Science and Technology for the Built Environment (2016) **00**, 1–32

ISSN: 2374-4731 print / 2374-474X online
DOI: 10.1080/23744731.2016.1163239

Taylor & Francis
Taylor & Francis Group

Modeling the impact of residential HVAC filtration on indoor particles of outdoor origin (RP-1691)

PARHAM AZIMI, DAN ZHAO, and BRENT STEPHENS*

Department of Civil, Architectural and Environmental Engineering, Illinois Institute of Technology, 3201 S Dearborn Street, Chicago, IL 60616, USA

Much of human exposure to airborne particles of outdoor origin, including fine particles smaller than 2.5 μm ($PM_{2.5}$) and ultrafine particles smaller than 0.1 μm (UFPs), occurs in residences. High-efficiency central HVAC filters are increasingly being used in residences, but questions remain about their effectiveness in reducing indoor $PM_{2.5}$ and UFPs of outdoor origin in homes operating under realistic conditions (e.g., with HVAC systems operating only to meet heating or cooling demands). Here dynamic building energy and indoor air mass balance modeling are combined to estimate the impacts of 11 HVAC filters (minimum efficiency reporting value [MERV] 5 through high-efficiency particulate air [HEPA]) on indoor concentrations of $PM_{2.5}$ and UFPs of outdoor origin in multiple vintages of prototypical single-family residences relying on either infiltration or mechanical ventilation systems in 22 U.S. cities. Results demonstrate that higher-efficiency HVAC filters can meaningfully reduce indoor proportions of outdoor $PM_{2.5}$ and UFPs inside residences, but home vintage, climate zone, and ventilation strategy strongly influence the outcomes due to widely varying air exchange rates, HVAC system runtimes, and sources of ventilation air. Higher efficiency filters had a greater impact in older, leakier homes relying on infiltration alone and in new homes relying on supply-only mechanical ventilation systems designed to meet ASHRAE Standard 62.2.

Introduction

A variety of adverse health effects is associated with elevated outdoor concentrations of fine particles less than 2.5 μm ($PM_{2.5}$; Pope et al. 2002; Pope and Dockery 2006; Miller et al. 2007; Bell et al. 2009; Brook et al. 2010; Fann et al. 2012) and number concentrations of ultrafine particles less than 0.1 μm (UFPs; Penttinen et al. 2001; von Klot et al. 2002; Stölzel et al. 2007; Weichenthal et al. 2007). Because Americans spend nearly 90% of their time indoors and almost 70% of their time at home, on average (Klepeis et al. 2001), and outdoor particles infiltrate and persist in buildings with widely varying efficiencies (Thatcher and Layton 1995; Thatcher et al. 2003; Williams et al. 2003; Rim et al. 2010; Chen and Zhao 2011; Stephens and Siegel 2012), much of human exposure to particulate matter of outdoor origin actually occurs indoors, particularly inside residences (Meng et al. 2005; Wallace and Ott 2011; Hodas et al. 2012, 2013; MacNeill et al. 2012, 2014; Baxter et al. 2013).

High-efficiency particle air filters are increasingly being used in central residential HVAC systems to reduce indoor concentrations of particulate matter of both indoor and outdoor origins (Burroughs and Kinzer 1998; Fugler et al. 2000; Brauner et al. 2007; MacIntosh et al. 2008, 2010; Stephens et al. 2010a, 2010b; Lin et al. 2011; Brown et al. 2014). Several previous investigations have explored the impacts of HVAC filters on particle concentrations in residences through a combination of measurements and models (Riley et al. 2002; Howard-Reed et al. 2003; Wallace et al. 2004; MacIntosh et al. 2010; Brown et al. 2014). However, many of these studies remain of limited value to organizations that set standards and guidelines for residential indoor air quality, such as ASHRAE, because they have (1) considered only a narrow range of particle sizes or classes, (2) relied on filter classifications other than the minimum efficiency reporting value (MERV) from ASHRAE Standard 52.2 (ASHRAE 2012), (3) investigated only a narrow range of HVAC filter efficiencies, (4) not considered the impacts of different types of mechanical ventilation systems, and/or (5) relied on simplistic assumptions for crucial input parameters or relatively simple time-averaged mass balance models. Questions remain about the effectiveness of higher efficiency HVAC filters for reducing indoor concentrations of particulate matter of outdoor origin in homes operating under realistic conditions, including having time-varying outdoor pollutant concentrations, air exchange rates (AERs), and HVAC systems that operate only to meet heating or cooling demands (which is the case in the vast majority of homes in the United States).

Therefore in this project, dynamic building energy simulations and indoor air mass balance models are combined to estimate the impacts of 11 types of central HVAC filters,

Received August 10, 2015; accepted February 1, 2016
Parham Azimi, Student Member ASHRAE. **Dan Zhao,** Student Member ASHRAE. **Brent Stephens, PhD,** Associate Member ASHRAE.
*Corresponding author e-mail: brent@iit.edu
Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/uhvc.

ranging from MERV 5 to high-efficiency particulate air (HEPA) filters, on the indoor proportion of fine and ultrafine particles of outdoor origin (i.e., both $PM_{2.5}$ and UFPs) in prototypical single-family homes located in 22 U.S. cities spanning all 15 U.S. climate zones (Azimi et al. 2015).

Methods

To perform the simulations, a number of reasonable assumptions are relied upon for model input parameters in addition to hourly outdoor pollutant data and meteorological conditions from the year 2012 (the most recent year for which outdoor $PM_{2.5}$ data were available in all chosen locations). A combination of BEopt (Christensen et al. 2006) and EnergyPlus (Crawley et al. 2001) were first used to model realistic home operation on an hourly basis for each scenario, including AERs and HVAC system runtimes. These parameters were then used as time-varying inputs to a dynamic indoor air mass balance model to estimate time-varying indoor concentrations of $PM_{2.5}$ and UFPs of outdoor origin over the course of the year under different filter scenarios. Six distinct prototypical home types were modeled, including three typical vintages of single-family homes relying on infiltration alone, and a typical new high-efficiency home relying on three different types of mechanical ventilation systems designed to meet ASHRAE Standard 62.2 (ASHRAE 2010). The same model home geometry is used in all scenarios, although building characteristics vary by vintage and location. A sensitivity analysis is also performed to evaluate the relative influence of various model input parameters and to explore the utility of using simpler time-averaged mass balance models compared to more detailed time-varying models. The following sections describe the selection of model locations, model home characteristics, model inputs, and methods for the energy and indoor air mass balance modeling.

Selection of model locations

The selection of locations for modeling was designed to capture all 15 U.S. climate zones, as well as the top 15 cities with the highest annual average outdoor $PM_{2.5}$ concentrations summarized in the most recent Integrated Science Assessment for Particulate Matter (data coverage includes 2005–2007; U.S. EPA 2009). A total of 22 cities were selected for modeling since some of the most polluted cities were in the same climate zone. Locations include Miami, FL (climate zone 1A); Houston, TX (2A); Phoenix, AZ (2B); Atlanta, GA (3A); Birmingham, AL (3A); Los Angeles, CA (3B); Riverside, CA (3B); San Francisco, CA (3C); New York, NY (4A); Philadelphia, PA (4A); St. Louis, MO (4A); Albuquerque, NM (4B); Seattle, WA (4C); Boston, MA (5A); Chicago, IL (5A); Detroit, MI (5A); Pittsburgh, PA (5A); Denver, CO (5B); Blaine (near Minneapolis), MN (6A); Colstrip, MT (6B); Bismarck, ND (7A); and Pinedale, WY (7B). This wide range of locations allows for modeling a wide range of outdoor particulate matter concentrations and building design and operational characteristics that influence indoor particle concentrations.

Model home characteristics

The same basic home geometry was used in each climate zone, although envelope insulation, airtightness, and particle penetration characteristics differed by both vintage and location. A 188-m^2 single-family home with three bedrooms, two bathrooms, 2.4-m-high ceilings, a natural gas furnace, and a central forced-air air-conditioning system was chosen as the basis for all vintages in all locations as it represents a very typical size and geometry for homes in the United States. The base home characteristics for each vintage are summarized in the following sections and are also described in full in Appendix A.

Homes relying on infiltration alone

Modern high-efficiency home

New energy-efficient homes were designed to have lower outdoor particle infiltration by incorporating well-insulated building envelopes, high airtightness (three air changes per hour at 50 Pa, or 3 ACH_{50}), and a properly sized high-efficiency heating and air-conditioning systems for each climate zone. Each city was assigned to a region of the United States (i.e., West, Midwest, Northeast, or South), and the most typical type of foundation for each region was identified for single-family homes in the area (U.S. Census Bureau n.d.). Homes had crawlspaces, basements, or concrete slab foundations, depending on location. All homes were modeled with wood frame construction, with R-values of walls, ceilings, and foundations and U-values and solar heat gain coefficient (SHGC) values of windows varying by climate zone according to the International Energy Conservation Code (IECC) 2012. The flow rates of each kitchen and bathroom exhaust fan were assumed to be 170 and 85 m^3/hr, respectively, using default values for fan efficiency in BEopt (0.18 W/(m^3/hr)). The kitchen range hood was assumed to operate 60 min/day (6:00 p.m.–7:00 p.m.), and the two bathroom fans were assumed to operate 60 min/day (7:00 a.m.–8:00 a.m.). This was held constant for all city and home vintage scenarios.

Typical existing home

Next, typical existing, older, and less-efficient homes were designed to have higher, yet still moderate, outdoor particle infiltration by incorporating moderately insulated building envelopes, typical airtightness (10 ACH_{50}), and larger and less-efficient heating and air-conditioning systems for each climate zone based on typical existing home characteristics in each area. Envelope characteristics were taken from two primary surveys of existing housing characteristics for homes built after 1979 (Huang et al. 1987, 1999). Homes again had crawlspaces, basements, or concrete slab foundations, depending on location. All homes were modeled with wood frame construction, with R-values of walls, ceilings, and foundations and U-values and SHGC values of windows varying by climate zone according to Huang et al. (1987, 1999).

Typical older vintage home

Finally, typical older vintage homes were designed to have the highest outdoor particle infiltration by incorporating poorly insulated building envelopes, low airtightness (20 ACH_{50}), and larger and less-efficient (and often undersized) heating and air-conditioning systems for each climate zone based on typical older vintage home characteristics in each location. Envelope characteristics were again taken from two primary surveys of existing housing characteristics for homes built between 1950 and 1979 (Huang et al. 1987, 1999). Homes again had crawlspaces, basements, or concrete slab foundations, depending on location. All homes were modeled with wood framed construction, with R-values of walls, ceilings, and foundations and U-values and SHGC values of windows varying by climate zone and vintage according to Huang et al. (1987, 1999). The same assumptions for exhaust fan operation as in the other two home types were included.

ASHRAE 62.2 compliance in new homes with mechanical ventilation systems

Next, only the new vintage home models were used to investigate the impacts of three common types of mechanical ventilation systems on indoor concentration of $PM_{2.5}$ and UFPs of outdoor origin. Older and existing homes are unlikely to have been built to meet the minimum ventilation requirements in ASHRAE Standard 62.2 using mechanical ventilation systems. In all cases, the minimum continuous mechanical ventilation airflow rate required was calculated using (ASHRAE Standard 62.2; ASHRAE 2010). The minimum mechanical ventilation airflow rate for the model homes used herein ($A_{floor} = 188$ m^2 and $N_{br} = 3$) is thus assumed to be 23.5 L/s (85 m^3/hr). This yields a minimum ventilation AER of 0.18 hr^{-1}:

$$Q_{fan,\min} = 0.05 A_{floor} + 3.5 (N_{br} + 1), \qquad (1)$$

where

$Q_{fan,\min}$ is the minimum mechanical ventilation flow (L/s),
A_{floor} is the floor area (m^2), and
N_{br} is the number of bedrooms (—).

Exhaust-only ventilation

In the exhaust-only mechanical ventilation approach, a small exhaust fan was assumed to operate 100% of the time with an airflow rate of 85 m^3/hr. Make-up air was assumed to be provided by infiltration through the building envelope. Since the addition of the exhaust fan will increase AERs and alter system runtimes, EnergyPlus was again used to model hourly AERs and HVAC system runtimes in each location assuming that the exhaust fan operates continuously.

Supply-only ventilation

In the supply-only ventilation system approach, outdoor particle penetration was assumed to occur through a combination of intentional mechanical supply in addition to incidental infiltration through the building envelope. A supply fan was assumed to operate 100% of the time with a constant airflow rate of 85 m^3/hr. In these cases, a constant ventilation rate of at least 0.18 hr^{-1} of ambient air was assumed to be supplied directly by the ventilation system and passed through a filter installed inside a small ventilating unit; any additional air exchange was assumed to occur due to infiltration through the building envelope.

Central fan integrated supply (CFIS) with continuous exhaust

Next, a CFIS system combined with continuous exhaust was considered. In this case, an 85-m^3/hr intermittent outdoor air supply was assumed to be ducted directly into the return plenum of the existing air handling unit and an 85-m^3/hr exhaust system was assumed to run continuously. Therefore, outdoor air was assumed to enter the indoor environment through a combination of (1) direct supply through the HVAC system when the HVAC system was operating to meet heating or cooling demands (and filtered by the central system filter) and (2) infiltration through the building envelope when the HVAC system was not operating. The portion of each depends on the modeled HVAC system runtimes. The CFIS system was assumed to operate with an HVAC system runtime equal to that from the exhaust-only ventilation system scenario (runtimes still varied based on location). ASHRAE Standard 62.2 was assumed to be met at all times by the continuous exhaust flow. Figure 1 schematically demonstrates the airflow and particle transport pathways in the homes relying on infiltration alone as well as the three mechanical ventilation system scenarios.

Modeling procedures

Indoor air mass balance models

In all cases, a discrete time-varying mass balance was utilized in a single well-mixed zone in the absence of indoor sources to estimate time-varying indoor concentrations of $PM_{2.5}$ and UFPs of outdoor origin. All dynamic indoor air mass balance simulations were performed in MATLAB R2014a (MathWorks, Inc., 2014). Any window or door opening was ignored in all cases for simplicity. The initial indoor concentration (at time $t = 0$) for each case was assumed to be equal to the steady-state concentration for that initial time period (from Equation 2), estimated using the modeled AER, outdoor particle concentration, penetration factor, deposition loss rate constant, and fractional HVAC system runtime at time $t = 0$.

Homes relying on infiltration alone

For the simulations involving homes relying on infiltration alone, the indoor particle concentration (of $PM_{2.5}$ or UFPs) of outdoor origin at each time step [$C_{i,in,inf}(t_n)$] was estimated using equation 2:

$$\begin{aligned} C_{i,in,inf}(t_n) = C_{i,in,inf}(t_{n-1}) + \Delta t \;\; \big[& P_i \lambda_{inf}(t_n)\, C_{i,out}(t_n) \\ & - \big(\lambda_{inf}(t_n) + \beta_i \\ & + f(t_n)\, \eta_{i,HVAC} \lambda_{HVAC}\big) \\ & \times C_{i,in,inf}(t_{n-1})\big], \end{aligned} \qquad (2)$$

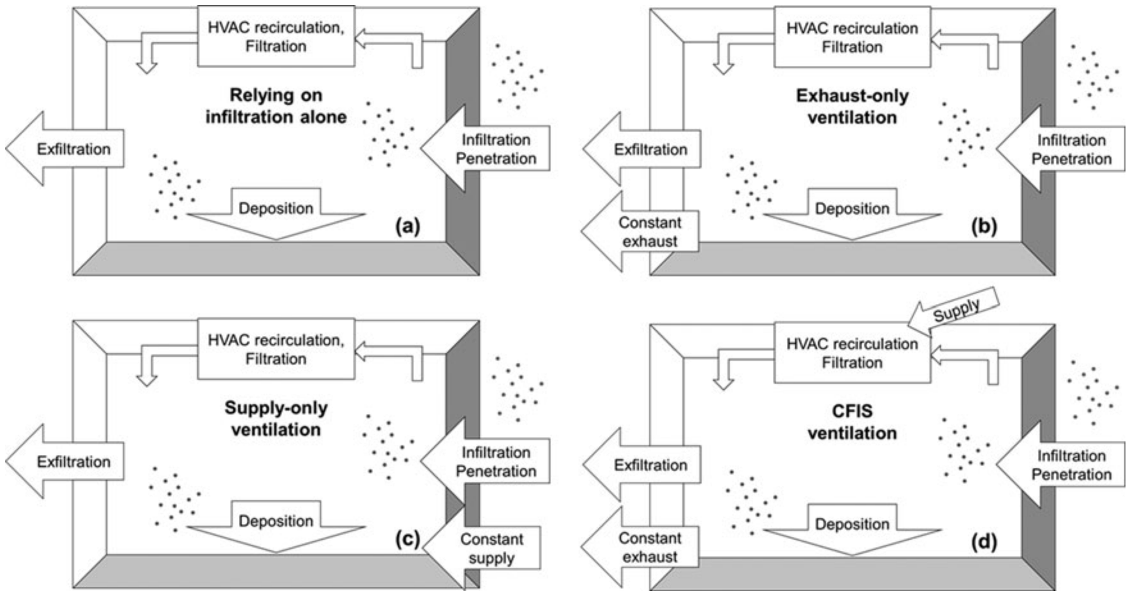

Fig. 1. Schematic representation of the airflow and particle transport pathways. a. In the homes relying on infiltration alone. b. In the homes relying on exhaust-only ventilation. c. In the homes relying on supply-only ventilation. d. In the homes relying on CFIS ventilation systems.

where

$C_{i,in,inf}\,(t_n)$ is the indoor $PM_{2.5}$ or UFP concentration of outdoor origin ($\mu g/m^3$ or $\#/m^3$),
P_i is the $PM_{2.5}$ or UFP penetration factor of the building envelope (—),
λ_{inf} is the AER due to infiltration (hr^{-1}),
$C_{i,out}$ is the outdoor $PM_{2.5}$ or UFP concentration ($\mu g/m^3$ or $\#/m^3$),
β_i is the first-order indoor particle deposition rate loss coefficient for $PM_{2.5}$ or UFP (hr^{-1}),
$\eta_{i,HVAC}$ is the $PM_{2.5}$ or UFP removal efficiency of the HVAC filter (—),
λ_{HVAC} is the HVAC system recirculation rate (HVAC airflow rate divided by volume, hr^{-1}),
f is the fractional operation time of the HVAC system (—),
t_n is the current time step (hr), and
t_{n-1} is the previous time step (hr).

One-minute intervals were used to improve model stability ($\Delta t = 0.01667$ h). Hourly input values relied upon for $C_{i,out}$, λ_{inf}, and f which were linearly interpolated to yield inputs at the 1-min time steps.

Exhaust-only ventilation

A similar procedure was then followed to estimate the time-varying indoor concentrations of $PM_{2.5}$ and UFPs of outdoor origin in only the modern high-efficiency homes, assuming one of the three different types of mechanical ventilation systems were installed and operating. Similar to homes relying only on infiltration alone, the time-varying indoor concentration of $PM_{2.5}$ and UFPs of outdoor origin in homes with exhaust-only ventilation systems was estimated using Equation 3. Because the supply air is assumed to infiltrate through the building envelope with exhaust-only ventilation systems, it was assumed that $PM_{2.5}$ and UFP penetration factors were the same as the penetration factors for the new homes without mechanical ventilation systems (described in subsequent sections). The HVAC recirculation rates (λ_{HVAC}) for the three scenarios with mechanical ventilation were assumed to be equal to the same value for new homes relying on infiltration alone;

$$\begin{aligned} C_{i,in,exhaust}\,(t_n) = {} & C_{i,in,exhaust}\,(t_{n-1}) \\ & + \Delta t \big[P_i \lambda_{total,exhaust}\,(t_n)\, C_{i,out}\,(t_n) \\ & \quad - (\lambda_{total,exhaust}\,(t_n) + \beta_i \\ & \quad + f_{exhaust}\,(t_n)\, \eta_{i,HVAC} \lambda_{HVAC}) \\ & \quad \times C_{i,in,exhaust}\,(t_{n-1}) \big], \end{aligned} \tag{3}$$

where

$C_{i,in,exhaust}\,(t_n)$ is the indoor concentration of $PM_{2.5}$ or UFPs of outdoor origin at each time step in new homes with exhaust-only ventilation systems ($\mu g/m^3$ or $\#/m^3$),
$\lambda_{total,exhaust}$ is the total AER in new homes with exhaust-only ventilation systems due to a combination of mechanical exhaust and infiltration (hr^{-1}), and
$f_{exhaust}$ is the fractional operation time of the central HVAC system in new homes with exhaust-only ventilation systems (—).

Supply-only ventilation

Similarly, the time-varying indoor $PM_{2.5}$ and UFP concentrations of outdoor origin for new homes with supply-only ventilation systems were estimated using equation 4. With supply ventilation, $PM_{2.5}$ and UFP penetration factors were assumed to depend not only on envelope infiltration but also on the removal efficiency of the dedicated mechanical ventilation system filter. Because most manufacturers have not adopted higher efficiency filtration systems in small residential ventilation units, it was assumed that supply-only mechanical ventilation systems utilize only a MERV 5 filter. Other higher efficiency filtration products do exist on the market, but the authors are not aware of their widespread use;

$$C_{i,in,supply}(t_n) = C_{i,in,supply}(t_{n-1}) + \Delta t \;\; \{[\lambda_{fan}(1-\eta_{i,supply}) + P_i(\lambda_{total,supply}(t_n) - \lambda_{fan})]\, C_{i,out}(t_n) - (\lambda_{total,supply}(t_n) + \beta_i + f_{exhaust}(t_n) \times \eta_{i,HVAC}\lambda_{HVAC}) \times C_{i,in,supply}(t_{n-1})\}, \quad (4)$$

where

$C_{i,in,supply}(t_n)$ is the indoor concentration of $PM_{2.5}$ or UFPs of outdoor origin at each time step in new homes with supply-only ventilation systems ($\mu g/m^3$ or $\#/m^3$),
λ_{fan} is the AER due to the 85 m^3/hr of supply air provided by the mechanical ventilation system (0.18 hr^{-1}),
$\lambda_{total,supply}$ is the total AER due to infiltration and ventilation combined (hr^{-1}),
f_{supply} is the fractional operation time of the central HVAC system in new homes with a supply-only ventilation system (—), and
$\eta_{i,supply}$ is the $PM_{2.5}$ or UFP removal efficiency of the supply ventilation system filter (MERV 5).

CFIS with continuous exhaust

Finally, time-varying indoor concentrations of $PM_{2.5}$ and UFPs of outdoor origin for the new homes with CFIS systems were estimated using Equation 5, which is a combination of both supply-only and exhaust-only ventilation scenarios depending on the operating status of the HVAC system:

$$C_{i,in,CFIS}(t_n) = C_{i,in,CFIS}(t_{n-1}) + \Delta t\,[\{P_i\lambda_{total,CFIS}(1-f_{HVAC,CFIS}) + f_{HVAC,CFIS}[\lambda_{fan}(1-\eta_{i,HVAC}) + P_i(\lambda_{total,CFIS}(t_n)-\lambda_{fan})]\}\, C_{i,out}(t_n) - (\lambda_{total,CFIS}(t_n) + \beta_i + f_{supply}(t_n)\,\eta_{i,HVAC}\lambda_{HVAC})\, C_{i,CFIS}(t_{n-1})], \quad (5)$$

where

$C_{i,in,CFIS}(t_n)$ is the indoor concentration of $PM_{2.5}$ or UFPs of outdoor origin at each time step in new homes with CFIS ventilation systems ($\mu g/m^3$ or $\#/m^3$),
$\lambda_{total,CFIS}$ is the total AER due to infiltration and ventilation combined in new homes with a CFIS ventilation system (hr^{-1}), and
$f_{HVAC,CFIS}$ is the fractional operation time of the central HVAC system in new homes with a CFIS ventilation system (—).

The total AER and fractional HVAC system operation times for the supply-only systems and CFIS with continuous exhaust system were assumed to be the same as those modeled for exhaust-only ventilation systems.

Collecting model input parameters

Initial BEopt and EnergyPlus simulations

The basic home geometry was first constructed in BEopt Version 2.2.0 in order to properly size the central air-conditioner and gas furnace and create an EnergyPlus input file (IDF file) for each vintage and location using only the base building characteristics. Each IDF file was then edited to correctly size heating and cooling equipment for each vintage and location based on knowledge of commonly available incremental air-conditioner and furnace capacities (i.e., in increments of 1.75 or 3.5 kW) and typical manufacturer-recommended airflow rates. This typically involved correctly sizing heating and cooling systems relative to the load in existing and new vintages and under-sizing heating and cooling systems in older vintage homes, which served to reflect more realistic operation than what was originally assumed in BEopt (Hopkins et al. 2011). Any deficits in capacity were assumed to either lead to thermal discomfort or be supplemented by window air-conditioning units or space heaters (without additional filtration), as would be somewhat common for older homes. Once systems were sized, it was assumed that each air-handling unit had a constant airflow rate of 193 m^3/hr per kW of cooling capacity and that airflow rates were the same for both heating and cooling operation; recent studies suggest that the latter is a reasonable assumption in many homes (Walker et al. 2012; Stephens 2014). This provided a constant recirculation rate for each home vintage and location for use throughout the remaining simulations.

Simulating hourly AERs and HVAC system runtimes in EnergyPlus

EnergyPlus Version 8.1.0 was then used to simulate hourly AERs and HVAC system runtimes for each model scenario. Simulation time steps were changed to six per hour to provide finer modeling resolution. Each home and location was modeled using actual meteorological year (AMY) data from 2012 to capture coinciding weather conditions during the same year for which outdoor particle concentration data were gathered (described in the next section). These historical weather files were purchased from White Box Technologies for all 22 cities (White Box Technologies 2014). Hourly AERs and HVAC system runtimes were then linearly interpolated at 1-min intervals and incorporated into the indoor air mass balance models as time-varying inputs.

Outdoor particulate matter concentrations

Hourly outdoor $PM_{2.5}$ data in each location were first gathered from the U.S. EPA's Air Quality System (AQS) data website for the year 2012 (U.S. EPA 2013). Missing values were taken from the next closest monitoring station or linearly interpolated between times before and after the missing observation. Because UFP concentrations are not measured across the United States in any consistent manner, reliance was on an approximate measure of UFP concentrations based on associations with NO_x. Through a literature review, several studies were identified that have found moderately strong

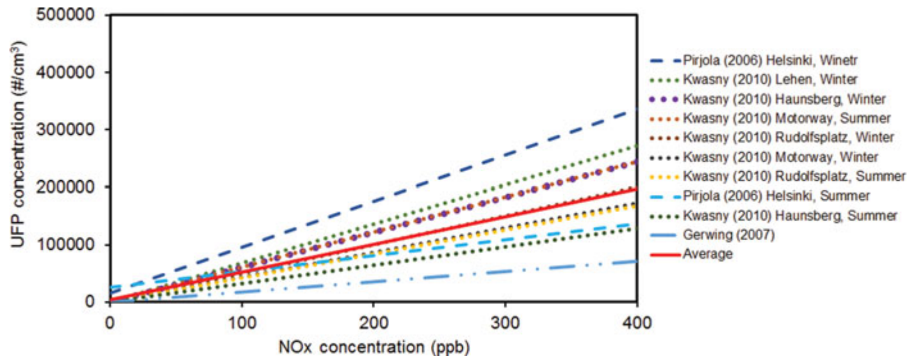

Fig. 2. Correlations between outdoor UFP and NO_x concentrations reported in several field studies.

correlations between outdoor UFP concentrations and NO_x concentrations (Pirjola et al. 2006; Gerwig et al. 2007; Kwasny et al. 2010; Health Effects Institute [HEI] 2013). Correlations from several locations across various time scales in the above-mentioned literature are shown in Figure 2, along with a linear regression fit through the existing study data that was used herein. While there is a clear increasing trend between UFP concentrations (measured sometimes on an hourly basis and sometimes on a daily basis), there is obvious scatter as well ($R^2 = 0.68$, but uncertainty is even higher because of uncertainty in the underlying regression coefficients making up each data point). Therefore, absolute values of UFP concentrations herein should be considered to be very approximate and with high uncertainty. While this introduces substantial uncertainty into the present model, these estimates can still serve to demonstrate the impact of HVAC filters on relative indoor–outdoor concentration ratios of UFPs for the 20 cities for which data were available (excluding Birmingham, AL, and Seattle, WA, because hourly NO_x data are not available for these two cities). All station characteristics are described in full in Appendix B.

HVAC filtration efficiency for $PM_{2.5}$ and UFPs

Estimates of HVAC filtration efficiency for both $PM_{2.5}$ and UFPs were based on a recent study in which a large number of outdoor particle size distributions were mapped, including those resulting after modification by typical size-resolved residential building envelope penetration factors, to size-resolved removal efficiency curves from typical HVAC filters that had received a MERV rating after tests were conducted in an ASHRAE Standard 52.2 test facility (Azimi et al. 2014). A summary of the filtration efficiency inputs for this work is provided in Figure 3, which provides the mean (± one standard deviation) estimate of $PM_{2.5}$ and UFP removal efficiencies for each MERV classification. These 11 filters were modeled herein, including MERV 5, 6, and 7 (×2, including both a low-performance and high-performance MERV 7); MERV 8, 10, and 12 (×2, including both low and high performance); MERV 14 and 16; and HEPA. The mean removal efficiency values for models were relied upon herein. Filters were specifically chosen that had been classified according to Standard 52.2 and received a MERV rating because of their high relevance to ASHRAE membership. The filters had not been

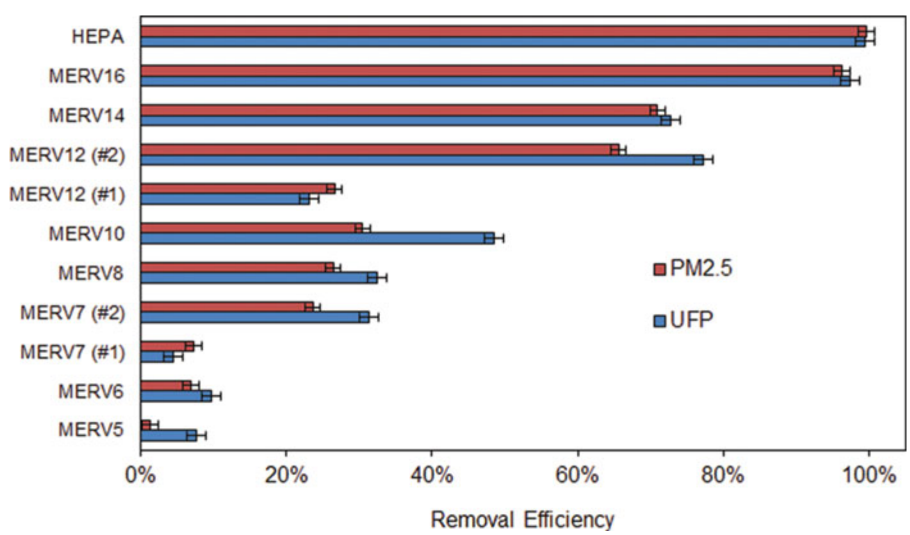

Fig. 3. Mean $PM_{2.5}$ and UFP removal efficiency for 194 outdoor particle size distributions and 11 representative HVAC filters listed by MERV, considering modification by typical residential infiltration factors (Azimi et al. 2014).

categorized by any other test method (e.g., EN 779), although approximate comparisons can be drawn between MERV and the EN 779 classes following Table 5 in Tronville and Rivers (2006).

Air handler airflow rates, and thus values for λ_{HVAC}, were assumed to be constant for all filter scenarios regardless of MERV. This is considered a reasonable assumption because (a) there are a variety of new high-efficiency filtration products on the market with extended depths that reduce pressure drop and maintain airflow rates (Stephens and Siegel 2013), (b) airflow rate reductions with permanent split capacitor (PSC) blowers are typically less than 10–15% for new higher pressure drop filters (Stephens et al. 2010a, 2010b, 2010c) and approximately 0% for electronically commutated motor (ECM) blowers (Walker et al. 2012; Stephens 2014), and (c) it allows the generalizing of results without specifying particular filtration products with specific pressure drop and airflow rate impacts. Moreover, it was also assumed that filters are replaced on a regular basis and that their removal efficiencies do not change with loading or time, again primarily for simplicity as well as a lack of real field data for $PM_{2.5}$ and UFP removal efficiencies.

Penetration factors and deposition loss rate coefficients for $PM_{2.5}$ and UFPs

Inputs for envelope penetration factors and indoor deposition loss rate coefficients for both $PM_{2.5}$ and UFPs were culled from recent literature. Deposition loss rate coefficients were kept constant for all locations and time periods, primarily for simplicity. Envelope penetration factors varied according to home type (new, existing, and old vintages) in order to reflect differences in penetration efficiency based on envelope airtightness (Stephens and Siegel 2012). It was assumed that building envelope penetration factors in new homes with mechanical ventilation systems were the same as in the new homes relying on infiltration alone. While this is considered a reasonable assumption, it is also feasible that the presence of mechanical ventilation systems (and particularly exhaust systems) would lead to a greater pressure difference across the envelope and potentially increase penetration factors for a given envelope compared to infiltration-only conditions. However, the authors are not aware of any measurements of this phenomenon in real buildings to date. Moreover, models suggest that the impact of increased pressure differences across idealized cracks on penetration factors would be small for most particle sizes for all but the smallest cracks (Liu and Nazaroff 2001).

Penetration factors for $PM_{2.5}$ were taken from the largest study of $PM_{2.5}$ penetration factors in residences that could be found: Williams et al. (2003), who reported mean $P_{PM2.5} = 0.72$ across nearly 40 homes, with a minimum of 0.11 and a maximum of 1.0. These discrete values were assigned to new, existing, and old vintages of homes, respectively. Penetration factors for UFPs were taken from the largest known of UFP penetration factors residences that could be found Stephens and Siegel (2012), who reported mean $P_{UFP} = 0.47$, with a minimum of 0.17 and a maximum of 0.70. These values were assigned to existing, new, and old vintages

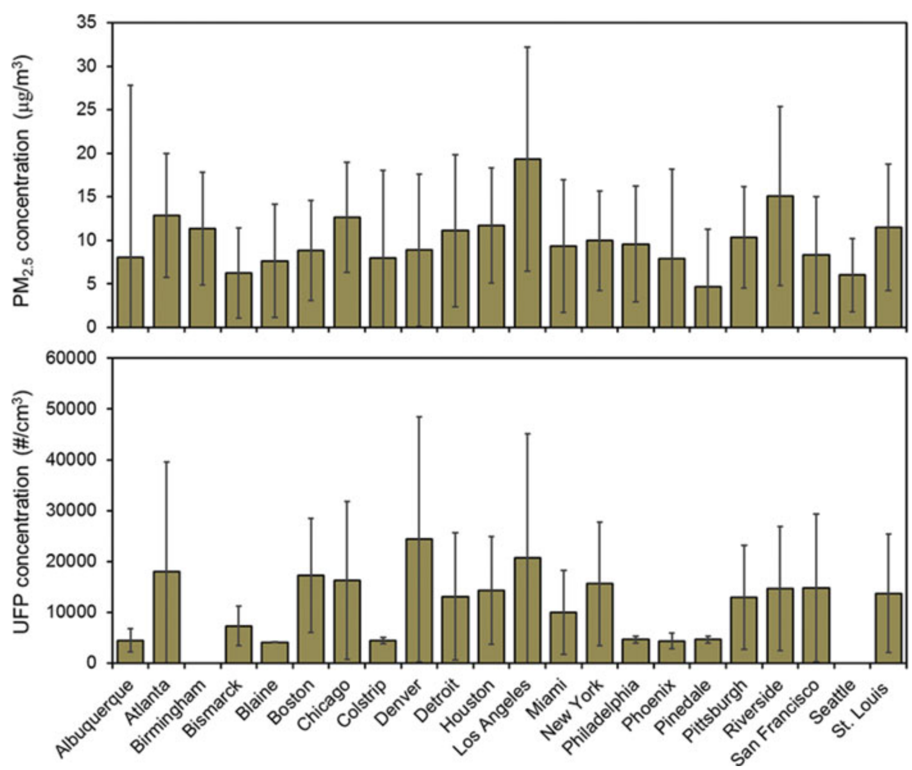

Fig. 4. Mean and standard deviation of hourly outdoor $PM_{2.5}$ and (estimated) UFP concentrations for each of the 22 U.S. locations over the entire year of 2012 ($n = 8760$ for each city).

of homes, respectively. Wallace et al. (2013) recently reported $PM_{2.5}$ and UFP deposition loss rate coefficients in over 50 homes in Canada in one of the largest studies known to date. Their median deposition loss rate coefficients were used and held constant across all home vintages and locations. Deposition loss rate coefficients used herein were 0.70 and 0.92 hr^{-1} for $PM_{2.5}$ and UFP, respectively.

Results

Outdoor $PM_{2.5}$ and UFP concentrations

Distributions of hourly outdoor $PM_{2.5}$ concentration data for the entire year of 2012 that were gathered from the U.S. EPA AQS data website (as well as estimated hourly UFP concentrations based on hourly NO_x concentrations) for all considered locations are shown in Figure 4.

Annual median outdoor $PM_{2.5}$ concentrations ranged from as low as ~5 $\mu g/m^3$ in Pinedale, WY, to as high as ~17 $\mu g/m^3$ in Los Angeles, CA. Thus, a wide variety of environments are well represented by these 22 locations. Similarly, the median estimated outdoor UFP concentration varied from ~4200 $\#/cm^3$ in Albuquerque, NM; Blaine, MN; and Phoenix, AZ, to ~20,000 $\#/cm^3$ in Denver, CO. Outdoor UFP concentrations in Birmingham, AL, and Seattle, WA, were not estimated because hourly NO_x outdoor concentration was not available in the AQS within a close enough proximity. The estimated UFP concentration ranges in some cities were small because the minimum UFP concentration (i.e., ~4200 $\#/cm^3$) was assumed for times when the reported outdoor NO_x concentration was zero. It should again be noted that these UFP concentration estimates are very approximate and primarily serve as a basis for modeling the ratio of indoor UFP concentrations relative to outdoor concentrations.

Modeled AERs, HVAC recirculation rates, and system runtime fractions

Table 1 shows average values of modeled hourly AERs, HVAC runtime fractions, and constant recirculation rates (airflow rates divided by the house volume) for the model year (2012) using EnergyPlus and the AIM-2 infiltration model in BEopt for old, existing, and new homes relying on infiltration alone as well as the new homes with the three types of mechanical ventilation systems in all selected locations. These data clearly demonstrate that both recirculation rates and fractional system runtimes were generally highest in old homes, lower in existing homes, and lowest in new homes when relying on infiltration alone and when using HVAC systems that operate only to meet heating and cooling demands. These relationships are intuitive, as newer more efficient homes are designed with properly sized HVAC systems to meet lower heating and cooling loads, while older homes will have higher loads and often under-sized HVAC systems that operate longer to meet the higher loads. In new homes with mechanical ventilation, a minimum ventilation rate of 85 m^3/hr was provided by either an exhaust or a supply fan, so the HVAC runtime (and therefore the product of HVAC system recirculation rate and hourly fractional runtimes) was somewhat higher than in new homes relying on infiltration alone due to slightly higher ventilation loads. These differences will necessarily influence the impact that higher efficiency HVAC filtration can have on indoor concentrations of outdoor particulate matter.

Modeled indoor concentrations of $PM_{2.5}$ and UFPs of outdoor origin

Figures 5 and 6 summarize results for modeled indoor $PM_{2.5}$ and UFPs in each location with the lowest efficiency filter installed: MERV 5. This provides a basis for comparison to the impacts of higher efficiency filters in the following sections while still demonstrating the predicted variations in outdoor particle infiltration based on both home type and location.

Annual average indoor concentrations of outdoor $PM_{2.5}$ with a MERV 5 filter installed ranged from 2.1 to 6.3 $\mu g/m^3$ in old homes, 1.0 to 3.1 $\mu g/m^3$ in existing homes, and only 0.09 to 0.28 $\mu g/m^3$ in new homes relying on infiltration alone. These data demonstrate that, on average, indoor concentrations of outdoor $PM_{2.5}$ in the old homes described herein with a MERV 5 filter are predicted to be approximately twice that of existing homes and 25 times that of new homes relying on infiltration alone. Predicted indoor $PM_{2.5}$ concentrations also varied in the new homes with mechanical ventilation systems depending on the ventilation scenario. For new homes with exhaust-only ventilation systems, annual average indoor $PM_{2.5}$ concentrations with a MERV 5 filter installed varied from ~0.15 to 0.5 $\mu g/m^3$. Indoor $PM_{2.5}$ concentrations were considerably higher in new homes with supply-only ventilation systems, varying from ~1.0 to 4.0 $\mu g/m^3$, because of the relatively low efficiency supply air filter. Finally, annual average indoor $PM_{2.5}$ concentrations in the homes with a CFIS ventilation system operating and a MERV 5 filter installed was estimated to be between the other two ventilation scenarios, ranging from 0.2 to 0.8 $\mu g/m^3$ depending on location.

Results for annual average indoor concentrations of outdoor UFPs with a MERV 5 filter installed followed similar patterns. Modeled annual average indoor UFP concentrations ranged from ~850 to 6000 $\#/cm^3$ in old homes, ~370 to 2660 $\#/cm^3$ in existing homes, and only ~66 to 544 $\#/cm^3$ in new homes relying on infiltration alone, to between ~200 and 800 $\#/cm^3$, ~800 and 3500 $\#/cm^3$, and ~250 and 1300 $\#/cm^3$ in new homes with exhaust-only, supply-only, and CFIS mechanical ventilation systems, respectively. These wide ranges in modeled indoor $PM_{2.5}$ and UFP concentrations reflect similar ranges observed in recent field studies reasonably well (Kearney et al., 2011; MacNeill et al., 2012, 2014; Stephens, 2015).

Modeled effectiveness of HVAC filters relative to MERV 5

Next, the filtration effectiveness (E_i) for $PM_{2.5}$ and UFPs for each higher rated efficiency HVAC filter was calculated by subtracting from unity the ratio of the annual average hourly indoor $PM_{2.5}$ or UFP concentration with the filter in question

Table 1. Summary of modeled hourly air AER, HVAC runtimes, and recirculation rates for the 3 homes types relying on infiltration alone and the new homes relying on mechanical ventilation systems in all 22 locations.

	Old homes, infiltration only			Existing homes, infiltration only			New homes, infiltration only			New homes with mechanical ventilation		
Location	Runtime (mean (±*SD*))	AER (mean (±*SD*))	Recirculation rate (1/hr)	Runtime (mean (±*SD*))	AER (mean (±*SD*))	Recirculation rate (1/hr)	Runtime (mean (±*SD*))	AER (mean (±*SD*))	RR Recirculation rate (1/hr)	Runtime (mean (±*SD*))	AER (mean (±*SD*))	Recirculation rate (1/hr)
Albuquerque, NM	0.23 (±0.26)	0.52 (±0.25)	7.4	0.12 (±0.14)	0.25 (±0.13)	5.9	0.12 (±0.13)	0.11 (±0.11)	3.7	0.14 (±0.15)	0.24 (±0.1)	3.7
Atlanta, GA	0.14 (±0.17)	0.37 (±0.17)	7.4	0.12 (±0.15)	0.21 (±0.11)	4.4	0.13 (±0.14)	0.10 (±0.11)	3.7	0.15 (±0.16)	0.24 (±0.1)	3.7
Birmingham, AL	0.14 (±0.17)	0.34 (±0.16)	7.4	0.13 (±0.16)	0.20 (±0.11)	4.4	0.13 (±0.15)	0.09 (±0.11)	3.7	0.15 (±0.17)	0.24 (±0.1)	3.7
Bismarck, ND	0.40 (±0.33)	0.97 (±0.57)	5.2	0.28 (±0.26)	0.50 (±0.29)	3.0	0.33 (±0.3)	0.12 (±0.10)	1.5	0.38 (±0.33)	0.21 (±0.19)	1.5
Blaine, MN	0.21 (±0.19)	0.52 (±0.22)	7.4	0.17 (±0.16)	0.28 (±0.12)	3.7	0.19 (±0.17)	0.11 (±0.11)	2.2	0.22 (±0.19)	0.23 (±0.1)	2.2
Boston, MA	0.15 (±0.14)	0.51 (±0.21)	6.7	0.13 (±0.12)	0.28 (±0.12)	3.7	0.17 (±0.15)	0.11 (±0.10)	2.2	0.19 (±0.17)	0.23 (±0.1)	2.2
Chicago, IL	0.17 (±0.15)	0.51 (±0.21)	7.4	0.16 (±0.15)	0.29 (±0.13)	3.7	0.17 (±0.15)	0.11 (±0.10)	2.2	0.19 (±0.17)	0.23 (±0.1)	2.2
Colstrip, MT	0.38 (±0.32)	1.07 (±0.56)	7.4	0.16 (±0.15)	0.53 (±0.28)	5.9	0.18 (±0.16)	0.18 (±0.12)	3.0	0.20 (±0.18)	0.28 (±0.11)	3.0
Denver, CO	0.29 (±0.29)	0.61 (±0.26)	7.4	0.11 (±0.12)	0.28 (±0.12)	5.9	0.12 (±0.13)	0.12 (±0.11)	3.7	0.14 (±0.14)	0.25 (±0.1)	3.7
Detroit, MI	0.19 (±0.16)	0.47 (±0.20)	6.7	0.16 (±0.15)	0.25 (±0.12)	3.7	0.18 (±0.16)	0.11 (±0.11)	2.2	0.21 (±0.18)	0.23 (±0.1)	2.2
Houston, TX	0.26 (±0.31)	0.44 (±0.23)	7.4	0.12 (±0.13)	0.21 (±0.12)	7.4	0.13 (±0.13)	0.09 (±0.11)	4.4	0.15 (±0.16)	0.24 (±0.1)	4.4
Los Angeles, CA	0.17 (±0.26)	0.38 (±0.15)	3.7	0.07 (±0.12)	0.22 (±0.10)	4.4	0.08 (±0.13)	0.09 (±0.11)	2.2	0.09 (±0.15)	0.23 (±0.1)	2.2
Miami, FL	0.21 (±0.19)	0.32 (±0.17)	7.4	0.18 (±0.13)	0.18 (±0.11)	4.4	0.16 (±0.12)	0.09 (±0.12)	4.4	0.18 (±0.14)	0.24 (±0.11)	4.4
New York, NY	0.15 (±0.14)	0.51 (±0.24)	7.4	0.13 (±0.13)	0.28 (±0.13)	3.7	0.15 (±0.17)	0.11 (±0.12)	2.2	0.23 (±0.19)	0.41 (±0.1)	2.2
Philadelphia, PA	0.15 (±0.14)	0.45 (±0.20)	7.4	0.11 (±0.12)	0.24 (±0.12)	4.4	0.18 (±0.17)	0.10 (±0.11)	2.2	0.21 (±0.19)	0.23 (±0.1)	2.2
Phoenix, AZ	0.38 (±0.38)	0.52 (±0.25)	7.4	0.17 (±0.18)	0.23 (±0.12)	7.4	0.16 (±0.17)	0.10 (±0.12)	5.2	0.18 (±0.19)	0.25 (±0.11)	5.2
Pinedale, WY	0.47 (±0.36)	0.96 (±0.48)	7.4	0.27 (±0.26)	0.45 (±0.23)	4.4	0.23 (±0.21)	0.16 (±0.12)	3.0	0.26 (±0.23)	0.27 (±0.11)	3.0
Pittsburgh, PA	0.21 (±0.20)	0.44 (±0.20)	5.9	0.17 (±0.18)	0.25 (±0.12)	3.0	0.22 (±0.21)	0.10 (±0.11)	1.5	0.25 (±0.23)	0.23 (±0.1)	1.5
Riverside, CA	0.16 (±0.22)	0.34 (±0.13)	7.4	0.09 (±0.13)	0.20 (±0.11)	7.4	0.08 (±0.11)	0.09 (±0.11)	4.4	0.09 (±0.12)	0.23 (±0.1)	4.4
San Francisco, CA	0.17 (±0.18)	0.54 (±0.21)	3.7	0.05 (±0.08)	0.29 (±0.12)	4.4	0.08 (±0.1)	0.12 (±0.11)	3.0	0.10 (±0.11)	0.24 (±0.1)	3.0
Seattle, WA	0.26 (±0.23)	0.43 (±0.13)	3.7	0.15 (±0.18)	0.24 (±0.09)	2.2	0.16 (±0.15)	0.10 (±0.12)	2.2	0.19 (±0.18)	0.4 (±0.1)	2.2
St. Louis, MO	0.17 (±0.18)	0.45 (±0.19)	7.4	0.13 (±0.15)	0.24 (±0.12)	4.4	0.19 (±0.20)	0.10 (±0.11)	2.2	0.22 (±0.22)	0.23 (±0.1)	2.2

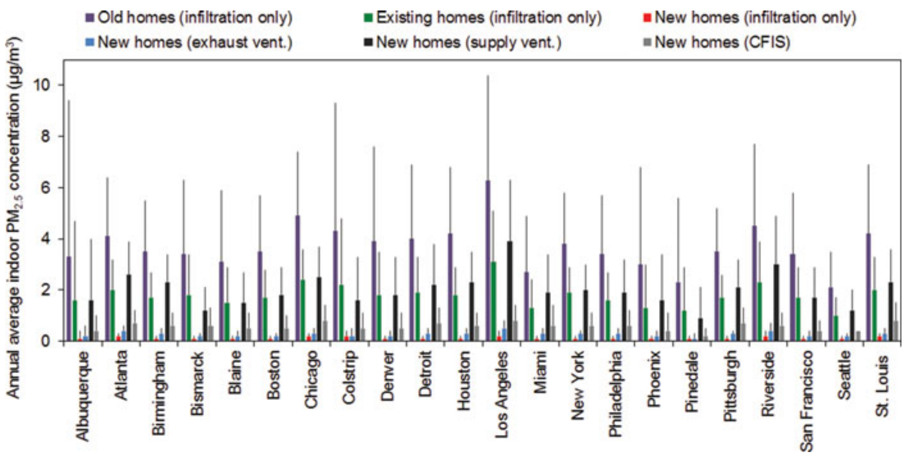

Fig. 5. The annual mean and standard deviation of modeled hourly indoor concentrations of $PM_{2.5}$ of outdoor origin in all 6 home types in all 22 locations with only a MERV 5 filter installed.

installed (i.e., MERV *j*) to the annual average hourly indoor $PM_{2.5}$ or UFP concentration when only a MERV 5 filter was installed, as shown in equation 6:

$$E_{i,MERV_j} = 1 - \frac{\bar{C}_{i,in,MERVj}}{\bar{C}_{i,in,MERV5}}, \tag{6}$$

where

$E_{i,MERVj}$ is the filtration effectiveness of a MERV *j* filter for $PM_{2.5}$ or UFP of outdoor origin,

$C_{i,in,MERVj}$ is the annual average estimate of hourly indoor concentration of $PM_{2.5}$ or UFP when a MERV *j* filter was used ($\mu g/m^3$ or $\#/m^3$), and

$C_{i,in,MERV5}$ is the annual average estimate of hourly indoor concentration of $PM_{2.5}$ or UFP when a MERV 5 filter was used ($\mu g/m^3$ or $\#/m^3$).

The effectiveness metric, as shown in Figure 7 for $PM_{2.5}$ and Figure 8 for UFPs, allows for a clear understanding of the influence of higher efficiency HVAC filters in each home and location. Moreover, it can also be used in conjunction with results from the previous section to predict annual average $PM_{2.5}$ or UFP concentrations in each location and each home type for each filter type simply by subtracting values from Figure 7 (for $PM_{2.5}$) or Figure 8 (for UFPs) from unity and multiplying by values from Figure 5 or 6, respectively.

The predicted effectiveness for $PM_{2.5}$ ranged from less than 5% for MERV 6 in mild climates, such as Los Angeles, CA, or San Francisco, CA, to as high as 50% for HEPA filters installed in older homes in extreme climates, such as Blaine, MN, or Houston, TX, in homes relying on infiltration only. For the new homes with exhaust-only and supply-only mechanical ventilation systems, modeled $PM_{2.5}$ effectiveness ranged from ∼3% for MERV 6 in mild climates to as high as 80% for HEPA filters. MERV 8 filters were predicted to yield between 10% and 25% effectiveness, on average, across all climates, housing types, and ventilation scenarios (i.e., a 10%–25% reduction in annual average indoor $PM_{2.5}$ of outdoor origin relative to a MERV 5 filter). Moving to a MERV 10 filter was predicted to yield only small increases in effectiveness (less than a few percent). Moving to a MERV 12 (#2, the higher efficiency

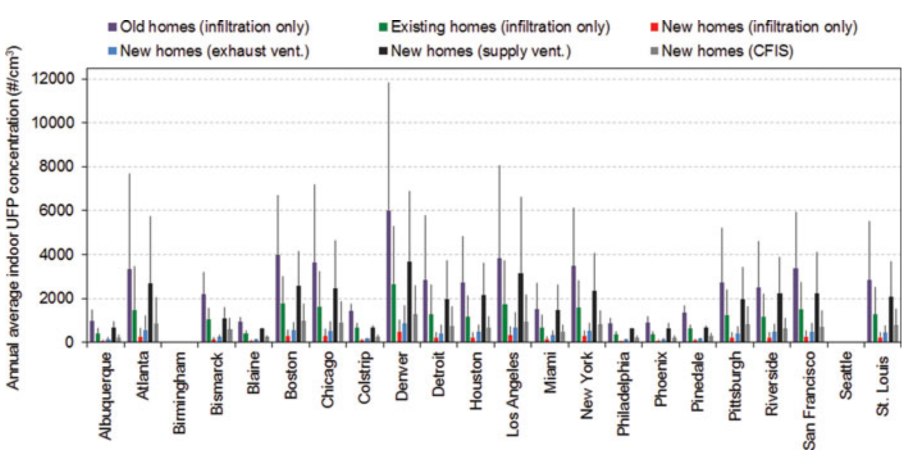

Fig. 6. The annual mean and standard deviation of modeled hourly indoor concentrations of UFPs of outdoor origin in all 6 home types in all 22 locations with only a MERV 5 filter installed; Birmingham, AL, and New York, NY, are omitted.

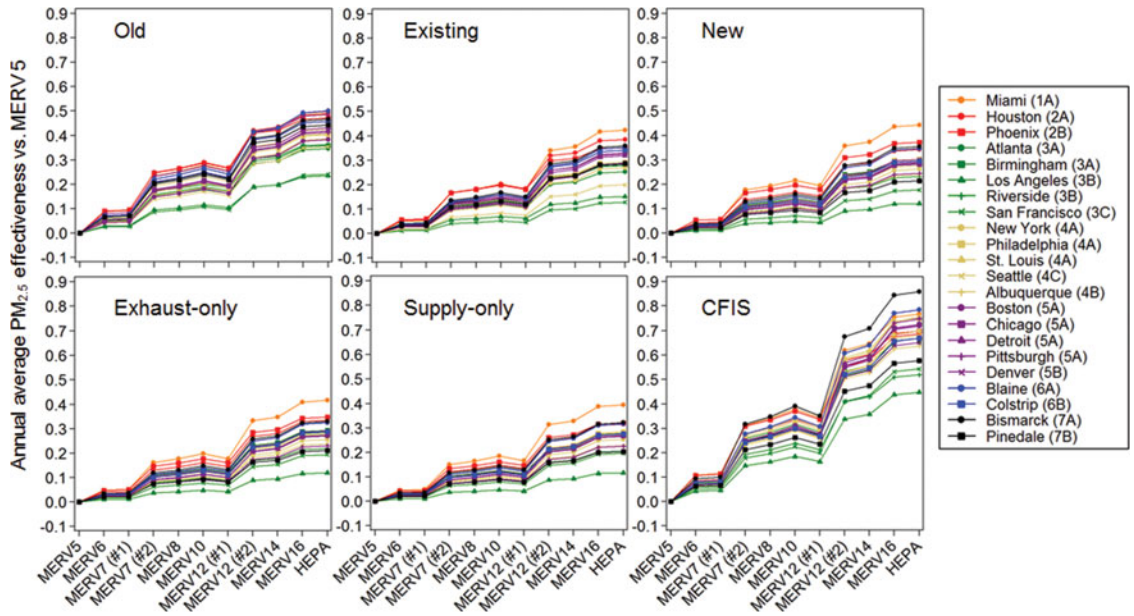

Fig. 7. Effectiveness of HVAC filters for indoor $PM_{2.5}$ of outdoor origin compared to MERV 5.

MERV 12 model) was predicted to yield a $PM_{2.5}$ effectiveness of 20% for both new and existing homes relying on infiltration as well as the new homes with exhaust-only and supply-only ventilation systems and over 30% for the old homes and new homes with CFIS ventilation systems. However, MERV 12 (#1) actually decreased $PM_{2.5}$ effectiveness relative to MERV 10 given its lower removal efficiency for $PM_{2.5}$, suggesting that knowledge of MERV alone may not be enough to predict the impacts of a particular filter. Moving to MERV 14 was predicted to increase effectiveness for $PM_{2.5}$ to between 23% and 40% (again highest for new homes with CFIS ventilation system). Finally, HEPA filtration was predicted to increase effectiveness for $PM_{2.5}$ to between 28% and 50%, on average. It is clear that higher efficiency HVAC filters can have the greatest impact on indoor concentrations of $PM_{2.5}$ of outdoor origin in the new homes with CFIS ventilation systems given that both supply and recirculated airstreams are passed through the central HVAC filters.

Similarly, the modeled effectiveness for UFPs ranged from less than 0% for MERV 7 (#1) in most climates to as high as 80% for HEPA filters installed in new homes with CFIS ventilation systems in extreme climates such as Pinedale, WY (with high HVAC operation times). Predicted annual average effectiveness values for UFPs of outdoor origin across all

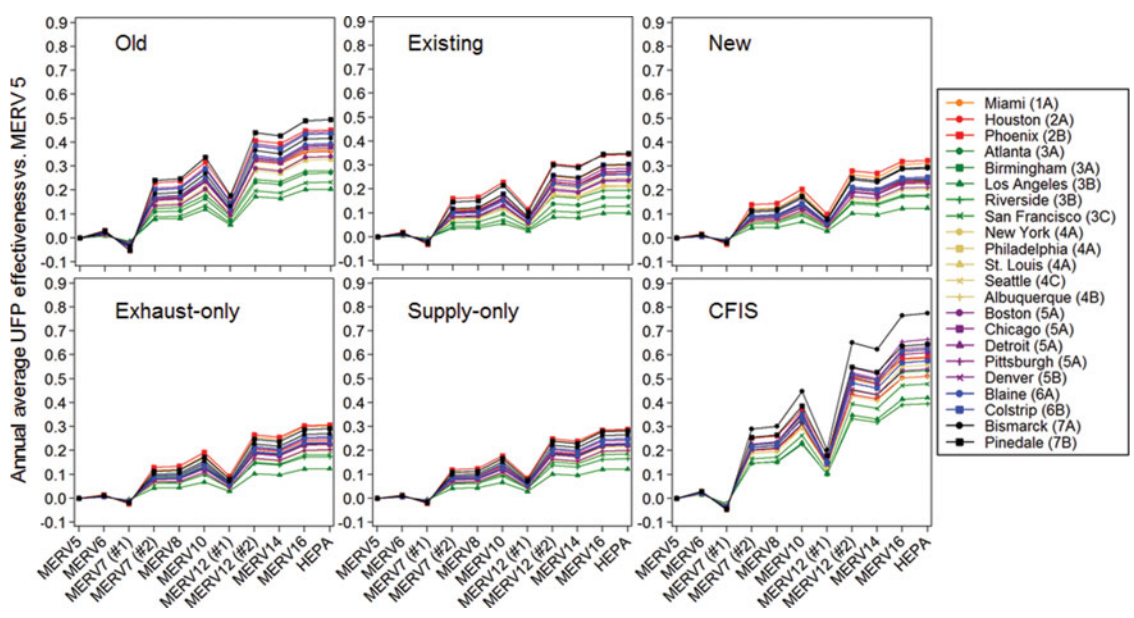

Fig. 8. Effectiveness of HVAC filters for indoor UFPs of outdoor origin compared to MERV 5.

homes and locations were: 9%–24% for MERV 8; 13%–30% for MERV 10; 20%–37% for MERV 12 (#2) and MERV 14; and 24%–50% for HEPA. Again, effectiveness was higher in new homes with CFIS ventilation systems, as well as in older homes relying on infiltration alone (due to longer system runtimes). Interestingly, for both $PM_{2.5}$ and particularly for UFPs, there appear to be only marginal gains in effectiveness for the highest efficiency filters (e.g., MERV 16 and HEPA) compared to MERV 12 or 14 filters, which suggests that there may be diminishing returns with the highest efficiency filters due to limitations in recirculation airflow rates and fractional HVAC system runtimes. Thus, factors other than rated removal efficiency and effectiveness (e.g., costs or system flow or pressure impacts) may be used to inform the decision to select the highest efficiency filters.

Overall, these results demonstrate that filter selection, home vintage, and climate zone all strongly influence the impact that HVAC filters can have on indoor proportions of outdoor $PM_{2.5}$ and UFPs inside residences that rely on HVAC systems to operate only to meet heating and cooling demands. HVAC filtration effectiveness for outdoor origin particulate matter (PM) was consistently highest in new homes with CFIS ventilation systems, followed by old homes relying on infiltration alone. Filtration effectiveness was approximately similar for the other four ventilation scenarios. Additionally, HVAC filtration effectiveness was predicted to be the greatest in residences located in climate zones with extreme weather such as Miami, FL; Houston, TX; Blaine, MN; and Bismarck, ND, in which HVAC systems have higher recirculation rates and runtime, while it was lowest in milder climate zones such as Los Angeles, CA; Riverside, CA; and San Francisco, CA.

Modeled infiltration factors

The same hourly modeled data were then used to estimate annual average infiltration factors (F_{inf}), or the indoor proportion of outdoor particles in the absence of indoor sources, for both $PM_{2.5}$ and UFPs, as another measure of filter effectiveness. This was accomplished both by using the dynamic mass balance data as well as a simpler time-averaged method using only long-term annual averages of key input parameters (e.g., AERs and HVAC system runtimes). In the first method, the average hourly indoor concentration of $PM_{2.5}$ and UFPs of outdoor origin was estimated over the entire model year and divided by the mean outdoor concentration of $PM_{2.5}$ and UFPs. This method allows for capturing dynamic changes and periods of time where outdoor concentrations, AERs, and HVAC system runtimes, which all varied at the same time. Results from the first method are shown across all filters and all locations in Figure 9.

The relative impacts of HVAC filters on $PM_{2.5}$ and UFP infiltration factors were reasonably similar across home types, particularly for existing and new homes relying on infiltration alone and new homes with exhaust-only and supply-only ventilation systems. However, the absolute impact of HVAC filters on infiltration factors varied widely by home type. The mean $PM_{2.5}$ infiltration factor was just under 0.40 in the old home with a MERV 5 filter installed, decreasing to under 0.25 with a HEPA filter installed. For existing homes, the mean $PM_{2.5}$ infiltration factor ranged from just under 0.20 with a MERV 5 filter to around 0.15 with a HEPA filter, suggesting that the impact of even the highest efficiency HVAC filtration is limited by low system runtimes. The mean $PM_{2.5}$ infiltration factor was consistently under 0.03 for the new home construction relying on infiltration alone, regardless of filter selection. The $PM_{2.5}$ infiltration factor in new homes with mechanical ventilation varied depending on the ventilation strategy. New homes with supply-only ventilation systems had the highest $PM_{2.5}$ infiltration factors among all ventilation system scenarios, ranging from 0.2 to 0.15 when MERV 5 and HEPA filters were installed, respectively. This value in new homes with CFIS ventilation systems was considerably lower, ranging from 0.06 to 0.03 when MERV 5 and HEPA filters were installed, respectively. The effect of higher efficiency HVAC filtration on absolute values of $PM_{2.5}$ infiltration factors in new homes with exhaust-only ventilation system was small, with infiltration factors remaining under 0.04 for all filters, regardless of efficiency.

Results for UFP infiltration factors were similar. The mean UFP infiltration factor ranged from ~0.22 in the old home with a MERV 5 filter installed to ~0.14 with a HEPA filter installed, from ~0.10 to ~0.08 in the existing home, and was consistently less than 0.02 with all filters in the new home relying on infiltration alone. The mean UFP infiltration factor ranged from ~0.15 to ~0.13 in new homes with supply-only ventilation systems and from ~0.06 to ~0.03 in new homes with CFIS ventilation systems with MERV 5 and HEPA filters installed, respectively, and remained under 0.03 with all filters in new homes with exhaust-only ventilation systems. These data again suggest that high-efficiency HVAC filtration is likely to have a much greater influence on indoor $PM_{2.5}$ and UFPs of outdoor origin in older, less efficient homes compared to newer, tighter, and more efficient homes relying on infiltration for ventilation air, as well as in new homes with supply-only mechanical ventilation system, because of typically very low efficiency filters in these types of ventilation systems.

Next, the $PM_{2.5}$ and UFP infiltration factors in each home were simply estimated by considering only the annual average values of key input parameters, including AERs and HVAC system runtimes. These time-averaged infiltration factors were calculated using Equation 7 for old, existing, and new homes relying on infiltration alone, and using Equations 8, 9, and 10 for new homes with exhaust-only, supply-only, and CFIS mechanical ventilation systems respectively. The goal was to explore the utility of this simpler time-averaged method where only inputs for AERs and HVAC system runtimes are known from an energy model, without the additional effort of gathering hourly outdoor air quality data from EPA AQS and performing the dynamic indoor air mass balance model;

$$F_{i,inf} = \frac{C_{i,in}}{C_{i,out}} = \frac{P_i \times \lambda_{inf}}{\lambda_{inf} + \beta_i + (f\eta_{i,HVAC}\lambda_{HVAC})}, \tag{7}$$

$$F_{i,inf,exhaust} = \frac{P_i \times \lambda_{total,exhaust}}{\lambda_{total,exhaust} + \beta_i + (f_{HVAC,exhaust}\eta_{i,HVAC}\lambda_{HVAC})}, \tag{8}$$

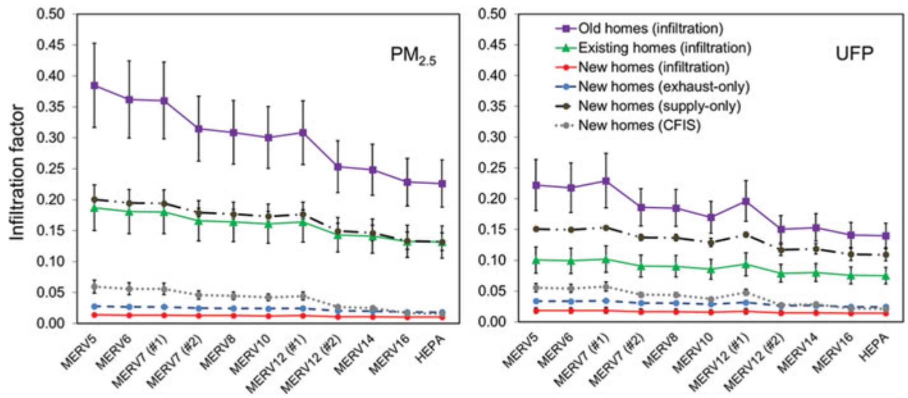

Fig. 9. Modeled annual average $PM_{2.5}$ and UFP infiltration factors with all 11 HVAC filters installed in each home type and ventilation system combination, averaged across all 22 locations.

$$F_{i,inf,supply} = \frac{\left(1-\eta_{i,supply}\right) \times \lambda_{fan} + P_i\left(\lambda_{total,supply} - \lambda_{fan}\right)}{\lambda_{total,supply} + \beta_i + \left(f_{HVAC,supply}\eta_{i,HVAC}\lambda_{HVAC}\right)}, \tag{9}$$

$$F_{i,inf,CFIS} = \frac{(1-f_{HVAC,CFIS})P_i\lambda_{total,CFIS} + f_{HVAC,CFIS}\left[(1-\eta_{i,HVAC})\lambda_{fan} + P_i\left(\lambda_{total,CFIS}-\lambda_{fan}\right)\right]}{\lambda_{total,CFIS}+\beta_i+(f_{HVAC,CFIS}\eta_{i,HVAC}\lambda_{HVAC})}. \tag{10}$$

Figure 10 shows the relationship between the annual average of modeled hourly $PM_{2.5}$ and UFP infiltration factors using the dynamic models (from previous sections) compared to the same estimates made using the simple method in Equations 7–10.

Interestingly, both methods were in very good agreement, with slopes near 1.0 and R^2 values greater than 0.99 for both $PM_{2.5}$ and UFPs. These data suggest that estimates of the long-term average of $PM_{2.5}$ and UFP infiltration factors can be made with reasonable accuracy and much less effort using only knowledge of long-term average AERs, HVAC system runtimes, and constant parameters, such as HVAC airflow and recirculation rates, envelope penetration factors, and deposition loss rate constants. This simplified time-averaged model allows for much less time intensity in estimates of the impact of residential HVAC filtration on indoor particles of outdoor origin.

Sensitivity to fundamental input parameters: Simplified infiltration factor modeling

Finally, given that both the simplified time-averaged infiltration factor model and the dynamic time-varying mass balance model yield approximately equivalent estimates of annual average infiltration factors for both $PM_{2.5}$ and UFPs, only the simplified model was used to evaluate the sensitivity of the results to fundamental input parameters of P, β, λ, η, f, and λ_{HVAC}. Details of the approach are provided in Appendix C. In summary, the results of the sensitivity analysis demonstrate that $PM_{2.5}$ penetration factors and UFP deposition loss rate coefficients (varied across the realistic ranges used herein) have the greatest impacts on estimates of $PM_{2.5}$ and UFP infiltration factors in the existing and new homes (both relying on infiltration and mechanical ventilation), respectively, but their influence is smaller relative to other factors in the old homes relying on infiltration only. HVAC filter removal efficiency has the second greatest influence on both $PM_{2.5}$ and UFP infiltration factors in almost all home vintage and mechanical ventilation scenarios. In old homes relying on infiltration alone, HVAC filter removal efficiency and AER have the greatest influence on $PM_{2.5}$ and UFP infiltration factors. It should be noted that the sensitivity analysis is also influenced by the range of values considered for each parameter, which highlights the importance of selecting a robust and reasonable range for each factor in these types of analyses. Moreover, these data demonstrate the fundamental influencing factors for $PM_{2.5}$ and UFP infiltration factors and can help prioritize data collection needs for improving input parameters for future modeling efforts.

Conclusion

Results from the simulations herein clearly demonstrate that higher-efficiency HVAC filters can meaningfully reduce indoor proportions of outdoor $PM_{2.5}$ and UFPs inside residences that either rely on infiltration for ventilation air or use mechanical ventilation. However, home vintage, climate zone, HVAC system operational characteristics, and mechanical ventilation system design and operation all strongly influence the results. In homes relying on infiltration alone and with HVAC systems that operate only to meet heating or cooling demands, high-efficiency HVAC filtration appears to have a greater influence on indoor $PM_{2.5}$ and UFPs of outdoor origin in older, less-efficient homes with longer system runtimes than in newer, tighter homes with smaller equipment and shorter runtimes. An exploration of several other mechanical ventilation and HVAC fractional runtime scenarios demonstrated that the influence of higher efficiency HVAC filtration on time-averaged $PM_{2.5}$ and UFP infiltration factors is predictably much greater in homes with supply-only mechanical ventilation systems (with low-efficiency supply filters), and that exhaust-only mechanical ventilation systems with airtight

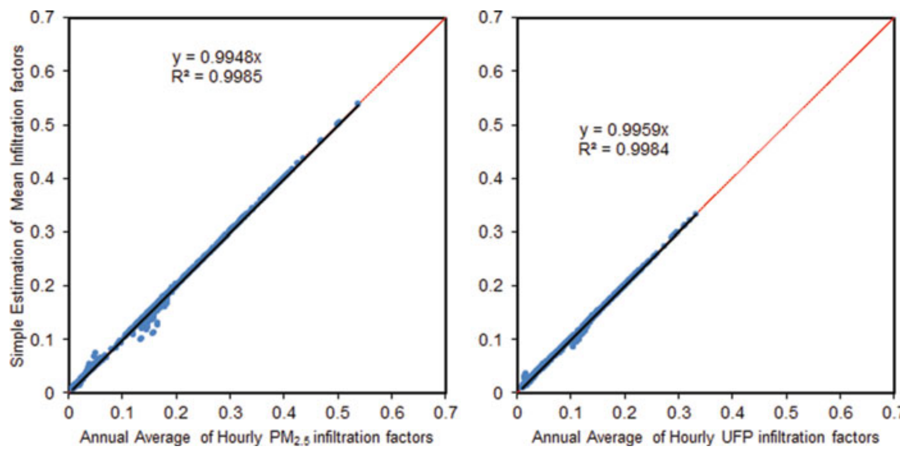

Fig. 10. Comparison between simple and complex estimates annual average infiltration factors of $PM_{2.5}$ and UFP for all locations and filters.

building enclosures or CFIS mechanical ventilation systems with high-efficiency filtration (i.e., MERV 12 or greater) can both be used to meet minimum ventilation requirements in ASHRAE Standard 62.2 while minimizing indoor exposures to particulate matter of outdoor origin relative to a supply-only mechanical ventilation system.

Acknowledgments

The authors would like to acknowledge the ASHRAE TC 2.4 membership and leadership and the RP-1691 Project Monitoring Subcommittee members, including Tom Justice, Michael Waring, Thad Ptak, Paolo Tronville, Bruce McDonald, and Don Thornburg for their helpful input on this work.

Funding

The authors extend their gratitude to ASHRAE for funding this research. Parham Azimi was also supported in part by a Graduate Student Grant-in-Aid award from ASHRAE.

References

ASHRAE. 2010. *Standard 62.2-2010, Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings*. Atlanta: ASHRAE.

ASHRAE. 2012. *Standard 52.2-2012, Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size*. Atlanta: ASHRAE.

Azimi, P., D. Zhao, and B. Stephens. 2014. Estimates of HVAC filtration efficiency for fine and ultrafine particles of outdoor origin. *Atmospheric Environment* 98:337–46, DOI: 10.1016/j.atmosenv.2014.09.007.

Azimi, P., D. Zhao, and B. Stephens. 2015. *Modeling the impact of residential HVAC filtration on indoor particles of outdoor origin. ASHRAE Research Project 1691-RP*, ASHRAE, Atlanta.

Baxter, L.K., J. Burke, M. Lunden, B.J. Turpin, D.Q. Rich, K. Thevenet-Morrison, N. Hodas, and H. Özkaynak. 2013. Influence of human activity patterns, particle composition, and residential air exchange rates on modeled distributions of PM2.5 exposure compared with central-site monitoring data. *Journal of Exposure Science and Environmental Epidemiology*, 3:241–47.

Bell, M.L., K. Ebisu, R.D. Peng, et al. 2009. Hospital admissions and chemical composition of fine particle air pollution. *American Journal of Respiratory and Critical Care Medicine* 179:1115–20, DOI: 10.1164/rccm.200808-1240OC.

Brauner, E.V., L. Forchhammer, P. Moller, L. Barregard, L. Gunnarsen, A. Afshari, P. Wahlin, M. Glasius, L.O. Dragsted, S. Basu, O. Raaschou-Nielsen, and S. Loft. 2007. Indoor particles affect vascular function in the aged: An air filtration-based intervention study. *American Journal of Respiratory and Critical Care Medicine* 177:419–25, DOI: 10.1164/rccm.200704-632OC.

Brook, R.D., S. Rajagopalan, C.A. Pope, J.R. Brook, A. Bhatnagar, A.V. Diez-Roux, F. Holguin, Y. Hong, R.V. Luepker, M.A. Mittleman, A. Peters, D. Siscovick, S.C. Smith, L. Whitsel, and J.D. Kaufman. 2010. Particulate matter air pollution and cardiovascular disease. *Circulation* 121:2331–78, DOI: 10.1161/CIR.0b013e3181dbece1.

Brown, K.W., T. Minegishi, J. Allen, J.F. McCarthy, J.D. Spengler, and D.L. MacIntosh. 2014. Reducing patients' exposures to asthma and allergy triggers in their homes: An evaluation of effectiveness of grades of forced air ventilation filters. *Journal of Asthma* 51(6): 585–94.

Burroughs, H.E.B., and K.E. Kinzer. 1998. Improved filtration in residential environments. *ASHRAE Journal* 40:47–51.

Chen, C., and B. Zhao. 2011. Review of relationship between indoor and outdoor particles: I/O ratio, infiltration factor and penetration factor. *Atmospheric Environment* 45:275–88, DOI: 10.1016/j.atmosenv.2010.09.048

Christensen, C., R. Anderson, S. Horowitz, A. Courtney, and J. Spencer. 2006. BEopt^{TM} software for building energy optimization: Features and capabilities. *National Renewable Energy Lab (NREL), Golden, CO*.

Crawley, D.B., L.K. Lawrie, F.C. Winkelmann, W.F. Buhl, Y.J. Huang, C.O. Pedersen, R.K. Strand, R.J. Liesen, D.E. Fisher, M.J. Witte, and J. Glazer. 2001. EnergyPlus: Creating a new-generation building energy simulation program. *Energy and Buildings* 33:319–31, DOI: 10.1016/S0378-7788(00)00114-6.

Fann, N., A.D. Lamson, S.C. Anenberg, K. Wesson, D. Risley, and B.J. Hubbell. 2012. Estimating the national public health burden associated with exposure to ambient $PM_{2.5}$ and ozone. *Risk Analysis* 32:81–95, DOI: 10.1111/j.1539-6924.2011.01630.x.

Fugler, D., D. Bowser, and W. Kwan. 2000. The effects of improved residential furnace filtration on airborne particles. *ASHRAE Transactions* 106:317–26.

Gerwig, H., G. Löschau, L. Hillemann, B. Wehner, A. Wiedensohler, A. Zschoppe, C. Peters, A. Rudolph, C. Johansson, J. Cyrys,

M. Pitz, R. Rücker, J. Novak, H.G. Horn, R. Caldow, and G.J. Sem. 2007. UFIPOLNET: Concentration of particle number distributions at 4 stations in Europe. http://www.tsi.com/uploadedFiles/_Site_Root/Products/Literature/Posters/UFIPOLNET_EAC07_gerwig_lecture.pdf

Health Effects Institute (HEI). 2013. *Understanding the health effects of ambient ultrafine particles*. Health Effects Institute, Boston, MA.

Hodas, N., Q. Meng, M.M. Lunden, D.Q. Rich, H. Özkaynak, L.K. Baxter, Q. Zhang, and B.J. Turpin. 2012. Variability in the fraction of ambient fine particulate matter found indoors and observed heterogeneity in health effect estimates. *Journal of Exposure Science and Environmental Epidemiology* 22:448–54, DOI: 10.1038/jes.2012.34.

Hodas, N., B.J. Turpin, M.M. Lunden, L.K. Baxter, H. Özkaynak, J. Burke, P. Ohman-Strickland, K. Thevenet-Morrison, J.B. Kostis, and D.Q. Rich. 2013. Refined ambient $PM_{2.5}$ exposure surrogates and the risk of myocardial infarction. *Journal of Exposure Science and Environmental Epidemiology* 23:573–80, DOI: 10.1038/jes.2013.24.

Hopkins, A.S., A. Lekov, J. Lutz, G. Rosenquist, and L. Gu. 2011. Simulating a nationally representative housing sample using EnergyPlus. L. Lawrence Berkeley National Laboratory report #LBNL-4420E, Berkeley, CA.

Howard-Reed, C., L.A. Wallace, and S.J. Emmerich. 2003. Effect of ventilation systems and air filters on decay rates of particles produced by indoor sources in an occupied townhouse. *Atmospheric Environment* 37:5295–306, DOI: 10.1016/j.atmosenv.2003.09.012.

Huang, J., J. Hanford, and F. Yang. 1999. Residential heating and cooling loads component analysis. Berkeley, CA: Lawrence Berkeley National Laboratory.

Huang, Y.J., R. Ritschard, J. Bull, S. Byrne, I. Turiel, D. Wilson, C. Hsui, and D. Foley. 1987. *Methodology and assumptions for evaluating heating and cooling energy requirements in new single-family residential buildings*. Berkeley, CA: Lawrence Berkeley National Laboratory.

Kearney, J., L. Wallace, M. MacNeill, X. Xu, K. VanRyswyk, H. You, R. Kulka, and A.J. Wheeler. 2011. Residential indoor and outdoor ultrafine particles in Windsor, Ontario. *Atmospheric Environment* 45:7583–93, DOI: 10.1016/j.atmosenv.2010.11.002.

Klepeis, N.E., W.C. Nelson, W.R. Ott, J.P. Robinson, A.M. Tsang, P. Switzer, J.V. Behar, S.C. Hern, and W.H. Engelmann. 2001. The National Human Activity Pattern Survey (NHAPS): A resource for assessing exposure to environmental pollutants. *Journal of Exposure Analysis and Environmental Epidemiology* 11:231–52, DOI: 10.1038/sj.jea.7500165.

Kwasny, F., P. Madl, and W. Hofmann. 2010. Correlation of air quality data to ultrafine particles (UFP) concentration and size distribution in ambient air. *Atmosphere* 1:3–14, DOI: 10.3390/atmos1010003.

Lin, L.-Y., H.-W. Chen, T.-L. Su, G.-B. Hong, L.-C. Huang, and K.-J. Chuang. 2011. The effects of indoor particle exposure on blood pressure and heart rate among young adults: An air filtration-based intervention study. *Atmospheric Environment* 45:5540–4, DOI: 10.1016/j.atmosenv.2011.05.014.

Liu, D.-L., and W.W. Nazaroff. 2001. Modeling pollutant penetration across building envelopes. *Atmospheric Environment* 35:4451–62, DOI: 10.1016/S1352-2310(01)00218-7.

MacIntosh, D.L., T. Minegishi, M. Kaufman, B.J. Baker, J.G. Allen, J.I. Levy, and T.A. Myatt. 2010. The benefits of whole-house in-duct air cleaning in reducing exposures to fine particulate matter of outdoor origin: A modeling analysis. *Journal of Exposure Science and Environmental Epidemiology* 20:213–24, DOI: 10.1038/jes.2009.16.

MacIntosh, D.L., T.A. Myatt, J.F. Ludwig, B.J. Baker, H.H. Suh, and J.D. Spengler. 2008. Whole house particle removal and clean air delivery rates for in-duct and portable ventilation systems. *Journal of Air & Waste Management Association* 58:1474–82.

MacNeill, M., J. Kearney, L. Wallace, M. Gibson, M.E. Héroux, J. Kuchta, J.R. Guernsey, and A.J. Wheeler. 2014. Quantifying the contribution of ambient and indoor-generated fine particles to indoor air in residential environments. *Indoor Air* 24:362–75, DOI: 10.1111/ina.12084.

MacNeill, M., L. Wallace, J. Kearney, R.W. Allen, K. Van Ryswyk, S. Judek, X. Xu, and A.J. Wheeler. 2012. Factors influencing variability in the infiltration of $PM_{2.5}$ mass and its components. *Atmospheric Environment* 61:518–32, DOI: 10.1016/j.atmosenv.2012.07.005.

MathWorks, Inc. 2014. MATLAB R2014a. *Natick*, MA.

Meng, Q.Y., B.J. Turpin, L. Korn, C.P. Weisel, M. Morandi, S. Colome, J. Zhang, T. Stock, D. Spektor, A. Winer, L. Zhang, J.H. Lee, R. Giovanetti, W. Cui, J. Kwon, S. Alimokhtari, D. Shendell, J. Jones, C. Farrar, and S. Maberti. 2005. Influence of ambient (outdoor) sources on residential indoor and personal $PM_{2.5}$ concentrations: Analyses of RIOPA data. *Journal of Exposure Analysis and Environmental Epidemiology* 15:17–28, DOI: 10.1038/sj.jea.7500378.

Miller, K.A., D.S. Siscovick, L. Sheppard, K. Shepherd, J.H. Sullivan, G.L. Anderson, and J.D. Kaufman. 2007. Long-term exposure to air pollution and incidence of cardiovascular events in women. *New England Journal of Medicine* 356:447–58, DOI: 10.1056/NEJMoa054409.

Penttinen, P., K.L. Timonen, P. Tiittanen, A. Mirme, J. Ruuskanen, and J. Pekkanen. 2001. Ultrafine particles in urban air and respiratory health among adult asthmatics. *European Respiratory Journal* 17:428–35.

Pirjola, L., P. Paasonen, D. Pfeiffer, T. Hussein, K. Hameri, T. Koskentalo, A. Virtanen, T. Ronkko, J. Keskinen, and T. Pakkanen. 2006. Dispersion of particles and trace gases nearby a city highway: Mobile laboratory measurements in Finland. *Atmospheric Environment* 40:867–79, DOI: 10.1016/j.atmosenv.2005.10.018.

Pope, C.A., R.T. Burnett, M.J. Thun, E.E. Calle, D. Krewski, K. Ito, and G.D. Thurston. 2002. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *Journal of the American Medical Association* 287:1132–41.

Pope, C.A., and D.W. Dockery. 2006. Health effects of fine particulate air pollution: Lines that connect. *Journal of Air & Waste Management Association* 56:709–42.

Riley, W.J., T.E. McKone, A.C.K. Lai, and W.W. Nazaroff. 2002. Indoor particulate matter of outdoor origin: Importance of size-dependent removal mechanisms. *Environmental Science and Technology* 36:200–7, DOI: 10.1021/es010723y.

Rim, D., L. Wallace, and A. Persily. 2010. Infiltration of outdoor ultrafine particles into a test house. *Environmental Science and Technology* 44:5908–13, DOI: 10.1021/es101202a.

Stephens, B. 2014. The impacts of duct design on life cycle costs of central residential heating and air-conditioning systems. *Energy and Buildings* 82:563–79, DOI: 10.1016/j.enbuild.2014.07.054.

Stephens, B. 2015. Building design and operational choices that impact indoor exposures to outdoor particulate matter inside residences. *Science and Technology for the Built Environment* 21:3–13, DOI: 10.1080/10789669.2014.961849.

Stephens, B., A. Novoselac, and J.A. Siegel. 2010a. The effects of filtration on pressure drop and energy consumption in residential HVAC systems. *Science and Technology for the Built Environment* 16: 273–94.

Stephens, B., and J.A. Siegel. 2012. Penetration of ambient submicron particles into single-family residences and associations with building characteristics. *Indoor Air* 22:501–13, DOI: 10.1111/j.1600-0668.2012.00779.x.

Stephens, B., and J.A. Siegel. 2013. Ultrafine particle removal by residential HVAC filters. *Indoor Air* 23:488–97, DOI: 10.1111/ina.12045.

Stephens, B., J.A. Siegel, and A. Novoselac. 2010b. Energy implications of filtration in residential and light-commercial buildings (RP-1299). *ASHRAE Transactions* 116:346–57.

Stephens, B., J.A. Siegel, and A. Novoselac. 2010c. *Energy implications of filtration in residential and light-commercial construction. ASHRAE Research Project-1299*, ASHRAE, Atlanta.

Stölzel, M., S. Breitner, J. Cyrys, M. Pitz, G. Wölke, W. Kreyling, J. Heinrich, H.-E. Wichmann, and A. Peters. 2007. Daily mortality and particulate matter in different size classes in Erfurt, Germany. *Journal of Exposure Science and Environmental Epidemiology* 17:458–67, DOI: 10.1038/sj.jes.7500538.

Thatcher, T.L., and D.W. Layton. 1995. Deposition, resuspension, and penetration of particles Within a residence. *Atmospheric Environment* 29:1487–97, DOI: 10.1016/1352-2310(95)00016-R.

Thatcher, T.L., M.M. Lunden, K.L. Revzan, R.G. Sextro, and N.J. Brown. 2003. A concentration rebound method for measuring particle penetration and deposition in the indoor environment. *Aerosol Science and Technology* 37:847–64, DOI: 10.1080/02786820300940.

Tronville, P., and R.D. Rivers. 2006. Global standards for filter testing. *ASHRAE Journal* 48:58–62.

U.S. Census Bureau. n.d. MCD characteristics of new housing. http://www.census.gov/construction/chars/completed.html.

U.S. EPA. 2009. *Integrated science assessment for particulate matter*. National Center for Environmental Assessment, Research Triangle Park, NC.

U.S. EPA. 2013. Download detailed AQS data. In: Technology Transfer Network (TTN) Air Quality System (AQS). http://www.epa.gov/ttn/airs/airsaqs/detaildata/downloadaqsdata.htm.

von Klot, S., G. Wölke, T. Tuch, J. Heinrich, D.W. Dockery, J. Schwartz, W.G. Kreyling, H.E. Wichmann, and A. Peters. 2002. Increased asthma medication use in association with ambient fine and ultrafine particles. *European Respiratory Journal* 20:691–702, DOI: 10.1183/09031936.02.01402001.

Walker, I.S., D.J. Dickerhoff, D. Faulkner, and W.J.N. Turner. 2012. *Energy implications of in-line filtration in California*. Lawrence Berkeley National Laboratory, Berkeley, CA.

Wallace, L., S.J. Emmerich, and C. Howard-Reed. 2004. Effect of central fans and in-duct filters on deposition rates of ultrafine and fine particles in an occupied townhouse. *Atmospheric Environment* 38:405–13, DOI: 10.1016/j.atmosenv.2003.10.003.

Wallace, L., W. Kindzierski, J. Kearney, M. MacNeill, M.-E. Héroux, and A.J. Wheeler. 2013. Fine and ultrafine particle decay rates in multiple homes. *Environmental Science and Technology* 47:12929–37, DOI: 10.1021/es402580t.

Wallace, L., and W. Ott. 2011. Personal exposure to ultrafine particles. *Journal of Exposure Science and Environmental Epidemiology* 21:20–30, DOI: 10.1038/jes.2009.59.

Weichenthal, S., A. Dufresne, and C. Infante-Rivard. 2007. Indoor ultrafine particles and childhood asthma: Exploring a potential public health concern. *Indoor Air* 17:81–91, DOI: 10.1111/j.1600-0668.2006.00446.x.

White Box Technologies. 2014. Historical hourly U.S. weather data, 2012. In: White Box Technologies Weather Data. http://weather.whiteboxtechnologies.com/home.

Williams, R., J. Suggs, A. Rea, I. Sheldon, C. Rodes, and J. Thornburg. 2003. The Research Triangle Park particulate matter panel study: Modeling ambient source contribution to personal and residential PM mass concentrations. *Atmospheric Environment* 37:5365–78, DOI: 10.1016/j.atmosenv.2003.09.010.

Appendix A: Home characteristics

Table A.1. Assumed home characteristics in different locations in the United States.

	City					
	Miami, FL			Houston, **TX**		
Climate zone	1A			2A		
Location (census region)	South			South		
Location (census division)	South Atlantic			West South Central		
Home type	Old	Existing	New	Old	Existing	New
Number of stories	1	1	1	1	1	1
Floor area (ft^2)	2,025	2,025	2,025	2,025	2,025	2,025
Orientation	Front door faces north	Front door faces north	Front door faces north	Front door faces north	Front door faces north	Front door faces north
Floor construction	Crawl, uninsulated	Basement, uninsulated	Slab, uninsulated	Crawl, uninsulated	Slab, 2-ft R-5 exterior XPS	Slab, uninsulated
Number of bedrooms	3	3	3	3	3	3
Number of bathrooms	2	2	2	2	2	2
Exterior wall materials	Brick, light	Aluminum, light	Vinyl, light	Brick, light	Wood, light	Vinyl, light
Wall insulation ($hr \cdot ft^2 \cdot °F/BTU$)	Uninsulated	R-11 fiberglass batt	R-13 fiberglass batt	Uninsulated	R-11 fiberglass batt	R-13 fiberglass batt
Wall characteristics	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.
Wall sheathing	OSB	OSB	OSB	OSB	OSB	OSB
Attic insulation ($hr \cdot ft^2 \cdot °F/BTU$)	R-7 fiberglass	R-27 fiberglass	R-30 fiberglass	Ceiling R-7 fiberglass	Ceiling R-27 fiberglass	Ceiling R-30 fiberglass
Attic space type	Vented	Vented	Vented	Vented	Vented	Vented
Window U-value ($BTU/hr \cdot ft^2 \cdot °F$)	1.1	0.49	1.2	1.1	0.49	0.65
Window SHGC	0.87	0.79	0.3	0.87	0.79	0.3
Window area, *F*, *B*, *L*, and *R* (ft^2)	20, 40, 20, 20	20, 40, 20, 20	43, 86, 43, 43	20, 40, 20, 20	20, 40, 20, 20	43, 86, 43, 43
Duct location	Crawlspace	Unfinished attic	Unfinished attic	Crawlspace	Unfinished attic	Unfinished attic
Duct insulation ($hr \cdot ft^2 \cdot °F/BTU$)	Uninsulated	R-4	R-8	Uninsulated	R-4	R-8
Duct leakage (%)	30.00	15.00	7.50	30.00	15.00	7.50
Envelope airtightness (ACH_{50})	20	10	3	20	10	3
Mechanical ventilation	None	None	None	None	None	None
HVAC equipment	5-ton AC unit	3-ton AC unit	3-ton AC unit	5-ton AC unit	5-ton AC unit	3-ton AC unit
Central air-conditioner type	6.8 SEER 1 stage	10 SEER 1 stage	16 SEER 1 stage	6.8 SEER 1 stage	10 SEER 1 stage	16 SEER 1 stage
Furnace type	78% AFUE gas furnace	90% AFUE gas furnace	98% AFUE gas furnace	78% AFUE gas furnace	90% AFUE gas furnace	98% AFUE gas furnace
Nominal cooling capacity (BTU/h)	60,000	36,000	36,000	60,000	60,000	36,000
Nominal heating capacity (BTU/h)	36,000	12,000	12,000	36,000	36,000	24,000

(Continued on the next page)

Table A.1. Assumed home characteristics in different locations in the United States. *(Continued)*

	City					
	Phoenix, AZ			**Atlanta**, GA		
Climate zone	2B			3A		
Location (census region)	West			South		
Location (census division)	Mountain			South Atlantic		
Home type	Old	Existing	New	Old	Existing	New
Number of stories	1	1	1	1	1	1
Floor area (ft^2)	2,025	2,025	2,025	2,025	2,025	2,025
Orientation	Front door faces north	Front door faces north	Front door faces north	Front door faces north	Front door faces north	Front door faces north
Floor construction	Slab, uninsulated	Slab, 2-ft R-5 exterior XPS	Slab, uninsulated	Crawl, uninsulated	Basement, uninsulated	Slab, uninsulated
Number of bedrooms	3	3	3	3	3	3
Number of bathrooms	2	2	2	2	2	2
Exterior wall materials	Brick, light	Stucco, medium/dark	Vinyl, light	Brick, light	Aluminum, light	Vinyl, light
Wall insulation ($hr{\cdot}ft^2{\cdot}°F/BTU$)	Uninsulated	R-13 fiberglass batt	R-13 fiberglass batt	Uninsulated	R-11 fiberglass batt	R-13 fiberglass batt
Wall characteristics	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.
Wall sheathing	OSB	OSB	OSB	OSB	OSB	OSB
Attic insulation ($hr{\cdot}ft^2{\cdot}°F/BTU$)	Ceiling R-11 fiberglass	Ceiling R-29 fiberglass	Ceiling R-30 fiberglass	Ceiling R-7 fiberglass	Ceiling R-27 fiberglass	Ceiling R-30 fiberglass
Attic space type	Vented	Vented	Vented	Vented	Vented	Vented
Window U-value ($BTU/hr{\cdot}ft^2{\cdot}°F$)	1.1	0.49	0.65	1.1	0.49	0.5
Window SHGC	0.87	0.79	0.3	0.87	0.79	0.3
Window area, *F*, *B*, *L*, and *R* (ft^2)	20, 40, 20, 20	20, 40, 20, 20	43, 86, 43, 43	20, 40, 20, 20	20, 40, 20, 20	43, 86, 43, 43
Duct location	Unfinished attic	Unfinished attic	Unfinished attic	Crawlspace	Unfinished attic	Unfinished attic
Duct insulation ($hr{\cdot}ft^2{\cdot}°F/BTU$)	Uninsulated	R-4	R-8	Uninsulated	R-4	R-8
Duct leakage (%)	30.00	15.00	7.50	30.00	15.00	7.50
Envelope airtightness **(ACH_{50})**	20	10	3	20	10	3
Mechanical ventilation	None	NONE	None	None	None	None
HVAC equipment	5-ton AC unit	5-ton AC unit	3.5-ton AC unit	5-ton AC unit	3-ton AC unit	3.5-ton AC unit
Central air-conditioner type	6.8 SEER 1 stage	10 SEER 1 stage	16 SEER 1 stage	6.8 SEER 1 stage	10 SEER 1 stage	16 SEER 1 stage
Furnace type	78% AFUE gas furnace	90% AFUE gas furnace	98% AFUE gas furnace	78% AFUE gas furnace	90% AFUE gas furnace	98% AFUE gas furnace
Nominal cooling capacity (BTU/h)	60,000	60,000	42,000	60,000	36,000	30,000
Nominal heating capacity (BTU/h)	72,000	24,000	12,000	96,000	48,000	36,000

	City					
	Birmingham, AL			**Riverside, CA**		
Climate zone	3A			3B		
Location (census region)	South			West		
Location (census division)	South Atlantic			Pacific South		
Home type	Old	Existing	New	Old	Existing	New
Number of stories	1	1	1	1	1	1
Floor area (ft^2)	2,025	2,025	2,025	2,025	2,025	2,025
Orientation	Front door faces north	Front door faces north	Front door faces north	Front door faces north	Front door faces north	Front door faces north
Floor construction	Crawl, uninsulated	Basement, uninsulated	Slab, uninsulated	Crawl, uninsulated	Slab, uninsulated	Slab, uninsulated
Number of bedrooms	3	3	3	3	3	3
Number of bathrooms	2	2	2	2	2	2
Exterior wall materials	Brick, light	Aluminum, light	Vinyl, light	Stucco, medium/dark	Stucco, medium/dark	Vinyl, light
Wall insulation (hr·ft^2·°F/BTU)	Uninsulated	R-11 fiberglass batt	R-13 fiberglass batt	Uninsulated	R-11 fiberglass batt	R-13 fiberglass batt
Wall characteristics	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.
Wall sheathing	OSB	OSB	OSB	OSB	OSB	OSB
Attic insulation (hr·ft^2·°F/BTU)	Ceiling R-7 fiberglass	Ceiling R-27 fiberglass	Ceiling R-30 fiberglass	Ceiling R-7 fiberglass	Ceiling R-25 fiberglass	Ceiling R-30 fiberglass
Attic space type	Vented	Vented	Vented	Vented	Vented	Vented
Window U-value (BTU/hr·ft^2·°F)	1.1	0.49	0.5	1.1	0.49	0.5
Window SHGC	0.87	0.79	0.3	0.87	0.79	0.3
Window area, *F*, *B*, *L*, and *R* (ft^2)	20, 40, 20, 20	20, 40, 20, 20	43, 86, 43, 43	20, 40, 20, 20	20, 40, 20, 20	43, 86, 43, 43
Duct location	Crawlspace	Unfinished attic	Unfinished attic	Crawlspace	Unfinished attic	Unfinished attic
Duct insulation (hr·ft^2·°F/BTU)	Uninsulated	R-4	R-8	Uninsulated	R-4	R-8
Duct leakage (%)	30.00	15.00	7.50	30.00	15.00	7.50
Envelope airtightness (**ACH_{50}**)	20	10	3	20	10	3
Mechanical ventilation	None	None	None	None	None	None
HVAC equipment	5-ton AC unit	3-ton AC unit	2.5-ton AC unit	5-ton AC unit	5-ton AC unit	3-ton AC unit
Central air-conditioner type	6.8 SEER 1 stage	10 SEER 1 stage	16 SEER 1 stage	6.8 SEER 1 stage	10 SEER 1 stage	16 SEER 1 stage
Furnace type	78% AFUE gas furnace	90% AFUE gas furnace	98% AFUE gas furnace	78% AFUE gas furnace	90% AFUE gas furnace	98% AFUE gas furnace
Nominal cooling capacity (BTU/h)	60,000	36,000	30,000	60,000	60,000	36,000
Nominal heating capacity (BTU/h)	96,000	36,000	24,000	72,000	36,000	24,000

(Continued on the next page)

Table A.1. Assumed home characteristics in different locations in the United States. *(Continued)*

	Climate zone					
	Los Angeles, **CA**			San Francisco, CA		
Location (census region) Location (census division) Home type	3B West Pacific South			3C West Pacific South		
Number of stories	Old	Existing	New	Old	Existing	New
Floor area (ft^2)	1	1	1	1	1	1
Orientation	2,025	2,025	2,025	2,025	2,025	2,025
Floor construction	Front door faces north	Front door faces north	Front door faces north	Front door faces north	Front door faces north	Front door faces north
Number of bedrooms	Crawl, uninsulated	Slab, uninsulated	Slab, uninsulated	Crawl, uninsulated	Slab, uninsulated	Slab, uninsulated
Number of bathrooms	3	3	3	3	3	3
Exterior wall materials	2	2	2	2	2	2
Wall insulation (hr·ft^2·°F/BTU)	Stucco, medium/dark	Stucco, medium/dark	Vinyl, light	Stucco, medium/dark	Stucco, medium/dark	Vinyl, light
Wall characteristics	Uninsulated	R-11 fiberglass batt	R-13 fiberglass batt	Uninsulated	R-11 Fiberglass Batt	R-13 fiberglass batt
Wall sheathing	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.
Attic insulation (hr·ft^2·°F/BTU)	OSB	OSB	OSB	OSB	OSB	OSB
Attic space type	Ceiling R-7 fiberglass	Ceiling R-25 fiberglass	Ceiling R-30 fiberglass	Ceiling R-7 fiberglass	Ceiling R-25 fiberglass	Ceiling R-30 fiberglass
Window U-value (BTU/hr·ft^2·°F)	Vented	Vented	Vented	Vented	Vented	Vented
Window SHGC	1.1	0.49	0.5	1.1	0.49	0.5
Window area, *F*, *B*, *L*, and *R* (ft^2)	0.87	0.79	0.3	0.87	0.79	0.3
Duct location	20, 40, 20, 20	20, 40, 20, 20	43, 86, 43, 43	20, 40, 20, 20	20, 40, 20, 20	43, 86, 43, 43
Duct insulation (hr·ft^2·°F/BTU)	Crawlspace	Unfinished attic	Unfinished attic	Crawlspace	Unfinished attic	Unfinished attic
Duct leakage	Uninsulated	R-4	R-8	Uninsulated	R-4	R-8
Envelope airtightness (%)	30.00	15.00	7.50	30.00	15.00	7.50
Mechanical ventilation **(ACH_{50})**	20	10	3	20	10	3
HVAC equipment	None	**NONE**	None	None	None	None
Central air-conditioner type	2.5-ton AC unit	3-ton AC unit	1.5-ton AC unit	2.5-ton AC unit	3-ton AC unit	2-ton AC unit
Furnace type	6.8 SEER 1 stage	10 SEER 1 stage	16 SEER 1 stage	6.8 SEER 1 stage	10 SEER 1 stage	16 SEER 1 stage
Nominal cooling capacity (BTU/h)	78% AFUE gas furnace	90% AFUE gas furnace	98% AFUE gas furnace	78% AFUE gas furnace	90% AFUE gas furnace	98% AFUE gas furnace
Nominal heating capacity (BTU/h)	30,000	36,000	18,000	30,000	36,000	24,000
Climate zone	48,000	24,000	12,000	48,000	36,000	24,000

	City					
	New York, NY			**Philadelphia**, PA		
Climate zone	4A			4A		
Location (census region)	Northeast			Northeast		
Location (census division)	Middle Atlantic			Middle Atlantic		
Home type	Old	Existing	New	Old	Existing	New
Number of stories	1	1	1	1	1	1
Floor area (ft^2)	2,025	2,025	2,025	2,025	2,025	2,025
Orientation	Front door faces north	Front door faces north	Front door faces north	Front door faces north	Front door faces north	Front door faces north
Floor construction	Basement, uninsulated	Basement, uninsulated	Basement, whole wall R-10 XPS	Basement, uninsulated	Basement, uninsulated	Basement, whole wall R-10 XPS
Number of bedrooms	3	3	3	3	3	3
Number of bathrooms	2	2	2	2	2	2
Exterior wall materials	Wood, light	Wood, light	Vinyl, light	Wood, light	Wood, light	Vinyl, light
Wall insulation ($hr \cdot ft^2 \cdot {}^\circ F/BTU$)	Uninsulated	R-13 fiberglass batt	R-13 fiberglass batt	Uninsulated	R-13 fiberglass batt	R-13 fiberglass batt
Wall characteristics	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.
Wall sheathing	OSB	OSB	OSB	OSB	OSB	OSB
Attic insulation ($hr \cdot ft^2 \cdot {}^\circ F/BTU$)	Ceiling R-7 fiberglass	Ceiling R-27 fiberglass	Ceiling R-38 fiberglass	Ceiling R-7 fiberglass	Ceiling R-27 fiberglass	Ceiling R-38 fiberglass
Attic space type	Vented	Vented	Vented	Vented	Vented	Vented
Window U-value ($BTU/hr \cdot ft^2 \cdot {}^\circ F$)	1.1	0.49	0.35	1.1	0.49	0.35
Window SHGC	0.87	0.79	0.3	0.87	0.79	0.3
Window area, *F*, *B*, *L*, and *R* (ft^2)	20, 40, 20, 20	20, 40, 20, 20	43, 86, 43, 43	20, 40, 20, 20	20, 40, 20, 20	43, 86, 43, 43
Duct location	Unfinished basement	Unfinished basement	Unfinished basement	Unfinished basement	Unfinished basement	Unfinished basement
Duct insulation ($hr \cdot ft^2 \cdot {}^\circ F/BTU$)	Uninsulated	R-4	R-8	Uninsulated	R-4	R-8
Duct leakage (%)	30.00	15.00	7.50	30.00	15.00	7.50
Envelope airtightness **(ACH_{50})**	20	10	3	20	10	3
Mechanical ventilation	None	None	None	None	None	None
HVAC equipment	5-ton AC unit	2.5-ton AC unit	1.5-ton AC unit	5-ton AC unit	3-ton AC unit	1.5-ton AC unit
Central air-conditioner type	6.8 SEER 1 stage	10 SEER 1 stage	16 SEER 1 stage	6.8 SEER 1 stage	10 SEER 1 stage	16 SEER 1 stage
Furnace type	78% AFUE gas furnace	90% AFUE gas furnace	98% AFUE gas furnace	78% AFUE gas furnace	90% AFUE gas furnace	98% AFUE gas furnace
Nominal cooling capacity (BTU/h)	60,000	30,000	18,000	60,000	36,000	18,000
Nominal heating capacity (BTU/h)	132,000	60,000	24,000	120,000	60,000	24,000

(Continued on the next page)

Table A.1. Assumed home characteristics in different locations in the United States. *(Continued)*

	City					
	St. Louis, MO			**Albuquerque**, NM		
Climate zone	4A			4B		
Location (census region)	Midwest			West		
Location (census division)	West North Central			Mountain		
Home type	Old	Existing	New	Old	Existing	New
Number of stories	1	1	1	1	1	1
Floor area (ft^2)	2,025	2,025	2,025	2,025	2,025	2,025
Orientation	Front door faces north	Front door faces north	Front door faces north	Front door faces north	Front door faces north	Front door faces north
Floor construction	Basement, uninsulated	Basement, whole wall 4-ft R-5 XPS	Basement, whole wall R-10 XPS	Slab, uninsulated	Slab, 2-ft R-5 exterior XPS	Slab, 2-ft R-10 exterior XPS
Number of bedrooms	3	3	3	3	3	3
Number of bathrooms	2	2	2	2	2	2
Exterior wall materials	Wood, light	Wood, light	Vinyl, light	Brick, light	Stucco, medium/dark	Vinyl, light
Wall insulation (hr·ft^2·°F/BTU)	Uninsulated	R-19 fiberglass batt	R-13 fiberglass batt	Uninsulated	R-13 fiberglass batt	R-13 fiberglass batt
Wall characteristics	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 24 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.
Wall sheathing	OSB	OSB	OSB	OSB	OSB	OSB
Attic insulation (hr·ft^2·°F/BTU)	Ceiling R-7 fiberglass	Ceiling R-32 fiberglass	Ceiling R-38 fiberglass	Ceiling R-11 fiberglass	Ceiling R-29 fiberglass	Ceiling R-38 fiberglass
Attic space type	Vented	Vented	Vented	Vented	Vented	Vented
Window U-value (BTU/hr·ft^2·°F)	1.1	0.49	0.35	1.1	0.49	0.35
Window SHGC	0.87	0.79	0.3	0.87	0.79	0.3
Window area, *F*, *B*, *L*, and *R* (ft^2)	20, 40, 20, 20	20, 40, 20, 20	43, 86, 43, 43	20, 40, 20, 20	20, 40, 20, 20	43, 86, 43, 43
Duct location	Unfinished basement	Unfinished basement	Unfinished basement	Unfinished attic	Unfinished attic	Unfinished attic
Duct insulation (hr·ft^2·°F/BTU)	Uninsulated	R-4	R-8	Uninsulated	R-4	R-8
Duct leakage (%)	30.00	15.00	7.50	30.00	15.00	7.50
Envelope airtightness (ACH_{50})	20	10	3	20	10	3
Mechanical ventilation	None	None	None	None	None	None
HVAC equipment	5-ton AC unit	3-ton AC unit	1.5-ton AC unit	5-ton AC unit	4-ton AC unit	2.5-ton AC unit
Central air-conditioner type	6.8 SEER 1 stage	10 SEER 1 stage	16 SEER 1 stage	6.8 SEER 1 stage	10 SEER 1 stage	16 SEER 1 stage
Furnace type	78% AFUE gas furnace	90% AFUE gas furnace	98% AFUE gas furnace	78% AFUE gas furnace	90% AFUE gas furnace	98% AFUE gas furnace
Nominal cooling capacity (BTU/h)	60,000	36,000	18,000	60,000	48,000	30,000
Nominal heating capacity (BTU/h)	140,000	60,000	24,000	140,000	48,000	24,000

	City					
	Seattle, WA			Chicago, IL		
Climate zone	4C			5A		
Location (census region)	West			Midwest		
Location (census division)	Pacific North			East North Central		
Home type	Old	Existing	New	Old	Existing	New
Number of stories	1	1	1	1	1	1
Floor area (ft^2)	2,025	2,025	2,025	2,025	2,025	2,025
Orientation	Front door faces north	Front door faces north	Front door faces north	Front door faces north	Front door faces north	Front door faces north
Floor construction	Crawl, uninsulated	Crawl, uninsulated	Slab, 2-ft R-10 exterior XPS	Basement, uninsulated	Basement, uninsulated	Basement, whole wall R-10 XPS
Number of bedrooms	3	3	3	3	3	3
Number of bathrooms	2	2	2	2	2	2
Exterior wall materials	Wood, light	Wood, light	Vinyl, light	Brick, light	Aluminum, light	Vinyl, light
Wall insulation (hr·ft^2·°F/BTU)	Uninsulated	R-11 fiberglass batt	R-13 fiberglass batt	Uninsulated	R-13 fiberglass batt	R-13 fiberglass batt
Wall characteristics	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.
Wall sheathing	OSB	OSB	R-5 XPS	OSB	OSB	R-5 XPS
Attic insulation (hr·ft^2·°F/BTU)	Ceiling R-11 fiberglass	Ceiling R-32 fiberglass	Ceiling R-38 fiberglass	Ceiling R-11 fiberglass	Ceiling R-32 fiberglass	Ceiling R-38 fiberglass
Attic space type	Vented	Vented	Vented	Vented	Vented	Vented
Window U-value (BTU/hr·ft^2·°F)	1.1	0.49	0.35	1.1	0.49	0.35
Window SHGC	0.87	0.79	0.3	0.87	0.79	0.3
Window area, *F*, *B*, *L*, and *R* (ft^2)	20, 40, 20, 20	20, 40, 20, 20	43, 86, 43, 43	20, 40, 20, 20	20, 40, 20, 20	43, 86, 43, 43
Duct location	Crawlspace	Unfinished attic	Unfinished attic	Unfinished basement	Unfinished basement	Unfinished basement
Duct insulation (hr·ft^2·°F/BTU)	Uninsulated	R-4	R-8	Uninsulated	R-4	R-8
Duct leakage (%)	30.00	15.00	7.50	30.00	15.00	7.50
Envelope airtightness (ACH_{50})	20	10	3	20	10	3
Mechanical ventilation	None	None	None	None	None	None
HVAC equipment	2.5-ton AC unit	1.5-ton AC unit	2-ton AC unit	5-ton AC unit	2.5-ton AC unit	1.5-ton AC unit
Central air-conditioner type	6.8 SEER 1 stage	10 SEER 1 stage	16 SEER 1 stage	6.8 SEER 1 stage	10 SEER 1 stage	16 SEER 1 stage
Furnace type	78% AFUE gas furnace	90% AFUE gas furnace	98% AFUE gas furnace	78% AFUE gas furnace	90% AFUE gas furnace	98% AFUE gas furnace
Nominal cooling capacity (BTU/h)	30,000	18,000	24,000	60,000	30,000	18,000
Nominal heating capacity (BTU/h)	84,000	36,000	24,000	140,000	72,000	36,000

(Continued on the next page)

Table A.1. Assumed home characteristics in different locations in the United States. *(Continued)*

	City					
Climate zone	Pittsburgh, PA 5A			Boston, MA 5A		
Location (census region)	Northeast			Northeast		
Location (census division)	Middle Atlantic			New England		
Home type	Old	Existing	New	Old	Existing	New
Number of stories	1	1	1	1	1	1
Floor area (ft^2)	2,025	2,025	2,025	2,025	2,025	2,025
Orientation	Front door faces north	Front door faces north	Front door faces north	Front door faces north	Front door faces north	Front door faces north
Floor construction	Basement, uninsulated	Basement, uninsulated	Basement, whole wall R-10 XPS	Basement, uninsulated	Basement, uninsulated	Basement, whole wall R-10 XPS
Number of bedrooms	3	3	3	3	3	3
Number of bathrooms	2	2	2	2	2	2
Exterior wall materials	Wood, light	Wood, light	Vinyl, light	Wood, light	Wood, light	Vinyl, light
Wall insulation (hr·ft^2·°F/BTU)	Uninsulated	R-13 fiberglass batt	R-13 fiberglass batt	Uninsulated	R-13 fiberglass batt	R-13 fiberglass batt
Wall characteristics	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.
Wall sheathing	OSB	OSB	R-5 XPS	OSB	OSB	R-5 XPS
Attic insulation (hr·ft^2·°F/BTU)	Ceiling R-38 fiberglass	Ceiling R-27 fiberglass	Ceiling R-38 fiberglass	Ceiling R-22 fiberglass	Ceiling R-27 fiberglass	Ceiling R-38 fiberglass
Attic space type	Vented	Vented	Vented	Vented	Vented	Vented
Window U-value (BTU/hr·ft^2·°F)	1.1	0.49	0.35	1.1	0.49	0.35
Window SHGC	0.87	0.79	0.3	0.87	0.79	0.3
Window area, *F*, *B*, *L*, and *R* (ft^2)	20, 40, 20, 20	20, 40, 20, 20	43, 86, 43, 43	20, 40, 20, 20	20, 40, 20, 20	43, 86, 43, 43
Duct location	Unfinished basement	Unfinished basement	Unfinished basement		Unfinished basement	Unfinished basement
Duct insulation (hr·ft^2·°F/BTU)	Uninsulated	R-4	R-8	Uninsulated	R-4	R-8
Duct leakage (%)	30.00	15.00	7.50	30.00	15.00	7.50
Envelope airtightness (ACH_{50})	20	10	3	20	10	3
Mechanical ventilation	None	NONE	None	None	NONE	None
HVAC equipment	4-ton AC unit	2-ton AC unit	1-ton AC unit	4.5-ton AC unit	2.5-ton AC unit	1.5-ton AC unit
Central air-conditioner type	6.8 SEER 1 stage	10 SEER 1 stage	16 SEER 1 stage	6.8 SEER 1 stage	10 SEER 1 stage	16 SEER 1 stage
Furnace type	78% AFUE gas furnace	90% AFUE gas furnace	98% AFUE gas furnace	78% AFUE gas furnace	90% AFUE gas furnace	98% AFUE gas furnace
Nominal cooling capacity (BTU/h)	48,000	24,000	12,000	54,000	30,000	18,000
Nominal heating capacity (BTU/h)	132,000	60,000	24,000	132,000	60,000	24,000

	City					
	Detroit, MI			Denver, CO		
Climate zone	5A			5B		
Location (census region)	Midwest			West		
Location (census division)	East North Central			Mountain		
Home type	Old	Existing	New	Old	Existing	New
Number of stories	1	1	1	1	1	1
Floor area (ft^2)	2,025	2,025	2,025	2,025	2,025	2,025
Orientation	Front door faces north	Front door faces north	Front door faces north	Front door faces north	Front door faces north	Front door faces north
Floor construction	Basement, uninsulated	Basement, uninsulated	Basement, whole wall R-10 XPS	Slab, uninsulated	Slab, 2-ft R-5 exterior XPS	Slab, 2-ft R-10 exterior XPS
Number of bedrooms	3	3	3	3	3	3
Number of bathrooms	2	2	2	2	2	2
Exterior wall materials	Brick, light	Aluminum, light	Vinyl, light	Brick, light	Stucco, medium/dark	Vinyl, light
Wall insulation ($hr·ft^2·°F/BTU$)	Uninsulated	R-13 fiberglass batt	R-13 fiberglass batt	Uninsulated	R-13 fiberglass batt	R-13 fiberglass batt
Wall characteristics	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.
Wall sheathing	OSB	OSB	R-5 XPS	OSB	OSB	R-5 XPS
Attic insulation ($hr·ft^2·°F/BTU$)	Ceiling R-11 fiberglass	Ceiling R-32 fiberglass	Ceiling R-38 fiberglass	Ceiling R-11 fiberglass	Ceiling R-29 fiberglass	Ceiling R-38 fiberglass
Attic space type	Vented	Vented	Vented	Vented	Vented	Vented
Window U-value ($BTU/hr·ft^2·°F$)	1.1	0.49	0.35	1.1	0.49	0.35
Window SHGC	0.87	0.79	0.3	0.87	0.79	0.3
Window area, *F*, *B*, *L*, and *R* (ft^2)	20, 40, 20, 20	20, 40, 20, 20	43, 86, 43, 43	20, 40, 20, 20	20, 40, 20, 20	43, 86, 43, 43
Duct location	Unfinished basement	Unfinished attic	Unfinished basement	Unfinished attic	Unfinished attic	Unfinished attic
Duct insulation ($hr·ft^2·°F/BTU$)	Uninsulated	R-4	R-8	Uninsulated	R-4	R-8
Duct leakage (%)	30.00	15.00	7.50	30.00	15.00	7.50
Envelope airtightness (ACH_{50})	20	10	3	20	10	3
Mechanical ventilation	None	None	None	None	None	None
HVAC equipment	4.5-ton AC unit	2.5-ton AC unit	1-ton AC unit	5-ton AC unit	4-ton AC unit	2.5-ton AC unit
Central air-conditioner type	6.8 SEER 1 stage	10 SEER 1 stage	16 SEER 1 stage	6.8 SEER 1 stage	10 SEER 1 stage	16 SEER 1 stage
Furnace type	78% AFUE gas furnace	90% AFUE gas furnace	98% AFUE gas furnace	78% AFUE gas furnace	90% AFUE gas furnace	98% AFUE gas furnace
Nominal cooling capacity (BTU/h)	54,000	30,000	12,000	60,000	48,000	30,000
Nominal heating capacity (BTU/h)	132,000	60,000	24,000	140,000	72,000	36,000

(Continued on the next page)

Table A.1. Assumed home characteristics in different locations in the United States. *(Continued)*

	City					
	Blaine, MN			Colstrip, MT		
Climate zone	6A			6B		
Location (census region)	Midwest			West		
Location (census division)	West North Central			Mountain		
Home type	Old	Existing	New	Old	Existing	New
Number of stories	1	1	1	1	1	1
Floor area (ft^2)	2,025	2,025	2,025	2,025	2,025	2,025
Orientation	Front door faces north	Front door faces north	Front door faces north	Front door faces north	Front door faces north	Front door faces north
Floor construction	Basement, uninsulated	Basement, whole wall 4-ft R-5 XPS	Basement, whole wall R-15 XPS	Slab, uninsulated	Slab, 2-ft R-5 exterior XPS	Slab, 4-ft R-10 exterior XPS
Number of bedrooms	3	3	3	3	3	3
Number of bathrooms	2	2	2	2	2	2
Exterior wall materials	Wood, light	Wood, light	Vinyl, light	Brick, light	Stucco, medium/dark	Vinyl, light
Wall insulation ($hr{\cdot}ft^2{\cdot}°F/BTU$)	Uninsulated	R-19 fiberglass batt	R-13 fiberglass batt	Uninsulated	R-13 fiberglass batt	R-13 fiberglass batt
Wall characteristics	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 24 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.
Wall sheathing	OSB	OSB	R-5 XPS	OSB	OSB	R-5 XPS
Attic insulation ($hr{\cdot}ft^2{\cdot}°F/BTU$)	Ceiling R-7 fiberglass	Ceiling R-32 fiberglass	Ceiling R-49 fiberglass	Ceiling R-11 fiberglass	Ceiling R-29 fiberglass	Ceiling R-49 fiberglass
Attic space type	Vented	Vented	Vented	Vented	Vented	Vented
Window U-value ($BTU/hr{\cdot}ft^2{\cdot}°F$)	1.1	0.49	0.35	1.1	0.49	0.35
Window SHGC	0.87	0.79	0.3	0.87	0.79	0.3
Window area, *F*, *B*, *L*, and *R* (ft^2)	20, 40, 20, 20	20, 40, 20, 20	43, 86, 43, 43	20, 40, 20, 20	20, 40, 20, 20	43, 86, 43, 43
Duct location	Unfinished basement	Unfinished basement	Unfinished basement	Unfinished attic	Unfinished attic	Unfinished attic
Duct insulation ($hr{\cdot}ft^2{\cdot}°F/BTU$)	Uninsulated	R-4	R-8	Uninsulated	R-4	R-8
Duct leakage (%)	30.00	15.00	7.50	30.00	15.00	7.50
Envelope airtightness (ACH_{50})	20	10	3	20	10	3
Mechanical ventilation	None	None	None	None	None	None
HVAC equipment	5-ton AC unit	2.5-ton AC unit	1-ton AC unit	5-ton AC unit	4-ton AC unit	2-ton AC unit
Central air-conditioner type	6.8 SEER 1 stage	10 SEER 1 stage	16 SEER 1 stage	6.8 SEER 1 stage	10 SEER 1 stage	16 SEER 1 stage
Furnace type	78% AFUE gas furnace	90% AFUE gas furnace	98% AFUE gas furnace	78% AFUE gas furnace	90% AFUE gas furnace	98% AFUE gas furnace
Nominal cooling capacity (BTU/h)	60,000	30,000	12,000	60,000	48,000	24,000
Nominal heating capacity (BTU/h)	140,000	72,000	36,000	140,000	96,000	48,000

	City					
	Bismarck, ND			Pinedale, WY		
Climate zone	7A			7B		
Location (census region)	Midwest			West		
Location (census division)	West North Central			Mountain		
Home type	Old	Existing	New	Old	Existing	New
Number of stories	1	1	1	1	1	1
Floor area (ft^2)	2,025	2,025	2,025	2,025	2,025	2,025
Orientation	Front door faces north	Front door faces north	Front door faces north	Front door faces north	Front door faces north	Front door faces north
Floor construction	Basement, uninsulated	Basement, whole wall 4-ft R-5 XPS	Basement, whole wall R-15 XPS	Slab, uninsulated	Slab, 2-ft R-5 exterior XPS	Slab, 4-ft R-10 exterior XPS
Number of bedrooms	3	3	3	3	3	3
Number of bathrooms	2	2	2	2	2	2
Exterior wall materials	Wood, light	Wood, light	Vinyl, light	Brick, light	Stucco, medium/dark	Vinyl, light
Wall insulation (hr·ft^2·°F/BTU)	Uninsulated	R-19 fiberglass batt	R-13 fiberglass batt	Uninsulated	R-13 fiberglass batt	R-21 fiberglass batt
Wall characteristics	Gr-1, 2 × 6, 24 in. o.c.	Gr-1, 2 × 4, 24 in. o.c.	Gr-1, 2 × 6, 24 in. o.c.	Gr-1, 2 × 6, 24 in. o.c.	Gr-1, 2 × 4, 16 in. o.c.	Gr-1, 2 × 6, 24 in. o.c.
Wall sheathing	OSB	OSB	R-5 XPS	OSB	OSB	OSB
Attic insulation (hr·ft^2·°F/BTU)	Ceiling R-7 fiberglass	Ceiling R-32 fiberglass	Ceiling R-49 fiberglass	Ceiling R-11 fiberglass	Ceiling R-29 fiberglass	Ceiling R-49 fiberglass
Attic space type	Vented	Vented	Vented	Vented	Vented	Vented
Window U-value (BTU/hr·ft^2·°F)	1.1	0.49	0.35	1.1	0.49	0.35
Window SHGC	0.87	0.79	0.3	0.87	0.79	0.3
Window area, *F*, *B*, *L*, and *R* (ft^2)	20, 40, 20, 20	20, 40, 20, 20	43, 86, 43, 43	20, 40, 20, 20	20, 40, 20, 20	43, 86, 43, 43
Duct location	Unfinished basement	Unfinished basement	Unfinished basement	Unfinished attic	Unfinished attic	Unfinished attic
Duct insulation (hr·ft^2·°F/BTU)	Uninsulated	R-4	R-8	Uninsulated	R-4	R-8
Duct leakage (%)	30.00	15.00	7.50	30.00	15.00	7.50
Envelope airtightness (ACH_{50})	20	10	3	20	10	3
Mechanical ventilation	None	None	None	None	None	None
HVAC equipment	3.5-ton AC unit	2-ton AC unit	1.5-ton AC unit	5-ton AC unit	3-ton AC unit	2-ton AC unit
Central air-conditioner type	6.8 SEER 1 stage	10 SEER 1 stage	16 SEER 1 stage	6.8 SEER 1 stage	10 SEER 1 stage	16 SEER 1 stage
Furnace type	78% AFUE gas furnace	90% AFUE gas furnace	98% AFUE gas furnace	78% AFUE gas furnace	90% AFUE gas furnace	98% AFUE gas furnace
Nominal cooling capacity (BTU/h)	42,000	24,000	12,000	60,000	36,000	24,000
Nominal heating capacity (BTU/h)	140,000	84,000	36,000	140,000	84,000	36,000

XPS = extruded polystyrene. o.c. = on center. OSB = oriented strand board. AFUE = annual fuel utilization efficiency.

Appendix B: Outdoor air pollutant station summary

Table B.1. Summary of selected stations for outdoor $PM_{2.5}$ from AQS.

			$PM_{2.5}$		
	Location	Selected stations	State code	County code	Site ID
1	Albuquerque, NM	Main station	35	1	23
		Supplementary station	35	1	29
2	Atlanta, GA	Main station	13	89	2
		Supplementary station	13	121	55
3	Birmingham, AL	Main station	1	73	2003
		Supplementary station	1	73	2006
4	Riverside, CA	Main station	6	65	8001
		Supplementary station	6	65	9001
5	Philadelphia, PA	Main station	34	7	10
		Supplementary station	34	19	1
		Supplementary station	34	13	3
		Supplementary station	34	39	4
		Supplementary station	34	39	2003
		Supplementary station	34	21	10
6	Boston, MA	Main station	25	25	42
		Supplementary station	25	25	85
		Supplementary station	25	27	43
		Supplementary station	25	21	23
7	St. Louis, MO	Main station	29	510	85
		Supplementary station	29	510	93
8	Chicago, IL	Main station	17	31	76
		Supplementary station	17	31	8
9	Pittsburgh, PA	Main station	42	3	8
		Supplementary station	42	3	64
10	Denver, CO	Main station	8	31	2
		Supplementary station	8	35	4
11	Detroit, MI	Main station	26	163	38
		Supplementary station	26	163	1
12	Blaine, MN	Main station	27	3	1002
		Supplementary station	27	75	5
13	Houston, TX	Main station	48	201	1035
		Supplementary station	48	201	1050
14	Los Angeles, CA	Main station	6	37	1103
		Supplementary station	6	37	1201
15	Miami, FL	Main station	12	86	6001
		Supplementary station	12	86	1016
16	Bismarck, ND	Main station	38	15	3
		Supplementary station	38	17	1004
17	Pinedale, WY	Main station	56	35	97
		Supplementary station	56	35	101
18	New York, NY	Main station	36	81	120
		Supplementary station	36	29	5
19	Phoenix, AZ	Main station	4	13	9997
		Supplementary station	4	13	2001
20	San Francisco, CA	Main station	6	75	5
		Supplementary station	6	77	1002
21	Colstrip, MT	Main station	30	87	1
		Supplementary station	30	93	5
22	Seattle, WA	Main station	53	33	80
		Supplementary station	53	33	37

Table B.2. Summary of selected stations for outdoor NO_x (for UFP estimates) from AQS.

			UFP		
	Location	Selected stations	State code	County code	Site ID
1	Albuquerque, NM	Main station	35	1	23
		Supplementary station	35	45	1005
2	Atlanta, GA	Main station	13	89	2
		Supplementary station	13	223	3
3	Birmingham, AL	Main station	N/A	N/A	N/A
4	Riverside, CA	Main station	6	65	1003
		Supplementary station	6	65	9001
		Supplementary station	6	65	12
		Supplementary station	6	65	5001
		Supplementary station	6	65	8001
5	Philadelphia, PA	Main station	34	7	2
		Supplementary station	34	41	7
		Supplementary station	34	13	3
6	Boston, MA	Main station	25	25	42
		Supplementary station	25	25	2
7	St. Louis, MO	Main station	29	510	86
		Supplementary station	29	95	34
8	Chicago, IL	Main station	17	31	76
		Supplementary station	17	31	4201
9	Pittsburgh, PA	Main station	42	3	8
		Supplementary station	42	3	10
10	Denver, CO	Main station	8	31	2
		Supplementary station	8	57	3
		Supplementary station	8	67	1004
11	Detroit, MI	Main station	26	163	19
		Supplementary station	26	163	93
12	Blaine, MN	Main station	27	3	1002
		Supplementary station	27	37	20
13	Houston, TX	Main station	48	201	1035
		Supplementary station	48	201	1050
14	Los Angeles, CA	Main station	6	37	1302
		Supplementary station	6	37	1201
		Supplementary station	6	37	1701
		Supplementary station	6	37	1103
		Supplementary station	6	37	9033
15	Miami, FL	Main station	12	86	4002
		Supplementary station	12	86	27
16	Bismarck, ND	Main station	38	15	3
		Supplementary station	38	17	1004
17	Pinedale, WY	Main station	56	35	97
		Supplementary station	56	35	101
		Supplementary station	56	35	99
18	New York, NY	Main station	36	81	124
		Supplementary station	36	33	7003
19	Phoenix, AZ	Main station	4	13	9997
		Supplementary station	4	19	1028
20	San Francisco, CA	Main station	6	75	5
		Supplementary station	6	77	1002
21	Colstrip, MT	Main station	30	87	1
		Supplementary station	30	83	1
		Supplementary station	30	31	17
		Supplementary station	30	27	6
22	Seattle, WA	Main station	N/A	N/A	N/A

Appendix C: Sensitivity to fundamental input parameters: Simplified infiltration factor modeling

We used only the simplified annual average model to evaluate the sensitivity of our results to fundamental input parameters of P, β, λ, η, f, and λ_{HVAC} using the simplified model. Table C1 shows the range of input parameters selected for each home type and vintage, including $PM_{2.5}$ and UFP penetration factors (P_i), deposition loss rate constants (β_i), HVAC filter removal efficiency (η), air exchange rate (λ), HVAC system runtime (f), and recirculation rate (λ_{HVAC}). The range of values was selected from a wide variety of literature sources and the midpoint between minimum and maximum values was used as the base reference point to individually test the sensitivity of changing each parameter one at a time. Therefore, results of this sensitivity analysis are presented relative to these ranges; selection of different parameter ranges will yield different magnitudes of sensitivity.

The sensitivity of time-averaged $PM_{2.5}$ and UFP infiltration factors to these ranges of input parameters was estimated by calculating the change in infiltration factor ($\Delta F_{i,inf}$) as a function of the proportional change in input parameter (ΔX_i) as shown in Equations S1 and S2.

$$\Delta X_i = \frac{x_i - x_{i,midpoint}}{x_{i,midpoint}} \tag{C1}$$

$$\Delta F_{i,inf} = F_{i,inf,x} - F_{i,inf,midpoint} \tag{C2}$$

where

x_i: model input parameter values
$x_{i,midpoint}$: midpoint value for model parameters
$F_{i,inf,x}$: $PM_{2.5}$ and UFP infiltration factor for different values of the model parameters (x)
$F_{i,inf,midpoint}$: $PM_{2.5}$ and UFP infiltration factor for midpoint values of the model parameters

Figures C1 and C2 show the resulting sensitivity of time-averaged $PM_{2.5}$ and UFP infiltration factors to changes in these fundamental model parameters.

In old homes relying on infiltration alone, the greatest influence on modeled infiltration factors was the filter removal efficiency. The air exchange rate had the second largest influence on $PM_{2.5}$ infiltration factors, as the range of air exchange rates used was large in these type of homes. The influence of $PM_{2.5}$ penetration factors increased for existing and new homes in comparison to old homes. In new homes relying on infiltration alone, the penetration factor had the greatest influence on $PM_{2.5}$ infiltration factors. In homes with mechanical ventilation, both the $PM_{2.5}$ penetration factor and filter removal efficiency had the largest influences on $PM_{2.5}$ infiltration factors. The influence of air exchange rates in new homes with mechanical ventilation was noticeably lower than in new homes relying on infiltration only, as the a continuous outdoor air ventilation of 85 m^3/hr provided in all ventilation scenarios reduces the range of air exchange rates in new homes with mechanical ventilation.

In old homes relying on infiltration alone, both filter removal efficiency and air exchange rates had the great influence on UFP infiltration factors. The influence of UFP penetration factors was lower in old homes compared to other factors but it increased for existing and new home scenarios, similar to $PM_{2.5}$. The influence of UFP deposition rate constants was greater than were the $PM_{2.5}$ deposition rate constants, as the reported range of UFP deposition rate constants in the literature was higher than for $PM_{2.5}$. In existing and new homes relying on infiltration alone and in all new home ventilation scenarios, the UFP deposition rate constant had the greatest influence on UFP infiltration factors. The impact of filter removal efficiency in the old homes relying on infiltration alone was greatest relative to the other home vintage and ventilation scenarios. The influence of air exchange rates on UFP infiltration factors was smaller in new homes with ventilation system compared to homes relying on infiltration alone, similar to the $PM_{2.5}$ estimates.

Together, the results demonstrate that $PM_{2.5}$ penetration factor and UFP deposition loss rate constants are predicted to have the greatest influence on $PM_{2.5}$ and UFP infiltration factors in existing and new homes (both relying on infiltration alone and mechanical ventilation), respectively, but their influence is smaller compared to other factors in the old homes relying on infiltration only. HVAC filter removal efficiency has the second greatest influence on both $PM_{2.5}$ and UFP infiltration factors in almost all home vintage and mechanical ventilation scenarios. We should note that our sensitivity analysis is greatly influenced by the range of values considered for each parameter, which highlights the importance of selecting a robust and reasonable range for each factor in these types of analyses. Moreover, these data demonstrate the fundamental influencing factors for $PM_{2.5}$ and UFP infiltration factors and can help prioritize data collection needs for improving input parameters for future modeling efforts.

Table C1. Range of each input parameter used in sensitivity analysis.

Parameter	Unit	Old	Existing	New infiltration only	New with ventilation	Reference
$PM_{2.5}$ penetration factor	—	0.70–1.00	0.40–0.70	0.11–0.40	0.11–0.40	Williams et al. (2003)
UFP penetration factor	—	0.52–0.70	0.34–0.52	0.17-0.34	0.17-0.34	Stephens and Siegel (2012)
$PM_{2.5}$ deposition rate	hr^{-1}	0.10–0.80	0.10–0.80	0.10–0.80	0.10–0.80	Williams et al. (2003)
UFP deposition rate	hr^{-1}	0.20–1.60	0.20–1.60	0.20–1.60	0.20–1.60	Wallace et al. (2013)
$PM_{2.5}$ removal efficiency	%	1.4–99.7	1.4–99.7	1.4–99.7	1.4–99.7	Azimi et al. (2014)
UFP removal efficiency	%	7.6–99.4	7.6–99.4	7.6–99.4	7.6–99.4	Azimi et al. (2014)
AER	hr^{-1}	0.32–1.07	0.18–0.52	0.09–0.18	0.23–0.28	Modeled with EnergyPlus
HVAC system runtime	—	0.14–0.47	0.05–0.28	0.08–0.33	0.09–0.38	Modeled with EnergyPlus
HVAC recirculation rate	hr^{-1}	3.7–7.41	2.22–7.41	1.48–5.93	1.48–5.93	Modeled with EnergyPlus

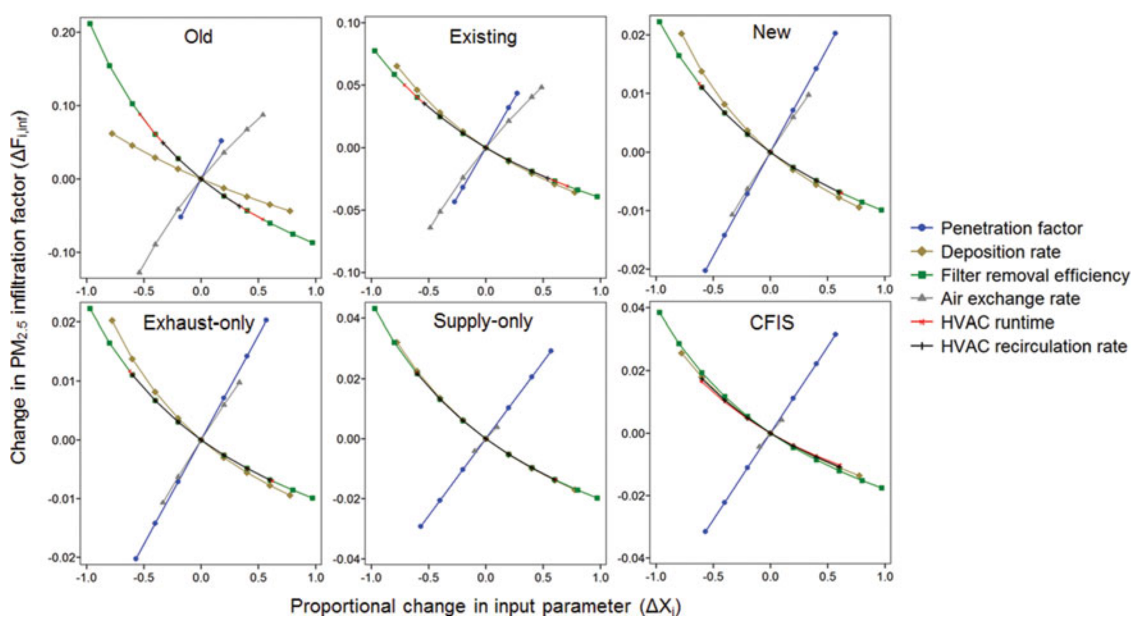

Fig. C1. Sensitivity of time-averaged $PM_{2.5}$ infiltration factors to changes in input parameters.

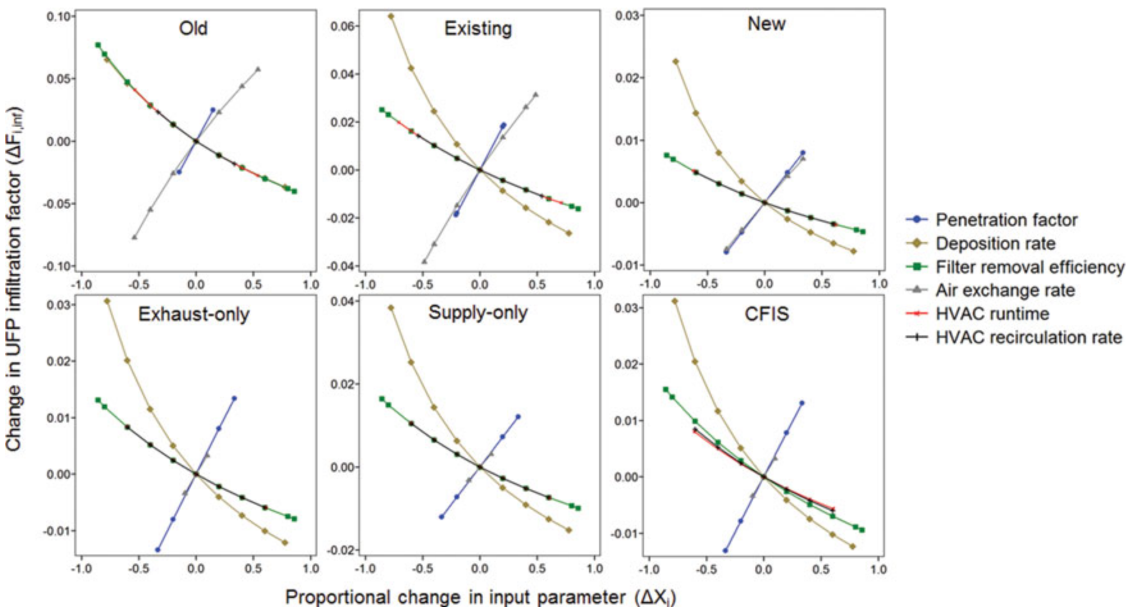

Fig. C2. Sensitivity of time-averaged UFP infiltration factors to changes in input parameters.