due to a lack of understanding/knowledge, when a threat has or has not already occurred, the age of typical HVAC systems, and possible actions when residents are not home.
5. Most guidelines do not discuss when to return to a "regular" mode of building operation. For a long-duration threat such as a radiological situation, future guidelines must address this concern – both the risks of exposure, and the thermal comfort of occupants (i.e., heat stress) in buildings.
6. As mentioned earlier, some ASHRAE guidelines are targeted toward modern HVAC systems found in newer (commercial) buildings. Some states are promoting the use of "smart" residential systems and electric systems such as heat pumps, but their integration is slow. It may be beneficial to consider adoption rates of these new technologies to see if guidelines can accelerate technology adoption. For example, a follow-on study should consider the adoption projections for these new systems from the U.S. Department of Energy's Buildings Technology Office.
7. Guidance for single-family homes is sparse. We believe a scientific study on exposure to radiological particles should be conducted. This would entail developing a model of the change in leakage over the past decade; benefits of suggested hardening scenarios, including consequences due to improper hardening; and "smart" or local filtration systems.
8. Rapid adoption of portable air cleaners could be one of the most significant risk mitigators for exposure to radiological particles that were not included in past guidance documents. The addition

of these systems could be an important consideration/recommendation for residential buildings, especially older single-family homes with more leakage.

9. Filtration in many residential homes has improved with the use and familiarity of industry-adopted MERV-numbered filters. Future studies should consider the complementary benefits of their adoption.
10. The particle size distribution of radiological particles depends on the exposure scenario. For common scenarios, notional particle size distributions exist. Research may be needed to review existing threats and the likely particle size distributions emitted from them. Their transport and fate within and around residences may be different from what was considered in past studies. Size-dependent guidelines, for example from RDD and nuclear surface bursts, were not found in this review but should be considered in future guidance documents.
11. Greater comfort with personal masks is another significant risk mitigator for residences that ought to be discussed in updated guidance documents.

Conclusions

1. Recent ventilation research predominantly focuses on preventing the spread of infectious diseases, leaving a research gap in the area of protecting building occupants from exposures related to outdoor CBRN incidents.
2. The latest radiological/nuclear-related research in this area is a continuation of previous studies recommending improved filtration combined with strategies to reduce infiltration.
3. We found minimal new (since 2016) research on HVAC guidance for residential buildings, including very little on radioactive particle exposure mitigation, potential for chronic exposures due to the spread of contamination and resuspension, and any analyses based on the particle size of the material.
4. Guidance for commercial buildings has not been updated with current research, most of which focuses on infectious disease spread. No guidance addresses exposure, accumulation on filters, or prolonged exposures due to persistence due to tracking and resuspension. New guidance/informational documents could be tailored for different stakeholders: (a) broad guidelines for the general homeowner, and (b) size-dependent considerations for trained analysts.
5. New research does not incorporate latest HVAC technologies (e.g., personal air cleaners, smart building technologies) and is a missed opportunity for improvements in safe sheltering.
6. Many references, sources, and guidance are dated. Federal, state, and city protective action guidance is based on sources from the early 2000s. This includes the oft-recommended hardening or sealing guidance in which we could find research from the early 2000s (and none since 2016) where plastic sheeting and duct tape effectiveness were tested. Feasibility and effectiveness have not been reconsidered in the current literature.
7. Guidance does not take into account different particle sizes generated by each type of nuclear scenario. While SIP is effective for large particles, it is less effective for smaller respirable particles. Modern residential heating or HVAC systems with higher filtration efficiencies can improve the mitigation of airborne concentrations of smaller particles (< 1 μm).

8. Guidance does not take into account temporal considerations of different nuclear scenarios. For example, there would likely be no warning in the event of an RDD release, while a NPP may be able to warn the public to prepare for a release. Guidance should be tailored depending on if the public has time to prepare.
9. New building ventilation standards significantly increase outdoor air intake to mitigate indoor risks such as infectious diseases. These guidelines are a poor choice for protection from an outdoor hazardous release such as an RDD or an IND.
10. Residential building envelopes have become tighter in recent years, but not enough to rely on them for “safe sheltering.”

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Appendix A: Building Protection Illustrated

Buildings can protect their occupants from exposure to outdoor airborne hazards. The magnitude and duration of that protection depends upon a number of factors, such as the nature of the hazardous material release (e.g., gas vs. particle phase), the duration of the outdoor hazardous material plume at the exposure location, and the type of building and its ventilation system. In some cases, building protection can reduce inhalation exposures by an order of magnitude or more, while in other cases, the degree of protection may depend upon an expedient exit from the building after the outdoor hazardous plume has passed (note: this scenario is not analyzed in this Appendix). The purpose of this Appendix is to illustrate how several interrelated key factors affect building protection.

For our purpose, we define building protection as:

$$Protection\ Factor \equiv \frac{Indoor\ Exposure}{Outdoor\ Exposure} = \frac{\int C_{Indoor}(t)dt}{\int C_{Outdoor}(t)dt} \qquad 1$$

A simplified box model has been widely used to describe the behavior of airborne contaminant concentrations indoors (Dillon, Sextro, et al., 2022), especially for residential buildings, the focus of our simplified analysis here. Assuming that the indoor concentrations, while time-dependent, are spatially uniform, yields:

$$\frac{dC_{Indoor}}{dt} = \lambda_{inf} * P * C_{Outdoor}(t) - (\lambda_{out} + \lambda_{loss}) * C_{Indoor}(t) \qquad 2$$

Integrating the ratio in equation 1 and defining the integral outdoor exposure to be unity, produces the equation for building protection:

$$PF = \frac{\lambda_{inf} * P}{(\lambda_{out} + \lambda_{loss})} \qquad 3$$

Building protection, in its simplest form, is the ratio of the rate at which outdoor hazardous contaminants enter the building to the rate at which they are removed or transform to non-hazardous species (e.g., radioactive decay),

where

λ_{inf} is the rate at which contaminant-bearing outdoor air enters the building (1/h)

λ_{out} is the rate at which contaminant-bearing indoor air exits the building (1/h)

$P\ (d_p)$ is the penetration fraction, i.e., the particle-size dependent efficiency by which particles penetrate the building shell (dimensionless)

λ_{loss} is the removal rate due to deposition (particle-size dependent), $\lambda_{dep}(d_p)$

plus the loss rate due to filtration (particle-size dependent), $\lambda_{filt}(d_p)$

plus the loss rate due to radioactive decay, λ_{rad}, all in units of (1/h)

For a typical residential building with a forced-air heating/cooling system, infiltration is the primary source of air entering the building, balanced by exfiltration (neglecting duct leakage, operation of the forced-air system doesn't affect infiltration or exfiltration), so λ_{inf} equals λ_{out}. Filtration of airborne particles is provided by any filters installed as part of the forced-air system and, when present, operation of any stand-alone air cleaning system located in the living space. Neglecting the latter, the particle loss rate due to filtration is then

$$\lambda_{filt}(d_p), = F_{filter}(d_p)*F_{fan}*R_{fan} \qquad 4$$

Where

$F_{filter}(d_p)$ is the particle-size dependent filtration efficiency (dimensionless)

F_{fan} is the fraction of time the forced air furnace recirculation fan is on, i.e., the fan's duty cycle (dimensionless)

R_{fan} is the air recirculation rate through the building driven by the furnace fan (= the volumetric flow rate of the fan (m^3/h) divided by the building volume (m^3); Q_{fan}/V_{house})

Equation 3 then becomes

$$PF = \frac{(\lambda_{inf}*P(d_p))}{\lambda_{inf} + F_{filter}(d_p)*F_{fan}*R_{fan} + \lambda_{dep}(d_p) + \lambda_{rad}} \qquad 5$$

The key parameters for estimating the amount of airborne material entering a typical residential building from a passing contaminant plume are given in the numerator in equation 5, namely the infiltration rate and the penetration factor. The key parameters describing the removal of these airborne contaminants from indoor air are shown in the denominator, specifically the exfiltration rate (= infiltration rate for most residences), a filtration term – consisting of the filtration efficiency, the fan duty cycle and the fan flow rate and house volume – the deposition loss rate and, for radionuclides, the radioactive decay constant. In the examples discussed below, radioactive decay is not included. It is worth noting that the time constant for particle removal indoors is of order hours (e.g., the total "decay" constant is ~0.5 to 10/h, which is the equivalent half-life of a few minutes to ~1-2 hours. Radioactive decay of radionuclides with half-lives longer than this range won't be a significant removal mechanism in terms of reducing indoor inhalation exposures to airborne radionuclides.

We use equation 2 to predict the indoor concentration-time profile of airborne contaminants entering from outdoors. For the examples discussed here, we rely on parameter values developed by (Dillon, Sextro, et al., 2022) and shown in Table A-1. We use them for two residential scenarios – one with high air exchange rates

(AER) and poor particle filtration (a filter rating of MERV5), and one with a low AER value and improved filtration (MERV11). The indoor concentration profiles resulting from a passing plume are shown in Figure A-1a and the associated exposure profiles are shown in Figure A-1b. Note that MERV (Minimum Efficiency Rating Values) are a standard reference value used to report a filter's ability to capture particles between 0.3 and 10 microns. The higher the MERV rating, the better the filter is at trapping particles in this size range.

Table A-1. Summary of the input parameters used in the present analysis*

Infiltration (air exchange rate)					
	High AER	1.4 air changes/hour			
	Low AER	0.2 air changes/hour			
			particle size (µm)		
	0.1	0.3	1	3	10
penetration (-)	0.71	0.86	0.91	0.74	0.19
deposition (1/h)	1.02E-01	1.21E-01	2.74E-01	1.02E+00	8.08E+00
filtration loss rate = filter efficiency * duty cycle * air recirculation rate					
	duty cycle	0.25 (-)	recirc rate	5.7 (1/h)	
MERV5 (1/h)	1.43E-02	1.43E-02	1.43E-01	5.70E-01	6.41E-01
MERV11 (1/h)	5.70E-01	5.70E-01	1.08E+00	1.35E+00	1.40E+00

* Particle data taken from (Dillon, Sextro, et al., 2022).

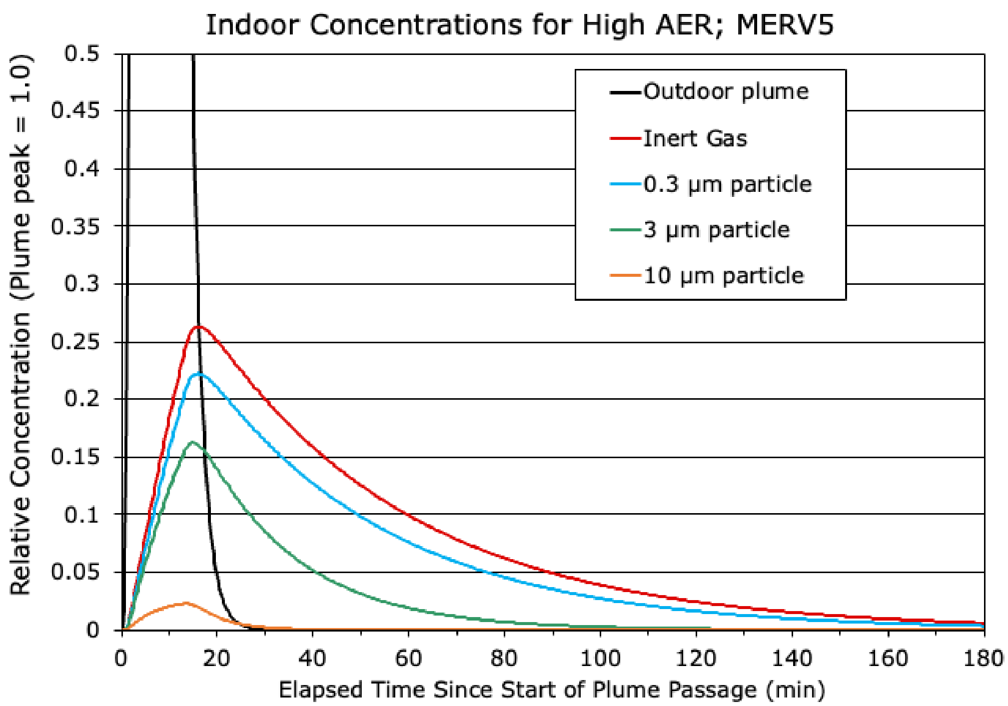


Figure A-1a. Indoor concentrations as a function of time resulting from a 30 min outdoor plume. The figure is truncated at a relative concentration of 0.5 to better highlight the indoor concentrations. Concentration profiles for an inert gas and for three different particle sizes are shown out to 3 h after the start of the plume passage.

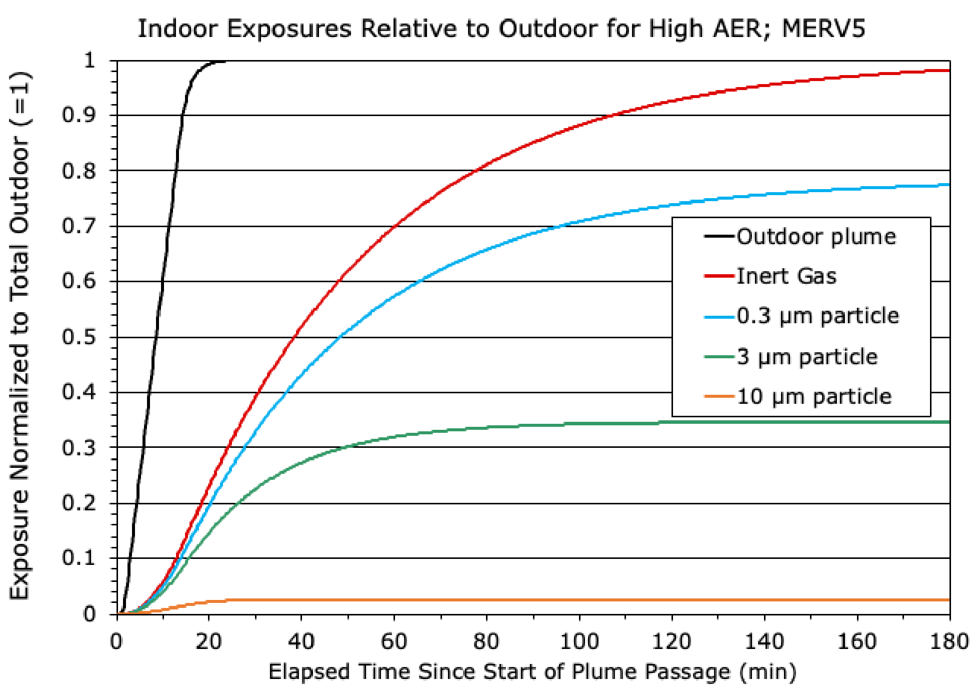


Figure A-1b. Exposures (= concentration x time) for the concentration profiles shown in Figure A-1a. Note that the exposure to the outdoor plume is normalized to 1.

As illustrated in Figure A-1a, buildings attenuate the ingress of contaminants from an outdoor plume, even for the case of an inert gas*, where only the ventilation rate controls the concentration profile (there are no deposition losses nor losses due to filtration). An interesting aspect of an inert gas is revealed in Figure A-1b, where the indoor exposure profile approaches that experienced outdoors. For this high AER case (infiltration rate = 1.4 1/h) the indoor/outdoor exposure ratio for the inert gas at 3 h is ~0.98. At an exposure time ~4 h, the indoor and outdoor exposures are essentially the same. For the low AER case (infiltration rate = 0.2 1/h), the indoor exposure at 3 h is ~44% of that outdoors and it takes ~25 h before the indoor/outdoor exposure ratio reaches 0.99.

The attenuation of particle concentrations indoors is greater due to the effects of lower penetration factor values (which decrease with increasing particle size) and higher removal rates by filtration and deposition. As can be seen, particle size is a key factor affecting airborne particle removal indoors. Submicron particles have low filtration efficiencies (even for moderately good filters) and smaller deposition rates, while larger particles – as shown by the results for the 3 µm particle size, and especially for 10 µm particles – have much higher removal rates (and thus lower exposures). These effects are displayed in Figure A-2, where the removal rates as a function of particle size are compared.

As also shown in Figure A-2, the total removal rate is somewhat lower for the low AER, MERV11 scenario due to the reduced exfiltration rate – which is partly compensated for by the increased filtration efficiency of the MERV11 filter. Deposition has a small removal effect for small particles (≤ 1 µm) but for particles larger than ~5 µm, it is the most significant removal mechanism.

* Kr-85 and Xe-133 – both of which are radioactive fission products – are examples of an inert gas.

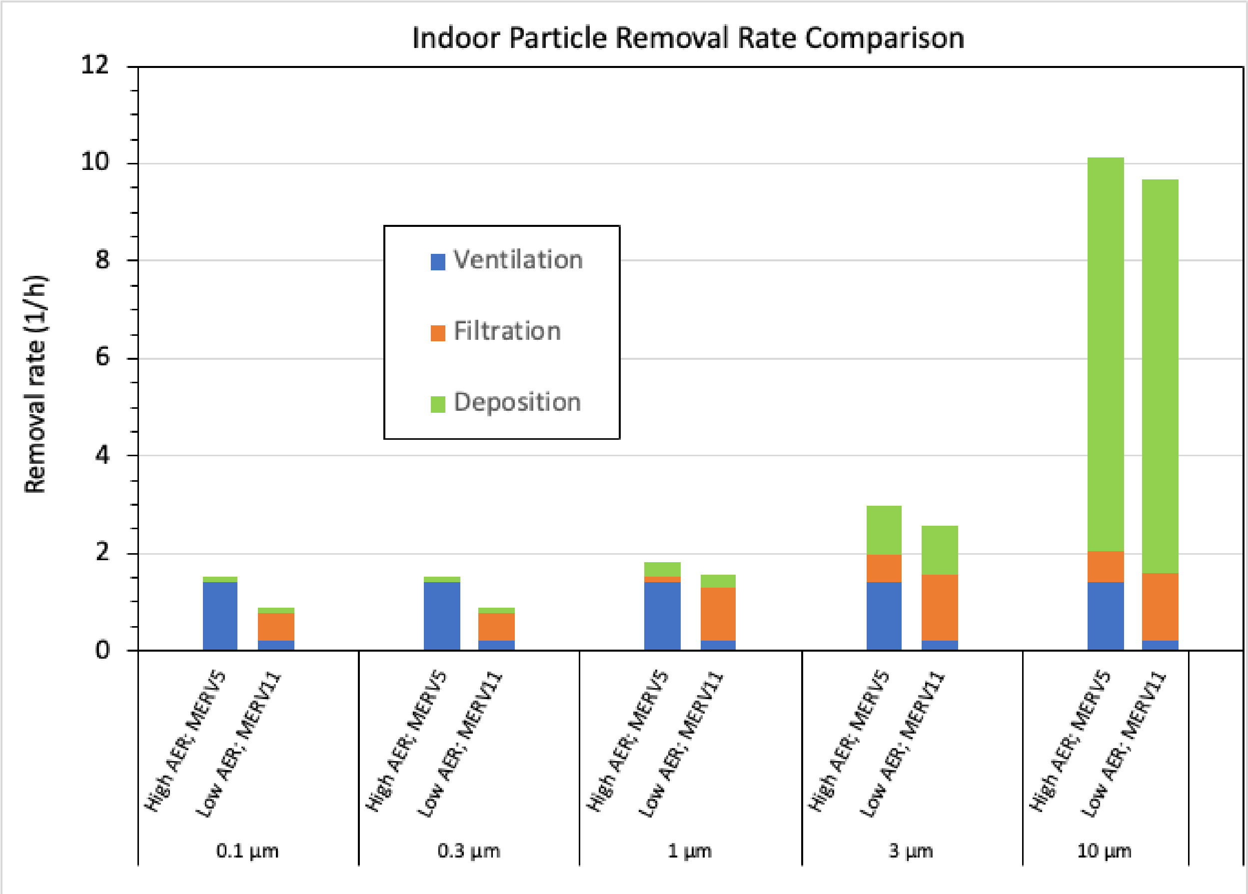


Figure A-2: The contributions of the three particle removal processes for the two illustrative scenarios as a function of particle size.

Appendix B: Websites and Resources for HVAC Guidance and Emergency Response

Federal Websites for Emergency Response

Center for Disease Control and Prevention (CDC):

1. Public action guidance for radiation emergencies, National Center for Environmental Health (2022): https://www.cdc.gov/nceh/radiation/emergencies/getinside.htm and also found here: https://www.cdc.gov/nceh/radiation/emergencies/index.htm?CDC_AA_refVal=https%3A%2F%2Femergency.cdc.gov%2Fradiation%2Findex.asp
    a. "If possible, turn off fans, air conditioners, and forced-air heating units that bring air in from the outside. Close fireplace dampers."
    b. Close and lock all windows and doors
    c. "get inside, stay inside, stay tuned"
    d. Infographic: Where to go
    e. Information is available on two different websites
2. Tips Before Entering a Shelter (2018): https://www.cdc.gov/nceh/radiation/emergencies/enteringshelter.htm
    a. Turn off fans, air conditioners, and forced-air heating units that bring air in from the outside. Close and lock all windows and doors, and close fireplace dampers.
    b. When you move to your shelter, use duct tape and plastic sheeting to seal any doors, windows, or vents for a short period of time in case a radiation plume is passing over (listen to your radio for instructions). Within a few hours, you should remove the plastic and duct tape and ventilate the room. Suffocation could occur if you keep the shelter tightly sealed for more than a few hours.
3. Radiation Emergencies website describes each type of release and includes an infographic for each (2018): https://www.cdc.gov/nceh/radiation/emergencies/moretypes.htm#power
    a. Nuclear explosion or improvised nuclear device
    b. Radiological dispersal device
    c. Nuclear power plant release
    d. The advice for each threat is the same: get inside, stay inside, stay tuned.
4. Frequently Asked Questions About a Nuclear Blast, National Center for Environmental Health (2018): https://www.cdc.gov/nceh/radiation/emergencies/nuclearfaq.htm
    a. "Shut off ventilation systems and seal doors or windows until the fallout cloud has passed. However, after the fallout cloud has passed, unseal the doors and windows to allow some air circulation."
5. Indoor Air Safety, National Center for Environmental Health (2018): https://www.cdc.gov/nceh/radiation/emergencies/airsafety.htm
    a. "Turn off fans, air conditioners, and forced-air heating units that bring air in from the outside, if possible. Close and lock all windows and doors. Close fireplace dampers."
    b. "By limiting the amount of outside air that gets into your place of shelter, you can reduce your exposure to radiation."
6. Stay Safe during a Wildfire (6/2023): https://www.cdc.gov/disasters/wildfires/duringfire.html
    a. Stay in a room you can close off from outside air
    b. Use a portable air cleaner, filter, or make your own DIY box fan unit.
    c. Wear a respirator or well-fitting mask.
    d. If you have a central air system, set it to recirculate mode and use a high efficiency filter.

7. Interactive School Ventilation Tool (May 27, 2022): https://www.cdc.gov/coronavirus/2019-ncov/community/schools-childcare/interactive-ventilation-tool.html
    a. This tool is designed for building managers or school administrators.
    b. How to use ventilation system to reduce concentration of viral particles
    c. Estimates the change in viral particle concentration by modifications to HVAC system
8. Interactive Home Ventilation Tool (April, 2023): https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/interactive-ventilation-tool.html
    a. This tool is designed for homeowners
    b. Designed for viral particles
    c. Estimates the change in viral particle concentration by modifications to HVAC system.
9. Stay Inside Video (2017): https://www.youtube.com/watch?v=ux8trcUoCC8
10. CDC Ventilation Guidelines to reduce COVID (May 2023):https://www.cdc.gov/coronavirus/2019-ncov/community/ventilation.html#:~:text=Aim%20for%205%20Air%20Changes,of%20germs%20in%20the%20air.

Central Intelligence Agency (CIA):
1. Chemical/Biological/Radiological Incident Handbook (10/1998): https://irp.fas.org/threat/cbw/CBR_hdbk.htm The target audience of this brief handbook is first responders. The guide describes in general terms all types of CBRN incidents and gives generalized guidance:
    a. *"If inside, and the incident is outside, stay inside. Turn off air conditioning, seal windows and doors with plastic tape."*

Department of Defense (DOD):
1. UFC 4-010-01 DoD Minimum Antiterrorism Standards For Buildings: United Facilities Criteria Program (2018): https://www.wbdg.org/ffc/dod
2. https://www.wbdg.org/FFC/DOD/UFC/ufc_4_010_01_2018_c2.pdf

Department of Homeland Security (DHS) and Ready.gov
1. Guidance for Radiation Emergencies (2023): https://www.ready.gov/radiation
    a. "If possible, turn off fans, air conditioners, and forced-air heating units that bring air in from the outside. Close windows and doors. Close fireplace dampers"
    b. "Some examples of radiation emergencies include: a nuclear detonation (explosion), an accident at a nuclear power plant, a transportation accident involving a shipment of radioactive materials, or an occupational exposure like in a healthcare or research setting. While the extent of the damage will vary, the steps to protect yourself from radiation are the same."
2. Guidance for Radiological Dispersal Device (2022): https://www.ready.gov/radiological-dispersion-device-old
3. Chemical or Hazardous Material Response (2023): https://www.ready.gov/hazmat
4. Wildfire Response (2022): https://www.ready.gov/wildfires
    a. Use high efficiency filters in your central air conditioning system to capture fine particles from smoke. If your system has fresh air intake, set the system to "recirculate" mode and close the outdoor intake damper.
    b. Wear an N95 mask
5. Sealing your Shelter (2019): https://www.ready.gov/faq/sealing-your-shelter-place-advance
    a. Shelter in place (2022): https://www.ready.gov/shelter
    b. Both websites give advice to seal windows and doors with plastic sheeting and tape

    c. "Sealing a room" is considered a temporary protective measure to create a barrier between you and potentially contaminated air outside. This type of sheltering in place requires pre-planning, by purchasing plastic sheeting and duct tape that you would keep in your emergency supply kit."
6. National Urban Security Technology Agency (NUSTL) has a collection of resources and fact sheets for nuclear/radiological response. "Radiological Dispersal Device (RDD) Response Guidance Planning for the First 100 Minutes" (2017): https://www.dhs.gov/publication/st-frg-rdd-response-guidance-planning-first-100-minutes

Department of Health and Human Services (HHS):

1. CBRN Response Guides (2022): https://asprtracie.hhs.gov/cbrn-resources
    a. Major Radiological or Nuclear Incidents: Potential Health and Medical Implications
    b. "Other aspects, such as turning away immediately from any large flash (to avoid the incoming blast wave) and shutting down building ventilation systems in debris / fallout areas may also be included in pre-event education."
    c. More resources emphasizing medical for radiation incidents: https://asprtracie.hhs.gov/technical-resources/32/radiological-and-nuclear/27
2. Radiation Emergency Medical Management website has a list of guidance docs are found here: https://remm.hhs.gov/keyguidancedocs.htm
    a. Quick Reference Guide: Radiation Risk (2016) – pdf
    b. A list of PAGS: https://remm.hhs.gov/pag.htm

Environmental Protection Agency (EPA):

1. Homeland Security and the Indoor Environment | US EPA
    a. Links to NIOSH, CDC and DHHS websites (redundant)
    b. These resources are each listed under their home org rather than in this EPA section
2. EPA Protective Action Guides for Radiological Incidents (2017): https://www.epa.gov/radiation/protective-action-guides-pags
    a. Incidents covered include: accidental release at a NPP, weapons facility or nuclear fuel manufacturing plant, transportation accident or terrorist act involving RDD.
    b. Target audience is public officials
    c. Guidance covers 3 phases of an incident and includes dosimetry guidelines
    d. Phase I guidance recommends SIP, evacuation and relocation.
3. Building Air Quality Guide (1991): no website, but this pdf is included in Resource folder.
    a. Guide is intended for building owners and facility managers
    b. Covers HVAC design, operation and mitigation of IAQ problems, including moisture, asbestos, radon and pollutants such as volatile compounds and carbon monoxide.
4. Radiation Emergencies and Preparedness (2019): https://www.epa.gov/radtown/radiation-emergencies-and-preparedness
    a. "Get inside, stay inside, stay tuned"
    b. Links to other sites
5. Wildfires and Indoor Air Quality (IAQ), Reduce your Smoke Exposure, (2023): https://www.epa.gov/indoor-air-quality-iaq/wildfires-and-indoor-air-quality-iaq
    a. Keep windows and doors closed,
    b. If you have an HVAC system with a fresh air intake, set the system to recirculate mode, or close the outdoor intake damper.
    c. Use a portable air cleaner or high-efficiency filter to remove fine particles from the air.
    d. If you have an evaporative cooler, avoid using it in smoky conditions because it can result in more smoke being brought inside

6. Protecting yourself from radiation (2023): https://www.epa.gov/radiation/protecting-yourself-radiation
    a. This website links to CDC guidance
    b. "Get inside, stay inside, stay tuned"
7. Federal Interagency Committee on Indoor Air Quality

Federal Register (FDA):

1. National Archives posted a FEMA document: Planning Guidance for Protection and Recovery Following RDD and IND Incidents (2008) https://www.federalregister.gov/documents/2008/08/01/E8-17645/planning-guidance-for-protection-and-recovery-following-radiological-dispersal-device-rdd-and

Food and Drug Administration (FDA):

1. Mostly focused on medical (pharmaceutical) interventions
2. Repeat CDC guidance to stay inside: https://www.fda.gov/emergency-preparedness-and-response/mcm-issues/radiological-and-nuclear-emergency-preparedness-information-fda

Federal Emergency Management Agency (FEMA):

1. Nuclear Shelter in Place Guidance (11/2021): https://www.fema.gov/emergency-managers/national-preparedness/plan/evacuation-shelter-in-place
    a. Nuclear SIP Guidance (4/2022): https://www.fema.gov/sites/default/files/documents/fema_shelter-in-place_guidance-nuclear.pdf Guidance is "Get In. Stay In. Tune In." Covers all types of residential, mobile and multi-story homes.
    b. Shelter in Place Pictogram Guidance (3/2022): This guidance covers chemical, active shooters, nuclear detonation and natural disasters. https://www.fema.gov/sites/default/files/documents/fema_shelter-in-place_guidance.pdf
    c. For chemical hazard, guidance is to SIP, seal doors and windows, turn off ventilation, use duct tape to seal windows.
    d. For nuclear detonations: SIP in basement "Get In. Stay In. Tune In." for 24 hours.
2. IS-156: Building Design for Homeland Security for Continuity of Operations: https://training.fema.gov/is/courseoverview.aspx?code=IS-156&lang=en
3. Resources and Training for Radiological Emergency Preparedness (2023): https://www.fema.gov/emergency-managers/practitioners/hazardous-response-capabilities/radiological
4. Reference Manual to Mitigate Potential Terrorist Attacks Against Buildings (2011): https://www.wbdg.org/FFC/DHS/bips_06.pdf
5. Primer for Design of Commercial Buildings to Mitigate Terrorist Attacks (2003): https://www.wbdg.org/FFC/DHS/fema427.pdf
6. PrepTalk by Brooke Buddemeier (2018): https://www.fema.gov/blog/preptalks-brooke-buddemeier-saving-lives-after-nuclear-detonation
    a. Discussion of modeling fall out after nuclear detonation
    b. Shelter-in place guidelines
    c. Response guides
7. More response guides downloaded to resource folder:
    a. Nuclear/Radiological Incident Annex (May 2023) – pdf
    b. Planning Guidance for Response to a Nuclear Detonation -3rd Edition (June 2023)
    c. Improvised Nuclear device Response and Recovery (2013) – pdf
    d. Nuclear Detonation Response Guide: Planning for the First 72 hours (March 2023)

Lawrence Berkeley National Lab (LBNL):

1. Chem-Bio Preparedness Website: https://indoor.lbl.gov/chem-bio-preparedness A research group that models how buildings can be operated to protect occupants from a chem/bio release.
2. LBNL Secure Buildings Tool: http://securebuildings.lbl.gov/
3. Smart Ventilation website: https://svach.lbl.gov/

Lawrence Livermore National Lab (LLNL):

1. National Atmospheric Release Advisory Center: https://narac.llnl.gov/ Provides expertise and tools to support emergency response in predicting and mapping the spread of hazardous atmospheric release.

National Institute of Environmental Health Sciences (NIEHS)

1. Disaster Preparedness & Responsehttps://tools.niehs.nih.gov/wetp/index.cfm?id=556 This site offers training, tools, and resources for workers. All types of natural disasters, spills and terrorist Attacks are included.
2. Radiological Dispersion Devices https://tools.niehs.nih.gov/wetp/index.cfm?id=936
3. This website includes Protecting Yourself During a Dirty Bomb Response (1/2008).
    a. This training tool is targeted for skilled support personnel
    b. Includes awareness in recognizing, identify RDD, radiation exposure, decontamination.
    c. No Info on SIP or building ventilation.

National Institute for Occupational Safety and Health (NIOSH):

1. Guidance for Protecting Building Environments from Airborne Chemical, Biological, or Radiological Attacks (2002): https://www.cdc.gov/niosh/docs/2002-139/default.html
    a. Guidance targets public and private buildings but not single family, low occupancy buildings and not high-risk industrial facilities.
    b. Chemical, biological and radiological threats are covered; however, advice is not specific to the type of threat.
    c. Ventilation advice includes evaluating control options such as on/off or zones, upgrading filtration while mentioning that gas-phase threats would not be removed with the average particulate filter system, infiltration and building tightness (reducing leakage).
2. NIOSH Emergency Preparedness and Response Program (2019): https://www.cdc.gov/niosh/docs/2019-149/
    a. This guidance is designed to protect emergency response and recovery personnel.
    b. The program offers guidance for natural disasters as well as CBRN
    c. Could not find any info regarding building ventilation rates
3. NIOSH Guidance for Filtration and Air Cleaning Systems to Protect Building Environments for Airborne Chemical, Biological, or Radiological Attacks (2003): https://www.cdc.gov/niosh/docs/2003-136/
    a. This detailed guidance document provides technical information focusing on installation, maintenance and use of HVAC air filtration systems and air cleaning systems.
    b. Guidance is specific to prepare for CBRN incident.
    c. The intended audience is technical staff of commercial buildings such as offices, schools, retail and public venues.

National Institute of Standards and Technology (NIST):

1. Indoor Air Quality and Ventilation Group | NIST The home of CONTAM and other NIST-developed IAQ and Ventilation modeling tools and information.
    a. No HVAC guidance for first responders or building managers
    b. CONTAM is multi-zone airflow model for advanced users

2. Scientific Research in Support of Homeland Security (2005): https://www.nist.gov/speech-testimony/scientific-research-support-homeland-security
    a. This website is a description of NISTs research efforts in support of homeland security.
3. Building Retrofits for Increased Protection against Airborne Chemical and Biological Releases (2007) NISTI 7379. https://www.nist.gov/publications/building-retrofits-increased-protection-against-airborne-chemical-and-biological
    a. A guide for building owners and managers to describe technologies to protect a building from CBRN incident
    b. Retrofits include tightening the building envelope, particle filtration, air cleaning, building pressurization, and location of air intakes, SIP and isolation of vulnerable spaces.
4. Quick Indoor CO2 (QICO2) Tool (7/2022): https://www.nist.gov/services-resources/software/quick-indoor-co2-qico2-tool
    a. This tool calculates CO_2 concentration in a building and is useful for estimating ventilation rates.
5. Virus Particle Exposure in Residences Tool (11/2022): https://www.nist.gov/services-resources/software/viper-virus-particle-exposure-residences
    a. Designed for home owner to estimate viral particle exposures in home
    b. This is a single zone air quality and ventilation tool
    c. Could help reduce exposure to a 1 µm sized virus particle from contagious occupant in a home.

Nuclear Regulatory Commission (NRC):

1. Guidance on what to do in a Nuclear Emergency (2020): https://www.nrc.gov/about-nrc/emerg-preparedness/in-radiological-emerg.html
    a. Describes power plant release as well as RDD
    b. Advice is to SIP with doors and windows sealed.
2. Definition of Dirty Bombs, including protective actions (2022): https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/fs-dirty-bombs.html
3. Webpage refers you to EPA PAGs.

Occupational Safety and Health (OSHA):

1. Radiation Emergency Preparedness and Response (no date): https://www.osha.gov/emergency-preparedness/radiation
2. Webpage containing many government resources plus links for every state (no date): https://www.osha.gov/emergency-preparedness/radiation/resources
3. Guidance and protective actions found here: https://www.osha.gov/emergency-preparedness/radiation/general-businesses
4. Bioterrorism: https://www.osha.gov/bioterrorism
5. There are webpages for wildfires and chemical threats as well

Readiness and Emergency Management for Schools (REMMS):

1. Guidance on improving building ventilation due to COVID: https://www.ed.gov/improving-ventilation-schools-colleges-and-universities-prevent-covid-19
    a. This guide offers strategies to improve ventilation in educational buildings with the aim of reducing the spread of COVID.
    b. Information is for building managers
    c. Cite guidelines from CDC and EPA including: maximizing outdoor intake, open windows, turn on fans, increase filtration to MERV13, and use CO_2 monitors to monitor ventilation rates.
2. Readiness and Emergency Management for schools (April 14, 2023): https://rems.ed.gov/K12NIMSImplementation

3. Shelter in place (Feb 16, 2023) : https://rems.ed.gov/Resources/Specific?Topic=ShelterinPlace
    a. This website offers guidance for natural disasters, COVID and SIP
    b. Guidance is generalized for any disaster and is targeted to educators
    c. No information on building ventilation during CBRN incident

NGOs Websites for Emergency Response

Air Infiltration and Ventilation Center (AIVC):

1. This organization is the International Energy Agency's center on energy efficient ventilation. https://www.aivc.org/
2. Their FAQ and Guideline website provides many useful definitions on building ventilation, but does not address emergency response of protective actions during a release. https://www.aivc.org/resources/faqs

American Institute of Architects (AIA):

1. *Building Security Through Design: A Primer for Architects, Design Professionals, and their Clients*, The American Institute of Architects, Washington DC, 2001
    a. Guidelines are for architects and design professionals
    b. An introduction to building security design

American Red Cross (FDA):

1. Nuclear Explosion and Radiation Emergencies https://www.redcross.org/get-help/how-to-prepare-for-emergencies/types-of-emergencies/nuclear-explosion-radiation-emergencies.html
    a. Protective actions are summarized from CDC and FEMA websites
    b. Focuses on nuclear detonation

American Society for Heating Refrigerating and Air-Conditioning Engineers (ASHRAE):

1. Society specializes in the science of building ventilation systems and publishes standards on building operation and ventilation https://www.ashrae.org/.
2. ASHRAE – Designing, Operating Safe HVAC Systems for Hazardous Spaces (Note: fee for book) https://www.ashrae.org/news/ashraejournal/designing-operating-safe-hvac-systems-for-hazardous-spaces
3. *ASHRAE Standard 241, Control of Infectious Aerosols (7/2023)*, establishes minimum requirements aimed at reducing the risk of disease transmission through exposure to infectious aerosols in new buildings, existing buildings, and major renovations. https://www.ashrae.org/technical-resources/bookstore/ashrae-standard-241-control-of-infectious-aerosols
    - Recommends higher outdoor airflow rates and increased filtration
4. *Building Ventilation and Pressurization as a Security Tool*, Andy Persily, ASHRAE Journal, September 2004.
5. ASHRAE Commercial: https://www.ashrae.org/technical-resources/commercial
6. ASHRAE Position Document on Filtration and Air Cleaning (2021)
7. Guidance for Building Operations During the COVID-19 Pandemic, by L. Schoen (May 2022). https://www.ashrae.org/news/ashraejournal/guidance-for-building-operations-during-the-covid-19-pandemic
8. Guidance for COVID-19 Risk Reduction in Residential Buildings (June 2021). Advocates for the use of personal air cleaners and enhanced building filtration with MERV 13 combined with increased intake of outside air. https://www.ashrae.org/file%20library/technical%20resources/covid-19/guidance-for-residential-buildings.pdf

9. Ventilation for Industrial Settings During the COVID-19 Pandemic (June 2021). https://www.ashrae.org/file%20library/technical%20resources/covid-19/ashrae-acgih-covid-19-white-paper.pdf

Conference of Radiation Control Program Directors (CRCPD):

1. Organization dedicated to radiation protection: https://www.crcpd.org/
2. Provides emergency responder guides in response to an RDD, including the first 12 hours. https://www.crcpd.org/mpage/RDD (last update 2006)
3. Guidance on a nuclear disaster is a website with links to other federal agencies and NGOs. No specific HVAC system guidance was available.

John Hopkins Center for Health Security (CHS):

1. Protecting Building Occupants from Exposure to Biological Threats (2008): https://centerforhealthsecurity.org/our-work/research-projects/completed-projects/protecting-building-occupants
    a. Addresses both naturally occurring biological threats as well as a terrorist attack
    b. Target audience is building owners
    c. HVAC Guidance includes enhancing filtration efficiency, reducing infiltration and increasing building pressurization
2. Rad Resilient City Preparedness Checklist Actions (2011): https://centerforhealthsecurity.org/our-work/research-projects/completed-projects/rad-resilient-city-initiative
    a. Guidelines address protective actions after a nuclear detonation
    b. Target audience are city leaders
    c. Advice focuses a preparedness checklist for SIP actions during fallout

International Atomic Energy Agency (IAEA):

1. Emergency preparedness and response https://www.iaea.org/topics/emergency-preparedness-and-response-epr Offers links to training materials, courses and technical guidance in emergency preparedness to member states. The organization provides: *"a range of technical guidance documents and tools, provide requirements, recommendations, guidelines and good practices for building a sound level of emergency preparedness and effective emergency response."*
    a. Emergency Preparedness and Response Information Management System (2021) https://www.iaea.org/publications/13462/emergency-preparedness-and-response-information-management-system-eprims
    b. Considerations in the Development of a Protection Strategy for a Nuclear or Radiological Emergency (2020): https://www.iaea.org/publications/14801/considerations-in-the-development-of-a-protection-strategy-for-a-nuclear-or-radiological-emergency
    c. There was no information on building ventilation, rather this site focuses on how to create emergency guidelines
    d. Action plan on Nuclear Safety https://www.iaea.org/topics/nuclear-safety-action-plan focuses on nuclear power plant safety

International Commission on Radiological Protection (ICRP):

1. Advice for the Public on Protection in Case of a Nuclear Detonation (no date): https://www.icrp.org/page.asp?id=611
    a. Protective actions in response to a nuclear detonation
    b. "go inside and stay inside"
    c. Guidelines are indicated for each time interval on the incident

    d. Uses CDC pictogram
    e. No info on HVAC systems

International Facility Management Association (IFMA):

1. https://www.ifma.org/ Offers training, resources and webinars for facility managers
2. Could not find any relevant information

National Academies of Sciences, Engineering and Medicine (NASEM):

1. Federal Facilities Council:https://www.nationalacademies.org/our-work/federal-facilities-council#sectionProjectScope
2. *Protection of Federal Office Buildings Against Terrorism*, Committee on the Protection of Federal Facilities Against Terrorism, Building Research Board, National Research Council, Washington DC, National Academy Press, 1988.
3. *Uses of Risk Analysis to Achieve a Balanced Safety in Building Design and Operations*, by Bruce D. McDowell and Andrew C. Lemer, Editors; Committee on Risk Appraisal in the Development of Facilities Design Criteria, National Research Council, Washington DC, National Academy Press, 1991.
    1. Risk analysis of building technology and design to enhance safety and protect property.
4. *Protecting Building Occupants and Operations from Biological and Chemical Airborne Threats*, National Research Council (2007). This report address building design, including ventilation systems, to protect occupants.

National Alliance for Radiation Readiness (NARR):

1. Tools are resources for emergency management officials https://www.radiationready.org/
2. Links to FEMA and CDC PAGs
3. No specific guidance for HVAC System operation

The National Council on Radiation Protection and Measurements (NCRP):

1. Radiation protection guides focusing on healthcare workers and research personnel. https://ncrponline.org/
2. *Responding to a Radiological or Nuclear Terrorism Incident: A Guide for Decision Makers*, Report No. 165 (2010) https://ncrponline.org/shop/reports/report-no-165-responding-to-a-radiological-or-nuclear-terrorism-incident-a-guide-for-decision-makers/ Provides a summary of recommendations for emergency planners.

National Institute of Building Science (NIBS):

1. Whole Building Design Guide (2017): Includes the paper "Chemical/Biological/Radiation (CBR) Safety of the Building Envelope https://www.wbdg.org/resources/chemicalbiologicalradiation-cbr-safety-building-envelope
    a. Design guides for the construction of safe and secure buildings
    b. Guide is for owners, architects and project managers
    c. Focuses on air flow patterns to limit airborne contamination for CRRN release
    d. Tighten building envelope and provide better filtration.
    e. Physical security of HVAC system components
2. PBS P100 Facilities Standards For The Public Buildings Service: https://www.wbdg.org/FFC/GSA/P100_2021.pdf
3. UFC 4-010-01 DoD Minimum Antiterrorism Standards For Buildings: United Facilities Criteria Program (2018): https://www.wbdg.org/ffc/dod

a. The purpose of this standard is to establish minimum engineering standards that incorporate antiterrorism (AT) based mitigating measures where no identified threat or level of protection has been determined
b. The intent of these standards is to reduce collateral damage and the scope and severity of mass casualties in the event of a terrorist attack.
c. https://www.wbdg.org/FFC/DOD/UFC/ufc_4_010_01_2018_c2.pdf

The US National Response Team (NRT):

1. Quick Reference guides in response to an RDD (2013) Resources – NRT This guide is intended to protect first responders with information on radiation exposure and dosage.

Pacific Gas and Electric (PGE):

1. Emergency Preparedness resources in response to nuclear power plant release specifically at Diablo Canyon Power Plant https://www.pge.com/en_US/safety/emergency-preparedness/nuclear-emergency/nuclear-emergency.page
2. Shelter in place guidance

Society of American Military Engineers (SAME):

1. https://www.same.org/ No guidelines and/or protective action guides are available.

State Websites for Emergency Response

Alabama:

1. Emergency Response Website refers the public to Ready.gov https://ema.alabama.gov/preparedness/

California:

1. Mostly focused on nuclear power plants. Protective action is to SIP. https://www.caloes.ca.gov/office-of-the-director/operations/planning-preparedness-prevention/planning-preparedness/nuclear-power-preparedness/
2. The Department of Public Health has website guidance in the event of a nuclear detonation: https://www.cdph.ca.gov/Programs/EPO/Pages/BI_Radiation-Emergencies_Nuclear-Blast.aspx The advice is to close all windows and doors and shelter in place.

Connecticut:

1. The Department of Public Health website has guidance in response to a nuclear or radiological event: https://portal.ct.gov/DPH/Public-Health-Preparedness/Main-Page/Nuclear-and-Radiological-Emergencies
2. Shelter in place guidance includes detailed instructions for sealing window and doors.
3. References Ready.gov website for nuclear power plants.

Minnesota:

1. Get inside, stay inside, stay tuned. https://www.health.state.mn.us/communities/ep/ltc/annexo.html

New York City:

1. Emergency response for nuclear incident (RDD) refers public to CDC https://www.nyc.gov/site/doh/health/emergency-preparedness/emergencies-radiological-nuclear-incident.page
2. Response for CBRN threat advice is to "Get inside, stay inside, stay tuned" https://www.nyc.gov/site/em/ready/hazardous-materials-chemical-spills-radiation.page

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Literature Review: Use of Heating, Ventilation, and Air Conditioning Systems for Controlling Airborne Contaminants

Date Published: May 2024

Office of Nuclear Regulatory Research

TABLE OF CONTENTS

INTRODUCTION

Emergency preparedness and response are key components of the U.S. Nuclear Regulatory Commission's (NRC's) public health and safety mission. Emergency preparedness ensures that adequate protective measures will be taken to protect public health and safety if an accident occurs. Protective actions are used to avoid or reduce radiation dose to the public. If an incident happens at a nuclear power plant that could result in an offsite radiological release exceeding the U.S. Environmental Protection Agency's (EPA's) protective action guides (PAGs), responsible plant personnel evaluate the situation and make timely protective action recommendations (PARs) to State and local government agencies. The responsible State or local officials then make protective action decisions and promptly relay those decisions to the public.

The NRC monitors a plant's PAR process to verify that plant personnel take or recommend appropriate actions. State and local agencies may independently assess the situation to make sure the appropriate protective action decisions are made. Finally, independent dose assessments performed during an accidental radiological release from a nuclear power plant help ensure that the optimal actions are taken.

A range of protective actions are available to reduce offsite radiation exposures during an accident, including evacuation, sheltering, and, as a supplement to these, the prophylactic use of potassium iodide when appropriate. The EPA's PAGs are in place to help authorities decide which actions to take at different times and for different areas. However, nuclear power plant accidents could be rapidly evolving events in which key information about the nature of the accident may not be available or reliable; this complicates the process of deciding on protective actions. While evacuation may be the fastest way to protect people near a nuclear power plant from an oncoming plume of radioactive material, it is often not the optimal choice for large areas, especially if the accident is expected to evolve slowly, allowing time for onsite mitigation. In addition, evacuation has inherent risks and can be resource intensive for local officials.

Sheltering, also referred to as sheltering-in-place (SIP), is an alternative protective action that has many benefits relative to evacuation. Sheltering is often more practical than evacuation for large or heavily populated areas. Sheltering is also beneficial when environmental, physical, or weather hazards impede evacuation, and it may be preferable for special populations who are not readily mobile. Sheltering uses a structure and its indoor air to temporarily separate people from a hazardous outdoor environment. The amount of protection afforded by sheltering varies with the type of building, the location of people within the building, the airtightness of the building, and the length of time the building is exposed to the outdoor contaminants.

The EPA's most recent PAG Manual (2017) provides guidance for evacuation and sheltering. At a high level, it states, "Sheltering-in-place should be preferred to evacuation whenever it provides equal or greater protection. Sheltering-in-place followed by informed evacuation may be most protective." It also outlines additional considerations to optimize the benefits of sheltering. For example, it states, "After confirmation that the plume has passed, continued sheltering-in-place should be re-evaluated…. Shelters may be opened to vent any airborne radioactivity trapped inside.” The previous EPA PAG Manual, issued May 1992, has more detailed guidance for sheltering. It states that for radiation releases in which inhalation is the primary exposure pathway, ventilation control is essential for effective sheltering. It also states, “Sheltering means staying inside a structure with doors and windows closed and, generally, with exterior ventilation systems shut off.”

Historically, sheltering has been implemented by securing a building’s heating, ventilation, and air conditioning (HVAC) systems and interior exhaust fans to maximize radiological protection during the passage of a radioactive plume. For illustration, the table below provides HVAC guidance from the emergency information brochure and calendar for several nuclear power plants. However, recent studies on the shelter efficiency of mechanically ventilated buildings indicate that the question of whether to secure HVAC may be more nuanced than previously thought; in particular, in some situations, securing HVAC may be actually increase, rather than decrease, the indoor concentrations of some contaminants. In addition, securing HVAC systems for prolonged periods of time could expose sheltering individuals to other risks, such as heat exhaustion. This body of research suggests that more detailed and nuanced guidance is needed on the use of HVAC systems during sheltering in a radiological emergency.

Plant Name	State	Sheltering Guidance Related to HVAC
Limerick Generating Station	Pennsylvania	Go indoors and stay there. Close all doors and windows and shut off any systems that draw in outside air, such as furnaces, fireplaces, and air conditioners. (link)
Oconee Nuclear Station	South Carolina	Go indoors and close all windows and doors. Turn off fans, heating and air conditioning that draw in outside air. Close all air intakes. Place your home or car system in internal recirculation if possible. (link)
Palo Verde Nuclear Generating Station	Arizona	If you are outside, go inside a building and close all doors and windows to protect yourself from outside air. Turn off heating, cooling, or ventilation systems that draw air from outside (recirculating air systems can be used). (link)
Sequoyah Nuclear Plant	Tennessee	Go indoors and stay there until further notice. Close all doors and windows. Shut off all systems that draw outside air into the house, such as furnaces, air conditioners, fireplace vents, and dampers. (link)
South Texas Nuclear Generating Station	Texas	Stay indoors, either inside your home or in a nearby building. Close all windows, doors, and fireplace dampers. Turn off any heating or cooling system that draws in air from the outside. Use portable fans or ceiling fans to circulate the air inside. (link)

Plant Name	State	Sheltering Guidance Related to HVAC
Vogtle Electric Generating Plant	Georgia	Stay indoors until further notice. Close all doors and windows. Turn off fans, heaters and air conditioners that use outside air. Use your heating or cooling system only to protect life or health. (link)

It is unclear whether and to what extent the available body of research on the use of HVAC systems to control airborne contaminants can inform guidance for use during radiological emergencies. Accordingly, the primary goal of this study was to investigate the available literature on HVAC effectiveness for reducing indoor air concentrations of an outdoor contaminant. We do not consider the secondary effects of the decision to use HVAC (e.g., detrimental changes to indoor air quality), nor do we investigate the contribution of indoor air pollutants due to the interior structure of the building or activities inside the building. We also disregard other factors, such as the costs and benefits of installing and operating HVAC systems for buildings. This work was completed to fulfill the research assistance request “Effectiveness of Application of HVAC Systems while Sheltering-in-Place” (Agencywide Documents Access and Management System Accession No. ML21239A428).

METHODOLOGY

This study began with a literature search to collect relevant information on the use of HVAC systems to reduce indoor air concentrations of an outdoor contaminant. The search was performed using a series of search strings on a database of publicly available, peer-reviewed literature, followed by a thorough review of citations from relevant papers, as well as studies they reference and studies that cite them. The search strings included both broad strings, such as [“ventilation” + “shelter” + “filter”], and more specific strings related to certain emergency events, health outcomes, or populations, in categories such as the following:

- emergency event types (e.g., “nuclear accidents”)
- specific emergency remediation strategies (e.g., “sheltering”)
- indoor air cleaning techniques (e.g., “filtration”)
- health outcomes (e.g., “ventilation effect on humans”)

Upon first pass, it was found that many of the papers identified as meeting the search parameters were focused on the protection provided by being inside a shelter but did not consider the use of HVAC. These papers were considered out of scope and were removed, leaving 11 papers on the topic of HVAC use while sheltering. Section 3 discusses each of the latter papers and provides relevant figures for illustration. The papers include both experimental studies and studies primarily based on modeling or theoretical results. They investigate a variety of shelter settings, including residential buildings, commercial/office buildings, and laboratory setups. They also address a range of HVAC considerations; some studies compare a set of buildings with HVAC installed to a separate set of buildings with natural ventilation, while others compare the same setting with and without mechanical ventilation. In addition, varying particle sizes are investigated. Studies on particles in the 0.1–10 micron (μm) range are considered most relevant, because that is the generally expected size of respirable particles of radioactive materials of concern that could be released off site from a nuclear power plant accident (DOE, 1994).

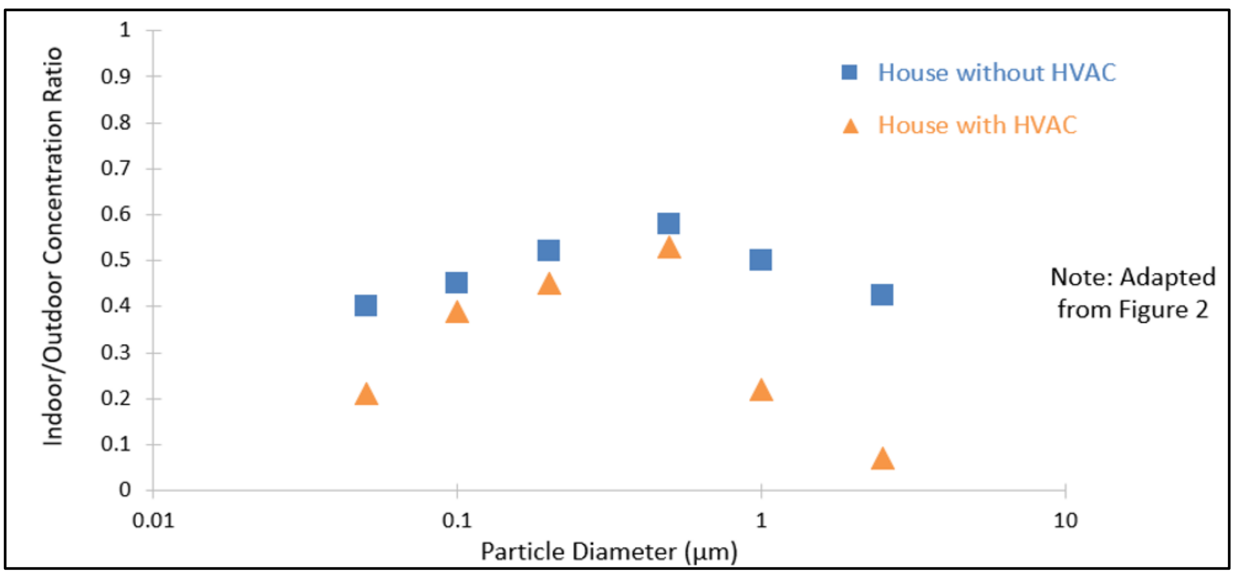
The appendix to this report provides a more exhaustive analysis of the relevant literature, including a large number of references with some relevance to HVAC use while sheltering. The purpose of the appendix is to provide additional information for interested readers, to add context to the evaluation performed in this report, and to explain the reasons for the selection of the most relevant references.

RELEVANT LITERATURE

This section discusses the relevant literature, providing bibliographical information and an overview of the research focus and relevant findings of each paper. Pertinent figures are also included. The studies are listed in chronological order. The appendix to this report contains additional analyses.

Thornburg et al. (2001)

Lead Author: Thornburg
Title: Penetration of Particles into Buildings and Associated Physical Factors. Part I: Model Development and Computer Simulations
Link: https://www.tandfonline.com/doi/abs/10.1080/02786820119886
Year: 2001
Journal: *Aerosol Science and Technology*, 34, 284–296
Research Type: Modeling
Setting: Residential and commercial buildings
Research Focus: Researchers calculated indoor/outdoor (I/O) concentration ratio for 0.05–2.5 μm simulated particles (to represent fine particulate matter (PM2.5)) for buildings with and without HVAC running.
Particle Size: 0.05–2.5 μm
Temporal Release Characteristics: “Relatively short-term simulation(s)” corresponding to activities such as cooking, smoking, and vacuuming
Implications for Sheltering: For a house with HVAC running, I/O is lower for simulated particles of size 1 μm and 2.5 μm. There were no calculations in which HVAC use was detrimental.
Illustrative Figure(s):



Simulated I/O concentration ratios for different particle sizes, with and without HVAC use (adapted from figure 2)

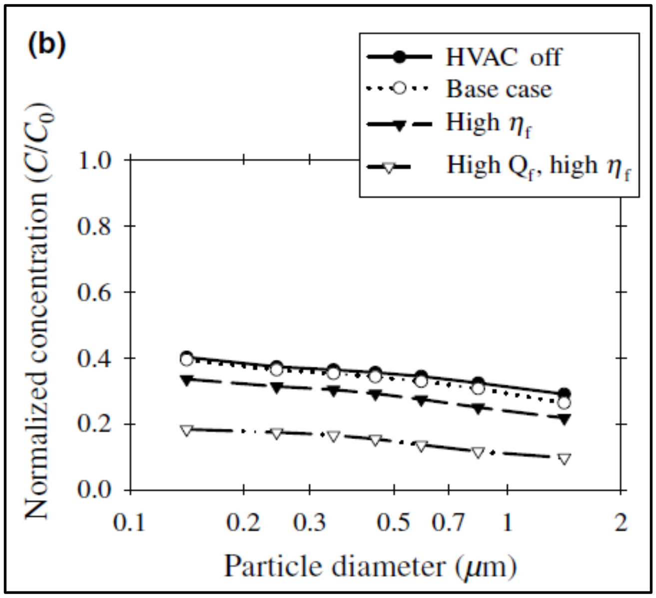
Bouilly et al. (2005)

Lead Author: Bouilly
Title: Effect of ventilation strategies on particle decay rates indoors: An experimental and modelling study
Link: https://www.sciencedirect.com/science/article/abs/pii/S135223100500422X
Year: 2005
Journal: *Atmospheric Environment*, 39, 4885–4892
Research Type: Experimental
Setting: Cubic test room with 2.5 meter sides
Research Focus: Researchers measured particle concentration evolution in a mechanically ventilated room to investigate the effects of ventilation strategies and the effects of air exchange rate on the size-resolved particle deposition rate.
Particle Size: 0.3–15 μm
Temporal Release Characteristics: 2 hours
Implications for Sheltering: This study highlights the importance of the physical location of the mechanical ventilation airflow path (inlet and outlet locations) for particles of diameter less than 5 μm. Indoor particle deposition is significantly increased when the airflow configuration is changed from a straight-line "top-to-top" configuration to a diagonal "top-to-bottom" configuration. This suggests that the physical configuration of a building's HVAC system could result in more or less deposition of radioactive particles indoors.

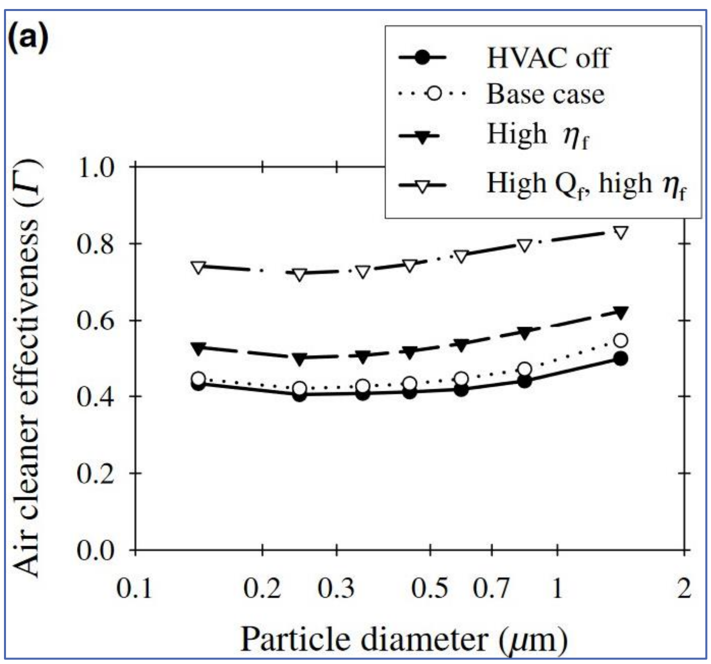
Ward et al. (2005)

Lead Author: Ward
Title: The effectiveness of stand alone air cleaners for shelter-in-place
Link: https://pubmed.ncbi.nlm.nih.gov/15737155/
Year: 2005
Journal: *Indoor Air*, 15, 127–134
Research Type: Modeling
Setting: Residential buildings
Research Focus: Researchers calculated I/O ratio as a function of particle size for zero to three portable high-efficiency particle arresting (HEPA) air cleaners with and without HVAC. Modeled particles of diameter 0.1–2 μm to represent a biological warfare agent.
Particle Size: 0.1–2 μm
Temporal Release Characteristics: Unspecified
Implications for Sheltering: This study shows that HVAC use can be beneficial in reducing the I/O ratio for the particle size range 0.1–1.5 μm, particularly with a higher flow rate and higher filter efficiency. It also shows that with a lower filter efficiency, HVAC use provides essentially no benefit in reducing indoor contaminant concentration.

Illustrative Figure(s):



I/O concentration ratio for different HVAC flow rates (Q_f) and HVAC filter efficiencies (η_f) (figure 4b); HVAC filter efficiencies increase from 0.28 to 0.65 for particle sizes of 0.1–0.2 µm to 1–2 µm



Air cleaner effectiveness for various HVAC filter efficiency scenarios; air cleaner effectiveness is lower in scenarios with high volumetric flow rate through the HVAC system and larger particle sizes (a lower gamma value represents greater effectiveness)

Persily et al. (2007)

Lead Author: Persily
Title: Building Retrofits for Increased Protection Against Airborne Chemical and Biological Releases
Link:
https://www.nist.gov/publications/building-retrofits-increased-protection-against-airborne-chemical-and-biological
Year: 2007
Journal: NIST Interagency/Internal Report (NISTIR)-7379
Research Type: Modeling
Setting: Various
Research Focus: The report evaluates various potential building retrofits to assess benefits and economics for protecting against chemical and biological releases.
Particle Size: 1–10 µm
Temporal Release Characteristics: 60-second particulate releases
Implications for Sheltering: The report finds that SIP with ventilation systems off is generally effective in reducing exposure, but far more so when a standalone recirculating filtration/air cleaning system is employed in the shelter (the study considers MERV 15 particle filters with an efficiency of 99.75 percent for 1 µm particles). Shutting down external air intake and ventilation systems early on (6 seconds and 30 seconds) during a release reduces initial contaminant concentrations but leads to higher concentrations later on during the shutdown (2 hours). Shutdowns of 1 minute and 5 minutes result in significantly higher concentrations than the baseline case. The report suggests that "unless a shutdown can be implemented very early in response to outdoor release, it may be better to leave the system running." Additionally, "purging" contaminated air (e.g., by maximizing outdoor air intake once release has ceased) seems effective in reducing exposure.

Jamriska et al. (2008)

Lead Author: Jamriska
Title: Effect of Ventilation and Filtration on Submicrometer Particles in an Indoor Environment
Link: https://onlinelibrary.wiley.com/doi/abs/10.1034/j.1600-0668.2000.010001019.x
Year: 2008
Journal: *Indoor Air*, 10, 19–26
Research Type: Experimental
Setting: Office building in Brisbane, Australia
Research Focus: Researchers measured indoor particle concentrations at various locations, sampling either unfiltered air, filtered air, or air that was filtered and cooled by air conditioning. The contaminant source was vehicle combustion aerosols from outside.
Particle Size: largely submicron, consistent with vehicle combustion aerosols
Temporal Release Characteristics: Unspecified
Implications for Sheltering: The study found that the HVAC system reduced particle concentrations by 34 percent. However, the study's documentation is limited, and it

does not explain the experimental setup and process in sufficient detail to allow for confident conclusions about an emergency sheltering situation with doors and windows closed.

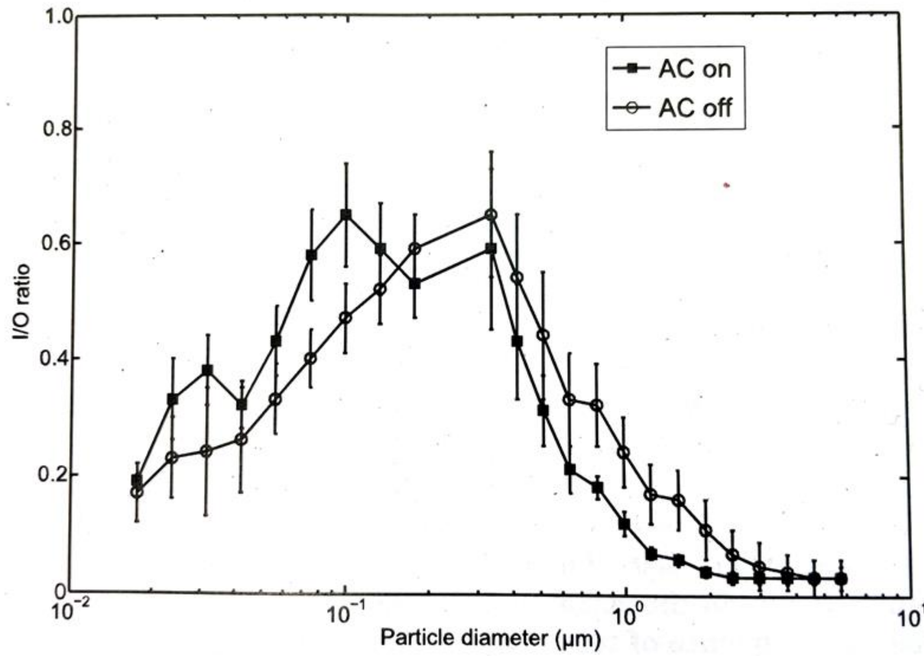
Park et al. (2014)

Lead Author: Park
Title: Effects of types of ventilation system on indoor particle concentrations in residential buildings
Link: https://onlinelibrary.wiley.com/doi/10.1111/ina.12117
Year: 2014
Journal: *Indoor Air*, 24, 629–638
Research Type: Experiment
Setting: Single-family apartments in urban and suburban Seoul, South Korea
Research Focus: Measurements were taken to quantify the influence of different ventilation systems on indoor particle concentrations in residential buildings. The ventilation systems included unbalanced mechanical ventilation, balanced mechanical ventilation, and natural ventilation.
Particle Size: 0.3–10 µm
Temporal Release Characteristics: Measured over the course of the day
Implications for Sheltering: The results of the study confirm that mechanical ventilation with filtration is more effective than natural ventilation in reducing indoor particle levels, particularly for fine particles.

Chen et al. (2016)

Lead Author: Chen
Title: Indoor and outdoor particles in an air-conditioned building during and after the 2013 haze in Singapore
Link:
https://www.sciencedirect.com/science/article/abs/pii/S0360132316300026?via%3Dihub
Year: 2016
Journal: *Building and Environment*, 99, 73–81
Research Type: Experimental
Setting: Singapore
Research Focus: Researchers measured I/O ratio with and without air conditioning for different particle sizes during normal weather and during periods of elevated wildfire haze. Mechanical ventilation was on for both measurements.
Particle Size: 0.01–10 µm
Temporal Release Characteristics: Continuous monitoring for 2 weeks
Implications for Sheltering: Limited. Because mechanical ventilation was operating during both measurements, the article is only informative about the use of air conditioning. The researchers hypothesized that I/O may be lower for certain particle sizes with air conditioning on because particles are removed onto the wet surface of the air conditioner's cooling coil.

Illustrative Figure(s):

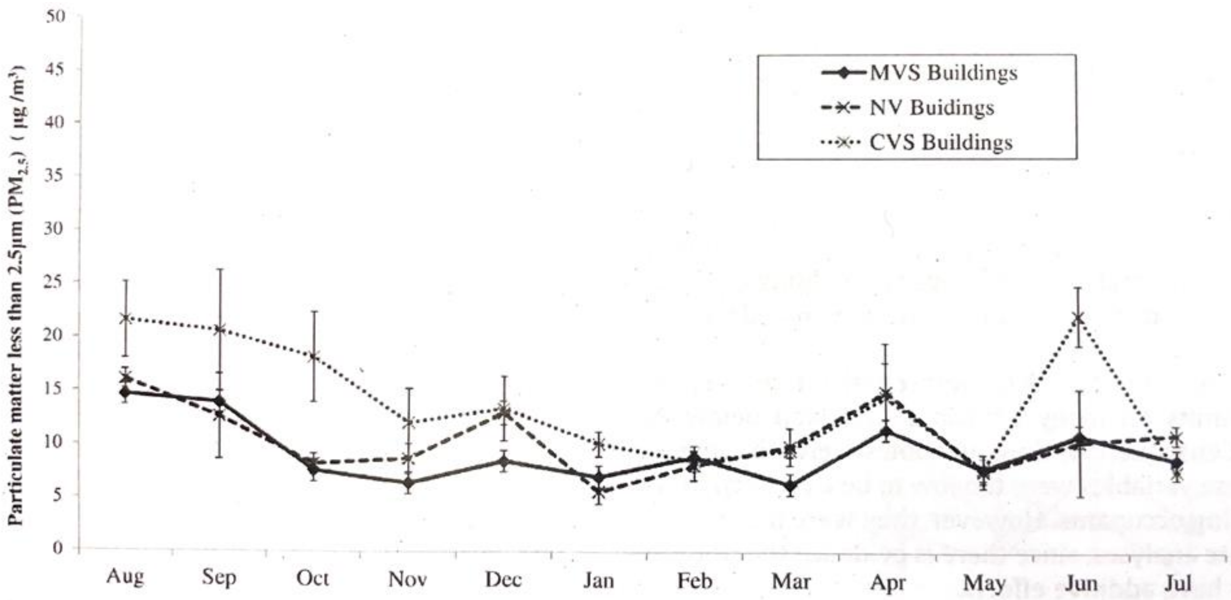


Size-resolved particle I/O ratios with air conditioning on and off (figure 5)

Irga and Torpy (2016)

Lead Author: Irga
Title: Indoor air pollutants in occupational buildings in a sub-tropical climate: Comparison among ventilation types
Link: https://www.sciencedirect.com/science/article/abs/pii/S0360132316300129
Year: 2016
Journal: *Building and Environment*, 98, 190–199
Research Type: Experimental
Setting: Office buildings in Sydney, Australia
Research Focus: Researchers measured contaminants (CO_2, CO, VOCs, NO, NO_2, SO_2, TSP, PM_{10}, PM2.5, and airborne fungi) in 11 buildings and compared them by ventilation type (mechanical, natural, or combined) each month for a year.
Particle Size: Varied, generally PM2.5–PM10
Temporal Release Characteristics: Continuous monitoring of ambient conditions
Implications for Sheltering: Limited. The study did not compare measurements for any individual building with and without HVAC in use. It may, however, be useful in illustrating seasonal variation.

Illustrative Figure(s):

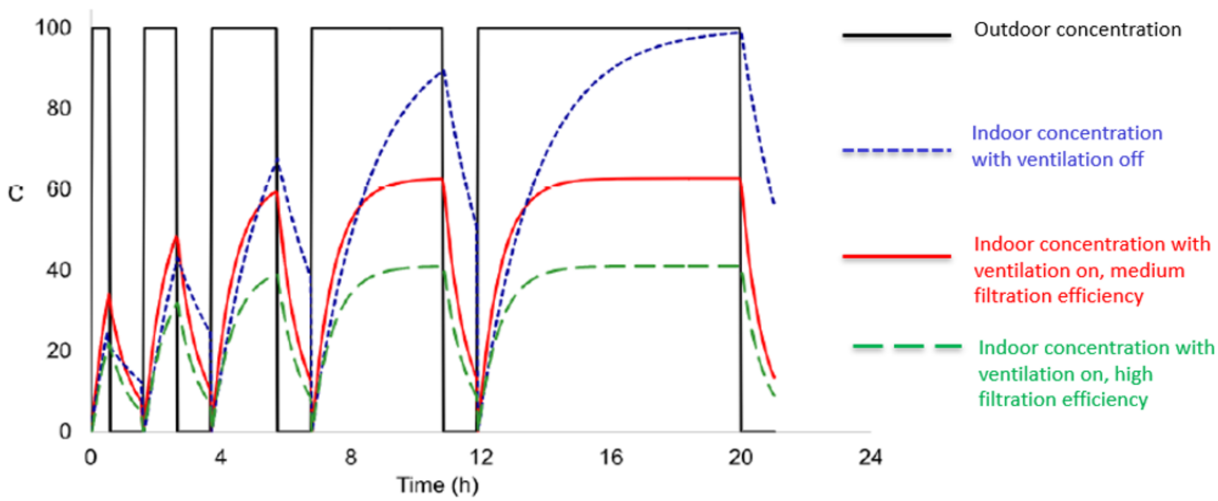


Average concentrations of PM2.5 in the atmosphere of buildings with different ventilation types, over a 12-month period (MVS = mechanical ventilation; NV = natural ventilation; CVS = combined or mixed ventilation system) (figure 4)

Kulmala et al. (2016)

Lead Author: Kulmala
Title: A tool for determining sheltering efficiency of mechanically ventilated buildings against outdoor hazardous agents
Link: https://www.sciencedirect.com/science/article/pii/S0360132316302414
Year: 2016
Journal: *Building and Environment*, 106, 245–253
Research Type: Experiment and modeling
Setting: Commercial building in urban Finland
Research Focus: Researchers calculated I/O for releases of 0.5, 1, 2, 4, and 8 hours with and without HVAC and with different HVAC efficiencies.
Particle Size: 0.3–5 µm
Temporal Release Characteristics: Very long-term continuous monitoring (4 months)
Implications for Sheltering: For release durations less than 2.5 hours, I/O is lower with HVAC off, while for release durations more than 2.5 hours, I/O is lower with HVAC running. The study recommends that “During long lasting releases it may be more beneficial to run the ventilation continuously to minimize occupant exposure, provided that the supply air filter is effective against the threat agent in question.”

Illustrative Figure(s):

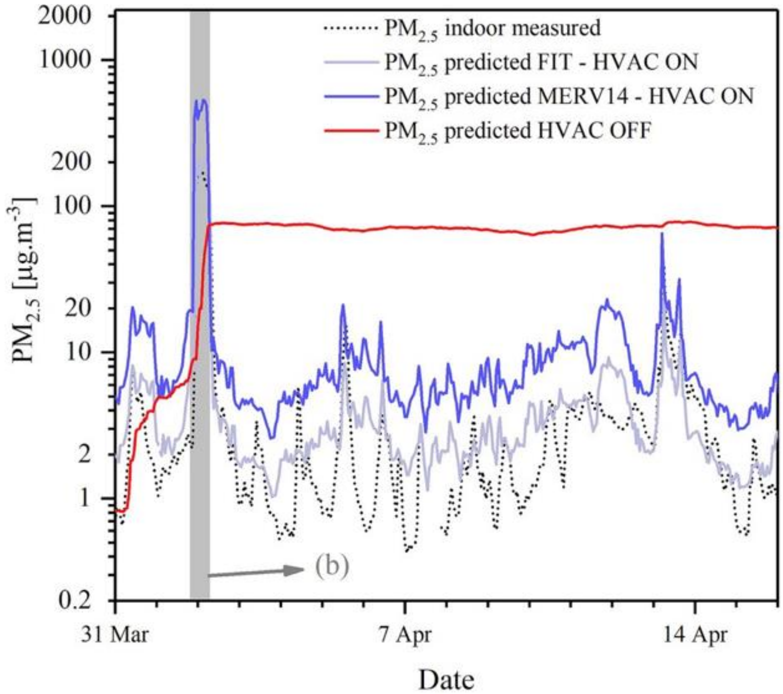


Simulated indoor concentrations for various cases (adapted from figure 11)

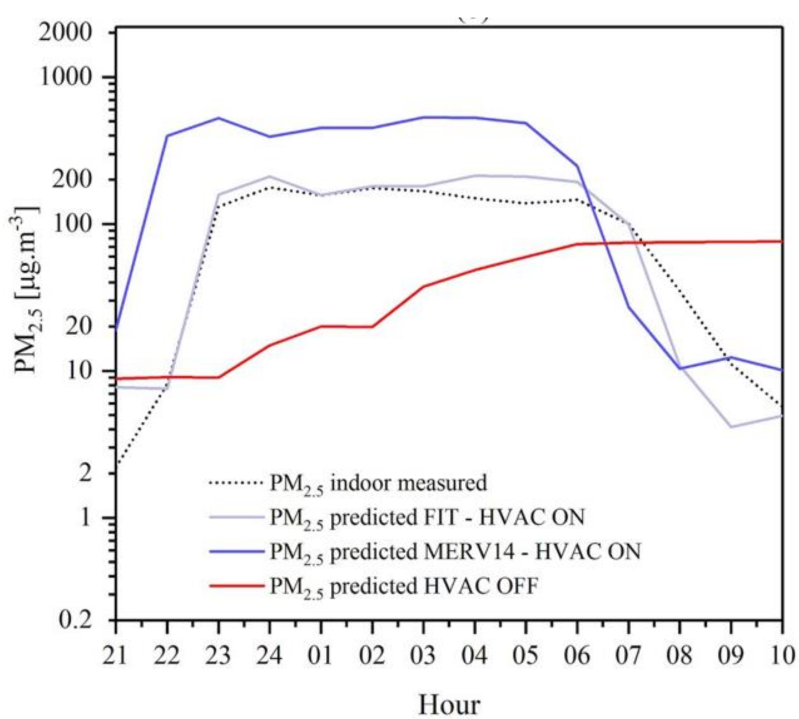
Argyropoulos et al. (2020)

Lead Author: Argyropoulos
Title: Measurements and modelling of particulate matter building ingress during a severe dust storm event
Link: https://www.sciencedirect.com/science/article/abs/pii/S0360132319306511
Year: 2020
Journal: *Building and Environment*, 167, 106441
Research Type: Experimental and modeling
Setting: Office building in Doha, Qatar
Research Focus: Researchers conducted a 2-month field campaign to measure and predict PM2.5 and PM10 infiltration in typical building environments during normal conditions and during a severe dust storm.
Particle Size: PM2.5–PM10
Temporal Release Characteristics: 2 months
Implications for Sheltering: The study's model predicts a lower pollutant concentration with HVAC off during the dust storm event for approximately the first 10 hours. However, after that time, it predicts a lower concentration of PM2.5 with HVAC on.

Illustrative Figure(s):



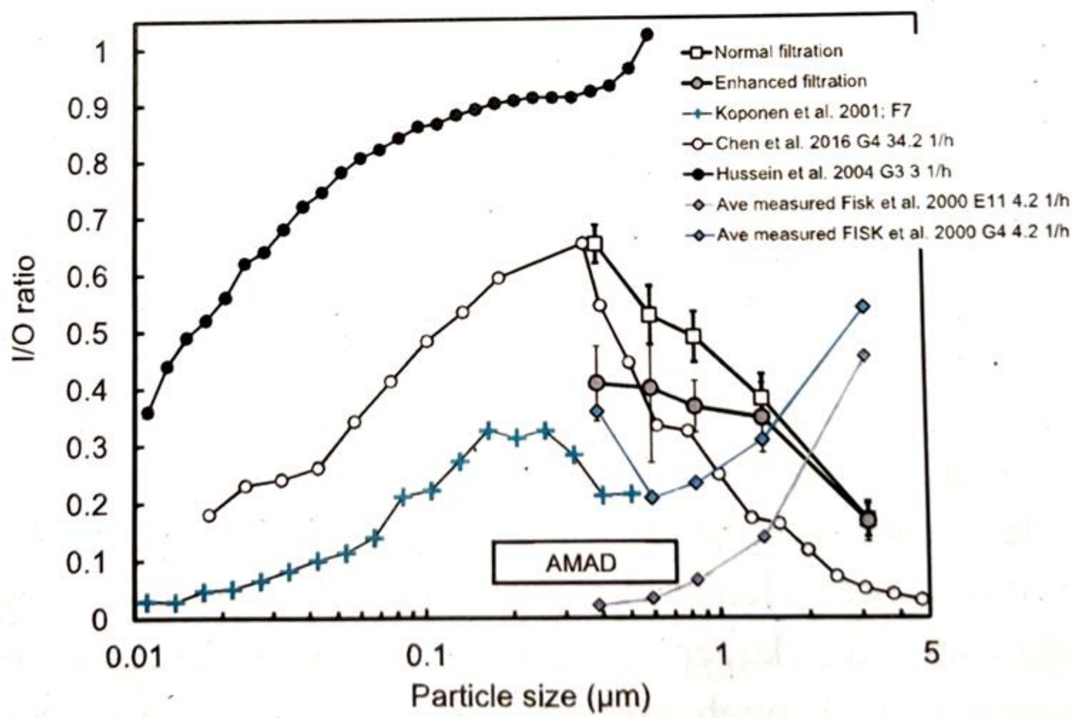
Comparison of indoor measured and predicted PM2.5 levels for a 16-day period including a dust storm event on April 2 (Figure 6a)



Comparison of indoor measured and predicted PM2.5 levels during the dust storm event on April 2 (figure 6b)

Kulmala et al. (2020)

Lead Author: Kulmala
Title: Effect of enhanced supply air filtration in buildings on protecting citizens from environmental radioactive particles
Link: https://link.springer.com/article/10.1007/s12273-020-0621-6
Year: 2020
Journal: *Building Simulation*, 13, 865–872
Research Type: Experimental and modeling
Setting: Office building near Helsinki, Finland
Research Focus: Field measurements were taken to determine the effectiveness of an electrically enhanced filter installed in an HVAC system for reducing indoor exposures to a simulated outdoor contaminant.
Particle Size: 0.3–5 μm
Temporal Release Characteristics: 4 months of continuous monitoring
Implications for Sheltering: For particles of diameter 0.5–1 μm, sheltering with enhanced filtration provides benefits relative to sheltering with normal filtration.
Illustrative Figure(s):



Comparison of particle-size-dependent I/O ratios for mechanically ventilated office buildings from several references with normal and enhanced filtration; size ranges of atmospheric radioactive particles after high-temperature nuclear accidents are shown for comparison (activity median aerodynamic diameter) (figure 5)

DISCUSSION AND CONCLUSION

There are few studies on the effectiveness of using HVAC systems to control airborne contaminants in an emergency situation requiring SIP. Many of the studies on SIP focus on the protection offered simply by being inside a building (without mentioning HVAC systems), or refer generically to “filters” as a means of filtering contaminated air. The lack of research specific to radiological events may be due to general acceptance of traditional HVAC guidance in the event of a nuclear accident. Within the available literature, multiple studies show that there are situations in which HVAC use may be beneficial for reducing indoor concentrations of an outdoor contaminant. For example, Thornburg et al. (2001) show that running HVAC reduces the I/O ratio for particles of diameter 1 μm by more than half, compared to not running HVAC. Kulmala et al. (2016) theorize that in a building with HVAC running and high filtration efficiency, the I/O ratio is approximately halved about 4 hours after the hypothetical plume arrives, relative to a situation with ventilation off.

However, the conclusions in the literature are too varied to show exactly when HVAC should be used. HVAC effectiveness depends on many factors, including but not limited to filtration efficiency and pressure drop, indoor air quality indicators such as humidity, I/O concentration differentials, building composition and materials, particle size, exchange rates, flow rates, and timing. Another potential source of uncertainty is that individuals may not be aware of the degree to which the HVAC system in the building in which they are sheltering draws in outside air.

The literature review presented here and in the appendix suggests the following conclusions:

- The decision of whether to run HVAC systems in the event of a radiological emergency is nuanced and is likely not as simple as the sheltering guidance currently suggests.

- The literature is in general agreement that I/O ratios of particles in the size range expected for radiological incidents can be decreased by the use of HVAC systems with filtration efficiencies consistent with those of modern HVAC filter systems drawing in outside air. Indoor air concentrations can be further decreased using standalone HEPA (or equivalent) filter systems.

- Shutting down external air intake and ventilation systems at an appropriate time during an incident (generally, early on) can be beneficial; conversely, poor timing can be detrimental. Similarly, it can be beneficial to “purge” air after plume passage. However, these strategies require special knowledge of when a release is over or diminished, and of the extent to which HVAC systems take in outside air and expel inside air.

- The physical configuration of the intake and ventilation systems and of the building itself affect the HVAC decision-making process.

Because the existing research applies mainly to events other than radiological releases, it leaves some important questions unanswered. Accordingly, further research is needed to establish a technical basis for any future updates to the guidance on HVAC use in a radiological emergency. Additional experiments or modeling may help identify best practices for radiological incidents. For example, it may be helpful to analyze scenarios analogous to radiological events (e.g., in terms of timing and particle sizes), then perform additional sensitivity analyses for parameters relevant to HVAC operation. Furthermore, HVAC-related guidance needs to be feasible to implement during an emergency (when additional protective measures, such as standalone air filters, may be unavailable), and decision-makers and the general public need to be ready and willing to implement it. The guidance should therefore take into account that there may be no one-size-fits-all rules applicable to all HVAC systems and buildings, and that people may be apprehensive about implementing processes that contradict traditional understanding of HVAC use. Experiments should be designed to address all of these considerations.

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APPENDIX A: ADDITIONAL INFORMATION

Additional Information and Works Cited for Use of HVAC Systems for Controlling Airborne Contaminants

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS AND ACRONYMS

ACH	air changes per hour
AER	air exchange rate
AEERL	Air and Energy Engineering Research Laboratory
AHAM	Association of Home Appliance Manufacturers
AMAD	activity median aerodynamic diameter
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASF	airborne sheltering factor
Bq	becquerel
CFD	computational fluid dynamics
CFR	*Code of Federal Regulations*
cm	centimeter
CO_2	carbon dioxide
Cs	cesium
DHS	U.S. Department of Homeland Security
DOE	U.S. Department of Energy
DRF	dose reduction factor
ECA	European Collaborative Action
EPA	U.S. Environmental Protection Agency
h	hour
HEPA	high-efficiency particle arresting
HVAC	heating, ventilation, and air conditioning
I	iodine
I/O	indoor/outdoor
IAQ	indoor air quality
LS	large structure
m	meter
mm	millimeter
MERV	minimum efficiency reporting value
MeV	megaelectronvolt
mSv	millisievert

NRC	U.S. Nuclear Regulatory Commission
O_2	oxygen
Pa	pascal
PADRE	Protective Action Dosage Reduction Estimator
PAG	protective action guide
PM	particulate matter
PNC	particle number concentration
PNSD	particle number size distribution
PPTG	passive perfluorocarbon tracer gas
PRISEM	Post-radiological Incident Shelter in Place vs. Evacuation Model
Ru	rubidium
S/V	surface-to-volume
SBS	sick building syndrome
SIP	sheltering in place
SS	small structure
Te	tellurium
μm	micron
VOC	volatile organic compound
WB	whole body

INTRODUCTION

One of the primary goals of U.S. Nuclear Regulatory Commission (NRC) regulations is to provide reasonable assurance of adequate protection of public health and safety. Historically, sheltering in place (SIP) has been implemented by securing a building's heating, ventilation, and air conditioning (HVAC) systems and interior exhaust fans to maximize radiological protection during the passage of a radioactive plume. However, recent studies show that mechanical filtration can increase the shelter efficiency of mechanically ventilated buildings. In addition, if HVAC systems are shut off for too long, sheltering individuals could face other risks, such as heat exhaustion.

In accordance with Title 10 of the *Code of Federal Regulations* (10 CFR) 50.47(b)(10), licensees are required to develop protective actions for emergency workers and the public, including consideration of evacuation, sheltering, and, as a supplement to these, the prophylactic use of potassium iodide. In SRM-M030924, "Briefing on Emergency Preparedness Program Status," dated October 3, 2003, the Commission directed the NRC staff to continue to evaluate NRC guidance on protective action recommendations (PARs) and update it as necessary to reflect the current state of knowledge.

The decision of whether to evacuate or shelter in a radiological emergency is based on PARs, protective action decisions, and protective action guides (PAGs). PARs are protective measures recommended by the nuclear power plant emergency response organization to offsite response organizations. Protective action decisions are measures taken in response to an actual or anticipated radiological release. PAGs identify the projected dose to an individual member of the public that warrants protective action. In accordance with 10 CFR 50.47(7), the public is periodically informed of how it will be notified and what initial actions should be taken in an emergency, including actions to take when sheltering.

A vast body of research exists on indoor control of airborne contaminants using HVAC systems. The purpose of this additional appendix is to report more exhaustively on the relevant literature, including the works cited in the accompanying report, on controlling airborne contaminants using mechanical ventilation in residential and commercial structures, beyond the use of HVAC specifically for SIP. Because the dynamic conditions and physical properties of a radiological release differ from those of other airborne contaminant releases, research from other fields of study provides only limited insights. Therefore, as a follow-on, this appendix identifies additional experimental and modeling efforts that are needed to study the application of HVAC systems specifically to controlling radiological contaminants.

The appendix begins by examining the basic concepts underlying current approaches to assessing health risks posed by indoor contaminants. This is followed by a survey of the most common methods of indoor ventilation, including their advantages and limitations, as well as recent academic viewpoints on their application to the control of indoor air quality (IAQ) while sheltering.

METHODOLOGY

This study began with a literature search to collect as much relevant information as possible on the use of HVAC systems for reducing indoor air concentrations of contaminants, in order to support guidance on risk-informed protective action strategies for HVAC use during radiological emergencies. The sections below describe the methodology and outcomes of the literature review.

Literature Review Methodology

The purpose of the literature review was to gather information on the use of HVAC while sheltering, and on the subsequent health effects of such use. The search was performed using a series of search strings on a database of publicly available literature, followed by a thorough review of citations from relevant papers, studies they reference, and studies that cite them.

The search strings included both broad strings, such as [“ventilation” + “shelter” + “filter”], and more specific strings related to certain emergency events, health outcomes, or populations, in categories such as the following:

- emergency event types (e.g., “nuclear accidents”)
- specific emergency remediation strategies (e.g., “sheltering in place”)
- indoor air cleaning techniques (e.g., “filtration”)
- health outcomes (e.g., “ventilation effect on human”)

A list of candidate studies that met the following criteria was then created:

- **Studies supported by detailed technical documentation:** Only studies with detailed supporting documentation were selected.

- **Primary source documents:** In cases where the same material was discussed in several documents, the document containing the original study (the primary reference) was selected, while the other documents (secondary references) were consulted for supplementary details (for example, literature reviews such as that of Thatcher et al. (2002) were used to identify studies and provide context).

- **Documents relevant to protection against nuclear exposure within the United States:** Studies were selected whose results were judged relevant to U.S. building construction and to protection against nuclear exposure from nuclear power plant accidents and radioactive dispersal devices in the United States.

- **Documents with unlimited distribution:** Studies and reports that had restricted access (e.g., Official Use Only documents) were excluded.

The literature search identified 300 unique papers, all of which were collected into a shared folder for further review. The relevance of each paper was evaluated from the title and abstract. The full text of each relevant paper was then reviewed.

Out of the original 300 papers, 190 were found to be relevant. After a closer review, 20 of these papers were excluded for various reasons (e.g., because they covered material beyond the scope of this report, or examined the same group and effect as another study). This left 170 papers for the final analysis.

Groups for Analysis

To allow for a robust analysis, the papers were sorted into three groups based on subject:

(1) effectiveness of HVAC for reducing indoor concentrations of pollutants
(2) effectiveness of SIP during radionuclide release
(3) indoor particle penetration and deposition

Exclusion Criteria

Papers were excluded from the analysis if either of the following reasons applied:

- The study was on too specific a topic (e.g., radionuclide dose reduction during medical procedures).

- The study did not distinguish clearly between natural and mechanical infiltration.

RESULTS

This section describes the results for each of the three study groups:

(1) experimental research
(2) modeling, simulation, or Monte Carlo analysis
(3) building types

Table A1 highlights the research methods and building types covered in the most relevant references.

Table A1 Research Methods and Building Types in Main References

Lead Author	Method	Building Types
Kulmala	Both experimental and modeling	Concrete four-story commercial building
Thornburg	Monte Carlo modeling	Commercial building and house
Langer	Multivariate linear regression models	567 residences in mainland France
Taylor	Simulation/geographical information system software	Dwellings
Irga	Experimental	11 typical Australian office buildings
Chen	Experimental	Mechanically ventilated and air-conditioned building
Ward	Transient and steady-state models	Residential building
Chan	Atmospheric dispersion model, IAQ model, and dose–response model	Community-scale buildings
Engelmann	Modeling	Residences, hospital, and office buildings
Hanley	Experimental	Residential building

The protection that buildings provide their occupants is often quantified in terms of the protection factor (Dillon et al., 2016). Protection factor is defined as the ratio of the "open field" dose (or dose rate) to the dose (or dose rate) experienced within the building, where, for radiation release, the open field dose is the radiation dose measured 1 meter (approximately 3 feet) above an infinite flat plane uniformly contaminated by radioactive exposure. On occasion, building protection is reported in terms of the reduction factor (also called the transmission factor), which is the inverse of the protection factor:

$$\text{Protection Factor} = \frac{D_o}{D} = \frac{\text{Unsheltered (Open Field) Dose}}{\text{Sheltered Dose}} \text{ or } \frac{\text{Unsheltered (Open Field) Dose Rate}}{\text{Sheltered Dose Rate}}$$

$$\text{Reduction Factor} = \frac{D}{D_o} = \frac{\text{Sheltered Dose}}{\text{Unsheltered (Open Field) Dose}} \text{ or } \frac{\text{Sheltered Dose Rate}}{\text{Unsheltered (Open Field) Dose Rate}}$$

Ventilation removes indoor-generated pollutants or dilutes their concentration. Seppänen et al. (1999) performed epidemiological research to find the optimum ventilation rates. The European Committee for Standardization (1998), Wargocki et al. (2002), and European Collaborative Action (ECA) (2003) contributed in this area by performing several laboratory and field experiments. Seppänen (2003) studied the effects of the operation and maintenance of ventilation systems. Kennedy (1995) estimated national and regional distributions for annual average air exchange rates (AERs) measured in U.S. residences.

Filtration efficiencies of 40 to 60 percent can bring a building into compliance with the ventilation rate standards of American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 62-1989, Ventilation for Acceptable Indoor Air Quality (ASHRAE, 1989; Yu and Raber, 1990). Zhao et al. (2007) estimated that HVAC systems in residential and commercial buildings can remove up to 22 percent and 95 percent of ozone, respectively. A group of European scientists (EUROVEN) elaborated on several causes of adverse health effects due to HVAC systems, including poor maintenance and hygiene in HVAC systems, intermittent operation of HVAC systems, lack of moisture control, and lack of control of HVAC system materials and loaded filters (Wargocki et al., 2002).

Chemical and sensory emissions of structural materials, ventilation systems, and HVAC components may also negatively affect IAQ (Fanger,1988). Measurements indicate that volatile organic compound (VOC) emission rates vary significantly across materials (Morrison and Hodgson, 1996; Morrison et al., 1998). The National Academies of Sciences, Engineering, and Medicine (2022) reported that to reduce radon risk, the U.S. Environmental Protection Agency's (EPA's) guidance on residential HVAC and filters (EPA, 2021) should be followed. The relationship between airflow and pressure drop is linear (Linder, 1970). The effects of radon during its decay period may be reduced by reducing the number of particles that attach to the radon daughters (Nazaroff et al., 1981; Sextro and Offermann, 1991; Sextro et al., 1986; Windham et al., 1978). Ventilation can be used to reduce high indoor temperatures, which cause sick building syndrome (SBS) symptoms, deteriorate air quality, lead to dry air in winter, and reduce work performance and productivity (ECA, 2003; Seppänen et al., 2003).

Humphreys et al. (2002) found that subjects' thermal state (as recorded by their comfort rating) was far more influential than any particular characteristic of the environment (including enthalpy) in deciding perceived air quality.

Saunders and Albright (1989) developed a method for monitoring two-dimensional flow with aerosol tracers and digital imaging analysis. Farrington and Hassani (1991) determined the flow field in an experimental room using infrared imaging. Anderson (1989) provides several methods to determine ventilation efficiency in a room. Lagus (1989) built an instrument to measure tracer gas. Lagus (1989) also developed new analytical techniques to improve tracer gas measurements with lower costs and lower instrument response time. The National Research Council (1996) reports that overall filtration efficiency was about 99.997 percent.

Farant et al. (1991) developed a design for office workstations to optimize the volume of fresh air delivered to occupants. Nielsen (1989), Murakami and Kato (1989), and Kurabuchi et al. (1989) studied airflow and diffusion within rooms. To model diffuser flow, one should consider rapid flow field changes, which require a small mesh size; however, for large rooms, a large mesh is more practical. Diffusers also contribute to energy efficiency because they affect the design of low-temperature air distribution systems. Schultz and Krafthefer (1989) researched diffuser flow using a room-sized chamber made by Honeywell, with several variable environmental controls. Bearg (1993) lists more than 10 distinct definitions of ventilation efficiency that have been proposed since 1981.

Personally controlled ventilation has good potential for architectural and building design. According to Drake et al. (1991), the Advanced Building Systems Integration Consortium has been involved with the design of advanced buildings since 1988. The advantages of certain designs include reinforced control of ventilation systems. Hedge et al. (1991) incorporated breathing zone filtration into office furniture, with the occupant able to control the ventilation rate. Laurikainen (1991) and Koganei et al. (1991) respectively describe the design of displacement ventilation systems and their applicability to Japanese offices. ASHRAE considered displacement ventilation in a research proposal from Technical Committee 2.2, “Effect of Displacement Ventilation on Indoor Air Quality and Thermal Comfort,” which was not approved. Strindehag (1991) performed a multiyear experiment with variable-volume HVAC designs controlled by carbon dioxide (CO_2) sensors. Bayer and Downing (1991) demonstrated a “total energy recovery system” using rotating heat-wheel heat transfer equipment. This design recovered 90 percent of the energy exhausted from the dwelling, with no impact on IAQ. The EPA and ASHRAE have organized, and forwarded to the building industry, information on designing buildings and choosing HVAC systems to ensure good IAQ.

Langer et al. (2016) performed a national survey on indoor environmental quality covering 567 residences in mainland France between 2003 and 2005. The survey included measurements of temperature, relative humidity, CO_2, and indoor air pollutants including 14 individual VOCs, 4 aldehydes, and particulate matter (PM10 and PM2.5). The measured indoor concentrations were analyzed for correlations with the following building characteristics: type of dwelling, period of construction, dwelling location, type of ventilation system, building material, attached garage, and retrofitting. It was found that VOC concentrations were dependent on the building characteristics; however, most of the indoor climate parameters and air pollutant concentrations were more strongly influenced by the sampling season than by the building characteristics. Multivariate linear regression models revealed that the indoor/outdoor (I/O) difference in specific humidity, a proxy for the number of occupants and their indoor activities, remained a significant predictor for most gaseous and particulate air pollutants. The other strong predictors, in descending order of importance, were outdoor concentration, smoking, attached garage, and AER.

Taylor et al. (2014) describe how to use building simulation to determine the indoor concentration of outdoor-sourced pollution for different housing typologies, and how to map the results using building stock models and geographical information system software. Their study used these tools to demonstrate the modifying effect of dwellings on occupant exposure to PM2.5 across London. They demonstrated a range of I/O ratios for PM2.5, finding that detached and semidetached dwellings were most vulnerable to high levels of infiltration. They found that I/O ratios of PM2.5 were lower in in central London than in outer London, an apparent inversion of exposure most likely caused by the prevalence of flats rather than detached or semidetached properties. Their study concluded that the indoor pollution levels in commercial buildings can vary significantly because of HVAC system operation, filters, and complex building geometries.

Irga and Torpy (2016) performed a field study of air pollutants in 11 indoor environments in Sydney over the course of a year, measuring I/O ratios for total suspended particulate matter, suspended particles less than 10 microns (μm) in diameter (PM10), and particulate matter less than 2.5 μm in diameter (PM2.5). They classified building ventilation systems as natural, mechanical, or mixed-type and assessed whether the ventilation type affected the prevalence and concentrations of indoor air pollutants. They found that the typical Australian office building has relatively good IAQ. Building ventilation type did affect IAQ, but not to the extent of affecting occupant health.

Effectiveness of HVAC for Sheltering in Place

Smith (2021) states that in the event of a radiological release, SIP can be considered as an alternative to wide-scale evacuation.

HVAC systems and high-efficiency filters can reduce the dose from radionuclide exposure; however, to justify the use of HVAC and ventilation when there is outdoor radionuclide release, it is necessary to study whether HVAC systems reduce indoor exposures and what conditions influence their effectiveness.

Ward et al. (2005) found that HVAC systems can be used for quick removal of indoor particles and therefore may be considered for SIP strategies following acts of bioterrorism. They developed a screening model to study particle removal by high-efficiency particle arresting (HEPA) HVAC filters. Through both transient and steady-state analysis of the model, they concluded that one to three portable HEPA HVAC filters could provide effective protection for SIP following outdoor contamination releases. Compared to the baseline with no HVAC, the use of HVAC could reduce contaminated particle concentrations by as much as 90 percent. The model further predicted that increasing particle size would decrease the relative effectiveness of

HEPA HVAC filters, because of increasing competition from particle deposition on indoor surfaces and removal by HVAC filters; however, the effect of particle size was small in most of the cases examined.

Chen et al. (2016) found that a mechanical ventilation system equipped with MERV 7 filters attenuated the penetration of outdoor particles into a building. Indoor particle concentrations, in the diameter ranges 0.3–1.0 μm and 1.0–2.5 μm, closely tracked the corresponding outdoor particle concentrations. For particles in the size range 0.01–1.0 μm, the size-resolved mean I/O ratios were in the range 0.12–0.65, with particles at 0.3 μm having the highest mean I/O ratio (0.59 with air conditioning and 0.64 without). The air conditioning and mechanical ventilation system with MERV 7 filters provided low singlepass removal efficiency (less than 30 percent) for particles with diameters of 0.01–1.0 μm. For particles larger than 0.2 μm, lower I/O ratios and higher removal efficiencies occurred with the air conditioning operating than with mechanical ventilation only.

Hanley et al. (1994) developed a test apparatus and procedure for quantifying the fractional filtration efficiency of air cleaners for particles of diameter 0.01–3 μm. They quantified the fractional efficiency of several in-duct air cleaners typical of those used in residential and office ventilation systems. They found that efficiency was highly dependent on particle size, flow rate, and dust load present on the air cleaner. A minimum in efficiency was often observed in the 0.1–0.5 μm diameter range. The presence of dust frequently increased an air cleaner's efficiency; however, some air cleaners showed little change or a decrease in efficiency with dust loading. The common furnace filter had fractional efficiency values of less than 10 percent over much of the measurement size range.

According to the National Academies of Sciences, Engineering, and Medicine (2022), infiltration efficiency in buildings can vary based on pollutant characteristics such as size, class, and chemical components of the particulate material; the source of ventilation air; human habits such as how often residents open and close windows and doors or use portable HVAC; the AER; and HVAC system usage time, filter type, and filter efficiency.

Chan et al. (2007) used three models to quantify community-scale SIP effectiveness: an atmospheric dispersion model to predict the outdoor concentrations resulting from a release, an IAQ model to predict the indoor concentrations resulting from various outdoor concentrations, and a dose–response model to predict the health effects of exposure to time-varying outdoor or indoor concentrations. To assess the dependence of SIP effectiveness on key controlling variables, Chan et al. used a Gaussian atmospheric dispersion model to predict outdoor concentrations, a well-mixed box model to predict indoor concentrations, and a power-law toxic-load model to predict the health consequences of exposure. They found that the release duration and the reciprocal of the building AER were two important time scales influencing SIP effectiveness. In particular, the higher the AER, the faster toxic materials could penetrate indoors, and consequently the closer the indoor peak concentration would come to the outdoor peak.

Thornburg et al. (2001) developed a time-dependent IAQ model, incorporating all potential particle sources and loss mechanisms, to study the relationship between outdoor particle concentrations and those found in indoor microenvironments. Through Monte Carlo simulations, they identified the mechanisms (such as particle loss during penetration through the building envelope) that modify the outdoor particle size distribution during transport into the interior of a building, calculated I/O concentration ratios, and estimated penetration factors as a function of particle size. They found that indoor particle generation and transport of outdoor particles through the HVAC system, respectively, were the most important contributors to the indoor concentration in residential and commercial buildings. The most significant removal mechanisms included ventilation through and particle removal by the HVAC filter if an HVAC system was present, and particle deposition on indoor surfaces if an HVAC system was not present. The modeled I/O concentration ratios varied between 0.05 and 0.5, depending on particle size and type of ventilation system, and agreed well with published experimental results. Penetration factors less than unity were modeled for particles with aerodynamic diameters larger than 0.2 µm if the AER and steady-state I/O concentration ratio were correlated during the simulations. The modeling of penetration factors less than unity for particles with aerodynamic diameters smaller than 0.2 µm would require additional correlation between the AER and particle deposition velocity. The results of Thornburg et al. (2001) support the possibility that appropriate experimental studies will yield penetration factors less than unity.

Table A2 shows parameters important to the work of Thornburg et al., as well as other relevant research on HVAC use.

Table A2 Important Parameters for HVAC Use

Lead Author	Parameters Important to Findings
Kulmala	HVAC filtration efficiency (higher efficiency brings more benefit as long as the pressure drop over the filter does not also increase)
Thornburg	HVAC duty cycle
Langer	Humidity, number of occupants and their indoor activities, outdoor concentration, smoking, presence of attached garage, period of construction
Taylor	Residential building type; location, height, orientation, sheltering, and permeability of building envelope; building geometry; building ventilation systems; weather and urban meteorology conditions such as urban street canyons; building occupant practices such as window opening and heating use; emissions from indoor sources such as cooking, smoking, cleaning, dusting, and showering
Irga and Torpy	Ventilation type, building materials, flooring type, building age, and population density

Chen	Particle size
Ward	Particle size
Chan	Release quantity and duration, meteorology, chemical toxicity, building AER, termination time
Engelmann	Time-integrated concentrations (DRF), AER, building age
Hanley	Particle size, flow rate, dust load present on the air cleaner

Model for Portable HVAC for Sheltering in Place (Ward et al., 2005) and Similar Studies

Ward et al. (2005) developed a model for both transient and steady-state conditions in a well-mixed residential building. This section presents their mathematical equations and parameter selection. Equation (1) shows a particle mass (or number) balance for a residential building:

$$V\frac{\mathrm{d}C}{\mathrm{d}t} = pQC_{\mathrm{o}} - QC - \eta_{\mathrm{f}}Q_{\mathrm{f}}C - v_{\mathrm{d}}AC - \eta_{\mathrm{pf}}Q_{\mathrm{pf}}C \quad (1)$$

The quantities in this equation are defined as follows:

Nomenclature

A	Collective area of all indoor surfaces (m^2)
α	Sum of particle removal factors (1/h)
C	Indoor particle mass or number concentration (mg/m^3 or $number/m^3$)
$C(t)$	Indoor particle mass or number concentration at time t (mg/m^3 or $number/m^3$)
$C(\infty)$	Indoor particle mass or number concentration at steady-state (mg/m^3 or $number/m^3$)
$C(\infty)_{nopf}$	Indoor particle concentration at steady-state without air cleaner(s) (mg/m^3 or $number/m^3$)
$C(\infty)_{pf}$	Indoor particle concentration at steady-state with air cleaner(s) (mg/m^3 or $number/m^3$)
C_o	Outdoor particle mass or number concentration (mg/m^3 or $number/m^3$)
CADR	Clean air delivery rate (m^3/h)
Γ	Air cleaner effectiveness relative to no air cleaner (–)
p	Fractional particle penetration efficiency (–)
Q	Volumetric infiltration rate into and out of house (m^3/h)
Q_f	Volumetric flow rate of air through HVAC system (m^3/h)
Q_{pf}	Volumetric flow rate of air through portable air cleaner (m^3/h)
t	Time (h)
V	Volume of house (m^3)
v_d	Surface-integrated particle deposition velocity (varies with particle size) (m/h)
η_f	Fractional removal efficiency associated with HVAC filter (varies with particle size) (–)
η_{pf}	Fractional removal efficiency for portable air cleaner (varies with particle size) (–)
λ	Rate of air exchange between the indoor and outdoor atmospheres (1/h)

The left-hand side of equation (1) is the derivative of particle mass (or particle number) with respect to time. The right-hand side of equation (1) shows the following:

- particle penetration into the home through infiltration from the outside atmosphere
- particle exhaust from indoor to outdoor air
- particle removal by filtration in an HVAC system
- particle removal by collective deposition mechanisms on indoor surfaces
- particle removal by a portable HVAC (the focus of Ward et al., 2005)

Most of these parameters depend on particle size; therefore, equation (1) must be applied separately for each particle size in the indoor environment.

The model of Ward et al. (2005) treats the indoor environment as a well-mixed reactor, with filtration in the HVAC system being the only source of particle removal (in particular, the model does not represent particle removal through deposition to HVAC system components such as cooling coils, fan blades, and duct walls).

Ward et al. (2005) calculated a typical home volume by multiplying an area of 157 m^2 (obtained from 2001 data from the U.S. Bureau of the Census) by an average ceiling height of 2.4 meters, for a volume of 377 cubic meters (m^3).

Based on the work of Liu and Nazaroff (2001, 2003), the penetration factor *p* can be set equal to one for all particle sizes under assessment. Particle penetration across the building envelope may be less than one for particles larger than 1 μm. For simplicity, Ward et al. (2005) assumed $p = 1$ in their study.

According to Murray and Burmaster (1995), the AERs in 2,844 American homes were found to be well fit by lognormal distributions. Ward et al. (2005) selected the median value of 0.5 per hour (h) for their base case and considered the 10 percent and 90 percent values of 0.2/h and 1.3/h for boundaries for this parameter.

Ward et al. (2005) used size-dependent deposition loss rates as determined by Riley et al. (2002) from the published literature. The HVAC filter efficiency (η_f) was determined for a typical residential furnace filter from experiments by Hanley et al. (1994). Ward et al. (2005) also evaluated the scenario of a new high-performance filter (Hanley et al., 1999). Table 1 shows the deposition loss rates and η_f values used by Ward et al. (2005). For the sake of comparison, Ward et al. (2005; 2003) also defined a base-case combination of the four parameters.

The results of Ward et al. (2005) serve as screening; future study is required to validate their methodology and to elaborate on specific model parameters and particle release situations. Note that Ward et al. (2005) do not evaluate indoor particle sources such as resuspension.

Through both experiments and modeling, Chen and Zhao (2011) reviewed the use of three parameters to study the relationship between indoor and outdoor particles: the I/O ratio, infiltration factor, and penetration factor. They concluded the following:

(1) The I/O ratio, which indicates the relationship between indoor and outdoor particle concentration, can vary greatly depending on indoor particle emission rates, building crack geometry, and AER, so it is not very helpful for understanding the relationship between indoor and outdoor particles.

(2) The infiltration factor is useful for qualifying the number of indoor particles contributed by the outdoor environment that avoid mixture with indoor particle sources.

(3) The penetration factor is the most relevant parameter for capturing the mechanism of penetration through cracks.

(4) The experimental results on the penetration factor agree well with the results predicted by the model of Liu and Nazaroff (2004) and the analytical and Eulerian models of Zhao et al. (2010). Further studies are needed to incorporate the influence of thermophoresis forces and airflow fluctuation into the existing models.

Ohba et al. (2020) determined the demographic and geographical distribution of thyroid equivalent doses for 1,200 children affected by the 2011 accident at the Fukushima Dai-ichi nuclear power plant, using data from a detailed questionnaire administered by the Fukushima Health Management Survey.

Shinohara and Yoshida-Ohuchi (2019) determined concentrations of radioactive cesium-137 (^{137}Cs) in indoor air during cleaning in 60 houses within the evacuation area near the Fukushima Dai-ichi nuclear power plant. They found that during dusting, radiocesium activity concentrations per cubic meter of indoor air (mean ± standard deviation (median)) were 6.8 ± 7.9 (4.7) and 1.6 ± 2.7 (0.78) becquerels (Bq)/m^3 for all particles with the aerodynamic diameter of aerosols and for PM2.5, respectively. Radiocesium activity concentrations decreased with decreasing aerodynamic diameter (mean concentrations were 0.099, 0.22, 0.41, 0.92, 2.2, and 2.9 Bq/m^3 for aerodynamic diameters of <0.25, 0.25–0.5, 0.5–1.0, 1.0–2.5, 2.5–6.6, and >6.6 µm, respectively); they were inversely proportional to the square of the distance from the Fukushima Dai-ichi nuclear power plant. Indoor ^{137}Cs radioactivity concentrations were significantly higher during dusting than during vacuuming. The mean deposited activities in an individual's tracheobronchial and alveolar regions during a 2-hour dusting period were estimated to be 1.9 and 2.8 Bq, respectively.

Bennett and Koutrakis (2005) determined the fraction of outdoor particles that reach an indoor environment and the inter- and intra-home variability of this value. The value depends on particle penetration efficiency and deposition rate. Bennett and Koutrakis (2005) present an alternative method for calculating the dynamic infiltration factor using time-dependent concentrations and air-exchange measurements. They discuss the limitations of calculating the penetration rate and deposition velocity independently and find that the I/O ratio often overestimates penetration efficiency. In their study, they calculated the dynamic infiltration factors for seven houses, generally for seven nights per house, for 17 particle size fractions. They found a mean infiltration factor, across houses, of 0.49 for the smallest particle size fraction (0.02–0.03 µm), which increased to 0.76 for the 0.2–0.3 µm size fraction and then decreased steadily to 0.32 for the largest size fraction (4–6 µm). They also determined the coefficients of variation across nights and homes; these were comparable, ranging between 0.07 and 0.18 for all size fractions up to 1 µm, with values up to 0.48 for larger size fractions.

Tan et al. (2015) found a method for estimating the ratio of indoor to outdoor airborne radioactivity, termed the airborne sheltering factor (ASF). Without a meaningful value for the ASF, it is difficult to assess inhalation doses to residents and evacuees even when outdoor radionuclide concentrations are available. Tan et al. (2015) developed a simple model and obtained the key parameters needed to estimate the ASF through data-fitting of selected indoor and outdoor airborne radioactivity measurement data obtained at a single location after the Fukushima accident. This model enables the ASF to be estimated for a variety of dwelling types, using the values for the AER, interior air volume, and inner surface area of the dwellings. The inhalation dose can be assessed from the building ASF, occupancy factor, and outdoor radioactivity data.

Takeyasu et al. (2013) estimated the committed effective dose to adults and the committed equivalent dose to the thyroids of infants through inhalation for various indoor and outdoor exposure scenarios. They demonstrated that the I/O airborne radionuclide concentration ratio had a dominant effect on the dose estimate. The committed effective dose to adults was estimated to be 0.098 millisievert (mSv), and the committed equivalent dose to the thyroids of infants was 1.8 mSv. These doses were about 1/6 and about 1/9, respectively, of the provisional estimates under such assumptions as continuous outdoor stay.

Haywood (2015) discusses the assessment of doses received by members of the public in the event of a radiological incident (either accident or deliberate release) and key uncertainties associated with assessment, such as the time distribution of the release.

Andersson et al. (2004) developed a model methodology for determining the factors contributing to dose in contaminated indoor environments and presented an example of its use. They found that after a major nuclear accident, it was important to consider doses from indoor deposition to humans, deposition on indoor surfaces, and inhalation in the indoor environment. They examined the impact of thermophoresis, electrophoresis, skin moisture, and wind speed on the deposition of contaminant aerosol; since previous measurements had indicated that elemental iodine could be a particularly problematic contaminant, they undertook experimental work to examine the process of deposition of this species to skin.

Zhao et al. (2019) captured representative diurnal and seasonal patterns of exposure to particles and investigated the driving factors in their variations, through measurements performed in 40 homes for around 2 weeks each in Leipzig and Berlin, Germany. These measurements encompassed PM10 and PM2.5 mass concentrations, particle number concentration (PNC) and particle number size distribution (PNSD), CO_2 concentration, and residential activities. Natural ventilation was dominant; the mean AERs calculated from CO_2 measurements were 0.2 h^{-1} and 3.7 h^{-1} with closed and opened windows, respectively. The main findings of Zhao et al. (2019) were that the residents of German homes were exposed to a significantly higher mass concentration of coarse particles outdoors than indoors; thus, indoor exposure to coarse particles could not be described by outdoor data. The median PNC diurnal cycles were generally lower indoors than outdoors (median I/O ratio 0.69). However, indoor exposure to particles was different in the cold and warm seasons. In the warm season, because windows were open longer, indoor sources contributed less, so that the indoor and outdoor PNC and PNSD were very similar. In the cold season, indoor sources caused strong peaks of indoor PNC that exceeded outdoor PNC, while the relatively low penetration factor and indoor particle losses, which were particularly effective in reducing the ultrafine PNC, led to a different particle exposure load than outdoors.

Martin et al. (2019) studied the highly volatile and high-yield fission products of cesium (^{134}Cs and ^{137}Cs) and iodine (^{129}I and ^{131}I), which were dispersed at considerable total activities after the Fukushima accident. Rather than investigating the distribution (and state) of these high-activity fission products, Martin et al. (2019) examined fragments of transition metals, rare earth elements, and actinides found adhered to organic samples collected from across Fukushima Prefecture. As well as varying enormously in their elemental composition, the entrapped particulates comprised a wide size range (150 nanometers to >10 µm). For particulates of certain compositions (including silver, cerium, samarium, and gold), their size was correlated with the distance at which they were found from the Fukushima Dai-ichi nuclear power plant. The distribution of other materials (including zirconium, lead, tin, and barium) could not be described by such a strongly negative linear trend. Although some of the material could be attributed to Fukushima, an alternate source would be necessary to account for much of it.

Mosley et al. (2010) performed a study in which they simulated in a chamber the processes of particle removal through the infiltration of air by the building envelope. The chamber consisted of two compartments, each having a volume of 19 m^3. Particles with aerodynamic diameters between 0.05 and 5 µm were generated in one compartment and then transported through simulated leakage paths to the other compartment under the action of applied pressure differentials. The leakage paths consisted of horizontal slits (0.508 millimeters (mm) high, 102 mm deep, and 433 mm wide) between aluminum plates. The penetration factor for each size of particle was determined by simultaneously measuring the concentrations in the two compartments as functions of time and solving the mass balance equations. The measured values were compared to the predictions of a mathematical model describing deposition through settling and diffusion. At applied pressures of 2 pascals (Pa), only 2 percent of 2 µm particles and 0.1 percent of 5 µm particles passed through the slits. At 5 Pa, 40 percent of 2 µm particles and less than 1 percent of 5 µm particles passed through the slits. At 10 Pa, 85 percent of 2 µm particles and less than 1 percent of 5 µm particles passed through the slits. At 20 Pa, 90 percent of 2 µm particles and 9 percent of 5 µm particles passed through the slits. The paper gives the measured deposition rate constants for particles 0.015 to 5 µm in diameter.

Rizzo and Tomarchio (2012) collected daily air samples in Palermo, Italy, to detect potential radioactive contamination after the Fukushima accident and to monitor its concentration. They detected the radionuclides ^{131}I, ^{134}Cs, and ^{137}Cs in most samples, as well as traces of ^{132}Te–^{132}I and ^{136}Cs in a few samples. The highest airborne concentrations were 883 µBq m^{-3} for ^{131}I (particulate only), 81 µBq m^{-3} for ^{137}Cs, and 70 µBq m^{-3} for ^{134}Cs.

Güngör et al. (2014) performed a similar study in Istanbul, Turkey, after the Fukushima accident. In air filter samples collected from the Çekmece Nuclear Research and Training Center area in Istanbul, on April 4, 2011, they detected traces of fission products (^{131}I, ^{134}Cs, and ^{137}Cs). They collected samples of airborne particles daily in air filters and radio-assayed them with a high-purity germanium detector. The ^{131}I, ^{134}Cs, and ^{137}Cs were estimated to have maximum activities of 1.03 ± 0.08, 0.25 ± 0.03, and 0.23 ± 0.03 μBq m^{-3}, respectively. Güngör et al. (2014) calculated the $^{134}Cs/^{137}Cs$ ratio to be between 1.09 and 0.85. They also calculated elimination times of 8.13 days for ^{137}Cs, 7.25 days for ^{134}Cs, and 6.82 days for ^{131}I.

Effectiveness of HEPA Filter HVAC Systems

When there is radioactive contamination in the air, all particles need to be eliminated using HEPA filters, because even small concentrations of radionuclides are harmful (Linder, 1970). HEPA filters are much more effective than regular air filters in eliminating small particles (see table A2), since they are made of filter paper with very fine fibers (less than 1 μm diameter). Their efficiency can be as high as 99.99 percent. HEPA filters are designed with several deep pleats that cause moderate pressure drop and low air velocity.

Table A3 Comparison of Air Filters by Removal Efficiency for Particles of Various Sizes (Linder, 1970)

Group	Efficiency	Removal efficiency (%) for particle size of:			
		0.3 μm	1.0 μm	5.0 μm	10.0 μm
I	Low	0 - 2	10 - 30	40 - 70	90 - 98
II	Moderate	10 - 40	40 - 70	85 - 95	98 - 99
III	High	45 - 85	75 - 99	99 - 99.9	99.9
HEPA	Extreme	99.97 min	99.99	100	100

Microbial Growth with HVAC Use

An HVAC system may fail to improve IAQ in buildings with inadequate design or maintenance. Woods (1989) provides the following figures for the frequency of design and maintenance issues:

- inadequate outdoor air—75 percent of buildings
- inappropriate energy management strategies—90 percent of buildings
- poor air distribution—65 percent of buildings
- contaminated duct linings—45 percent of buildings
- inadequate condensate drains—45 percent of buildings
- inadequate filtration—55 percent of buildings
- humidifier problems—30 percent of buildings

These problems may lead to numerous issues related to IAQ. Woods (1989) identifies that 45 percent of buildings with problems show “significant microbiological contamination” due to deficiencies in design, construction, or maintenance.

HVAC systems can cause outside air pollution (Walter, 1988) and odors (Hujanen et al., 1991). Morey (1988) shows that biocontaminants can be reduced by lack of water and nutrients, and notes that porous insulation inside ducts can become dirty and wet. (Dirty surfaces provide nutrients to microorganisms.) A study sponsored by the EPA Air and Energy Engineering Research Laboratory (AEERL) evaluated relationships between structure moisture content and microbial growth. Foarde et al. (1992) used a chamber to estimate microbial growth on structural materials such as ceiling tile at various levels of relative humidity. They demonstrated that microbial growth on building materials could result from moisture contents much lower than those examined in the literature.

Ager and Tickner (1983), Morey et al. (1986), and Morey (1988) state that biocontamination problems can occur when building HVAC maintenance is poor. Thus, regardless of HVAC design, maintenance is always needed: filters need to be changed frequently, drain pipes must be flushed, etc. Researchers have explored the following questions related to maintenance of biocontaminated HVAC systems:

- Is it appropriate to use porous materials in ducts (Morey and Williams, 1991)?
- If porous materials become biocontaminated, should they be cleaned or replaced? Morey and Williams (1991) recommend replacing them, but duct cleaners recommend cleaning them (Indoor Air Quality Update, 1991).
- Are biocides needed? Morey and Williams (1991) state, “The use of biocides is never a solution to this problem [contaminated porous insulation].” Biocides may not be effective in the long term, and they may have harmful toxic effects if dispersed in an HVAC system. Continuous use of biocides in an occupied dwelling is not safe, although current practices include the injection of ozone into ductwork.

The Environmental Health Committee of ASHRAE (with partial funding from EPA/AEERL) sponsored research project TRP-662, “Air Pollution Sources in HVAC Systems.” Future ASHRAE projects include “Urban Pollution Design Criteria for Building Ventilation Inlets and Exhaust” and “Evaluation of Strategies for Controlling Indoor Concentrations of Gaseous Contaminants during Construction and Renovation.”

The studies described above have two key implications. First, HVAC maintenance practices should be reinforced through courses, publications, and standards. Second, design optimization requires the evaluation of microbial growth in HVAC systems.

Table A4 summarizes the situations in which HVAC use is either beneficial or detrimental, based on the most relevant papers reviewed here. In most cases, HVAC use is recommended.

Table A4 Situations in which HVAC Use Is Beneficial or Detrimental

Lead Author	Situations in which HVAC Use Is Beneficial	Situations in which HVAC Use Is Detrimental
Kulmala	Releases longer than ~2.5 h, especially with improved HVAC filtration efficiency	Releases shorter than ~2.5 h
Thornburg	For particles with aerodynamic diameters greater than 0.5 μm	None
Langer	To reduce indoor concentrations of PM10 and PM2.5	None
Taylor	In commercial buildings, where indoor pollution levels are much lower thanks to HVAC system operation, filters, and complex building geometries	None
Irga and Torpy	To reduce concentrations of fungi, which are higher in buildings with natural or mixed ventilation	None
Chen	For particles of diameter 0.01–1.0 μm, for which MERV 7 filters provide up to 30% removal efficiencies when air conditioning is on; also, for particles of diameter 0.17–2.5 μm (lower I/O ratios)	For particles smaller than about 0.1 μm, for which the I/O ratio tends to be higher with air conditioning on than without
Ward	For sheltering following acts of bioterrorism, since HVAC can be used for quick removal of indoor particles	None
Chan	After an outdoor plume has passed, when people should ventilate their shelters to minimize exposure to residual indoor contamination	None
Engelmann	In buildings with electrostatic and high-efficiency filters (where I/O ratios of 0.07 and 0.08 were observed)	None
Hanley	With a charged-fiber filter, which appears to have significantly increased initial filtration efficiency	None

In-Room HVAC Units

To reduce or eliminate HVAC system contamination, it is often more effective to control pollutants near their source than to use centralized HVAC (Owen et al., 1990). In-room HVAC units can be used for this application; however, studies and testing are needed to optimize their position in a room and their capacity, as well as to identify any restrictions or limits on their use.

The Association of Home Appliance Manufacturers (AHAM) provides a test procedure for in-room HVAC units (AHAM, 1987), which allows the estimation of the unit's initial removal efficiency using the theory of perfectly mixed reactor vessels. In-room HVAC units continuously recirculate the air from discharge to suction; their effectiveness for allergen control has been studied (Nelson et al., 1988). Offermann et al. (1985) have tested their effectiveness in controlling in-room respirable particles.

Daisey and Hodgson (1989) performed an experiment similar to the AHAM procedure to eliminate VOCs and nitrogen dioxide using in-room HVAC. They found that the AHAM procedure works better for gases than for particles. It may be useful to study the efficiency of particle removal through HVAC as a function of particle size.

As described above (see table A2), Thornburg et al. (2001) developed a time-dependent IAQ model incorporating all potential particle sources and loss mechanisms, to study the relationship between indoor and outdoor particle concentrations. Figure A1 is adapted from figure A2 of Thornburg et al. (2001), which shows the I/O concentration ratios as a function of particle size for three building types: (1) a commercial building, (2) a house with HVAC, and (3) a house without HVAC. In figure A1, the house data are highlighted. For particle sizes between 0.1 and 0.9 µm, the results for the houses with and without HVAC are close, although the house with HVAC always has slightly lower contaminant concentrations. However, for particle sizes smaller than 0.1 µm or larger than 0.9 µm, the house with HVAC has much lower contaminant concentrations. The results of Thornburg et al. (2001) thus show that HVAC use is beneficial.

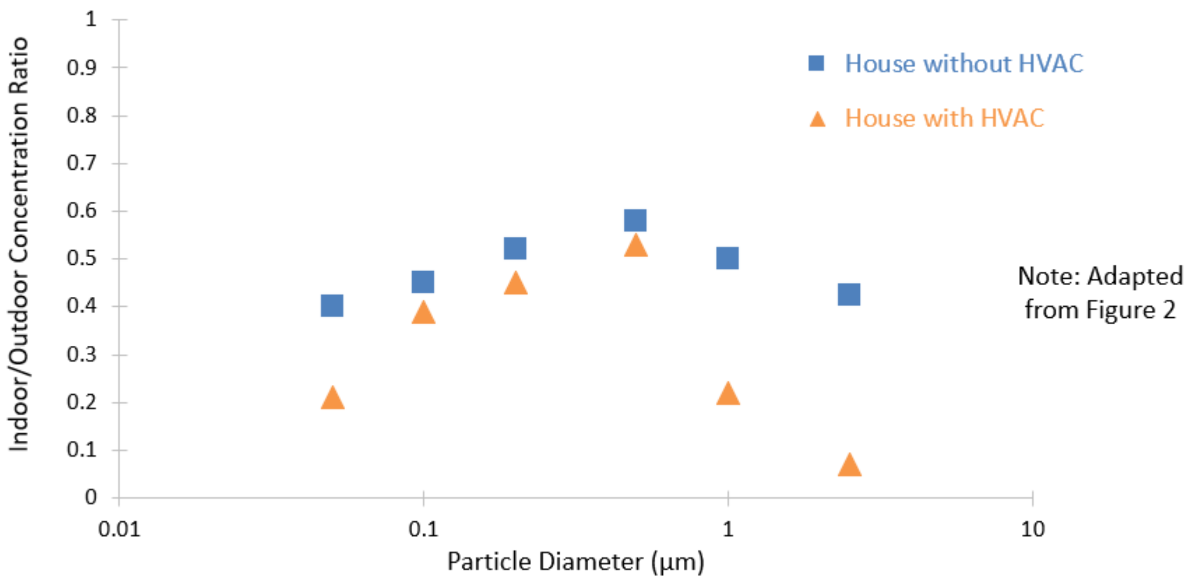

Figure A1 I/O concentration ratio versus particle diameter (Thornburg et al., 2001)

Sheltering in Place during Radiological Release

SIP is one means of protection against radiation exposure; the reduction factor it provides for radiation exposure is determined by the ratio of indoor to outdoor cumulative radioactivity doses. The reduction factor can be calculated by studying the air exchange between the indoor and outdoor environments (Hirouchi et al., 2021).

Indoor radioactivity concentration can be determined by simulating the air exchange and indoor concentration of radionuclides (Brenk and De Witt, 1987; Roed and Goddard, 1991; Lee et al., 2014). The indoor radionuclide concentration depends primarily on the AER, indoor deposition rate, and penetration factor. Hirouchi et al. (2021) defined the indoor deposition rate as the rate at which nuclides are eliminated from indoor air through deposition on floors, walls, and ceilings. The penetration factor is the ratio of the concentration in a parcel of air immediately after it enters a building to the concentration in that parcel immediately before entry.

Kulmala et al. (2016) developed a tool for modeling indoor particle concentrations due to outdoor contaminants. The tool numerically solves the simplified mass balance equation describing the size-resolved behavior of airborne particles, using as input experimentally obtained data on particle concentrations outdoors, in the supply air, and indoors. By eliminating the effect of indoor sources, the tool accurately determines the size-resolved I/O ratio for fine particles. Figure A2 shows the concentration of the contaminates over time. The solid black line represents the outdoor concentration, which is considered to be the maximum (100 percent). In the first couple of hours, the dotted blue line, which shows the indoor concentration with HVAC off, is lower than the lines for the concentration with HVAC on. After a few hours, however, the houses with

HVAC on have much lower contamination concentrations. The better the filter efficiency, the lower the contamination concentrations.

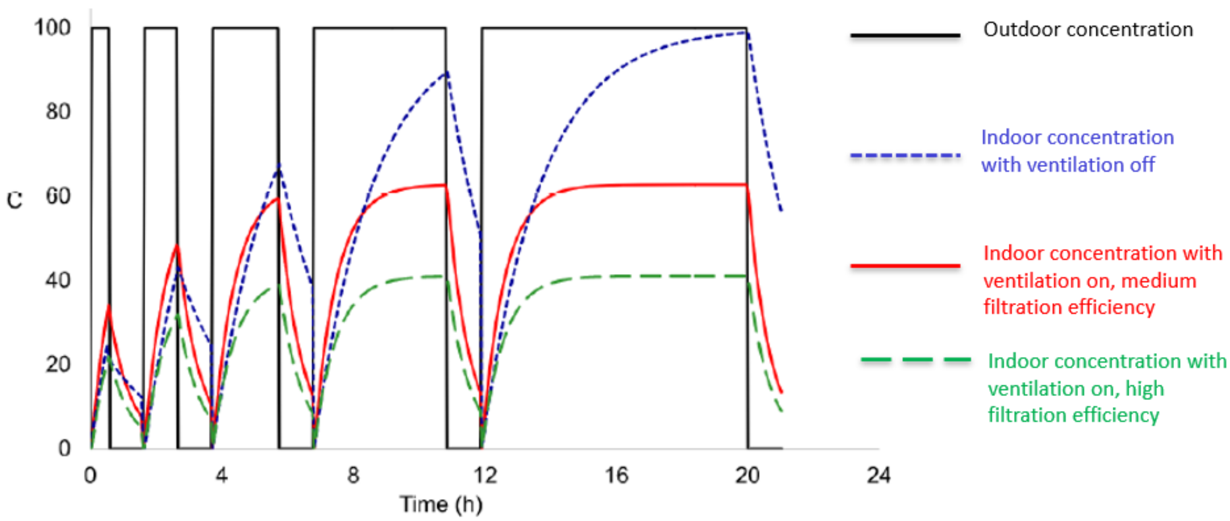

Figure A2 Tool from Kulmala et al. (2016) showing concentration versus time

Hirouchi et al. (2017) calculated the reduction factor of SIP for internal exposure in Japanese dwellings, using the AER found in Japanese houses. Because data were lacking for Japan, they used the penetration factor and indoor deposition rate determined in other countries. However, the penetration factor and indoor deposition rate may differ between Western and Japanese houses, since these parameters are linked to building construction materials (Hussein et al., 2009; Liu and Nazaroff, 2001; Thatcher et al., 2003). The literature shows that these parameters have ambiguity (Hirouchi et al., 2021). Therefore, Hirouchi et al. (2021) investigated these parameters for Japanese dwellings to find the reduction factor for SIP.

Internal exposures in the early phases of nuclear release are mainly from iodine. Three states of iodine can be discharged into the environment (Hirouchi et al., 2021): (1) solid particulate iodine compounds, (2) elementary iodine (I_2) in a gaseous state, and (3) organic iodine in a gaseous state (e.g., CH_3I). Organic iodine does not stick to walls or floors because it has low reactivity, but I_2 sticks to walls and floors because of its high reactivity (Hirouchi et al., 2021). The particulate iodine released from the Chernobyl accident ranged in size from 0.3 to 1 μm (Hirouchi et al., 2021). Its behavior may be studied by studying that of any particles of the same diameter.

Hirouchi et al. (2021) developed data on the indoor deposition rate and penetration factor for I_2 and particles in Japanese dwellings through two experiments: (1) the “house experiment,” conducted in real Japanese dwellings, and (2) the “laboratory experiment,” performed inside a chamber in which various climate factors, such as temperature, humidity, and AER, could be adjusted. Because I_2 is toxic, Hirouchi et al. (2021) did not use this radionuclide directly in their house experiment. Instead, they conducted laboratory experiments for I_2; the results were not exactly the values that would be associated with a house. Hirouchi et al. (2021) found a correlation for specific parameters between a real house and a chamber. They assessed parameters for I_2 using only laboratory experiments, then used a correlation factor to convert these parameters to the values for a house.

Hirouchi et al. (2021) computed the penetration factor and indoor deposition rate using a compartment model simulating the indoor setting and the air exchange between the inside and outside environments. This model is the same as that of Hirouchi et al. (2017). It consists of three compartments: outdoor air, indoor air, and indoor surfaces (including floor, ceiling, and walls). The air exchange is driven by natural ventilation only. The transfer from air to surfaces is driven by deposition only. The equation for temporal change in indoor concentration is as follows:

$$\frac{dC_I}{dt} = P\lambda_e C_O - (\lambda_e + \lambda_d + \lambda) C_I,$$

where C_I is the indoor concentration (m^{-3}), C_O is the outdoor concentration (m^{-3}), P is the penetration factor (dimensionless, $P \leqslant 1$), λ_e is the AER (h^{-1}), λ_d is the indoor deposition rate (h^{-1}), and λ is the decay constant (h^{-1}). Hirouchi et al. (2021) set λ equal to 0 because they used stable elements. The unknowns in equation (6) are the AER, penetration factor, and indoor deposition rate.

Rajhans (1989) and Lane et al. (1989) studied building performance and ventilation to understand building ventilation systems and to measure AER and ventilation effectiveness. Several researchers in the United States and abroad have used computational fluid dynamics (CFD) techniques to model flow in rooms (Jones, 1990; Kurabuchi et al., 1989; Murakami and Kato, 1989; Nielsen, 1989). In these studies, the flow field of the room is computed using the Navier-Stokes equations, and experiments are performed to validate the models. The models produce velocity and turbulence fields for the rooms studied. Baker et al. (1989) showed how CFD techniques could be used to design building ventilation systems.

Kim et al. (1990) developed a three-dimensional microscopic model which neglected turbulence effects and assumed spherical airflow exit from the diffuser; using this model, they evaluated the correlation between the AER and the pollutant in a room. Yamamoto et al. (1993) developed a two-dimensional “ventilation helper” microscopic model utilizing menus and graphical data entry. This model evaluates changes in ventilation effectiveness due to changes in supply duct and contaminant source location.

In rooms, airflow patterns over contaminant sources are not clear; this limits the use of existing equations to model ventilation effectiveness. Dunn and Tichenor (1988) considered a thin-film source in their model of sink effects in well-mixed emissions test chambers. Source/sink experimental studies have been performed by Tichenor (1989), Tichenor et al. (1991), Black et al. (1991), and Saarela and Sandell (1991). Sparks et al. (1990) integrated a source/sink model into a building model to estimate concentration in a room. A study performed by Guo et al. (1990) defines the boundary layer transport problems as two resistances in series. Sollinger et al. (1993) provide chamber emissions data that show a spike in total mass emissions at high AERs.

He et al. (2005) investigated indoor air in residential houses in Brisbane, Australia, to quantify the particle deposition rate of size-classified particles ranging from 0.015 to 6 μm. They measured particle size distribution from cooking, under two different ventilation conditions, in 14 houses. They also evaluated the changes in particle size distribution and PM2.5 concentration as a function of time. The pattern found by He et al. (2005) for the deposition rate as a function of particle size is similar to that of other studies; however, the actual deposition rates differ across studies because of the calculation methods.

For Hirouchi et al. (2021), the indoor deposition rate was greater for larger particles in both the laboratory experiment and the house experiment. This is consistent with other experiments and theories (Lai and Nazaroff, 2000; Lai, 2004; Thatcher et al., 2002). Thatcher et al. (2003) found an indoor deposition rate of 0.01–1 h^{-1} for particles of diameter 0.1–1 μm, based on particle size and house type, for houses with furnishings and ventilation to mix the inside air. The indoor deposition rate depends on house furnishings, ventilation (Thatcher et al., 2002), and surface roughness (Hussein et al., 2009). The indoor particle deposition rate found by Hirouchi et al. (2021) was smaller than that of Thatcher et al. (2003), because the former did not consider ventilation. Differences in furnishings and surface roughness (floor material) contribute to the lower deposition rate.

Hirouchi et al. (2021) also performed experiments to understand how the indoor deposition rate depends on the floor material, by changing the material at the bottom of the chamber. Hussein et al. (2009) found that the indoor deposition rate was lower for smooth surfaces than for rough surfaces. The experiments of Hirouchi et al. (2021) indicated that the highest indoor deposition rate occurred on carpets, followed by tatami mats, wood floors, and stainless steel, consistent with the conclusions of Hussein et al. (2009).

According to Liu and Nazaroff (2001), the penetration factor of a building depends on the building material. Thatcher et al. (2003) determined that the penetration factor was 0.5–1 for particles of sizes 0.1–1 μm, depending on the building and the range of AERs. Hirouchi et al. (2021) concluded that the penetration factor was independent of the building, although the penetration factor in their experiment matched the penetration factor in experiments conducted in Western houses.

In the experiments of Hirouchi et al. (2021), the major penetration paths by which particles entered the testing rooms were through windows and doors. The testing rooms had window frames made of aluminum and doors made of wood. Because all testing rooms used similar materials, the penetration factors did not change from house to house. However, the penetration factor is correlated with the AER, which is different in each house. The difference between the penetration factors obtained by Thatcher et al. (2003) and Hirouchi et al. (2021) is mainly due to the difference in airflow rates, which arises from the different AERs.

The penetration factor is associated with the characteristics of species, gap length, gap height, and number of bends (Liu and Nazaroff, 2001). In the study of Hirouchi et al. (2021), the gap characteristics (e.g., gap length and height, number of bends) in the particle experiments are similar to those in the I_2 experiments. Thus, the difference between the particle and I_2 penetration factors arises from the respective characteristics of particles and I_2, such as reaction probability, travel time in gaps, and deposition rate.

Lee et al. (2014) used a nonlinear regression methodology to study size-resolved particle deposition rates for ultrafine and submicrometer particles with unknown background concentrations. They performed their experiment for a nonsourced setting, and then later for a sourced setting, in a well-mixed dwelling. They found that the particle deposition rate was a function of particle size and ranged from 0.68 ± 0.10 to 5.03 ± 0.20 h^{-1} (mean ± standard error). Air exchange had an insignificant impact on particle deposition when there was forced air mixing. However, for several size categories, the correlation between AER and particle deposition rates showed a possible influence of air exchange on particle deposition. Future research should apply the results of Lee et al. (2014) to study the individual or combined impact of air exchange and air mixing on particle deposition rates, to explore human exposure to ultrafine and submicrometer particles during SIP.

Spencer (1962) developed a theory of structure shielding from fallout gamma radiation for elementary structure types, such as density interfaces, foxholes, shielded foxholes or basements, light superstructures, vertical walls, blockhouses, vents, compartmentalization effects, and mazes. Graphs are presented for engineering calculations, including many obtained from angular distributions of the exposure dose. Results are given for a fission spectrum and for cobalt-60 and ^{137}Cs sources. This information was obtained from modeling; experimental data are also mentioned.

Hubbell and Spencer (1964) provided theoretical analyses, descriptions of laboratory experiments, and field test data on the penetration of fallout gamma rays and neutrons. Figure A3 shows some simple absorbers analyzed in their study that can be combined to make real structures. For example, an underground shelter is a combination of a shielded foxhole with a maze entrance and possibly a maze ventilation system. An aboveground shelter is a blockhouse that consists of a vertical wall with vents, together with an overhead slab that shields like a shielded basement or foxhole. Most frame houses are simple light superstructures. A large apartment building combines a blockhouse with vertical walls, compartmentation, vents, and in-and-down configurations. Note that the air–ground density interface plays an important role in structure shielding. Table 10 in Hubbell and Spencer (1964) shows experiments and calculations for existing buildings and other structures.

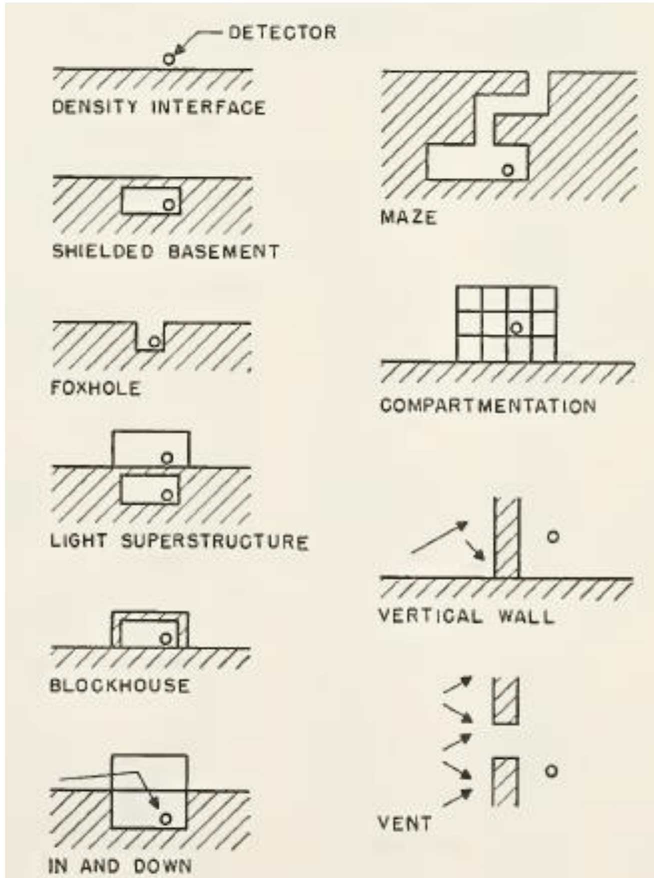

Figure A3 Simple geometries (Hubbell and Spencer, 1964)

Chan et al. (2004) state that SIP is effective for large-scale outdoor releases. They recommend SIP for releases with a duration of a few hours or less, because the building envelope can reduce the I/O air exchange and filter some biological or chemical contamination, while toxic materials can also be deposited onto indoor surfaces. Tightening of the building envelope and improved filtration can increase the effectiveness of SIP. Table A5 shows the leakage and air infiltration rates of U.S. residential houses under different weather conditions (Chan et al., 2004).

Table A5 Typical Normalized Leakage and Air Infiltration Rates of U.S. Residential Houses under Various Weather Conditions (Chan et al., 2004)

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

Dickson (2013) developed a model and performed experiments to evaluate the shielding provided by U.S. residential structures against radiation. The validated computational models for housing units and new protection factors in Dickson (2013) represent a first step in improving evaluation capabilities and reducing the uncertainty in quantifying shelter quality. They also provide an alternative to the data historically relied upon, and they demonstrate that homes can serve as effective shielding tools to reduce radiological risk to the general population.

Yu et al. (2003) developed the RESRAD-BUILD computer code to model the potential radiological dose incurred by an individual who works or lives in a building contaminated with radioactive material. This code calculates the transport of radioactive material within the building from one compartment to another, using an IAQ model that accounts for the transport of radioactive dust particulates and radon progeny due to air exchange, deposition and resuspension, and radioactive decay and ingrowth.

Chan et al. (2005) analyzed more than 70,000 air leakage measurements in houses across the United States to relate leakage area—the effective size of all penetrations of the building shell—to readily available building characteristics (such as building size, year built, geographic region, and various construction characteristics). After adjusting for the lack of statistical representativeness of the data, Chan et al. (2005) found that the distribution of leakage area normalized by floor area was approximately log-normal.

The Federal Emergency Management Agency (2018) states that the duration of SIP is incident-dependent and varies by jurisdiction size, location, and resources. The characteristics of SIP are incident-specific, and circumstances such as a community's demographics, infrastructure, resources, authorities, and decision-making process drive the relevant protective actions.

Sorensen et al. (2002) states that to determine whether SIP is appropriate, emergency planners must be able to predict the outdoor plume concentration of the toxic chemicals that will occur in the risk area, estimate the concentration that will occur inside the buildings in which people seek shelter, and calculate the indoor estimated level of exposure. The emergency planning tool Protective Action Dosage Reduction Estimator (PADRE) allows planners to assess the expected dosage reduction from implementing alternative protective actions under different scenarios.

Dickson and Hamby (2016) described a simplified method for calculating source-term-dependent building protection and shielding factors for generic one- and two-story housing-unit models. Typically, radionuclide-independent factors are applied generically to external dose coefficients to account for the radiation shielding effects of indoor residences. In reality, the shielding effectiveness of each housing unit would change over time as the radionuclide mixture and gamma-ray energy spectrum changed, owing to physical effects such as deposition, radioactive decay, weathering, and decontamination efforts. Thus, to realistically estimate the shielding effectiveness of a particular building, it is necessary to derive factors for multiple photon energy spectra. However, it is impractical to develop factors specific to a spectrum of photons emitted by every radionuclide of interest. Therefore, Dickson and Hamby (2016) performed Monte Carlo simulations for 16 monoenergetic photon energies, from 0.10 to 3.0 megaelectronvolts (MeV), to characterize the three-dimensional radiation fluence through each housing unit produced by two idealized, yet realistic, environmental exposure scenarios. They used the results of these simulations to develop fitted logarithmic functions (extrapolated to 0.0 MeV) to correlate an estimated factor to any monoenergetic photon energy up to 3.0 MeV. To verify these functions, another series of Monte Carlo simulations was performed for a selected set of radionuclides to develop radionuclide-specific building protection and shielding factors.

Jetter and Whitfield (2005) evaluated the effectiveness of expedient SIP in a residence for protection against airborne hazards, as outlined in guidance to the public provided by the U.S. Department of Homeland Security (DHS). They developed an improved method of determining the airflow rate for a shelter inside a house. Participants following the DHS guidance applied expedient sheltering measures (plastic sheeting and duct tape) to a room inside a test house. Measured airflow rates were used to determine protection factors for various scenarios. Protection factors were calculated for the house and shelter under various occupancy times, weather conditions, and outdoor exposure times for hazardous agents. Protection factors ranged from 1.3 to 539, depending on the conditions. Jetter and Whitfield (2005) found that proper sealing substantially increased the effectiveness of the shelter. They note that SIP is most beneficial if people enter shelters before the arrival of a cloud of hazardous agent, and exit shelters as soon as the cloud has passed over; on the other hand, SIP can be detrimental if people enter or exit shelters too late. In most scenarios, CO_2 and oxygen (O_2) concentrations inside the shelter are not likely to reach dangerous levels, but they could do so under certain conditions, which may particularly affect individuals with respiratory problems.

Thatcher and Layton (1995) measured aerosol concentrations and particle size distributions indoors and outdoors at a two-story residence in California in the summer. They collected all indoor samples from a single central sampling point in the downstairs living area. They measured the deposition rate for supermicron particles by raising the particle concentration indoors and simultaneously measuring air infiltration rates and particle concentration decay rates. For particles 1–5 μm in diameter, the deposition velocity closely matched the calculated settling velocity. For particles larger than 5 μm, the deposition velocity was less than the calculated settling velocity, probably because the particles were nonspherical. The penetration factor for supermicron particles was calculated using the experimentally determined deposition velocities and I/O particle ratios when no resuspension or generation activities were present. A penetration factor of one was found, indicating that the building shell was not effective at removing infiltrating particles. Resuspension was measured under various conditions and was found to have a significant impact on indoor particle concentration. In particular, a person walking into a room could increase the particle concentration by 100 percent for some supermicron particle sizes. For light activity with four people in the residence, Thatcher and Layton (1995) found a resuspension rate between 1.8×10^{-5} and 3.8×10^{-4} h^{-1} for supermicron particles, assuming a particle density of 1 gram/m^3. These calculated rates may be lower than actual rates, because of assumptions made about the particle size distribution of the floor dust.

Champlin and D'Aloia (2020) developed a decision-making analysis tool that calculates the total dose received during a radiological release for a person inside various types of shelter. The calculation uses models developed to account for the shielding effects that the shelter would provide for the dose pathways of groundshine, cloudshine, and inhalation. The tool developed—the Post-radiological Incident Shelter-in-Place vs. Evacuation Model (PRISEM)—can calculate both the reduction in dose provided by shelters and the dose incurred during evacuation, so that decision-makers can compare the two options directly when choosing protective actions. Champlin and D'Aloia (2020) found that SIP was extremely helpful in some scenarios, as the accumulated dose received while sheltered was much smaller than the dose levels under the predetermined PAG for much of the population.

Hirouchi et al. (2018) state that the effectiveness of sheltering against internal exposure can be expressed by the I/O ratio of radioactivity concentrations. The indoor concentration is controlled by the indoor-to-outdoor air exchange and the indoor behavior. These phenomena are captured by the natural AER, indoor deposition rate, and penetration factor, which have been investigated in Western countries but cannot be applied to Japanese houses, since they depend on dwelling characteristics, such as airtightness, and environmental factors, such as wind speed.

Sugitatsu (2020) assessed the effectiveness of SIP and estimated doses for a radioactive release from a hypothetical accident involving a small modular reactor. Sugitatsu (2020) investigated releases of radioactive material from station blackout and loss-of-coolant accidents, estimated shielding factors for one-story and two-story houses, and evaluated the effects of roof and wall materials on projected doses.

Monzen et al. (2014) measured absorbed dose rates in the indoor and outdoor air at evacuation sites in Fukushima Prefecture using gamma-ray measuring devices, then calculated individual radiation exposure by assessing the radiation dose reduction efficiency (defined as the ratio of absorbed dose rate in indoor air to absorbed dose rate in outdoor air) of wood, aluminum, and reinforced concrete buildings. They found that between March and July 2011, the dose reduction efficiencies of wood, aluminum, and reinforced concrete buildings were 0.5560.04, 0.1560.02, and 0.1960.04, respectively. The dose reduction efficiency of wood structures was 1.4 times higher than that reported by the International Atomic Energy Agency. The dose reduction efficiency of reinforced concrete structures was similar to previously reported values; that of aluminum structures had not previously been reported. Dose reduction efficiency increased in proportion to the distance from the Fukushima Dai-ichi nuclear power plant at 8 of the 18 evacuation sites. Time variations did not reflect dose reduction efficiencies at evacuation sites, although absorbed dose rates in outdoor air decreased. These data suggest that dose reduction efficiency depends on structure types, levels of contamination, and evacuee behaviors at evacuation sites.

Choi and Kang (2017) investigated the infiltration of ambient PM2.5 through the building envelope in 11 apartment housing units in Korea. To maintain a consistent I/O pressure difference in all tests, they implemented the onsite infiltration test method, by using a blower-door depressurization procedure. They found an average infiltration factor of 0.65 ± 0.13 (average ± standard deviation), with a minimum of 0.38 and a maximum of 0.88. The relationship between the building airtightness data and the infiltration factors suggests that ambient PM2.5 would more strongly affect a leaky housing unit with high ACH50 (air changes per hour at 50 pascals pressure differential), or a high specific effective leakage area.

Choi and Kang (2018) performed onsite field experiments on 14 apartment housing units located in urban areas in Korea to measure the I/O ratios of number concentrations of size-resolved particles (in diameter ranges of 0.3–0.5, 0.5–1.0, 1.0–3.0, 3.0–5.0, 5.0–10.0, and >10.0 µm). For consistency and to examine the effects of pressure differences, they used a blower-door depressurization procedure to control the I/O pressure difference at 10, 30, and 50 Pa in all tests. Simultaneously, they measured the air leakage characteristics of housing units, using the typical blower-door pressurization-depressurization test method to correlate air leakage data and I/O ratios. As expected, they found that moderately airtight housing units (ACH50 ≤ 4.4) show lower I/O ratios than average leaky housing units (ACH50 > 4.4); still, the averaged I/O ratios of finer particles (0.3–0.5, 0.5–1.0, and 1.0–3.0 µm) in the moderately airtight housing units were 0.75, 0.59, and 0.61 at an I/O pressure difference of 50 Pa, and 0.62, 0.51, and 0.49 at 10 Pa. This means that residents in moderately airtight Korean multifamily housing units with relatively small envelope area may still be exposed to high indoor concentrations of fine particles originating outdoors.

Indoor Particle Penetration and Deposition

Some outdoor pollutants—such as car engine exhaust, stack emissions, and ambient SO_2, NO_x, ozone, and pollens—can enter buildings through infiltration, natural ventilation, or HVAC systems. The dispersion of particles to a dwelling, then through the envelope and into the dwelling, should be investigated, as should the resulting IAQ issues. The following are among the principal areas of research needed:

- entry of polluted outdoor air through the HVAC system
- outdoor air leaks through the building envelope

Polluted air can enter a building through the HVAC system if the outdoor air intake is not installed correctly. Morey (1988) gives some information about improper intakes.

Nazaroff and Cass (1986, 1989) developed two models to describe indoor air space pollution. The first model estimates the concentrations of NO_x and ozone for indoor air; the second simulates aerosol size distributions. Concentrations from source emissions, AERs, and filtration efficiencies can be calculated using these models.

Thatcher et al. (2003) performed particle measurements in two houses to determine the correlation between particle penetration and indoor deposition. Their experiments had three phases: (1) particle loss rate measurement following forced elevation of indoor particle concentrations, (2) quick reduction in particle concentration using ventilation through pressurization of the houses with HEPA-filtered air, and (3) particle concentration measurement after house pressurization. They found that particle concentration decay when indoor concentrations were elevated and losses from deposition were larger than gains from particle infiltration. They used a transient two-parameter model to analyze how large differences in indoor concentration lead to the separation of penetration and deposition losses. They found that in the two houses studied, as particle diameters increased from 0.1 to 10 µm, penetration factors fell from about 1 to 0.3 and deposition loss rates grew from 0.1 to 5 h^{-1}. The drop in penetration factor with increasing particle size was less visible in the house with the larger normalized leakage space.

Model from Thatcher et al. (2003)

Indoor particle concentration arises from a balance of the particle sources and sinks in the indoor environment. The following equation explains the indoor concentration of particles of a given size and composition:

$$\frac{\partial C_I}{\partial t} = (C_o P - C_I)\lambda_v - C_I \beta + G + S + F + K + H$$

where C_I and C_o are respectively the indoor and outdoor particle concentrations at time t (per cubic centimeter (cm^{-3})), t is time (h), P is the penetration factor, λ_v is the AER (h^{-1}), β is the deposition loss rate (h^{-1}), G is the rate of formation of particles indoors (cm^{-3} h^{-1}), S is the rate of particle generation through gas-particle conversion (cm^{-3} h^{-1}), F is the rate of particle formation through chemical reaction (cm^{-3} h^{-1}), and K and H express the change in particle sizes through coagulation and hygroscopic growth, respectively (cm^{-3} h^{-1}). Thatcher et al. (2003) assumed that coagulation (K), hygroscopic growth (H), and formation (F) had no effect on indoor particle concentrations for the conditions and particle size domains in their experiments.

Indoor sources (G) were avoided by using a vacant space and operating equipment, such as pumps, that generate particles outdoors. Thus, Thatcher et al. (2003) assumed that G was insignificant. Some experiments yielded overly complex results because of the dissociation and vaporization of ammonium nitrate particles (S); Thatcher et al. (2003) therefore ignored conditions with high ammonium nitrate concentrations.

Deposition and penetration losses significantly affect both indoor particle concentrations and exposures. It is complicated to separate the effects of these factors, since they are activated at the same time in the experiment. Thatcher et al. (2003) developed a method for calculating size-resolved penetration factors and deposition loss rates in full-scale homes; however, there is some uncertainty in their method, since it was applied in only two houses. Thatcher et al. (2002) suggested that indoor particle deposition rates (which affect indoor particle concentrations) depend on particle size, furniture, and indoor air velocity.

Argyropoulos et al. (2020) study techniques for predicting PM2.5 and PM10 infiltration in typical commercial and office building environments during severe dust storms. They conducted a 2-month field campaign to capture such an event in Doha, Qatar, and developed a modeling methodology based on the one-way coupling of a multizone and CFD software. Their predicted levels were in fair agreement with the measurements for both the dust storm and typical days, with improved agreement when the efficiency of the ventilation filters was estimated from measurements rather than being extracted from specification sheets. The predictions of their model were found to conform with physical reality.

Lange (1995) measured the filter factor of the building envelope, and the average indoor deposition velocity, using beryllium-7 (^{7}Be) as a marker. When the first cloud of radioactive material from the Chernobyl accident passed over Denmark, this experiment was in process and I/O ratios were measured for a series of radionuclides. Dose reduction factors (DRFs) were estimated to be between 0.27 and 0.49 for particulate iodine and cesium with an AER of 0.4 h^{-1}. The size-specific I/O ratio of ^{7}Be-labeled particles were estimated using two impactors. Radionuclide concentration was measured by gamma spectrometry. The activity distributions were measured with an eight-stage Berner impactor from Hauke GmBH; they are characterized by their activity median aerodynamic diameter (AMAD). The same distributions were estimated for ^{137}Cs, rubidium-103 (^{103}Ru), and tellurium-132 (^{132}Te): the AMAD ranged from 0.5 to 0.85 μm and tended to increase with increasing distance from the point of release, because of a slow growth from coagulation during transport. Particulate I-131 exhibited a different distribution: the size range was wider and had a lower AMAD of 0.4–0.5 μm. The deposition velocities estimated from these data, with the assumption of no filtration, matched the deposition velocities measured with artificial markers. Lange (1995) showed that filtration by the building envelope is insignificant for particle sizes of 0.35–2.8 μm.

For the EPA Office of Toxic Substances, GEOMET Technologies developed the Multichamber Consumer Exposure Model, which calculates indoor exposures for chemicals released from household goods in buildings with up to four zones (GEOMET Technologies, Inc., 1989). The input for the model includes time-varying emission rates for a contaminant in each zone of the house, outdoor concentrations, and occupied zones. The user can either enter the infiltration and interzonal flow rates and zone volumes as input, or use a data set for a specific type of residence and geographic location.

Engelmann (1991) calculated DRFs for plutonium and found that the DRF was very low for tight buildings, particularly for plumes of short duration. These findings imply that SIP is an effective protective action for releases of radionuclides whose primary pathway is inhalation. The sensitivity of the DRF to the rate of interior deposition of the contaminant should be considered the best estimates in the research of Engelmann (1991). The interior deposition velocity depends on the movement of air in the shelter and on the length of time since the contaminant entered the shelter.

The Indoor Air Quality Model for Personal Computers estimates concentrations for a multizone indoor environment, simulating various microenvironments (Owen et al., 1989).

The AEERL IAQ model INDOOR (Sparks and Tucker, 1990; Sparks et al., 1990) is integrated with emission factors for sources and a data set of interzonal flows; it can model concentrations throughout the EPA test house.

The COMIS infiltration model is a modular computer program developed by Feustel et al. (1989) and Feustel (1990). Work on the model began in 1988 at a workshop held at Lawrence Berkeley National Laboratory. COMIS provides both IAQ and infiltration modeling.

CONTAM, the General Indoor Air Pollution Concentration Model developed by the National Institutes of Standards and Technology, is based on a multizone environment. CONTAM models different rooms in the building with uniform concentrations. It simulates infiltration, dilution, and exfiltration by specifying interzonal flows for each pathway. CONTAMps is a PC-based version with graphical user interface (Axley, 1990).

Persily (1986) performed tracer gas experiments to measure AER and evaluate building ventilation effectiveness but found it difficult to apply tracer gas in the rooms of a large building; he therefore stated that the results were ambiguous. Crawford and O'Neill (1989) reached similar conclusions.

Building outdoor air rates have been measured using CO_2 and SF_6 as tracers (Bearg and Turner, 1989). Bearg and Turner also had problems with tracer gas research in large buildings, because conditions are not uniform throughout a large building, and airflow does not come solely from the HVAC system.

The passive perfluorocarbon tracer gas (PPTG) technique, originally developed by Russell N. Dietz, is explained by Zarker (1989). The PPTG technique provides an average AER, over a period from 1 week to months long, for various building zones. One can calculate the AER from room dimensions, the concentration in the sorption tube, temperature, and emission rates. If various tracer gases are used, multizone buildings can also be studied, as done, for example, by Fisk et al. (1985). Crawford and O'Neill (1989) presented a multizone airflow model applying one tracer gas, which they later validated in a three-zone test facility located at the University of Illinois (O'Neill and Crawford, 1990).

Guidelines for Sheltering in Place

U.S. Environmental Protection Agency Guidelines

The EPA's mission is to protect human health and the environment through research, public outreach, and the development and enforcement of regulations on a wide range of environmental topics. The EPA regulates the manufacturing, processing, distribution, and use of chemicals and other pollutants; it also determines safe tolerance levels for chemicals and other pollutants in food, animal feed, and water.

Many public structures can provide shelter protection to significantly reduce whole-body (WB) and thyroid dose from exposure to radioactive gaseous fission products released during a nuclear power plant accident. Protective sheltering is an attractive option if shelter-access timing is ideal, but its effectiveness diminishes almost linearly with access delay time after cloud arrival. The protection afforded by sheltering against inhalation exposures that would result in thyroid dose depends on the number of air changes taking place over the period of exposure to airborne radioactive cloud material. Sheltering protection for WB exposures depends on the attenuation of gamma radiation originating from the airborne cloud source, the number of air changes during cloud exposure, and (to a lesser extent) the attenuation of gamma radiation originating from the ground fallout around the shelter structure. Accordingly, optimum ventilation control (low AERs during cloud passage) is more effective for reducing thyroid dose than WB dose, and it is more effective for reducing WB dose in large structures (LSs) than in small structures (SSs). Generally, LSs such as office buildings, multistory apartment complexes, and department stores provide significantly more protection from WB exposures than smaller structures such as single-family dwellings—by a factor of about 4.5 for low AERs and another factor of 3 for representative AERs. That is, if AER is low, then SS sheltering will reduce WB dose by a factor of 2.5 to 3, and LS sheltering will reduce them by a factor of about 12. For representative AERs, SS and LS sheltering will reduce WB dose by factors of about 2.3 and 6–9, respectively; see EPA-520/1-78-001A, "Protective Action Evaluation, Part I: The Effectiveness of Sheltering as a Protective Action against Nuclear Accidents Involving Gaseous Releases," issued April 1978 (Anno and Dore, 1978).

WB dose can be further reduced in a shelter structure through the use of expedient filtration (e.g., by stuffing cracks and openings with cloth or paper) to reduce the natural AER or radioactive material ingress, as discussed on page 10 of EPA-520/1-78-001A. Another means of respiratory protection is to cover the nose and mouth with towels, handkerchiefs, or toilet paper; for example, a crumpled handkerchief (or one folded into eight or more layers), a towel folded into three or more layers, or toilet paper in three or more layers can reduce inhaled radioactive material (EPA-520/1-78-001A considers particulate iodine) by a factor of about 10. In an SS, however, the reduction in WB dose is not appreciable—about 2.5 percent for low AERs and about 15 percent for representative AERs. In an LS, the reduction in WB dose is greater—about 13 percent for low AERs and about 70 percent for representative AERs. The difference between

SS and LS shelters is less clear for thyroid dose protection than for WB dose protection, because the general structure type is more nebulously correlated with building AERs than with gamma radiation attenuation properties. The variability in the AER—an important parameter affecting thyroid exposure—prevents meaningful estimates of the thyroid DRF of SS and LS shelters. Accordingly, LSs may not offer any protective advantage over SSs—or vice versa—for thyroid dose reduction, owing to any number of factors (e.g., open portals, filtering action, air conditioning, structural integrity). Either SS or LS sheltering, however, can reduce thyroid dose by a factor of 20–70 for low AERs and a factor of 4–10 for representative AERs. These ranges correspond to cloud exposure periods of 0.5–3 hours, for which the DRF increases (although not linearly) with the AER (or number of air changes).

Another important parameter affecting the thyroid DRF (and also the WB DRF, to a lesser extent) is the ingress fraction, which EPA-520/1-78-001A treats as an effective filtering action. Thyroid DRF values scale linearly with whatever value is assumed for the ingress fraction. Expedient filtration (i.e., reducing radioiodine ingress and/or ventilation by stuffing openings and cracks or using handkerchiefs and towels for respiratory protection) may be even more effective for reducing thyroid dose than WB dose; it reduces thyroid dose by a factor of about 10. Protection against WB dose decreases linearly with the amount of radioiodine penetrating to the occupied spaces of a shelter structure. The decrease is more apparent for LSs than for SSs, because of differences in gamma ray attenuation from sources outside the shelter; it is also related to the number of air changes that take place during the cloud exposure period. In its DRF estimates, EPA-520/1-78-001A assumes an ingress fraction of 0.51 for radioiodine, based on a limited review of experimental work. This assumption implies that radioiodine sources collect at certain locations in shelter structures, which may represent “hotspots”; individuals near these collection points may undergo local exposure resulting in dose increase. However, EPA-520/1-78-001A simply notes this point without attempting to deal with it. In view of current uncertainty about penetration of radioiodine into structures that could be used as shelters, it is essential to have more experimental results.

The degree of WB dose protection afforded by shelter structures as a function of cloud exposure time depends largely on the relative contributions of the exposure modes. The larger the external dose contribution from the penetration of gamma radiation into the shelter, relative to the WB inhalation dose, the smaller the impact of cloud exposure time on shelter effectiveness. For example, for an SS, where gamma ray penetration is more important, the DRF will remain relatively constant for cloud exposure periods up to several hours. If the AER is low, protection may even increase somewhat over time—by only about 15 percent—because of changes in the radioisotope source mix due to decay.

For LS shelters, where the WB dose component from gamma ray penetration is less important than in SS shelters, the degree of protection again remains nearly constant for cloud exposure periods up to several hours, assuming the AER is low; however, for representative AERs, the relative protection from sheltering diminishes significantly over time—for example, by a factor of about 1.7 for a 3-hour cloud exposure period as compared with a 0.5-hour period. The results of this analysis strongly support the use of ventilation rate control to minimize the number of air changes during SIP, especially for LSs. Maintaining low AER is even more important for thyroid dose reduction (for either LSs or SSs), as the loss in protection for a 3-hour cloud exposure period relative to a 0.5-hour period amounts to a factor of about 2.5 for a representative AER of one air change per hour.

SS shelter protection for WB doses tends to increase with cloud arrival time because of radioisotope decay and corresponding changes in radionuclide proportions. For LS shelters, by contrast, protection remains nearly constant with cloud arrival time, because the inhalation dose component is larger; this is even more true for thyroid dose protection. With increasing AER, shelter protection for WB dose diminishes more for LSs than for SSs. For a low AER ($L = 0.125\ h^{-1}$) as compared with a high AER ($L = 4\ h^{-1}$), SS shelter protection decreases by a factor of about 1.32, whereas LS shelter protection decreases by a factor of about 2.7; thyroid dose protection decreases by a factor of about 6. For the WB DRF, the attenuation of gamma radiation from airborne radioactive material outside the shelter structure is more important than that of ground fallout around the shelter. Also, gamma ray attenuation affects DRF more strongly for SSs than for LSs, whereas the reverse holds for the AER. Specifically, for SS shelters, doubling gamma ray attenuation increases WB dose protection by about 80 percent, whereas halving the AER increases it by only about 8 percent. For LS shelters, doubling gamma ray attenuation increases WB dose protection by 50 percent, whereas halving the AER increases it by 20 percent.

The penalty in shelter protection for remaining in the shelter after the cloud exposure period depends on the number of air changes taking place during cloud passage coupled with the relative contribution to the dose from inhalation. When the AER is low, WB dose protection does not fall significantly in either an SS or an LS, regardless of how long individuals remain in the shelter after cloud passage. In an SS, WB dose protection is affected very little; in an LS, shelter effectiveness may fall by 10–20 percent for individuals remaining in the shelter up to about an hour after cloud passage. The penalty is much greater for the thyroid dose: the DRF may fall by a factor of about 1.2–3, relative to ideal shelter-timing conditions, should individuals remain in the shelter for up to an hour after cloud passage.

The attractiveness of SIP depends on the ratio of the projected dose to the dose in the PAG. Generally speaking, when that ratio is comparable to the reciprocal of the DRF, SIP is effective as an emergency protective action. Furthermore, if the projected dose is so large as to cause acute injury, and the predicted time of cloud arrival prevents effective evacuation, a reduction in dose by even a factor of 2–3 may be quite important. For total dose reduction, combining SIP with evacuation during cloud exposure (as opposed to SIP alone) may be an attractive option.

The combination of SIP with evacuation becomes increasingly attractive as the degree of protection offered by a shelter structure decreases and/or the cloud exposure period increases. That is, for WB dose reduction, the SIP/evacuation option is generally more attractive for SSs than LSs, and for high AERs than low ones. The AER considerations are more important for LSs than for SSs, especially for thyroid dose protection. Logistically, the SIP/evacuation option may be attractive for cloud arrival times that would preclude effective evacuation coupled with increasing periods of cloud exposure.

It is not possible to quantitatively estimate the extent to which the conclusions about SIP effectiveness in EPA-520/1-78-001A can be applied to the release of particulate airborne radioactive material from a nuclear incident. There are two reasons for this: (1) the relative contribution of radioactive particulates to the total dose depends on the extent of their release, and (2) the ingress of particulate fission products into shelter structures may differ from that assumed in EPA-520/1-78-001A for gaseous radionuclides. Overall, however, shelters are likely to offer more protection (to varying degrees) than indicated in EPA-520/1-78-001A for gaseous fission products. Therefore, it would be conservative to apply the DRF values in EPA-520/1-78-001A to particulate release material.

Some further considerations should be mentioned. Shelter structures will be increasingly effective in reducing inhalation exposure doses as proportions of particulate release increase, simply because of effective filtering action. Shelter structures also tend to be more effective for reducing WB dose than thyroid dose; however, variations in the dose component contributions complicate this correspondence. In general, the more the WB dose for nonshelter conditions (unprotected) can be attributed to particulates, the more effective sheltering becomes. LS shelters generally offer more protection than SS shelters for equivalent particulate release situations.

Both experimental and analytical work is needed to accurately assess the protective advantage of sheltering. In the experimental arena, the extent of radioactive ingress into potential shelter structures is still uncertain. Therefore, an effort should be undertaken to obtain reliable measurements using representative structures (or models) under controlled shelter-structure conditions and a variety of correlated meteorological conditions. If possible, the experiment should also address representative particulate ingress.

It could also be useful to measure WB external gamma dose from airborne cloud material for shelter structures on an I/O dose basis. Of course, this may be difficult since it would require the intentional controlled release of airborne radioactive material. It may be possible to obtain such measurements in conjunction with experimental programs carried out to verify computer codes used to predict offsite doses (e.g., the Health and Safety Laboratory programs of the New York State Energy Research and Development Authority).

In the analytical arena, it would be useful to estimate shelter protection for specific cases, based on more definite shelter characteristics corresponding to specific locations. The principal parameters to consider would be gamma ray attenuation, finite-source geometry correction factors, AER, fallout deposition, and cloud arrival time. Also needed is model improvement for radionuclide source components. To that end, it would be useful to assess the effect of parent-daughter decay on shelter DRF, along with specific attenuation and finite-source geometry correction actions for each radionuclide.

Finally, sheltering protection should be estimated for radioactive airborne releases that contain particulate material. Such research would focus on the extent and nature of the particulates and their ingress into shelter structures. DRF estimates would also be made using the type of model used in EPA-520/1-78-001A for gaseous fission-product releases.

Protective Action Guide Manual

SIP is a low-cost, low-risk protective action that can provide protection efficiency ranging from zero to almost 100 percent, depending on the type of release, the type of shelter available, the duration of the plume passage, and climatic conditions. Planners and decision-makers should therefore consider implementing SIP when projected doses are below 1 rem (10 mSv) over the first 4 days, as stated in EPA-400/R-17/001, "PAG Manual: Protective Action Guides and Planning Guidance for Radiological Incidents," issued January 2017 (EPA, 2017).

For special populations (e.g., those who are not readily mobile), SIP may be preferred as a protective action at projected doses of up to 5 rem (50 mSv) over 4 days. When environmental, physical, or weather hazards impede evacuation, SIP may be justified at projected doses up to 5 rem (50 mSv) for the general population (and up to 10 rem (100 mSv) for special populations). It is also comparatively easy to communicate with sheltering populations. Dose projections use a 4-day exposure duration, but the duration of sheltering is intentionally not specified, because this is an incident-specific decision.

Choosing between evacuation and SIP is far from an exact science, particularly in light of time constraints that may prevent thorough analysis at the time of an incident. The selection process should be based on realistic or best-estimate dose models and should take into account the unavoidable dose incurred during evacuation and potential failure scenarios for SIP (e.g., leaking ventilation systems).

SIP should be preferred to evacuation whenever it provides equal or greater protection. SIP followed by informed evacuation may be the most protective option.

CONCLUSION

Based on a review of the body of literature on HVAC effectiveness during sheltering, additional experimental work and modeling or simulation studies on this topic may be beneficial. There is considerable information available on general SIP effectiveness and the ability of filters to reduce airborne contaminant concentration, but comparatively little specifically related to radiological release scenarios. Additional quantitative data are necessary to support updates to SIP/HVAC guidance. Specifically, the following work is recommended:

- **Additional experimental research on HVAC system effectiveness and strategies under conditions analogous to nuclear accidents.** These experiments may consider nuclear accident timing, flow and exchange rates, and particle sizes. The existing literature does not adequately investigate HVAC strategies in view of nuclear accident progression timelines and characteristics. It will also be necessary to resolve numerous data gaps and inconsistencies (e.g., in relation to particle sizes and deposition rates expected during a nuclear accident) and to benchmark existing HVAC models and tools.

- **Additional modeling and simulation exercises designed to simulate a large number of variables relevant to HVAC and filtration performance during nuclear accidents.** These variables may include filter location and type, I/O concentration ratios, building type and physical layout, environmental indicators, and timing. In developing guidance, decision-makers would benefit from understanding how the most pertinent variables affect dose metrics for SIP and HVAC usage. Sensitivity analyses may also help isolate the most meaningful variables influencing HVAC effectiveness. Modeling and simulation efforts could be augmented through the use of machine learning techniques to generate large data sets based on physical laws governing various variables.

- **Pinpointing of potential updates to existing guidance based on the most recent data and models.** This would include the identification of additional areas of research and quantitative data generation necessary to support updates to guidance.

- **Collation of experimental research and model development into a decision-making tool for nuclear accident PARs.** This tool may incorporate advanced analytical decision-making tools such as fuzzy logic, to help decision-makers sift through the often imprecise and vague information available in the immediate aftermath of a nuclear accident. Ideally, the tool would enable straightforward and nuanced protective action decisions to be derived even from information that is ambiguous, incomplete, and qualitative.

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