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Protecting building occupants against the inhalation of outdoor-origin aerosols

Michael B. Dillon [a,*], Richard G. Sextro [a,b], W. Woody Delp [b]

[a] Atmospheric, Earth, and Energy Division, Lawrence Livermore National Laboratory, Mailstop L-103, Livermore, CA, 94551, USA
[b] Indoor Environment Group, Energy Analysis and Environmental Impacts Division, Energy Technologies Area, Lawrence Berkeley National Laboratory, Berkeley, CA, 94720, USA

HIGHLIGHTS

- We estimate the protection US buildings provide against airborne particulate hazards.
- We compile published deposition, penetration, filtration, and building operation data.
- Protection varies widely by occupancy type, particle size, and airborne loss rate.
- Variability within a given building type is similar to variability between different types.
- Results are placed in context with previously reported measurements.

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ABSTRACT

During normal operations, buildings can protect their occupants from outdoor airborne particle hazards of all types, including airborne pollutants. A long-term international research effort has advanced our knowledge of building protection physics. Recently we have developed an operationally efficient, regional-scale methodology - Regional Shelter Analysis - to account for both building protection effects and the typical distribution of people in and among buildings. To provide input to this capability, we estimate here the degree of protection afforded by the currently existing US building stock. We first assemble and summarize the published literature relevant to indoor particle losses including (a) deposition to indoor surfaces, (b) losses that occur when particles penetrate through the building envelope, and (c) heating, ventilation and air conditioning (HVAC) system filtration efficiencies as well as general building operating conditions. Building protection against inhaling particulate hazards varies strongly, by orders of magnitude, according to particle size, airborne particle loss rate, and to a lesser extent building use (occupancy). Protection increases modestly as particle size increases from 0.1 to 1 μm and significantly as particle size increases from 1 to 10 μm. Model results are placed in context with previously reported measurements. Suggestions for future work, including enhanced validation datasets are provided.

1. Introduction

Building occupants can be exposed to outdoor-origin, airborne particles – including but not limited to urban air pollution, wildfire smoke, wind-blown dust, infectious aerosols, and accidental releases of toxic industrial chemicals. These exposures can be sufficient to result in acute and chronic lung disease, heart disease, or various infectious diseases (Nadadur and Hollingsworth, 2015; Brook et al., 2010; Pope and Dockery, 2006; Kaufman et al., 2016; Stone et al., 2019; Dillon and Dillon, 2020). Buildings can provide significant protection to their occupants – reducing exposures by an order of magnitude in many cases and even more in some situations.

Historically, much of the research on building protection has been performed on a hazard-by-hazard basis – e.g., radiological, acute chemical, chronic chemical (air quality), and biological. Furthermore, sheltering has long been recognized as an important protective action. Some early efforts were motivated by reducing the consequences of a nuclear reactor accident and provided the initial theoretical basis for assessing building protection from the inhalation of radioactive gases and airborne particles (US Nuclear Regulatory Commission, 1975; Anno

* Corresponding author. Atmospheric, Earth, and Energy Division, Lawrence Livermore National Laboratory, Mailstop L-103, Livermore, CA, 94551, USA.
E-mail address: dillon7@llnl.gov (M.B. Dillon).

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and Dore, 1978a; Anno and Dore, 1978b; Slade, 1968). These early efforts had limited understanding of some key physics, including particle deposition, and so underestimated the extent to which buildings could protect their occupants. Notable subsequent work by Engelmann (1992) estimated the effects of building ventilation rates on indoor exposures to 2 μm Pu aerosols as a function of plume duration. With respect to indoor air quality, key early experimental work was performed by Alzona et al. (1979), who studied the influence of various parameters including deposition on the ratio of indoor to outdoor particle concentrations, and Yocum et al. (1971), who performed a more comprehensive study for several building types as a function of season. Shair and Heitner (1974), who focused primarily on ozone exposures, developed one of the first comprehensive indoor-outdoor air quality models. Substantial subsequent work on air quality and building protection has been performed and been summarized in prior review papers, e.g., (Diapouli et al., 2013; Chen and Zhao, 2011; Goldstein et al., 2021). Research in support of the US Chemical Stockpile Emergency Preparedness Program provided key advances in understanding the benefits and practice of sheltering to reduce acute chemical hazards (Rogers et al., 1990; Blewett et al., 1996). These studies and subsequent research have been codified into construction and retrofit guidance, e.g., (Persily et al., 2007; Smilowitz et al., 2006). Finally, recent concerns about wildfire smoke exposure has led to similar recommendations for using the protective and sheltering properties to reduce occupant smoke exposures, e.g., (Stone et al., 2019). Additional building protection and sheltering papers are presented and discussed in Dillon and Dillon (2019).

A general building protection evaluation methodology has not been available for the US building stock. As a consequence, building protection considerations are not routinely incorporated into many current population exposure, risk, and casualty assessments, which may lead to overestimates of population exposures and risks. This could result in misallocation of resources to the populations that are not most at risk or amenable to assistance. Similarly, population level dose-response relationships - often derived by estimating ambient (outdoor) exposures and then tuning dose-response relationship parameters to best match the spatial distribution of illness reports, e.g. (Oliveri Conti et al., 2007; Ostro, 2004; Wilkening, 2006) - may underestimate the true potency of an exposure hazard. Recently we have developed an operationally efficient, regional-scale methodology - called Regional Shelter Analysis (RSA) - to account for both building protection and the distribution of people in and among buildings (microenvironments) (Dillon et al., 2019; Dillon and Dillon, 2019). The RSA approach can generate predictions to support decision makers on multiple operational levels, ranging from individual buildings and neighborhoods to larger regions. One key

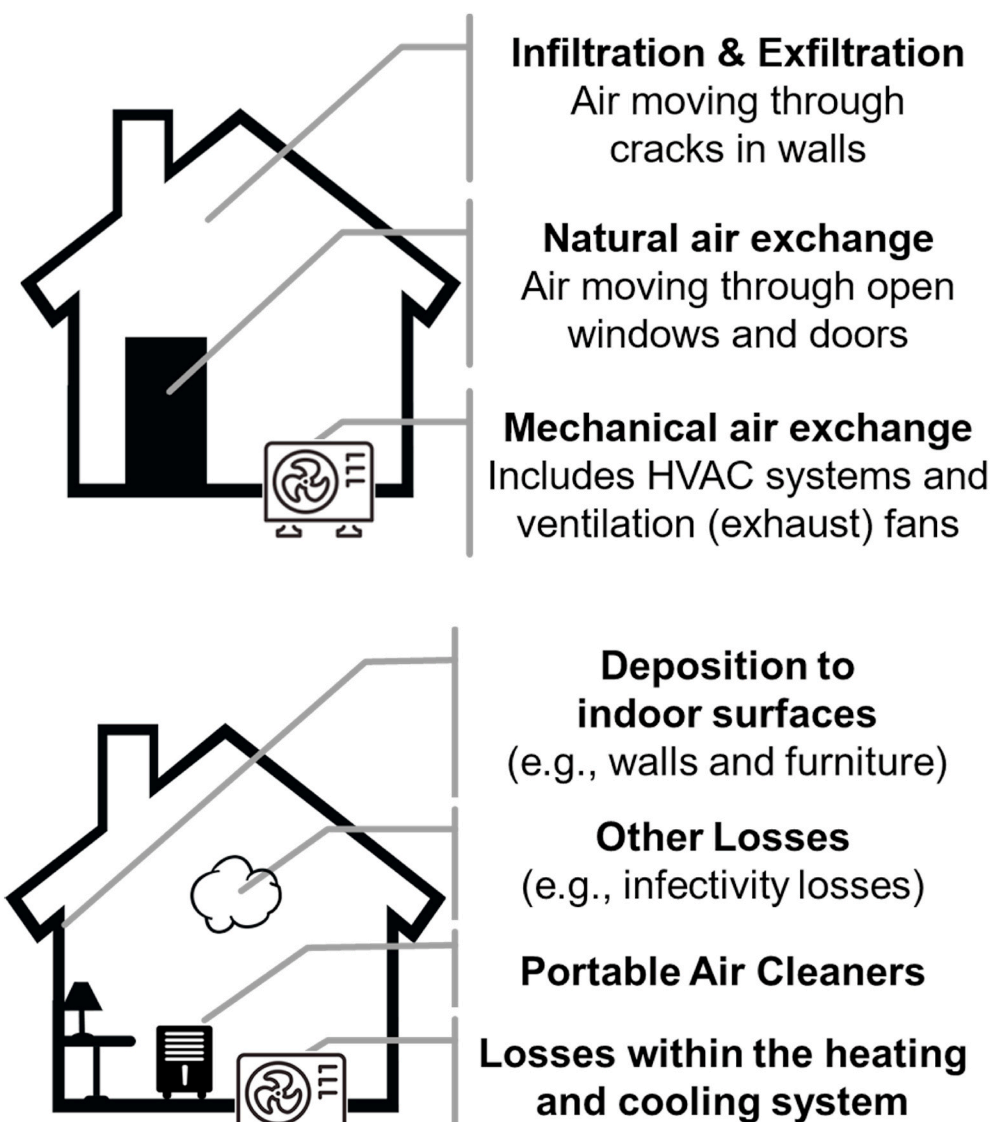

Fig. 1. Illustrations of (top) mechanisms by which airborne material can travel between the outdoor and indoor environments and (bottom) indoor loss mechanisms.

aspect of this capability is the ability to use multiple input datasets, with default values used where higher fidelity datasets are not available.

To provide default building protection estimates for the RSA capability, we present here both a modeling architecture and a compilation of relevant parameter data to estimate US building protection. The parameter estimates are based on normal building operations (passive protection) for buildings with closed windows and do not include any additional active sheltering measures. We also discuss potential future work that would enable more accurate protection assessments using localized data.

2. Theory

Outdoor airborne particles enter buildings via several air flow pathways: through mechanical ventilation (e.g., HVAC systems), natural ventilation (e.g., open windows), and/or infiltration (e.g., through exterior wall cracks). These first two transport pathways are illustrated in the top panel of Fig. 1 for buildings with and without an HVAC system (transport via fomites or tracking is not considered here). Once indoors, airborne particles are removed from the indoor air through (a) air leaving the building through mechanical ventilation, natural ventilation or exfiltration, (b) active filtration within ventilation systems (if present); (c) deposition on indoor surfaces (particle resuspension is not considered here); and (d) other removal processes, including chemical reactions, stand-alone indoor air filtration systems, and the loss of infectivity of airborne microorganisms, among others. The latter three loss terms are illustrated in the bottom panel of Fig. 1.

Modeling indoor contaminant concentrations requires choosing among a variety of mathematical and conceptual models with increasing complexity, ranging from simple, single compartment models to multizone models to highly detailed computational fluid dynamics models. While increasingly detailed and complex models may reduce modeling conservatism and uncertainty, the number and required fidelity of the input parameters also increases, see (Keil, 2000) for a general discussion. Since our goal is to provide a broad, consistent, high-level assessment across a range of building categories and, as a practical matter, detailed parameters values are not generally available for many buildings of interest, we make two key modeling assumptions which are consistent with prior studies (Alzona et al., 1979; Shair and Heitner, 1974; Thatcher et al., 2003; Nazaroff, 2004). First, indoor air volumes can be represented as a single compartment. Second, airborne particle concentrations within that single compartment are spatially uniform. We note that due to the air change mechanisms, outdoor-origin contaminants can have a relatively uniform indoor spatial distribution. For example in modeling indoor concentrations of outdoor-origin ozone, Hayes (1991) demonstrated that the indoor/outdoor ozone concentration ratio was insensitive to the degree of indoor mixing in both single and multicompartment models for residential and office buildings. Also, for context, the mixing time constants for both buoyant and mechanical airflow conditions in laboratory studies of room mixing, 10 min to <1 h, are shorter than the indoor exposure times of interest for many hazards of interest (Nazaroff, 2004; Rim and Novoselac, 2008).

These assumptions are codified in the single-box model, Equation (1a) which can be used to describe the time evolution of indoor airborne particle concentrations. This study includes the additional, commonly used assumption that the transport and loss terms, i.e., the λ parameters, are independent of both time and air concentration on the timescales of interest. Equation (1a) thus reduces to Equation (1b). Equation (2), the general transmission factor (TF) equation, which reflects the protection buildings provide against outdoor-origin aerosols, includes the additional assumptions that (a) initial (t = 0) indoor air concentrations are zero and (b) material removed from the indoor air is not reintroduced at a later time (e.g., no resuspension of deposited particles). The transmission factor is also called the building exposure ratio. The transmission factor is mathematically identical to the widely used infiltration factor, the steady state ratio of indoor to outdoor concentrations. The latter term can be considered to be a special case of the more general transmission factor concept. We use transmission factor here as it can explicitly account for time-varying concentrations (such as a contaminant plume passing by a building).

$$\frac{dC_{Indoor}}{dt} = \lambda_{in} \cdot C_{Outdoor}(t) - (\lambda_{out} + \lambda_{internal}) \cdot C_{Indoor}(t) \tag{1a}$$

$$C_{Indoor}(t) = \lambda_{in} \cdot \int_0^t C_{Outdoor}(\tau) \cdot e^{-(\lambda_{out} + \lambda_{internal})(t-\tau)} d\tau \tag{1b}$$

$$Transmission\ Factor \equiv \frac{Sheltered\ (Indoor)\ Exposure}{Unsheltered\ (Outdoor)\ Exposure} = \frac{\int C_{Indoor}(t)dt}{\int C_{Outdoor}(t)dt} = \frac{\lambda_{in}}{(\lambda_{out} + \lambda_{internal})} \tag{2}$$

where.

- t is time (h);
- τ is an integration variable (h);
- $C_{Indoor}(t)$ is the indoor particle air concentration at time t (g m^{-3});
- $C_{Outdoor}(t)$ is the outdoor particle air concentration at time t (g m^{-3});
- λ_{in} is the rate at which outdoor airborne material enters the building – typically via infiltration or ventilation and includes losses that occur during transport from outdoor to indoor (h^{-1});
- λ_{out} is the rate at which indoor airborne material exits the building – typically via exfiltration or ventilation (h^{-1}); and
- $\lambda_{internal}$ is the rate at which indoor airborne material is lost within the building – typically by deposition to surfaces or by filtration (h^{-1}).

We apply the general TF equation based on the principal mechanisms by which outdoor and indoor air is exchanged and the details of how indoor airborne particles are lost in buildings. For this high-level analysis, we create two broad building categories – buildings with and buildings without HVAC systems. Both equations assume that windows and doors are closed. Equation (3R) applies to buildings with an air recirculation system, which in US homes are typically residential forced air furnace systems, see Fig. 2 (top panel). Outdoor airborne material enters the building only through the infiltration pathway. When the forced-air furnace fan is on, the air filter, if present removes a fraction of indoor airborne particles. Equation (3H) applies to buildings with an active HVAC system, which in the US are typically non-residential buildings, see Fig. 2 (bottom panel). Outdoor airborne material enters the building through either infiltration or the HVAC system outdoor air intake. The HVAC system air filter removes airborne particles from both the entering and recirculating air. This equation implicitly assumes that the HVAC system fan duty cycle is 100% (the system is always moving building air, although not necessarily heating or cooling it).

$$TF = \frac{(\lambda_{inf} \cdot L_{inf})}{\lambda_{inf} + (F_{filter} \cdot F_{r,fan} \cdot r_{fan} + \lambda_{dep} + \lambda_{generic})} \tag{3R}$$

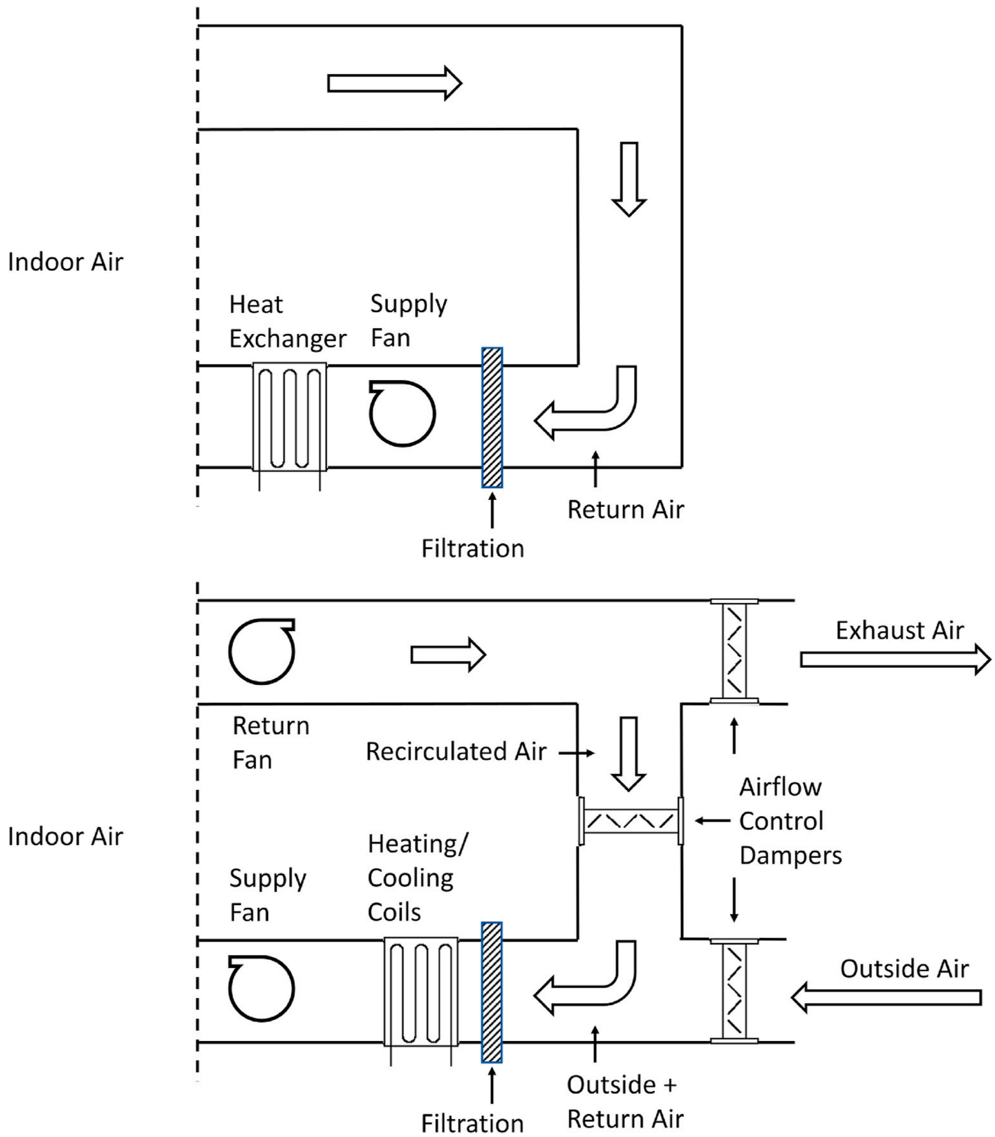

Fig. 2. Schematic diagrams of typical mechanical air flow systems for buildings with (top panel) a forced air furnace, typical of US residential buildings, and (bottom panel) with an active HVAC system, typical of US non-residential buildings.

$$TF = \frac{\left(\lambda_{inf}\cdot L_{inf} + v_{fan}\cdot F_{oa}\cdot\left(1 - F_{filter}\right)\right)}{\lambda_T + \left(F_{filter}\cdot v_{fan}\cdot(1 - F_{oa}) + \lambda_{dep} + \lambda_{generic}\right)} \tag{3H}$$

where.

λ_{inf} is the natural air infiltration rate at which air enters a building, i.e., the air change rate (h^{-1});
$L_{inf}(particle\ size)$ is the particle-size dependent efficiency by which particles can penetrate the building shell (dimensionless);
$\lambda_{dep}(particle\ size)$ is the particle-size dependent indoor deposition loss rate [= deposition velocity × surface/volume ratio] (h^{-1});
$\lambda_{generic}$ is the "generic" first-order airborne decay (loss) rate, e.g., radioactive decay or infectivity loss rate (h^{-1});
$F_{filter}(particle\ size)$ is the particle-size dependent filtration efficiency (dimensionless);
$F_{r,\ fan}$ 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 rate at which a building volume of air recirculates through the furnace systems when the fan is on (h^{-1});
v_{fan} is the rate at which a ventilation or HVAC supply fan delivers air to the building when the fan is on and combines the outside and recirculation air rates (building volume h^{-1});
F_{oa} is the fraction of outdoor air passing through the HVAC supply fan (dimensionless); and
λ_T is the total building ventilation rate [= sum of the infiltration and mechanical ventilation rates] (h^{-1}).

3. Parameter values

We estimate the protection associated with a set of representative US buildings based on building parameter values specified in this section. While there are several building type taxonomies, we have adapted the US Department of Homeland Security (DHS) HAZUS convention for building use types (also called building occupancy types) (US Department of Homeland Security, 2013) as a means of defining a broad, yet generalizable range of building types. Based on this approach, we have created 37 building categories for our modeling, as shown in Table 1. Table 1 column "Building airflow type" assigns the appropriate airflow equation type (Equation 3R or 3H) to all of the 37 building use types. Table 1 also specifies the appropriate parameter descriptors associated

Table 1
Mapping between building use types and the corresponding transmission factor equation and parameter values.

Occupancy class	Building use type [a]	Building use type description	Building airflow type	R parameters (λ_{inf}, $F_{r,fan}$, r_{fan}) [b]	H parameters (v_{fan}, λ_T, F_{oa}) [c]	Surface to Volume Ratio (m^{-1})	Filtration category [d]
Residential	RES1	All single-family dwellings	R	SFH	N/A	2	Single family
	RES1 (no central air)	Single-family dwellings without a central air system	R	SFH	N/A	2	Single family (no central air)
	RES1 (central air)	Single-family dwellings with a central air system	R	SFH	N/A	2	Single family (central air only)
	RES2	Manufactured (Mobile) home	R	MH	N/A	2	Single family
	RES3A	Multi-family dwelling: duplex	R	SFH	N/A	2	Single family
	RES3B	Multi-family dwelling: 3–4 units	R	Apt w/o corridors	N/A	2.4	Low quality
	RES3C	Multi-family dwelling: 5–9 units	R	Apt w/o corridors	N/A	2.4	Low quality
	RES3D	Multi-family dwelling: 10–19 units	R	Apt w/o corridors	N/A	2.4	Low quality
	RES3E	Multi-family dwelling: 20–49 units	H	N/A	Apt w corridors	2.4	Low quality
	RES3F	Multi-family dwelling: 50+ units	H	N/A	Apt w corridors	2.4	Low quality
	RES4, Guest	Temporary lodging (e.g., hotel/motel)	H	N/A	Hotel, guest rooms	2	Low quality
	RES5, Guest	Institutional dormitory (e.g., military, college, jails)	H	N/A	Hotel, guest rooms	2	Low quality
	RES6, Guest	Nursing home	H	N/A	Hotel, guest rooms	2	Low quality
	RES4, Common	Temporary lodging (e.g., hotel/motel)	H	N/A	Hotel, common areas	2	Low quality
	RES5, Common	Institutional dormitory (e.g., military, college, jails)	H	N/A	Hotel, common areas	2	Low quality
	RES6, Common	Nursing home	H	N/A	Hotel, common areas	2	Low quality
Commercial	COM1	Retail trade (e.g., stores)	H	N/A	Retail	2	Medium quality
	COM2	Wholesale trade (e.g., warehouses)	H	N/A	Warehouse	1	Low quality
	COM3	Personal and repair services (e.g., service station/shop)	H	N/A	Retail	2	Low quality
	COM4	Professional/technical services (e.g., offices)	H	N/A	Office	2	Standard office
	COM5	Banks	H	N/A	Office	2	Standard office
	COM6	Hospital	H	N/A	Health Care	2	Very high quality
	COM7	Medical office/clinic	H	N/A	Health Care	2	Standard office
	COM8	Entertainment and recreation (e.g., restaurants/bars)	H	N/A	Restaurant	2	Medium quality
	COM9	Theaters	H	N/A	Retail	2	Medium quality
Industrial	IND1	Heavy industry (e.g., factory)	H	N/A	Warehouse	1	Low quality
	IND2	Light industry (e.g., factory)	H	N/A	Warehouse	1	Low quality
	IND3	Food/drugs/chemicals (e.g., factory)	H	N/A	Warehouse	1	High quality
	IND4	Metals/minerals processing (e.g., factory)	H	N/A	Warehouse	1	Low quality
	IND5	High technology (e.g., factory)	H	N/A	Warehouse	1	Very high quality
	IND6	Construction (e.g., office)	H	N/A	Warehouse	1	Low quality
Agricultural	AGR1	Agriculture	H	N/A	Warehouse	1	Low quality
Religious	REL1	Church/non-profit	H	N/A	Retail	2	Low quality
Governmental	GOV1	General services (e.g., office)	H	N/A	Office	2	Standard office
	GOV2	Emergency response (e.g., police/fire station/eoc)	H	N/A	Office	2	Medium quality
Educational	EDU1	Grade schools	H	N/A	School	2	Medium quality
	EDU2	Colleges/universities (does not include group housing)	H	N/A	School	2	Medium quality

[a] HAZUS building occupancy type adapted from (US Department of Homeland Security, 2013). Single-box modeling may not adequately represent the indoor airborne particle concentrations for some parking garages (COM10) and so we excluded this building use type from our analysis.
[b] R = filtered recirculation. Values selected from the distributions defined in Table 2.
[c] H = HVAC system. Values selected from the distributions defined in Tables 3 and 4.
[d] Values selected from the distributions defined in Tables 5 and 6

with building infiltration, ventilation, and filtration. As one might expect, parameters derived from previous experimental or modeling studies do not necessarily conform to the HAZUS taxonomy. For the residential buildings, the mapping between the prior work and the HAZUS category is straightforward. For the other building types, the mapping of other HAZUS categories is less clear and there are limited published data available. For these cases, we made parameter estimates based on best engineering judgment and adapted the available input data to conform to the HAZUS building types, as described below and in greater detail in Supplemental Material S1. Supplemental Material S2 contains the raw data used to construct the parameter distributions. It is worth noting that our use of parameter distributions for the Monte Carlo modeling will capture some of the inherent variability in these parameter choices.

3.1. Air flows (λ_{inf}, $F_{r,fan}$, r_{fan}, v_{fan}, λ_T, F_{oa})

The rate at which outdoor and indoor air is exchanged has been the subject of numerous studies - driven in part by interests in reducing the energy used to heat or cool entering outdoor air and in part by concerns

Table 2
Airflow parameters used in RES1, RES2, RES3A, RES3B, RES3C, and RES3D buildings. We assume a log-normal parameter distribution.

Parameter	Geometric mean (units)	Geometric standard deviation (dimensionless)	Reference
λ_{inf} – SFH [a]	0.44 (h^{-1})	2.04	(Persily et al., 2010; El Orch et al., 2014)
λ_{inf} – MH [a]	0.42 (h^{-1})	1.86	Persily et al. (2010)
λ_{inf} - APT w/o corridors [a]	0.23 (h^{-1})	1.82	Persily et al. (2010)
$F_{r,\ fan}$	0.25 (dimensionless)	1.85	El Orch et al. (2014)
r_{fan}	5.7 (h^{-1})	1.26	El Orch et al. (2014)

SFH = single family home (used for RES1 and RES3A).
MH = manufactured home (used for RES2).
APT w/o corridors = multifamily dwelling buildings that do NOT have corridors (RES3B to RES3D).
[a] This parameter value assumes doors and windows are closed.

Table 3
Select parameters values for representative building use types that have an HVAC system. We assume a triangular parameter distribution.

	Mode	Maximum	Minimum
Supply fan rate, v_{fan} (h^{-1})			
Restaurant	7.0	13	6.1
Office	3.8	25	1.1
School	3.1	11	2.8
Retail	3.7	9.1	2.0
Health care	5.8	18	3.9
Warehouse	0.9	1.0	0.6
Hotel, guest rooms	1.0	1.4	0.6
Hotel, common areas	4.2	6.6	1.9
Apt w corridors	7.4	7.6	7.2
Fraction of outside air, F_{oa} (dimensionless)			
Restaurant	0.5	0.7	0.0
Office	0.1	1.0	0.0
School	0.2	0.6	0.1
Retail	0.1	0.6	0.0
Health care	0.1	0.2	0.1
Warehouse	0.05	0.06	0.04
Hotel, guest rooms	1.0	1.0	1.0
Hotel, common areas	0.13	0.17	0.09
Apt w corridors	0.05	0.08	0.02
Natural air infiltration rate, λ_{inf} (h^{-1})			
Restaurant	0.5	1.9	0.01
Office	0.12	1.2	0.0
School	0.3	1.2	0.02
Retail	0.2	0.8	0.0
Health care	0.05	0.9	0.0
Warehouse	0.3	1.0	0.05
Hotel, guest rooms	0.0	0.0	0.0
Hotel, common areas [a]	0.3	1.2	0.0
Apt w corridors	$\lambda_T - v_{fan} \cdot F_{oa}$ (see Table 4 for λ_T)		

[a] Assumes infiltration rates are the same for the (i) other rooms and (ii) whole building.

Table 4
Percentile distribution for the total building air ventilation rate, λ_T (h^{-1}) for apartments that DO have corridors (RES3E and RES3F) from (Persily et al., 2010).

$P_{1\%}$	$P_{5\%}$	$P_{25\%}$	$P_{50\%}$	$P_{75\%}$	$P_{95\%}$	$P_{99\%}$
0.23	0.33	0.42	0.46	0.54	0.71	0.87

about the potential of exposures to indoor air pollutants, e.g. (Yaglou et al., 1936; Hollowell et al., 1980; Liddament and Orme, 1998; Sundell et al., 2011; Maddalena et al., 2015; ASHRAE, 2013), and references therein. Typically, prior studies describe either individual building results or are building-class specific, including single-family homes, multi-family dwellings, multistory ('low-rise' and 'high-rise') office buildings, health care facilities, restaurants, warehouses, retail stores, and schools. We summarize here the data used to derive the model air flow parameter input distributions, which are provided in Table 2 (residential) and Tables 3 and 4 (non-residential), respectively. Supplemental Material S1 provides a more detailed analysis and the data compilation is given in Supplemental Material S2.

For residential buildings, the provided air infiltration parameter (λ_{inf}) distributions account for variation across different US buildings and operating conditions and for the different seasons and times of the day. For non-residential buildings, the equivalent distributions are not available. We assume a triangular distribution, where the average values are derived from prior annual and nationally representative analyses based on US Department of Energy Commercial Reference Buildings (which are a suite of detailed computer models intended to represent the construction and use of most new and existing US commercial building types). Nationally representative air infiltration rates were not available and so we use annual average values relevant to Chicago, IL. Finally, US warehouse values were not available and so we used values provided by the UK Chartered Institution of Building Service Engineers (CIBSE, 2006). Bounding cases reflect the extrema present in the compiled dataset of the prior studies, see Supplemental Materials S1 and S2.

For residential structures, the air change rate is controlled by infiltration. We use the distribution of representative infiltration rates (λ_{inf}) derived for 1990s US single family homes, duplexes, manufactured homes, and apartments without HVAC systems (Persily et al., 2010), see Table 2. Since we are not aware of another broadly representative dataset, we follow El Orch et al.'s (2014) estimates of furnace recirculation fan duty cycle ($F_{r,fan}$) and furnace system recirculation rate (r_{fan}) for the single family homes and duplexes. Due to similar building use and lack of other representative data, we also use these parameter distributions for manufactured homes and apartments without HVAC systems. For apartments, we follow Persily et al. (2006) and establish two categories of apartment buildings – those without and those with internal corridors. We assume that small apartment buildings (RES3B, RES3C and RES3D, see Table 1) fall under the first category and so do not have HVAC systems. For larger apartment buildings (buildings containing internal corridors, RES3E and RES3F), we have adopted the approach taken by Persily et al. (2006, 2010), where the all apartments on a given story are assumed to be served by a single HVAC system. In addition, fresh (outdoor) air is supplied to the corridor, which then flows into the apartments. We use the NIST reference building modeling studies (Persily et al., 2006, 2010; Ng et al., 2012) to estimate the HVAC parameters used in Equation (3H), see Tables 3 and 4 for the relevant parameter distributions.

In the US, nonresidential structures generally contain HVAC systems. We develop data for the λ_{inf}, v_{fan}, F_{oa}, and λ_T parameter distributions for 9 representative building types or subtypes: Restaurants, Offices, Schools, Retail, Health Care, Warehouses, Hotels (guest rooms and common spaces), and Apartments with corridors (as noted above). The average (mode) values (see Table 3) are derived from analyses of the US Department of Energy Commercial Reference Buildings (Ng et al., 2012, 2013; Deru et al., 2011). We supplemented these data with average natural infiltration rate values used by the CIBSE (Chartered institution of building services Engineers, 2006). Finally, the bounding cases (minimum and maximum) are based on the extrema present in our compilation of building data and analyses, including data from experimental studies conducted in a wide range of non-residential building types (Persily et al., 2006; Ng et al., 2012, 2013; Deru et al., 2011; Chartered institution of building services Engineers, 2006; Bennett et al., 2011; Polidori et al., 2013; Persily and Gorfain, 2008; Wargocki et al., 2004; Chao and Chan, 2001; Hotchi et al., 2006; Chan et al., 2015).

For Hotels (RES4), dormitories (RES5), and nursing homes (RES6), we have assumed that there are different air handling mechanisms in the common use spaces (e.g., lobby, restaurants/dining areas, corridors) and in the sleeping areas (e.g., guest rooms). As a means of bounding the results, we assume that there is minimal mixing between these two regions of these buildings. We thus develop separate building protection estimates – one for guest rooms and the other for the rest of the building, see Table 3.

3.2. Particle deposition loss rate (λ_{dep})

Indoor particle concentrations are reduced by deposition to indoor surfaces. The indoor behavior of particles, and their deposition to indoor surfaces, has been extensively studied and the physics of indoor airborne particles is reasonably well understood both experimentally and theoretically, see for example (Lai and Nazaroff, 2000; Nazaroff, 2004). Particle deposition loss rates are primarily controlled by particle size, the indoor surface to volume ratio, and, to some extent, turbulence conditions within a given space. We treat airborne particles as chemically inert, with negligible thermophoretic or electrostatic interactions with surfaces within buildings. We can thus generalize the published deposition loss rates across the range of indoor surfaces and building types of interest in this work.

Fig. 3 shows particle deposition velocity (v_{dep}) data taken from a set of studies curated for an upcoming critical review paper; these data are compiled in Supplemental Material S2. The data points shown represent a wide variety of airflow (turbulence) conditions, particle-sizes, experimental conditions, and, to a lesser extent, particle source types, e.g., ambient aerosols, cooking generated aerosols, and environmental tobacco smoke. In some cases, the studies took place in room size chambers, with and without furnishings (Thatcher et al., 2002; Afshari and Reinhold, 2008; Byrne et al., 1995; Lai et al., 2002; Mosley et al., 2001; Offermann et al., 1985; Xiao et al., 2020; Xu et al., 1994). In other cases, the measurements took place in both test houses and normally operated residences, with and without furnishings, where the authors have taken care to minimize (or in some cases eliminate) the impact of any indoor sources (Abt et al., 2000; Byrne, 1995; Chao et al., 2003; Chen et al., 2012; Emmerich and Nabinger, 2001; Fogh et al., 1997 ; Hill et al., 2001; Howard-Reed et al., 2003; Thatcher et al., 2003; Thatcher and Layton, 1995; Wallace et al., 2004; Zhao and Stephens, 2017). We have included the few comparable, size-resolved particle deposition rate data reported for other building types (offices and schools) (Chen et al., 2012; Tran et al., 2017). In all cases, the data shown reflect deposition to indoor surfaces and so do not include losses to mechanical ducts, filters, and/or HVAC heating/cooling elements. From Equation (4a), we derive the particle-size-specific indoor deposition loss rate distribution (λ_{dep}) using a Monte Carlo analysis with Equation (4b), which in turn are derived from these data. Fig. 3 shows the data and corresponding polynomial fit. Supplemental Material S1 provides the details of the fitting procedure.

$$\lambda_{dep} = v_{dep} \cdot S/V \quad (4a)$$

$$\begin{aligned} log_{10}(v_{dep}(particle\ size)) = &\ 0.52\ (\pm 0.05)\ [log_{10}(particle\ size)]^2 \\ &+ 0.95\ (\pm 0.03)\ log_{10}(particle\ size) \\ &- 4.42\ (\pm 0.02) \end{aligned} \quad (4b)$$

where.

$v_{dep}(particle\ size)$ is the particle-size-dependent indoor deposition velocity (m s^{-1}) and
S/V is the indoor surface to volume ratio (m^{-1}).

3.3. Particle penetration efficiency (L_{inf})

Buildings are often (at least partially) depressurized with respect to ambient conditions, resulting in outdoor air containing airborne particles being drawn into buildings, infiltrating through (a) unplanned openings in the building shell, e.g., cracks, construction joints, etc. or (b) open windows or doors. During infiltration due to pressure differentials, airborne particles may deposit onto surfaces that comprise the building shell, resulting in a loss of airborne material prior to outdoor air entering the main indoor building volume. The penetration efficiency, which measures the fraction of airborne particles of a given size that pass through the building shell into the indoor air space, is dependent upon the nature and physical dimensions of the infiltration pathway through the building shell, the airflow rate through those pathways, and the particle-size distribution of the infiltrating contaminant aerosol (see review by Chen and Zhao (2011) and references therein). Penetration efficiency values (L_{inf}) from residences, offices, and schools are shown in Fig. 4. These values are taken from a set of studies curated for an upcoming critical review paper (Thatcher et al., 2003; Chao et al., 2003; Zhao and Stephens, 2017; Emmerich and Nabinger, 2001; Chen et al., 2012; Tran et al., 2017). We derive the particle-size-specific penetration efficiency distribution using a Monte Carlo analysis with Equation (5), which in turn is derived from these data. Fig. 4 shows the data and corresponding polynomial fit. Supplemental Material S1 provides the

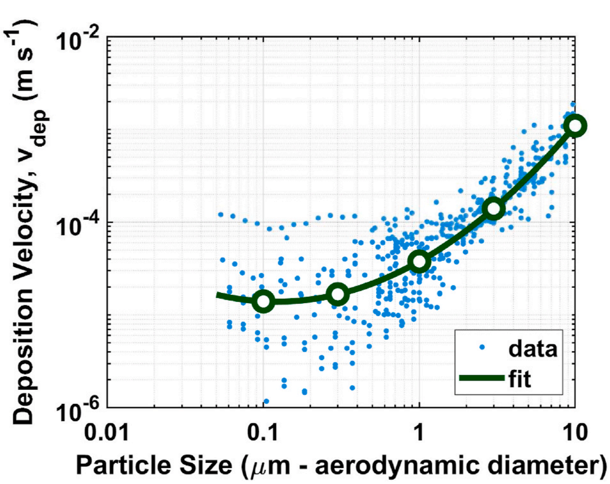

Fig. 3. Indoor particle deposition velocities. Open circles indicate median values used in the modeling based on the fit to the data discussed in Supplemental Material S1.

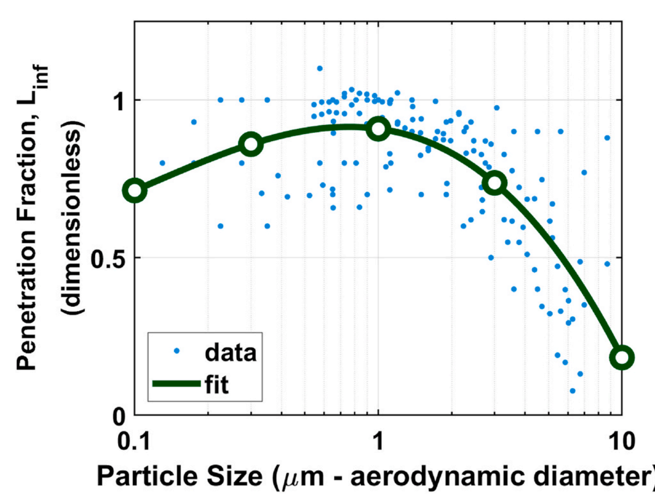

Fig. 4. Outdoor to indoor particle penetration factor. Some penetration fraction measurements exceed 1. These measurements have associated error bars (not shown) that overlap 1. Open circles indicate median values used in the modeling based on the fit to the data discussed in Supplemental Material S1.

details of the fitting procedure.

$$L_{inf}(particle\ size) = -0.16\ (\pm 0.12)\ [log_{10}(particle\ size)]^3 - 0.46\ (\pm 0.06)\ [log_{10}(particle\ size)]^2 - 0.10\ (\pm 0.06)\ log_{10}(particle\ size)\ +\ 0.91\ (\pm 0.17) \tag{5}$$

3.4. HVAC and furnace particle filtration efficiency (F_{filter})

For buildings with operating HVAC systems, the major pathway for outdoor air entering the building is through the outdoor air intake of the mechanical air handling system. Most HVAC systems have at least some particle filtration capability that will remove airborne particles from both the outdoor air entering the building through the mechanical system and the recirculating indoor air. We summarize here the data used to derive the input parameter distributions. Supplemental Material S1 provides a more detailed discussion and analysis.

For our modeling, we selected five HVAC/furnace filter categories to span a range of particle loss due to filtration. For four of these categories we used filter efficiency data associated with Minimum Efficiency Reporting Values (MERV) of (1) high-efficiency MERV 14 and 15; (2) medium efficiency MERV 11 and 12; (3) low efficiency MERV 7 and 8; and (4) poor efficiency MERV 5. The MERV 5 category is also used here to account for particle loss in poor quality, poorly installed, and/or missing filters where other components of the HVAC/furnace system still provide some particle loss. The fifth, “no filter” category is applied to residential cases in which the HVAC/furnace system is non-existent or provides no significant filtration, e.g., wall or floor furnaces. We utilized a consistent set of data from (a) lab-based performance studies of new filters with varying dust loading (Research Triangle Institute, 2004a; Research Triangle Institute, 2004b; Research Triangle Institute, 2004c; Research Triangle Institute, 2004d; Research Triangle Institute, 2003a; Research Triangle Institute, 2004e; Research Triangle Institute, 2004f; Research Triangle Institute, 2004g; Research Triangle Institute, 2004h; Research Triangle Institute, 2003b; Research Triangle Institute, 2003c; Research Triangle Institute, 2004a,b; Research Triangle Institute, 2004i; Owen et al., 2014) and (b) filters exposed in real buildings (Owen et al., 2014). Following the procedure discussed in Supplemental Material S1, we derive the single pass filtration efficiency distribution for each HVAC/furnace filter category used in our modeling, see Table 5.

Table 5
Filtration efficiency (F_{filter}, dimensionless) by air filter MERV rating and particle-size.

Air-filter MERV rating	Airborne particle size (μm)	Percentile distribution for the filtration efficiency (F_{filter}, dimensionless)						
		$P_{1\%}$	$P_{5\%}$	$P_{25\%}$	$P_{50\%}$	$P_{75\%}$	$P_{95\%}$	$P_{99\%}$
No filter	0.1	0	0	0	0	0	0	0
	0.3	0	0	0	0	0	0	0
	1	0	0	0	0	0	0	0
	3	0	0	0	0	0	0	0
	10	0	0	0	0	0	0	0
5	0.1	0.00	0.00	0.00	0.01	0.04	0.18	0.29
	0.3	0.00	0.00	0.00	0.01	0.04	0.18	0.29
	1	0.05	0.05	0.07	0.10	0.18	0.69	0.83
	3	0.28	0.28	0.32	0.40	0.64	0.95	0.98
	10	0.22	0.22	0.29	0.45	0.83	0.94	0.98
7 to 8	0.1	0.03	0.03	0.12	0.20	0.24	0.33	0.37
	0.3	0.03	0.03	0.12	0.20	0.24	0.33	0.37
	1	0.15	0.27	0.51	0.69	0.81	0.90	0.92
	3	0.51	0.58	0.93	0.96	0.98	0.99	1.00
	10	0.61	0.62	0.95	0.99	1.00	1.00	1.00
11 to 12	0.1	0.04	0.04	0.07	0.40	0.56	0.92	0.94
	0.3	0.04	0.04	0.07	0.40	0.56	0.92	0.94
	1	0.22	0.25	0.42	0.76	0.91	0.99	0.99
	3	0.67	0.68	0.87	0.95	0.99	1.00	1.00
	10	0.67	0.67	0.85	0.98	1.00	1.00	1.00
14 to 15	0.1	0.64	0.68	0.80	0.86	0.92	0.99	0.99
	0.3	0.64	0.68	0.80	0.86	0.92	0.99	0.99
	1	0.86	0.90	0.96	0.98	0.99	1.00	1.00
	3	0.98	0.99	0.99	1.00	1.00	1.00	1.00
	10	0.99	0.99	1.00	1.00	1.00	1.00	1.00

Table 6
Distributions of MERV ratings by filtration category used. The category distribution specifies the assumed fraction of HVAC/furnace filter category filters in use (dimensionless).

Filtration category	HVAC/Furnace distribution fraction (dimensionless)				
	No filter	MERV5	MERV7 to MERV8	MERV11 to MERV12	MERV14 to MERV15
Single family (residences) [a]	0.35	0.36	0.20	0.07	0.03
Single family (no central air)	1.00	0.00	0.00	0.00	0.00
Single family (central air only)	0.00	0.55	0.30	0.10	0.05
Standard office (buildings)	0.00	0.20	0.55	0.10	0.15
Low quality (air filtration)	0.00	0.65	0.30	0.05	0.00
Medium quality (air filtration)	0.00	0.45	0.45	0.05	0.05
High quality (air filtration)	0.00	0.00	0.25	0.50	0.25
Very high quality (air filtration)	0.00	0.00	0.00	0.00	1.00

[a] This distribution includes both the HVAC/furnace filter rating distribution for the 65% of US homes with central air systems as well as the 35% of the US homes that lack a central air system (no filter).

For modeling purposes, we assign each building use type an overall filtration category, see Table 1, which corresponds to our estimated distribution of filter media types and quality that are in use – as represented by the HVAC/furnace filter categories described in the previous paragraph. We represent the filtration efficiency distributions, Table 6, as a weighted collections of representative air filters selected to (a) span the range of installed filter ratings (MERV 5, 7 to 8, 11 to 12, and 14 to 15 filters) and (b) be compatible with prior literature surveys of building filtration efficiency. Our rationale for selecting these distributions is briefly discussed as follows. The *single family* category represents single-family homes and duplexes and we have adopted the MERV rating distribution used by El Orch et al. (2014). Only 65% of US homes have a central air (e.g., forced air furnace) system and so for the 35% of US homes using other heating systems, e.g., radiators, we assume the F_{filter} parameter in Equation (3R) is zero (the “no filter” case). In addition to the general single-family home category, we perform two sensitivity studies that consider only homes (a) possessing or (b) lacking central air systems. The *standard office* category represents well-maintained office buildings and the corresponding air filter distribution is based on the reported distribution of filter ratings in the Summarized Data of the US Environmental Protection Agency’s Building Assessment Survey and Evaluation Study (Filtration Systems - Filter Ratings Table in Whole Building HVAC Characteristics, Test Space HVAC Characteristics (US Environmental Protection Agency, 2021)). ASHRAE Standard 52.2 data are used to convert filter dust spot efficiency/holding capacity values into MERV ratings (ASHRAE, 2012; Chipley et al., 2003). The *low quality* category represents office and non-office commercial buildings as well as some multi-family housing buildings with relatively poor air filtration. The corresponding air filter distribution is based on values observed in 32 commercial buildings (Bennett et al., 2011). The *medium quality* category is an approximate average of the low quality and standard office categories. The *very-high quality* category represents buildings that are specifically built to minimize particle air concentrations, e.g., hospitals and high-tech manufacturing.

4. Results

4.1. Calculations

For each building use type in Table 1, we determine the TF distributions for 25 different airborne particle cases (five discrete particles sizes, 0.1, 0.3, 1, 3, 10 μm aerodynamic diameter, and five first order airborne loss rates, $\lambda_{generic} = 0, 0.1, 1, 5,$ and $10\ hr^{-1}$) in four steps. First, we performed a Monte-Carlo calculation of the building protection factor 10,000 times for each case using the relevant equation specified in Table 1. For each Monte-Carlo instance, a separate, independent random number was selected from each input parameter probability distribution. For the apartment buildings with corridors (RES3E and RES3F), this assumption resulted in unphysical results approximately 20% of the time due to natural air infiltration rates being below zero (these rates are calculated as the difference between the total ventilation rate and the ventilation rate due to outdoor air transport through the mechanical system). These nonphysical cases were removed from subsequent analysis. For discrete distributions, we first generate a uniformly distributed random number between 0 and 1 and then use (a) linear interpolation to infer the parameter value from Tables 4 and 5 or (b) select the discrete value from Table 6. Due to the Monte Carlo sampling process, there are small differences in the outputs for building types that use identical input parameter distributions, e.g., RES3B, RES3C and RES3D.

4.2. US building protection results

Building protection depends on particle-size (over the range of 0.1 to 10 μm), generic airborne loss rate (over the range of 0 to $10\ h^{-1}$), and, to a lesser extent, building use type. Overall, building protection values range over many orders of magnitude. For some building types, building protection for a given particle-size and decay rate varies by more than an order of magnitude. This variability reflects our best estimate of the expected variability in US building construction, operation, and weather conditions. Notably, the residential building types examined (single family homes, manufactured homes, and multi-unit apartment buildings) have a generally similar (with a factor of 2) transmission factor distribution. The transmission factors predicted for RES1 structures with and without a central furnace are similar suggest that for typical residences, filtration is a minor contributor to building protection (for typical residences, the furnace fan duty cycle is ~25% and filtration efficiency is relatively low). Detailed results for each building use type are provided as a spreadsheet in Supplemental Material S3.

We focus the remaining discussion of our results on six common and illustrative building categories. The six building categories consist of three residential building categories: single family houses (RES1 and RES3A), small apartment buildings with 3–19 units (RES3B, RES3C, and RES3D), and large apartment buildings with 20–50+ units (RES3E and RES3F). The three non-residential building categories are: retail stores (COM1), office buildings (COM4, COM5 and GOV1), and schools (EDU1). The building use types within each category all have the same

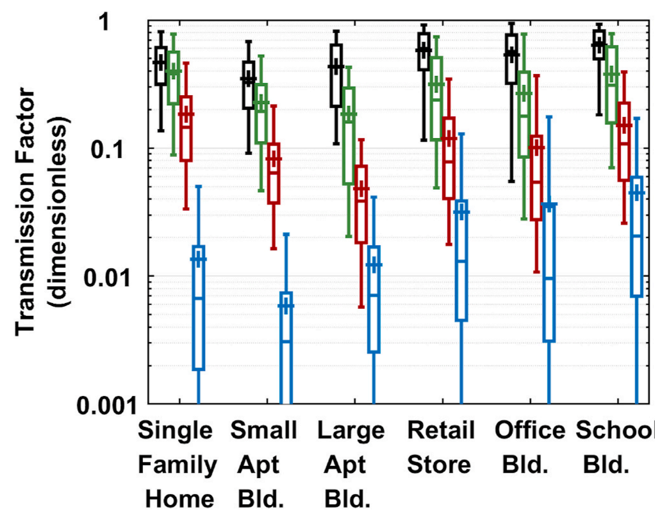

Fig. 6. Transmission factor distributions for select building types by particle size for the no airborne loss case ($\lambda_{generic} = 0\ h^{-1}$). Box and whisker plot shows the median (line), inner quartile (box), 5 and 95 percentiles (whiskers), and mean (+symbol). Particle diameter varies from left to right for each building type: black, 0.1 μm; green, 1 μm; red, 3 μm; and blue, 10 μm.

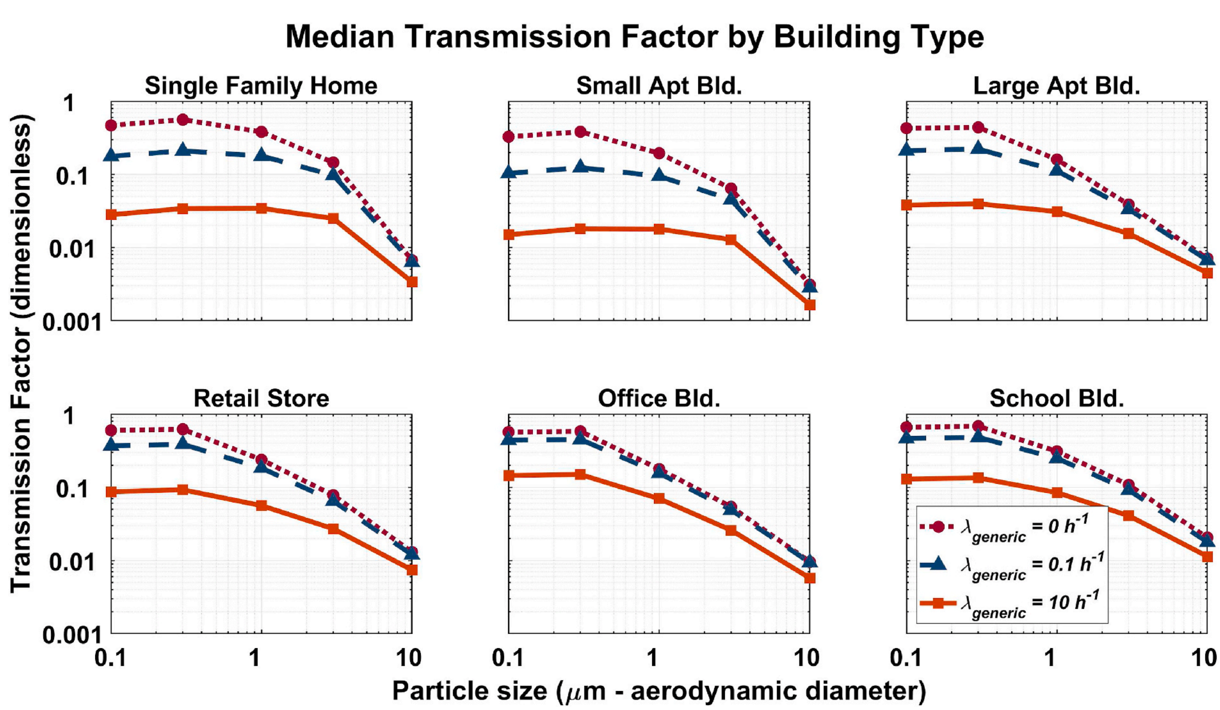

Fig. 5. Median transmission factor for select building types and airborne loss rates.

transmission factor equation, filtration category, and input parameters (see Table 1). As a consequence, the transmission factor modeling results are identical.

Fig. 5 shows the median TFs for the six selected building use types, illustrating the effects of particle size and generic loss rate. The top row shows residential buildings while the bottom row shows selected non-residential buildings. The pattern is similar across the six building types, with modest changes in protection as particle size increases from 0.1 to ~1 μm and significant increases in protection as particle size increases from ~1 to 10 μm. These large decreases in transmission factor are mainly due to the fact that larger particles have higher indoor deposition loss rates and greater filtration efficiencies. For particles smaller than ~1 μm, the transmission factor is more sensitive to the generic airborne loss rate.

Fig. 6 shows transmission factor distributions for 0.1, 1, 3, and 10 μm sized particles for the no airborne loss case ($\lambda_{generic} = 0\ h^{-1}$) using a box and whisker graph for each particle size. The variability within a given building use type (and particle-size) reflects the variability in US building construction, operation, and weather conditions. Fig. S4(a-c) shows the transmission factor distribution for the 0, 1, and 10 h^{-1} airborne loss rates for all building types. Broadly, the variability within a building type (due to differences in US building construction, operation, and weather conditions) is comparable to, and in many cases larger than, the variability between different building types.

4.3. Comparison with prior work

It is challenging to provide a formal validation of our results as (a) most building use types have not been examined in detail (especially in the HAZUS taxonomy) and (b) experimental studies that provide nationally and seasonally representative building protection estimates for any building type have not been performed. Some literature is available for semi-quantitative comparison and, despite the significant limitations noted, is discussed here to provide the reader context.

The Diapouli et al. (2013) literature review of residential observational studies reports an average $PM_{2.5}$ (particles between 0.1 and 2.5 μm in diameter) building transmission factor of 0.7 (range of 0.4 to 0.85). This result is similar to the 0.3 to 0.8 range reported by later studies (Chen and Zhao, 201; Shi et al., 2017). We note that each primary study typically reported the average from a collection of buildings and that individual building results can vary. These observational results overlap our predicted TF of 0.4 (95% range of 0.09 to 0.8) for 1 μm particles infiltrating US single family homes (RES1). The comparison between prior studies and our modeling results should be interpretated with caution due both the anecdotical nature of the data as well as known analysis biases. For example, Diapouli et al. (2013) estimated $\lambda_{internal}$ values of 0.2 h^{-1} (range of 0.1 h^{-1} to 0.4 h^{-1}), lower than most of the existing occupied home particle deposition rate data. Furthermore, non-deposition loss terms can be considerable, e.g., 0.9 h^{-1} average filtration loss for 1 μm diameter particles for residences fitted with a MERV 7 rated filter. This discrepancy may be due to the method Diapouli et al. (2013) used to estimate within building particle loss rate (and transmission factors) which is known to have systematic bias (Bennett and Koutrakis, 2006). Our results are also consistent with the El Orch et al. (2014) single family building results. This agreement is expected as our residential model is closely related to the *El Orch et al.* model.

Prior work on office buildings is less extensive than for residential buildings; however, existing office building data show transmission factor estimates broadly comparable to those produced by our model. One notable effort studied a single modern office building for a week and found that the central 50% of the indoor/outdoor ratio values ranged between (a) 0.15 to 0.19 for 0.1 to 0.3 μm particles and (b) 0 to 0.03 for 1 to 2.5 μm particles (Chatoutsidou et al., 2015). The reported values are consistent with the 5 to 25 percentile transmission factors predicted for the office model (COM4): (a) (0.06 to 0.3) for both 0.1 and 0.3 μm particles and (b) (0.03 to 0.09) and (0.01 to 0.03) for 1 μm and 3 μm particles, respectively.

5. Summary and conclusions

Buildings can protect their occupants from outdoor airborne hazards. The degree to which buildings protect their occupants depends on both building- and contaminant-related factors. In this paper, we describe a building protection methodology based upon a broadly applicable taxonomy of the US building stock and an extensive compilation of published data describing the air flow and airborne particle behavior parameters. Our results illustrate the effects of building type, particle size and airborne decay rate on building transmission factor.

While we believe that the detailed literature reviews performed to select model input parameter distributions represent an advance over prior, broad-scale US building protection estimates; some parameter values are based on limited existing data combined with best engineering judgement. The present methodology can be used with improved input parameter distributions to provide more accurate protection estimates. There are, for example, detailed building and environmental data sets available for selected geographic regions, e.g. (Chan et al., 2005, 2007, 2008; Ng et al., 2018), that yield estimates of the regional and seasonal variation in key airflow parameters. The use of such parameters would facilitate better understanding of the variation of building protection across the US and under different weather conditions.

Modeling and physics enhancements could improve upon the "proof of principle" capability we have described here. For example, improved building data would allow distinctions to be made between building use types currently assumed to be identical, including the broad range of buildings in the Industrial occupancy class shown in Table 1. In addition, there are currently no robust models or data sets to permit the incorporation of the potentially important effects of window opening (the current results assume windows are closed). The use of more complex models, such as the NIST CONTAM model (Dols and Polidoro, 2020), could elucidate the spatial differences within multizone buildings. Use of these models would increase requirements for more and higher fidelity input data for actual buildings, of which only a limited amount of information is available in the literature. Other features that could be incorporated into the current methodology are particle resuspension from indoor surfaces or from indoor fomites exposed outdoors. Lastly, the inclusion of aerosol coagulation, chemical phase change (e.g., particle to gas or vice versa), or thermophoretic or electrostatic interactions with building surfaces would allow consideration of nanometer scale particles or particles composed of chemical species that readily volatize, e.g., (Yu et al., 2013; Lunden et al., 2003; Johnson et al., 2017; Hodas and Turpin, 2014; Holve et al., 1990).

CRediT authorship contribution statement

Michael B. Dillon: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Richard G. Sextro:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **W. Woody Delp:** Methodology, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosenv.2021.118773.

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