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Penetration of ambient submicron particles into single-family residences and associations with building characteristics

Abstract This work improves knowledge of particle penetration into buildings by (i) refining a particle penetration test method that minimizes the duration and invasiveness required by individual tests without sacrificing accuracy, (ii) applying the method in an unoccupied manufactured test house and 18 single-family homes in Austin, Texas, USA, and (iii) exploring correlations between particle penetration and building characteristics, including results from blower door air leakage tests. The mean ($\pm$s.d.) measured penetration factor of submicron particles (20–1000 nm, not size-resolved) was 0.47 ± 0.15 in 19 residences that relied on infiltration for ventilation air, ranging from 0.17 ± 0.03 to 0.72 ± 0.08. Particle penetration factors (P) and outdoor particle source terms ($P \times$ air exchange rates) were both significantly and positively correlated with results from blower door air leakage tests. Outdoor particle source terms were also significantly and negatively correlated with the year of construction. These results suggest that occupants of leakier and older homes are exposed to higher indoor concentrations of outdoor submicron particles than those in tighter and newer homes, and that simple air leakage tests may be able to provide an approximate prediction of outdoor particle infiltration into single-family residences.

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Key words: Particulate matter; Infiltration; Blower door; Single-family residential; Measurements; Indoor exposures to outdoor particles.

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Practical Implications

Results from this work suggest that knowledge of simple building characteristics (i.e., the year of construction and blower door test results) may be used to predict the ability of outdoor particles to infiltrate into single-family residences, which could facilitate easier estimates of indoor exposures to outdoor particulate matter across the building stock. The methods within can also be extended to other buildings and can be used to assess possible changes in penetration factors because of envelope retrofits. Because outdoor particle size distributions were not measured during this study, these tests should also be repeated with size-resolved particle instrumentation.

Introduction

Increased outdoor airborne particulate matter has been consistently associated with increased risks of respiratory symptoms, cardiopulmonary mortality, and lung cancer (e.g., Brook et al., 2010; Miller et al., 2007; Pope and Dockery, 2006; Pope et al., 2002). Similarly, elevated outdoor ultrafine particles (<100 nm in diameter) have also been associated with increased total and cardiorespiratory mortality (Stölzel et al., 2007) and have been shown to exacerbate asthma symptoms (von Klot et al., 2002; Penttinen et al., 2001; Weichenthal et al., 2007). Associations between elevated airborne particulate matter and adverse health effects are often made in large epidemiological studies using outdoor measurements; however, because particles can penetrate indoors where people spend the majority of their time (Klepeis et al., 2001), much of their exposure to particles of outdoor origin often occurs inside buildings, particularly in residences (Allen et al., 2004; Bhangar et al., 2011; Kearney et al., 2011; Meng et al., 2005, 2009).

Additionally, although indoor particle concentrations are influenced by both indoor and outdoor sources, there is some evidence that particles of outdoor origin may be more detrimental to human health than indoor-generated particles (Ebelt et al., 2005; Koenig et al., 2005). Large cohort studies of adverse health effects from personal exposures to outdoor particulate matter are generally prohibitively expensive (e.g., Cohen et al., 2009); thus, appropriate models may be used to more accurately and inexpensively predict indoor exposures to particles of outdoor origin using ambient concentrations made at central monitoring sites (Hering et al., 2007; Wu et al., 2005). However, to better predict human exposure to airborne particulate matter, it is important to better understand the ability of outdoor particles to infiltrate through building envelopes (e.g., Isakov et al., 2009; Sioutas et al., 2005; Thornburg et al., 2001).

In buildings that rely on infiltration for ventilation air, which represent the majority of residential buildings in the U.S., outdoor particles can transport indoors via leaks in the building envelope. The process is dependent on several factors, including the geometry of openings, indoor–outdoor pressure differences, the amount of airflow through openings, air exchange rates (AERs), and particle size (e.g., Liu and Nazaroff, 2001, 2003; Rim et al., 2010). Specific particle penetration field experiments have been conducted by only a few researchers (e.g., Chao et al., 2003; Rim et al., 2010; Thatcher and Layton, 1995; Thatcher et al., 2003), in part because they are non-standardized, invasive, time-consuming, and often result in large experimental uncertainties.

Two potential opportunities to improve knowledge of particle penetration into buildings are to (i) refine penetration test methods to improve accuracy and minimize the duration and invasiveness required by individual tests, and (ii) because particle penetration is in part a function of leak geometries in building envelopes, investigate the potential to infer information about particle penetration from building characteristics, including results from easy and cost-effective standardized building air leakage tests. Thus, this work (i) refines a particle penetration test methodology, (ii) applies it in an unoccupied manufactured test house and 18 single-family homes in Austin, Texas, USA, and (iii) explores correlations between measured particle penetration parameters and building characteristics, including results from blower door tests.

Background

Previous investigations of the penetration of outdoor airborne particulate matter have generally occurred in four forms, including: (i) modeling efforts (Liu and Nazaroff, 2001); (ii) laboratory measurements of building envelope structures (Liu and Nazaroff, 2003; Mosley et al., 2001); (iii) measurement of indoor–outdoor concentration ratios (or 'infiltration factors') during periods free of indoor sources (e.g., Abt et al., 2000; Bennett and Koutrakis, 2006; Bhangar et al., 2011; Fogh et al., 1997; McAuley et al., 2010), which are sometimes coupled with models to estimate penetration factors from measured data (e.g., Long et al., 2001; Lunden et al., 2003; Vette et al., 2001; Williams et al., 2003; Zhu et al., 2005); and (4) specific particle penetration methods applied in buildings (Chao et al., 2003; Rim et al., 2010; Thatcher and Layton, 1995; Thatcher et al., 2003). Chen and Zhao (2011) present an extensive review of many of these studies, but the previous studies on specific particle penetration methods provide the most relevant motivation for this work.

Thatcher and Layton (1995) measured size-resolved (0.3–25+ μm) particle concentrations indoors and outdoors at a single-family residence while simultaneously measuring AER with tracer gas decay. They determined size-resolved deposition rates of particles by artificially elevating indoor particle concentrations and solving for the subsequent indoor loss rate, and subtracting out the AER. Size-resolved penetration factors were estimated using steady-state indoor–outdoor concentration ratios during periods free of indoor sources, the measured AER, and the previously estimated decay rate. Thatcher et al. (2003) performed similar simultaneous size-resolved (0.1–10 μm) particle measurements indoors and outdoors at two homes. A three-part experimental approach was used to (i) elevate indoor particle concentrations and measure the subsequent particle decay rate, (ii) rapidly reduce particle concentrations below background levels by supplying HEPA-filtered outdoor air, and (iii) remove the HEPA filter and measure the subsequent particle concentration 're-bound' period, where indoor particle concentrations increased because of the penetration of outdoor particles. Thatcher et al. (2003) also happened to report results of blower door air leakage tests in the two homes, and penetration factors in the leakier home were greater than or equal to the tighter home for every particle size, which provides motivation for the central hypothesis in this work that particle penetration factors and building characteristics are correlated.

Chao et al. (2003) performed particle penetration experiments in six residential high-rise apartment buildings. Their method consisted of a two-part experimental approach while AER was measured with tracer gas decay: (i) indoor particle concentrations (0.02–10 μm, not size-resolved and 0.5–10 μm, with some size-resolution) were initially elevated by opening doors and windows, which introduced outdoor particles, and (ii) windows and doors were closed and the residences were left undisturbed for approximately 3 h. Indoor particle concentrations were measured as they decreased to background levels, and outdoor particle concentrations were measured for 30 min before and after the decay test. The indoor loss rate was estimated from a number balance on the decay period, and the penetration factor was estimated from the measured pseudo-steady-state I/O concentration ratio and the previous estimates of AER and the indoor loss rate.

Most recently, Rim et al. (2010) measured size-resolved infiltration factors, deposition rates, and penetration factors of ultrafine particles (<100 nm) at an unoccupied test house during two conditions: (i) with doors and windows closed and (ii) with one window open approximately 7.5 cm. They monitored simultaneous I/O particle concentrations for approximately 60 h at a time, as their method of solving for penetration factors and indoor loss rates involved minimizing the sum of absolute differences between modeled and observed indoor number concentrations, which required substantial changes in the measured data to solve accurately. We have taken aspects of each of these previous test methods into consideration in refining a penetration test protocol that could be performed relatively quickly in a larger number of homes.

Methods

Because outdoor particle concentrations can fluctuate over short time scales, we refined the penetration test method from Chao et al. (2003), which consisted of an indoor particle elevation procedure and measurement of the subsequent concentration decay, to incorporate simultaneous measurements of indoor and outdoor particle concentrations. We performed particle penetration tests twice in an unoccupied manufactured test house and once in each of 18 single-family homes in Austin, Texas, USA, from July 2011 to September 2011. The homes were a sample of convenience and remained unoccupied during each test period. Upon arrival to each house, two identical particle monitors (both TSI P-Trak Model 8525) were installed: one indoors in a central location (usually in the kitchen or living room) and one immediately outside of the home (installed either inside the house with a probe inserted through a taped window or outdoors in an area shielded from direct sunlight and precipitation). Both particle instruments logged data simultaneously at 1-min intervals and were located approximately 1 m off the ground. The particle monitors were allowed to operate for at least 10 min before proceeding with the full test procedure to eliminate bias in the early stages of operation (Wallace et al., 2010). These condensation particle counters measure the total number concentration of particles from 20 nm to 1 μm in diameter; thus, our measurements were not size-resolved. Because penetration factors should be dependent on outdoor particle size distributions, this represents one limitation to our study. However, because the majority of outdoor particle number concentrations are typically smaller than 100 nm in diameter, these submicron measurements are generally representative of total ultrafine particle number concentrations (Kearney et al., 2011; Wheeler et al., 2011).

At the same time that particle instrumentation began logging, a CO_2 monitor [TSI Q-Trak Model 8550 (TSI, Minneapolis, MN, USA)] was installed outside of the house for a period of 5–30 min, also logging at 1-min intervals. An Energy Conservatory Model 3 Minneapolis Blower Door fan and frame was then installed in one of the doorways, and a 3–5 point depressurization test was first performed, followed by a pressurization test, both generally in accordance with ASTM E 779 (2010). Immediately following blower door tests, the blower door fan was left operating to pressurize the space and a door or window was opened on an opposite end of the house. This encouraged cross-ventilation, elevated indoor particle concentrations near outdoor levels, and replaced the existing indoor aerosol with particles of outdoor origin, which was necessary because the particle monitors were not size-resolved (so indoor and outdoor aerosols must be from the same distribution to obtain accurate estimates of penetration factors and indoor loss rates).

During the indoor particle elevation period, the central HVAC fan was operated in the fan-only mode (no heating or cooling), mixing fans were installed throughout the house (two box fans were used in far corners of most of the homes), and all accessible ceiling fans were operated to achieve well-mixed conditions. Only one home did not have a central HVAC system. In some homes, the HVAC filter was temporarily removed to encourage greater initial indoor particle elevation. After the initial particle elevation, the blower door fan and frame was removed and all doors and windows were closed. The CO_2 monitor was brought inside to a central location near the indoor particle monitor and CO_2 was injected from a small compressed cylinder ($\sim$20 kg full), which was typically performed in front of a fan in a far region of the house to encourage mixing and avoid local concentration spikes on the central CO_2 monitor. After a few minutes of injection, when noticeable elevations in indoor CO_2 concentrations were observed (twice background or more), CO_2 injection ceased and, if the HVAC filter had been removed, it was re-installed. The house was left unoccupied for a period of 2–4 h to measure the decay of indoor particle concentrations to a background level that was eventually impacted by the infiltration of outdoor particles. Finally, upon re-entry to the house, another outdoor CO_2 measurement was made for several minutes, and the average of the two outdoor CO_2 measurements was used as a constant outdoor value during the decay period.

One of the homes, a new unoccupied model home built and owned by a local construction company (Site 14), had an energy recovery ventilator (ERV) unit installed; thus, it was tested twice: once with the unit operating (representing a singular case of mechanical ventilation) and once without the ERV operating (representing a case of infiltration). Initial blower door tests at Site 14 revealed the house to be particularly air tight, and outdoor particle sources were unlikely to contribute significantly to indoor particle concentrations during the typical 2–4 h test period. Thus, the order of events was switched to first measure I/O particle concentration ratios after an overnight period free of occupants, followed by the elevation and decay procedure. This methodology change is likely necessary in most very tight homes.

Additionally, we performed two penetration tests in an unoccupied manufactured test house ('UTest House') located at a research campus at the University of Texas at Austin using two different methods: (i) our refined particle decay and infiltration method, and (ii) a modified version of the concentration-rebound method from Thatcher et al. (2003), where two large portable HEPA filters were first operated indoors overnight and then were switched off the next morning to allow indoor concentrations to rebound to normal background levels. Subsequently, indoor particle concentrations were elevated by the same procedure of providing outdoor air through open doors and windows, and then, the windows and doors were closed and the indoor particle loss rate was measured. The AER was measured at each stage, and several climatic conditions (i.e., wind speed, wind direction, and indoor and outdoor temperature and relative humidity) were measured using a Davis Vantage Pro 2 (Davis Instruments Group, Hayward, CA, USA) weather station logging at 5-min intervals. The weather station was used to ensure that the two experiments were performed during similar climatic conditions to investigate the repeatability and precision of the two methods.

Finally, to investigate the validity of our assumption of well-mixed environments at the homes, a quality assurance procedure involved measuring AERs in two of the 19 homes (~10% of the homes) in two separate locations: (i) using the CO_2 monitor in the usual central location and (ii) with another CO_2 monitor in a far corner of the home. AERs were estimated separately using data from the two locations, and a comparison was made between the two estimates.

Parameter estimations

Once data were collected at each home, parameter estimates were performed using a statistical software package, Stata Version 11 (StataCorp LP, College Station, TX, USA). In the absence of indoor sources, total indoor particle number concentrations of diameter 20–1000 nm (C_{in}, no. per cm^3) were described with a mass balance on a well-mixed indoor environment, as shown in Equation 1.

$$\frac{\mathrm{d}C_{\mathrm{in}}}{\mathrm{d}t} = P\lambda C_{\mathrm{out}} - (\lambda + k)C_{\mathrm{in}} \tag{1}$$

where t = time (h), P = particle penetration factor (dimensionless), λ = air exchange rate (AER, per h), C_{out} = outdoor particle concentration (no. per cm^3), and k = indoor particle loss rate (per h, because of deposition to surfaces and removal by HVAC systems and filters, if operating). Other potential indoor loss mechanisms (e.g., particle resuspension, evaporation, or coagulation) were assumed to be negligible (e.g., Rim et al., 2010). The first portion of indoor decay data that was not yet affected by outdoor particle sources was first used to estimate the indoor particle decay rate (k, per h) from a nonlinear least squares regression performed with the solution to the particle number balance in Equation 2, shown in Equation 3.

$$\frac{\mathrm{d}C_{\mathrm{in}}}{\mathrm{d}t} = -(\lambda + k)C_{\mathrm{in}} \tag{2}$$

$$C_{\mathrm{in},t} = C_{\mathrm{in},t=0}e^{-(\lambda+k)t} \tag{3}$$

where $C_{\mathrm{in},t}$ is the time-varying indoor particle concentration and $C_{\mathrm{in},t=0}$ is the initial indoor particle concentration at time $t = 0$. Two unknown parameters were estimated in this step: k and $C_{\mathrm{in},t=0}$. This portion of the data was identified graphically by plotting the natural log of measured indoor particle concentrations vs. time and identifying only the initial portion of the data that was log-linear. This usually consisted of the first 10–30 min of data, depending on $C_{\mathrm{in},t=0}$, AER, and installed filtration efficiency. AERs were estimated using a least squares estimation with the analytical solution to the well-mixed mass balance in Equation 4 of the concentration of tracer gas (CO_2) in accordance with ASTM E 741 (2006).

$$\frac{\mathrm{d}C_{\mathrm{g,in}}}{\mathrm{d}t} = \lambda C_{\mathrm{g,out}} - \lambda C_{\mathrm{g,in}} \tag{4}$$

where $C_{\mathrm{g,in}}$ and $C_{\mathrm{g,out}}$ are the indoor and outdoor tracer gas concentrations (ppm CO_2) and λ is the AER (per h). There were no known indoor sources of CO_2 during the actual decay period, and all indoor CO_2 decay data were used from the entire test period (2–4 h). Two unknown parameters were estimated in this step (λ and $C_{\mathrm{g,in},t=0}$), and $C_{\mathrm{g,out}}$ was averaged over the outdoor measurement periods that occurred before and after tests.

Subsequently, estimates of k and λ were used with all of the indoor–outdoor particle concentration data to solve for the penetration factor (P) using a nonlinear least squares estimation on the forward-marching discretized form of Equation 1, shown in Equation 5. This solution approach was also used by Thatcher et al. (2003) and Rim et al. (2010), which is another important deviation from the methodology in Chao et al. (2003).

$$C_{\mathrm{in},t} = C_{\mathrm{in},t-1} + \left(P\lambda C_{\mathrm{out},t-1} - (\lambda + k)C_{\mathrm{in},t-1}\right)\Delta t \tag{5}$$

Uncertainty in P during each experiment was estimated using the relative standard errors of parameter estimates (P, k, and λ) from the nonlinear regressions and the average uncertainty in the two particle monitors, all added in quadrature. Uncertainty between the two particle monitors was taken as 10%, which was the average measured difference between the two particle counters when colocated during three separate colocation periods throughout the testing period. This level of uncertainty is similar to that recently found by Wallace et al. (2010), who reported a mean precision with these instruments of 10%, without any consistent positive or negative bias.

Blower door tests

Blower door air leakage tests were performed at each home with an Energy Conservatory Model 3 Blower Door and DG-700 pressure gauge at a variety of indoor–outdoor pressure differences (usually 3–5 points) to establish a relationship between the flow through the building envelope leaks, Q (m^3/s), and the indoor–outdoor pressure difference, ΔP (Pa), as shown in Equation 6 (ASTM E 1827, 2007).

$$Q = C\Delta P^n \tag{6}$$

where C is a flow coefficient (m^3/s/Pa^n) and n is a pressure exponent (dimensionless). The flow coefficient (C) is directly correlated to the total leakage area in a building envelope. The pressure exponent (n) is limited to values between 0.5 and 1.0 and is often found to be near 0.65 for the typical combined leakage pathways in buildings (ASHRAE, 2005). A pressure exponent of 0.5 describes short leaks with high flow rates and high Reynolds numbers that can be treated as orifice flow with negligible frictional losses and an exponent of 1 corresponds to low flow rates and low Reynolds numbers in long cracks dominated by laminar frictional losses.

Leakage characteristics were also used to calculate the flow at a pressure difference of 50 Pa (Q_{50}, m^3/h), and the relationship in Equation 7 was used to determine an effective leakage area, ELA (m^2, or the area with a discharge coefficient of 1 that would have the same flow at a specified reference pressure).

$$\mathrm{ELA} = C\Delta P_{\mathrm{ref}}^{n-0.5}\sqrt{\frac{\rho}{2}} \tag{7}$$

where P_{ref} = a reference pressure (4 Pa) and ρ = air density (assumed 1.2 kg/m^3). Additionally, blower door data were used to calculate a Normalized Leakage parameter (NL), as shown in Equation 8 (ASHRAE, 2004), and the air changes per hour at an indoor–outdoor pressure difference of 50 Pa (ACH$_{50}$, per h), as shown in Equation 9.

$$\mathrm{NL} = 1000\frac{\mathrm{ELA}}{A_f}\left(\frac{H}{2.3m}\right)^{0.3} \tag{8}$$

$$ACH_{50} = \frac{Q_{50}}{V} \tag{9}$$

where A_f (m^2), H (m), and V (m^3) are the floor area, height, and volume of the building, respectively. Floor areas of the homes were either measured or taken from the Travis Central Appraisal District database of home appraisals (TCAD, 2011), and volumes of the homes were estimated by multiplying floor areas by the average measured ceiling height.

A primary goal of this work is to explore the ability to infer particle penetration from blower door results and building characteristics (e.g., the year of construction); thus, nonparametric statistical tests were performed to assess potential correlations between measured variables. Additionally, Shapiro–Wilk tests were performed to assess whether measured values fit a normal or log-normal distribution; the closest fit to each distribution was determined by visual inspection and by the largest values of the Shapiro–Wilk test statistic, W.

Results

Table 1 provides a summary of the 19 homes tested in this study, including the year of construction, the floor area and volume of each home, and the type and location of HVAC filter(s) that were installed. The types of filters were noted according to ASHRAE

Table 1 Building characteristics from all test homes

Site	Year built	Floor area (m^2)	Volume (m^3)	Filter efficiency[a]	Filter location
UTest House	2008	110	250	No filter installed	
1	1961	72	189	MERV <5	Unit
2	1938	92	235	MERV 8	Grille
3	1984	119	311	MERV 6–8	Unit
4	1920	131	372	MERV 6–8	Unit
5	1950	67	167	MERV 12	Grille
6	1975	171	443	MERV 6–8	Unit
7	1935	24	56	No central A/C	
8	1996	169	412	MERV 8	Unit
9	1955	120	293	MERV >16	Unit
10	1979	103	272	MERV <5	Grille
11	1959	54	129	MERV 7	Unit
12	1996	201	490	MERV 7	Grille
13	1969	177	434	~MERV 11	Unit
14	2011	156	427	MERV 8	Grilles
15	1990	237	721	MERV <5	Grille
16	1926	96	279	MERV <5	Unit
17	1917	78	222	MERV <5	Grille
18[b]	1948	125	312	MERV 6–8	Grille
Mean	1966	122	339		
s.d.	30	53	178		

[a] Approximate European equivalents (Standard EN 779): MERV <5 ~ G1–G2; MERV 6–8 ~ G3–G4; MERV 11–12 ~ F6; MERV >16 ~ >F9 (Tronville and Rivers, 2006).

[b] Site 18 had recently undergone major renovations to its envelope.

Standard 52.2 (ASHRAE, 2007), as determined either by the manufacturer or by visual approximation based on filter media. The age of homes ranged from 1917 to 2011, with a mean year built of 1966. Although the homes were a sample of convenience and do not reflect all single-family homes in the U.S., they may be generally representative of the age of single-family homes in Austin, Texas. A Wilcoxon matched-pairs signed-rank test revealed no significant difference in the distribution of year built from our sample and U.S. census data (US Census Bureau, 2011).

Most central HVAC systems in U.S. residences have supply and/or return ductwork installed in exterior unconditioned spaces (e.g., attics, crawlspaces, or attached garages). Filters are usually installed either at air-handling units or at return grilles. In our sample of 19 homes, 18 homes had central HVAC systems (all but Site 7), and all but one of those homes (Site 14) had supply ductwork installed in exterior spaces. Return ductwork locations were varied, installed indoors in several homes, and in attics, garages, and crawlspaces in others. Seventeen of the 18 homes with central HVAC systems were tested with filters left in place (all but the UTest House). Nine homes had a filter installed at the air-handling unit, immediately upstream of the blower fan. Eight homes had a filter installed in return grille(s), upstream of any return duct system.

Example test result, comparison to other methods, and quality control

Figure 1 provides an example of data from the primary particle penetration test method as performed in one of the test sites (Site 5). Figure 1a provides an example of all of the I/O particle concentration data, which includes an initial decay period, followed by changes in indoor concentrations because of the penetration of outdoor particles. Figure 1b provides a log-linear plot of the initial decay period that was used to solve for k.

Two particle penetration methods were performed in the unoccupied UTest House during times of similar climatic conditions (i.e., similar wind speed, direction, and I/O temperature difference). A modified version of the penetration test method from Thatcher et al. (2003) was performed on July 29, 2011, with the HVAC system operating in the fan-only mode without a filter installed. During the test, the AER was approximately 0.47 ± 0.02/h, and resulting estimates of P and k were 0.33 ± 0.04 and 0.44 ± 0.03/h, respectively. Similarly, our refined penetration method closely resembling that used in Chao et al. (2003) was conducted on August 15, 2011, and estimates of AER, P, and k were 0.48 ± 0.01, 0.34 ± 0.04, and 0.56 ± 0.03/h, respectively. These results suggest that both methods can be used to accurately measure penetration factors with precision and repeatability.

The well-mixed assumption has previously been validated in the unoccupied UTest House (Stephens and Siegel, 2012), but AERs were also measured in two separate locations in Sites 16 and 17. In these cases, one CO_2 monitor was installed in a central location (as per normal) and one monitor was installed in a far corner of the home. The estimated AERs from the two locations differed by approximately 2% at Site 16 and approximately 3% at Site 17, suggesting that the operation of HVAC fans, ceiling fans, and two mixing fans was sufficient to ensure well-mixed conditions in the test homes.

Full experimental results

Penetration tests. Table 2 provides a summary of all of the particle penetration factors (P), indoor loss rates (k), AERs (λ), outdoor source terms ($P \times \lambda$), and mean outdoor particle concentrations (C_{out}) measured at each of the sites in this study (±associated uncertainty or s.d.). Penetration factors of 20–1000 nm particles

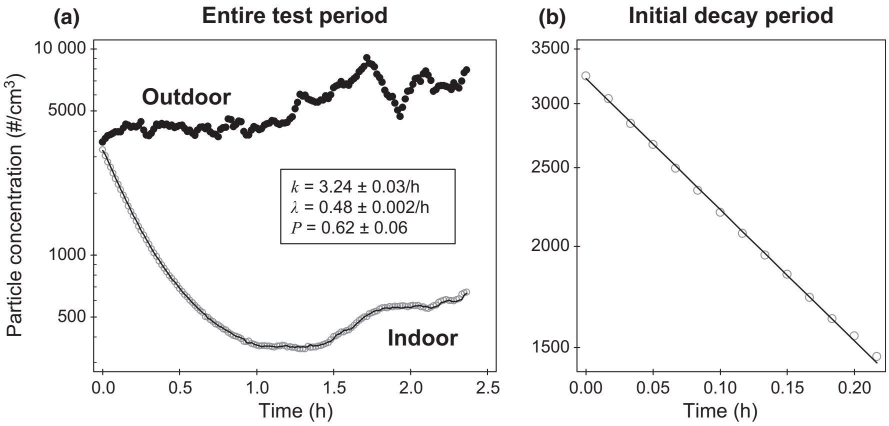

Fig. 1 Example test result from Site 5: (a) utilizing a forward-marching scheme on the entire test period to estimate P (Equation 5), with λ previously estimated from CO_2 decay (Equation 4) and k estimated from the first-order decay (Equation 3) on the first portion of particle data shown in (b). Note that the vertical axis is on a log scale in both plots. Particle concentration represents the total number concentration of 20–1000 nm particles. The correlation coefficient between measured and predicted indoor particle concentrations was >0.99 at this location and was similarly high in all locations

Table 2 Particle (20–1000 nm) penetration test results from all homes in the study

Site	Penetration factor, P	Indoor loss rate, k (per h)	AER, λ (per h)	Outdoor source, $P \times \lambda$ (per h)	Outdoor particle concentration, C_{out} (no. per cm^3)[a]
UTest House[b]	0.34 ± 0.04	0.56 ± 0.03	0.48 ± 0.01	0.16 ± 0.02	13,660 ± 2720
1	0.34 ± 0.04	1.40 ± 0.04	0.37 ± 0.01	0.13 ± 0.01	9730 ± 3800
2	0.65 ± 0.08	0.68 ± 0.02	0.38 ± 0.01	0.24 ± 0.03	4790 ± 2430
3	0.46 ± 0.06	2.19 ± 0.08	0.36 ± 0.01	0.16 ± 0.02	20,950 ± 1370
4	0.72 ± 0.08	1.68 ± 0.05	0.67 ± 0.01	0.48 ± 0.05	5780 ± 1710
5	0.62 ± 0.06	3.24 ± 0.04	0.49 ± 0.01	0.30 ± 0.03	5320 ± 1390
6	0.60 ± 0.08	1.07 ± 0.06	0.23 ± 0.01	0.14 ± 0.02	11,420 ± 4860
7	0.38 ± 0.12	1.03 ± 0.05	0.16 ± 0.01	0.06 ± 0.02	10,200 ± 3470
8	0.57 ± 0.07	1.18 ± 0.03	0.18 ± 0.01	0.10 ± 0.01	4290 ± 1340
9	0.61 ± 0.09	2.50 ± 0.05	0.30 ± 0.01	0.19 ± 0.03	5630 ± 1390
10	0.39 ± 0.06	0.91 ± 0.02	0.18 ± 0.01	0.07 ± 0.01	3520 ± 590
11	0.52 ± 0.06	1.44 ± 0.04	0.56 ± 0.01	0.29 ± 0.03	7020 ± 4040
12	0.51 ± 0.06	0.55 ± 0.02	0.38 ± 0.01	0.19 ± 0.02	5530 ± 5180
13	0.43 ± 0.05	1.21 ± 0.04	0.20 ± 0.01	0.09 ± 0.01	15,390 ± 2370
14a[c]	0.17 ± 0.03	0.55 ± 0.01	0.13 ± 0.01	0.02 ± 0.01	11,260 ± 7490
14b[c]	0.78 ± 0.09	0.61 ± 0.02	0.51 ± 0.01	0.39 ± 0.04	5900 ± 650
15	0.32 ± 0.07	0.31 ± 0.01	0.18 ± 0.01	0.06 ± 0.01	4910 ± 520
16	0.66 ± 0.08	0.66 ± 0.02	0.93 ± 0.01	0.62 ± 0.07	7390 ± 8680
17	0.46 ± 0.05	1.34 ± 0.05	0.95 ± 0.01	0.44 ± 0.05	6300 ± 2800
18	0.26 ± 0.06	0.46 ± 0.01	0.34 ± 0.01	0.09 ± 0.02	6330 ± 2040
Mean[d]	0.47 (AM)	1.01 (GM)	0.33 (GM)	0.15 (GM)	7470 (GM)
s.d.[d]	0.15 (s.d.)	1.85 (GSD)	1.80 (GSD)	2.33 (GSD)	1.6 (GSD)

[a] Mean ± s.d. measured during test.
[b] UTest House measurements are from the refined particle decay test method performed on August 15, 2011.
[c] Site 14 was tested twice: once without an ERV unit with an outdoor air supply operating (14a) and once with the ERV unit operating (14b).
[d] Summary statistics exclude Site 14b (n = 19). Means and standard deviations are arithmetic (AM, s.d.) or geometric (GM, GSD), as noted.
AER, air exchange rates; ERV, energy recovery ventilator.

ranged from 0.17 ± 0.03 in Site 14a to 0.78 ± 0.09 in Site 14b. Site 14b had an ERV unit installed and operating during the test, which supplied outdoor air directly into the return plenum downstream of the filter; thus, its high measured penetration factor was a result of intentional mechanical ventilation. Site 14b is excluded from further analyses because of this unique condition. Site 14a represents a separate test at the same home with the ERV outdoor air supply taped, so that the home relied on infiltration alone during the test period.

The largest value of P in unmodified homes relying on infiltration was 0.72 ± 0.08, measured at Site 4. Overall, the mean (±s.d.) penetration factor (P) in the 19 test homes relying on infiltration was 0.47 ± 0.15 (Shapiro–Wilk $W = 0.97$; $p = 0.85$), and the geometric mean indoor loss rate measured with mixing fans and HVAC fans operating with existing filters installed (k) was 1.01/h (GSD = 1.85; Shapiro–Wilk $W = 0.98$; $p = 0.97$). As previously mentioned, these measured values for P and k are not size resolved, so they represent values weighted by the outdoor particle size distributions, which were not measured in this study. The geometric mean AER during the test period was 0.33/h (GSD = 1.80; Shapiro–Wilk $W = 0.96$; $p = 0.53$).

Blower door tests. Table 3 shows results from blower door depressurization tests that were performed at each site. Pressurization tests were also performed but the data are not shown here, as they are generally less accurate for characterizing envelope leakage alone because they account for intentional leakage pathways that are normally closed, such as dryer vents and kitchen exhausts (ASTM E 1827, 2007; Sherman, 1995).

A wide spread in leakage parameters was observed, with a geometric mean leakage coefficient (C) of 0.074 m^3/s/Pa^n (GSD = 2.056; Shapiro–Wilk $W = 0.98$; $p = 0.92$), ranging from 0.021 to 0.373 m^3/s/Pa^n. Similarly, values of NL, ranged from 0.17 to 3.60, with a geometric mean of 0.68 (GSD = 2.17; Shapiro–Wilk $W = 0.98$; $p = 0.91$). The distribution of leakage parameters in these homes was relatively similar to the distribution in single-family homes across the U.S. (GM of NL = 0.54; GSD = 2.0 in Chan et al., 2005). Blower door tests were performed without supply registers and return grille(s) closed or taped, so measured leakage parameters account for both envelope and duct leaks, if present.

Factors influencing particle penetration

To investigate our hypothesis that particle penetration is associated with building characteristics, including results from blower door tests, we performed Spearman's rank correlations between several measured parameters, including particle penetration factors (P), AER, outdoor particle source terms ($P \times$ AER),

Table 3 Blower door test results from depressurization tests in all 19 homes

Site	C (m^3/s/Pa^n throu)	n	ELA (cm^2)	NL	ACH_{50} (per h)
UTest House	0.052	0.61	476	0.43	8.3
1	0.056	0.62	508	0.71	11.8
2	0.129	0.62	1176	1.32	22.0
3	0.058	0.70	587	0.49	10.2
4	0.172	0.76	1914	1.46	32.4
5	0.072	0.64	681	1.02	19.0
6	0.091	0.64	864	0.50	9.2
7	0.015	0.74	162	0.68	17.5
8	0.028	0.73	301	0.18	4.3
9	0.072	0.74	779	0.67	16.1
10	0.045	0.68	448	0.30	5.5
11	0.087	0.56	734	1.41	21.5
12	0.070	0.68	694	0.44	7.3
13	0.081	0.68	813	0.49	9.8
14a[a]	0.039	0.72	411	0.27	5.6
14b[a]	0.045	0.68	448	0.30	5.5
15	0.056	0.68	556	0.26	4.0
16	0.373	0.61	3372	3.60	52.3
17	0.167	0.58	1458	1.92	26.7
18	0.148	0.66	1429	1.17	22.3
Mean[b]	0.074 (GM)	0.67 (AM)	723 (GM)	0.68 (GM)	12.7 (GM)
s.d.[b]	2.056 (GSD)	0.06 (s.d.)	2 (GSD)	2.17 (GSD)	2.0 (GSD)

[a] Site 14 was tested twice: once with an energy recovery ventilator (ERV) unit with a dedicated outdoor air supply taped shut (14a) and once with the ERV unit left open (14b).

[b] Summary statistics exclude Site 14b (n = 19). Means and standard deviations are arithmetic (AM, s.d.) or geometric (GM, GSD), as noted.

ELA, effective leakage area; NL, normalized leakage.

indoor particle loss rates (k), and several potentially influential parameters, including blower door results (C, ELA, ACH_{50}, NL, and n) and building characteristics (floor area, volume, and year built). Results are shown in Table 4.

Two sites were excluded from this analysis: Site 14b did not rely on infiltration as previously mentioned, and Site 18 had undergone major renovations to its envelope; thus, its blower door results were large but measured values of P and AER were low, suggesting that the nature of leakage paths had been affected by renovations. Because some of these variables are independent of each other, but others are not (e.g., ELA, ACH_{50}, and NL are functions of C and n, volume is a function of floor area, and $P \times$ AER is a function of P), we used a p-value of < 0.01 to identify significant relationships and minimize false positives. As a more conservative measure, we used a p-value of < 0.001 to identify the strongest relationships in Table 4 (0.05 divided by 21 = 0.002, where 21 is the number of comparisons between seven truly independent variables (P, AER, k, C, n, floor area, and year built). Additionally, Spearman's rank correlation coefficients in Table 4 that are greater than approximately 0.50 may also be indicative of a marginally significant relationship ($p < 0.05$).

Particle penetration factors (P) and outdoor source terms ($P \times$ AER) were significantly and positively correlated with several factors, with the strongest relationships occurring with leakage coefficients (C) from blower door tests (Spearman's $\rho = +0.71$ between P and C; $p < 0.001$; Spearman's $\rho = +0.82$ between $P \times$ AER and C; $p < 0.001$). Both P and $P \times$ AER were also significantly correlated with other blower door parameters, including ELA, ACH_{50}, and NL. Additionally, $P \times \lambda$ was significantly and negatively correlated with the year of construction of the homes (Spearman's $\rho = -0.63$ between $P \times$ AER and year built; $p < 0.01$), primarily because older homes were also leakier (Spearman's $\rho = -0.65$ between year built and C; $p < 0.01$). P was marginally correlated with both year built and AER (Spearman's $\rho = -0.58$ between P and year built; $p < 0.05$; Spearman's $\rho = +0.56$ between P and AER; $p < 0.05$). AER was also higher in leakier buildings (Spearman's $\rho = +0.77$ between AER and NL; $p < 0.001$). Overall, these findings are generally intuitive: 20–1000 nm particles penetrated more efficiently through leakier (and to a lesser extent, older) building envelopes.

One important phenomenon that has been previously observed is that as outdoor total particle number

Table 4 Spearman's rank correlations between particle penetration factors (P), outdoor particle source terms ($P \times$ AER), indoor particle loss rates (k), blower door results (C, ELA, ACH_{50}, NL, and n), and building characteristics (floor area, volume, and year built)[a]

	P	AER	$P \times$ AER	k	C	ELA	ACH_{50}	NL	n	Floor area	Volume
AER	0.56										
$P \times$ AER	**0.78***	**0.95***									
k	0.44	0.33	0.42								
C	**0.71***	**0.77***	**0.82***	0.28							
ELA	**0.70**	**0.72***	**0.78***	0.23	**0.99***						
ACH_{50}	**0.63**	**0.74***	**0.79***	0.47	**0.74***	**0.69**					
NL	**0.60**	**0.77***	**0.79***	0.45	**0.77***	**0.72***	**0.98***				
n	−0.01	−0.59	−0.40	0.11	−0.40	−0.33	−0.29	−0.40			
Floor area	−0.11	−0.36	−0.32	−0.39	−0.06	0.04	**−0.62**	**−0.62**	0.39		
Volume	−0.07	−0.35	−0.30	−0.41	0.00	0.09	−0.57	−0.57	0.38	**0.99***	
Year built	−0.58	−0.56	**−0.63**	−0.47	**−0.65**	**−0.62**	**−0.90***	**−0.90***	0.15	0.57	0.53

[a] Excludes Site 14b and Site 18 (N = 18). Bold values represent significant relationships at $p < 0.01$.

*Significant at $p < 0.001$.

AER, air exchange rates; ELA, effective leakage area; NL, normalized leakage.

concentrations increase, particle count median diameters typically decrease (e.g., Zhang and Zhu, 2012), which suggests that large increases in outdoor particle concentrations are primarily because of increases in smaller particles. Because smaller outdoor particles may be less likely to penetrate through envelopes (e.g., Liu and Nazaroff, 2001; Rim et al., 2010), we also explored the data for correlations between measured values of P and the average total outdoor particle number concentration at each site (C_{out}). There was a small negative correlation between P and mean outdoor particle concentrations (Spearman's $\rho = -0.30$; $p = 0.23$), suggesting that P may have also varied with changes in outdoor concentrations (and thus outdoor particle size distributions), although the relationship was not statistically significant. However, because particle distributions were not measured in this study, this phenomenon should be explored with size-resolved measurements and a larger sample in future work.

Although significant correlations between particle penetration and building factors were found, we were also interested in the predictive ability of blower door tests to infer particle penetration factors. Figure 2 shows measured penetration factors (P) plotted vs. leakage coefficients (C), which was the strongest relationship observed in Table 4. We observed an approximate power–law relationship with C, and Figure 2 also shows results from a nonlinear least squares estimation that was used to fit the data to an empirical relationship.

While there was a significant and positive empirical relationship between P and building air leakage characteristics, the results are largely influenced by extreme values and the ability of blower door tests to accurately predict values of P appears low (with an R^2 of only 0.35). Given the relationship in this subset of homes, if a single-family detached home had a leakage coefficient of, for example, 0.3 $\mathrm{m^3/s/Pa}^n$, our best estimate of the penetration factor for 20–1000 nm particles would be 0.67 ± 0.22. Similarly, our best estimate of P at a tighter home (e.g., $C = 0.05\ \mathrm{m^3/s/Pa}^n$) would be 0.44 ± 0.23. The central estimates of P would be different, but the difference would not be significant, as their confidence intervals would overlap.

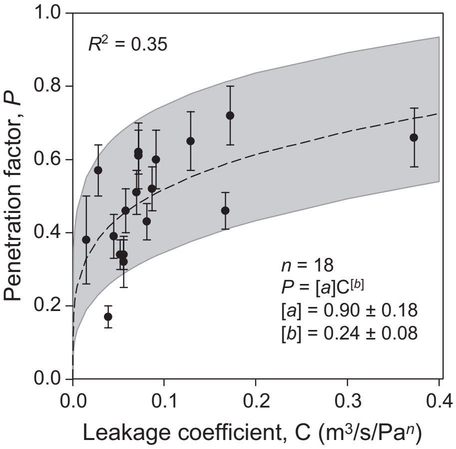

Fig. 2 Particle penetration factor (P) vs. leakage coefficient from blower door air leakage tests (C). The dashed line represents the best estimates of a coefficient and exponent from a power–law relationship. The shaded area represents one standard error from the power–law relationship in both directions. Data from Sites 14b and 18 are again excluded from this analysis ($n = 18$)

However, outdoor particle penetration into buildings is also a function of AER, which is similarly associated with results from blower door air leakage tests and the year of construction (Table 4). Thus, to investigate the predictive ability of blower door test results and building characteristics to infer outdoor particle source terms ($P \times \mathrm{AER}$), Figure 3 plots particle source terms vs. three blower door parameters (ELA, NL, and ACH_{50}) of 18 unmodified homes relying on infiltration (again excluding Sites 14b and 18).

Strong linear relationships with outdoor particle source terms ($P \times \mathrm{AER}$) were observed with all three leakage parameters from blower door tests (with values of R^2 ranging from 0.78 for ELA to 0.85 for ACH_{50}), which suggests that blower door tests may be used to predict outdoor submicron particle source terms in single-family homes with relatively low uncertainty. However, large values of blower door leakage parameters are particularly important in these relationships, as the data from tighter homes (e.g., $P \times \mathrm{AER} < 0.2$ and $\mathrm{NL} < 1$) tend to be grouped, often without a significant relationship observed (e.g., Spearman's $\rho = +0.33$ between $P \times \mathrm{AER}$ and NL if $\mathrm{NL} < 1$; $p = 0.30$).

Overall, the observed relationships between particle penetration and blower door tests are particularly important for exposure implications given the amount of existing knowledge on envelope leakage in buildings across the U.S. For example, Chan et al. (2005) estimated the nationwide distribution of NL values from blower door tests in single-family homes in the U.S. Table 5 shows the approximate distribution of NL in both low-income and all homes in the U.S. for five ranges of NL (<0.5, 0.5–1, 1–2, 2–3, and 3–4) and also lists mean (±s.d.) values of P, AER, and $P \times \mathrm{AER}$ measured in our sample of 18 single-family homes relying on infiltration, split by the same ranges of NL (again excluding Sites 14b and 18).

The values in Table 5 show that mean values of both P and $P \times \mathrm{AER}$ from this study increased with each increasing bin of NL. Chan et al. (2005) estimated that approximately 50% of all homes in the U.S. have a NL value <0.5, and mean (±s.d.) values of P and $P \times \mathrm{AER}$ from the eight homes of our sample in that range were 0.40 ± 0.12 and 0.11 ± 0.06/h, respectively. The leakiest approximately 20% of all homes in the U.S. have an estimated $\mathrm{NL} > 1$, and we measured

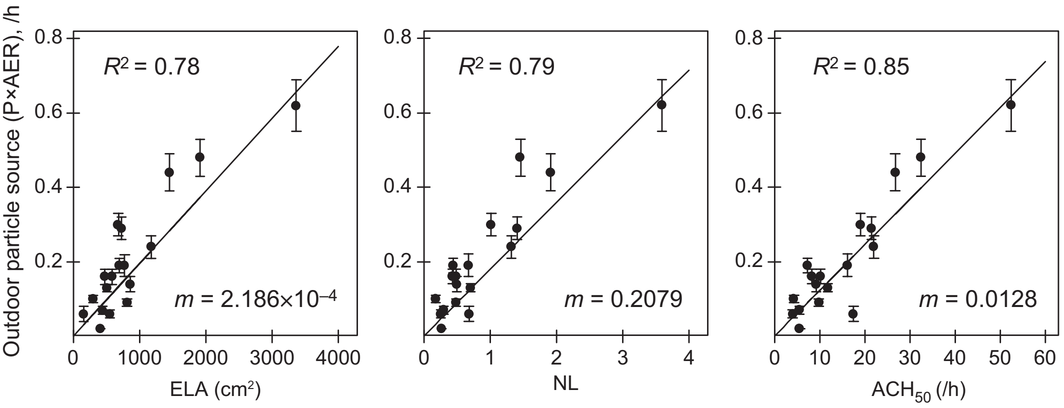

Fig. 3 Linear regressions of outdoor particle source terms ($P \times \mathrm{AER}$) vs. three blower door air leakage parameters. Note that 'm' = the regression slope. This analysis excludes data from Site 14b and Site 18 ($N = 18$). AER, air exchange rates

Table 5 Summary of measured values of P and $P \times$ AER from this study ($n = 18$), split by normalized leakage values (NL), with a comparison to the estimated distribution of NL values across the U.S. building stock

	Estimated percentage of homes in the U.S.[a]		Measured values from this study[b]			
NL	All homes combined (%)	Low-income homes (%)	n	P Mean (s.d.)	AER, per h Mean (s.d.)	$P \times$ AER, per h Mean (s.d.)
<0.5	~50	~20	8	0.40 (0.12)	0.26 (0.13)	0.11 (0.06)
0.5–1	~30	~30	4	0.48 (0.14)	0.27 (0.09)	0.13 (0.05)
1–2	>15	~35	5	0.59 (0.10)	0.61 (0.22)	0.35 (0.10)
2–3	<5	>10	0	n/a	n/a	n/a
3–4	<1	<5	1	0.66 (n/a)	0.93 (n/a)	0.62 (n/a)

[a] Estimated from Chan et al. (2005).
[b] Excludes Sites 14b and 18.
AER, air exchange rates.

mean (± s.d.) values of P and $P \times \mathrm{AER}$ of 0.60 ± 0.10 and 0.40 ± 0.14/h, respectively, in our sample of six homes with NL > 1. Conversely, approximately 50% of all low-income homes in the U.S. have an NL > 1 and, according to our data, likely have proportionately higher values of particle penetration factors and outdoor particle source terms. These data suggest that, if all else remains equal, a greater fraction of low-income home occupants are likely exposed to higher indoor levels of outdoor submicron particles than other populations, which might explain some of the additional susceptibility to particulate matter that has been shown for low-income demographics (e.g., Finkelstein et al., 2003; Sacks et al., 2010; Wilson et al., 2007).

Finally, we explored the relationship between measured particle penetration factors and source terms and the year of construction of the homes in this sample. Figure 4 shows measured values of P and $P \times \mathrm{AER}$ from the 18 unmodified sites relying on infiltration (again excluding Sites 14b and 18), plotted against the year in which each home was built. Linear regressions were performed and results from parameter estimations are shown in the figures.

Significant decreasing trends in both P and $P \times \mathrm{AER}$ with year built were observed. The year of construction

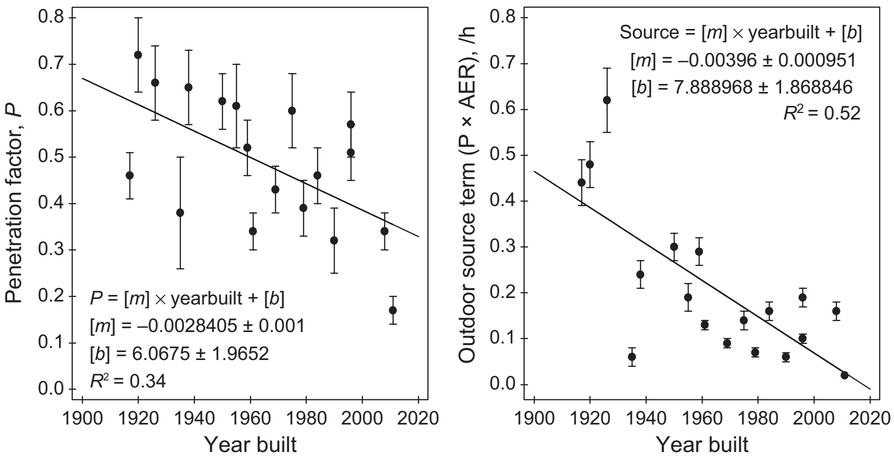

Fig. 4 Particle penetration factors (P) and outdoor source terms ($P \times \mathrm{AER}$) vs. year of construction of 18 of the homes in our sample. Sites 14b and 18 are both excluded from this figure. Regression results include the slope and intercept, standard errors of both parameters, and R^2 values. AER, air exchange rates

appears to be a better predictor of outdoor source terms than particle penetration factors alone ($R^2 = 0.52$ vs. 0.34). Regression results suggest that, as an example, if a single-family home was built in 2000, it likely has values of $P = 0.39 \pm 0.18$ and $P \times \text{AER} = 0.07 \pm 0.02$/h. Similarly, a home built in 1950 would likely have values of $P = 0.53 \pm 0.25$ and $P \times \text{AER} = 0.27 \pm 0.09$/h. Confidence intervals overlap for estimates of P, but predicted outdoor particle source terms would be significantly different. These data suggest that better estimates of population exposure to submicron particulate matter in single-family homes could possibly be made with only simple details on home construction. Additional size-resolved measurements in a larger number of homes would allow for a more refined analysis.

Discussion

The range of measured penetration factors for 20–1000 nm particles herein (0.17 ± 0.03–0.72 ± 0.08 in 19 homes relying on infiltration) is relatively large compared with most other studies of particle penetration in the same size range (Chao et al., 2003; Rim et al., 2010; Thatcher et al., 2003), although most studies have typically been limited in their number of test homes. However, one larger study, Williams et al. (2003) estimated a similarly wide range of penetration factors for $PM_{2.5}$ in 37 residences from a similar distribution of home ages, as P ranged from 0.11 to 1.0. Their mean value of 0.72 was considerably higher than that measured in this study, although the type of particle measurements also differed.

One of the major limitations in this study is the use of particle equipment that was not size resolved. However, we do have some confidence from previous studies that particle penetration factors may not vary widely across the 20 nm–1 μm particle sizes that were measured herein (Chen and Zhao, 2011; Rim et al., 2010). Measurements with our instrumentation are generally considered representative of ultrafine particles (e.g., Bhangar et al., 2011; Kearney et al., 2011; Wheeler et al., 2011), but we recommend that similar measurements be made in a sample of buildings using size-resolved instrumentation to more fundamentally investigate particle penetration and relationships with blower door test results.

Because the HVAC systems were operating in all but one home during our tests, measured values of P account for particle penetration both across building envelopes and through any return duct leaks that might exist. Ductwork is typically installed in unconditioned spaces in the U.S., and unintentional duct leaks can increase air infiltration rates (Persily et al., 2010). Duct leakage is common in single-family homes in Austin, TX (Rhodes et al., 2011), but we did not perform duct leakage measurements and have no knowledge of particle concentrations in areas where return ducts were located in this study (often in attics, garages, or crawlspaces). However, in a previous study of a different sample of residential and light-commercial buildings in Austin (Stephens et al., 2011), we measured a mean return duct leakage fraction of only 4% (ranging from 0 to 17%). The homes in this study were from the same general building stock, although only one home was included in both studies. Additionally, in this sample, only eight homes had filters installed in return grille(s) upstream of return ductwork, where return duct penetration could be most meaningful. The other homes either had no return ductwork installed outside conditioned space or had filters installed downstream of potential return duct leaks. Therefore, we have some confidence that return duct leaks likely contributed only a small or negligible amount to overall particle penetration in most homes in this sample.

Conversely, measured values of k account for losses because of the combined effects of deposition to indoor surfaces, removal by HVAC filters, deposition to HVAC ductwork, and loss by exfiltration through supply duct leaks, although experiments were not performed to establish relative contributions to particle removal. In general, particle loss rates increased with increasing rated filter efficiency, as mean (±s.d.) values of k measured in the 19 homes were 0.92 ± 0.46, 1.09 ± 0.60, and 2.32 ± 1.03/h with MERV < 5 ($n = 5$), MERV 6-8 ($n = 9$), and MERV 11+ ($n = 3$) filters installed in the operating HVAC systems, respectively. These values in well-mixed environments are likely higher than what would have been measured without the use of mixing fans and ceiling fans (Thatcher, 2002), but because the simultaneous operation of ceiling fans and HVAC systems is not an unlikely condition, particularly in the warm climate of Austin, these values may be considered generally representative of some actual operation periods. Thus, distributions of P, $P \times \text{AER}$, and k from Table 2 may actually be appropriate for improving exposure estimates in single-family homes in Austin during some typical operating periods.

The refined penetration test method used herein combined aspects of previous test methods to reduce the test duration without sacrificing accuracy, which is important if an experimental method is going to be used widely in actual field settings. With this method, we were able to very quickly perform experiments in a relatively large number of homes with a relatively low level of invasiveness. These measurements and relationships with building characteristics are important for population exposures, as over 70% of residential buildings in the U.S. are single-family dwellings (DOE, 2009). Similar measurements should also be repeated in other areas and other types of buildings to get better estimates of the distribution of particle penetration factors (P) and outdoor source terms ($P \times \text{AER}$) in more types of buildings, which could ultimately allow epidemiological studies to adopt more specific population exposures from regional or local ambient data. Additionally, the methods herein may be used to assess changes in the ability of a building to protect indoor environments from outdoor particulate matter after undergoing weatherization retrofit measures, as data from one site herein suggests (Site 18, which had undergone major envelope renovations had relatively small measured values of P and $P \times \mathrm{AER}$ even though it was nominally an older home).

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References

Abt, E., Suh, H.H., Catalano, P. and Koutrakis, P. (2000) Relative contribution of outdoor and indoor particle sources to indoor concentrations, *Environ. Sci. Technol.*, **34**, 3579–3587.

Allen, R., Wallace, L., Larson, T., Sheppard, L. and Liu, L.J.S. (2004) Estimated hourly personal exposures to ambient and nonambient particulate matter among sensitive populations in Seattle Washington, *J. Air Waste Manag. Assoc.*, **54**, 1197–1211.

ASHRAE (2004) ASHRAE Standard 119. Air leakage performance for detached single-family residential buildings.

ASHRAE (2005) *ASHRAE Handbook of Fundamentals: Chapter 27*, Atlanta, GA, USA, ASHRAE.

ASHRAE (2007) *Standard 52.2: Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size*, Atlanta, GA, USA, American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASTM E 1827 (2007) *Standard Test Methods for Determining Airtightness of Buildings Using an Orifice Blower Door*, West Conshohocken, PA, USA, ASTM.

ASTM E 741 (2006) *Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution*, West Conshohocken, PA, USA, ASTM.

ASTM E 779 (2010) *Standard Test Method for Determining Air Leakage Rate by Fan Pressurization*, West Conshohocken, PA, USA, ASTM.

Bennett, D. and Koutrakis, P. (2006) Determining the infiltration of outdoor particles in the indoor environment using a dynamic model, *J. Aerosol Sci.*, **37**, 766–785.

Bhangar, S., Mullen, N.A., Hering, S.V., Kreisberg, N.M. and Nazaroff, W.W. (2011) Ultrafine particle concentrations and exposures in seven residences in northern California, *Indoor Air*, **21**, 132–144.

Brook, R.D., Rajagopalan, S., Pope, C.A., Brook, J.R., Bhatnagar, A., Diez-Roux, A.V., Holguin, F., Hong, Y., Luepker, R.V., Mittleman, M.A., Peters, A., Siscovick, D., Smith, S.C., Whitsel, L. and Kaufman, J.D. (2010) Particulate matter air pollution and cardiovascular disease, *Circulation*, **121**, 2331–2378.

Chan, W., Nazaroff, W., Price, P., Sohn, M. and Gadgil, A. (2005) Analyzing a database of residential air leakage in the United States, *Atmos. Environ.*, **39**, 3445–3455.

Chao, C.Y.H., Wan, M.P. and Cheng, E.C.K. (2003) Penetration coefficient and deposition rate as a function of particle size in non-smoking naturally ventilated residences, *Atmos. Environ.*, **37**, 4233–4241.

Chen, C. and Zhao, B. (2011) Review of relationship between indoor and outdoor particles: I/O ratio, infiltration factor and penetration factor, *Atmos. Environ.*, **45**, 275–288.

Cohen, M.A., Adar, S.D., Allen, R.W., Avol, E., Curl, C.L., Gould, T., Hardie, D., Ho, A., Kinney, P., Larson, T.V., Sampson, P., Sheppard, L., Stukovsky, K.D., Swan, S.S., Liu, L.-J.S. and Kaufman, J.D. (2009) Approach to estimating participant pollutant exposures in the multi-ethnic study of atherosclerosis and air pollution (MESA Air), *Environ. Sci. Technol.*, **43**, 4687–4693.

DOE (2009) Buildings energy data book [WWW Document]. *Table 2.2.2: Share of Households, by Housing Type and Type of Ownership, as of 2005*. Available at: http://buildingsdatabook.eren.doe.gov/TableView.aspx?table = 2.2.2 (accessed 08 September 2010).

Ebelt, S.T., Wilson, W.E. and Brauer, M. (2005) Exposure to ambient and nonambient components of particulate matter: a comparison of health effects, *Epidemiology*, **16**, 396–405.

Finkelstein, M.M., Jerrett, M., DeLuca, P., Finkelstein, N., Verma, D.K., Chapman, K. and Sears, M.R. (2003) Relation between income, air pollution and mortality: a cohort study, *Can. Med. Assoc. J.*, **169**, 397–402.

Fogh, C., Byrne, M., Roed, J. and Goddard, A. (1997) Size specific indoor aerosol deposition measurements and derived I/O concentrations ratios, *Atmos. Environ.*, **31**, 2193–2203.

Hering, S.V., Lunden, M.M., Thatcher, T.L., Kirchstetter, T.W. and Brown, N.J. (2007) Using regional data and building leakage to assess indoor concentrations of particles of outdoor origin. Aerosol Sci. Technol, *Aerosol Sci. Technol.*, **41**, 639–654.

Isakov, V., Touma, J.S., Burke, J., Lobdell, D.T., Palma, T., Rosenbaum, A. and Ozkaynak, H. (2009) Combining regional- and local-scale air quality models with exposure models for use in environmental health studies, *J. Air Waste Manag. Assoc.*, **59**, 461–472.

Kearney, J., Wallace, L., MacNeill, M., Xu, X., VanRyswyk, K., You, H., Kulka, R. and Wheeler, A.J. (2011) Residential indoor and outdoor ultrafine particles in Windsor Ontario, *Atmos. Environ.*, **45**, 7583–7593.

Klepeis, N.E., Nelson, W.C., Ott, W.R., Robinson, J.P., Tsang, A.M., Switzer, P., Behar, J.V., Hern, S.C. and Engelmann, W.H. (2001) The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants, *J. Expo. Anal. Environ. Epidemiol.*, **11**, 231–252.

von Klot, S., Wölke, G., Tuch, T., Heinrich, J., Dockery, D.W., Schwartz, J., Kreyling, W.G., Wichmann, H.E. and Peters, A. (2002) Increased asthma medication use in association with ambient fine and ultrafine particles, *Eur. Respir. J.*, **20**, 691–702.

Koenig, J.Q., Mar, T.F., Allen, R.W., Jansen, K., Lumley, T., Sullivan, J.H., Trenga, C.A., Larson, T.V. and Liu, L.J.S. (2005) Pulmonary effects of indoor- and outdoor-generated particles in children with asthma, *Environ. Health Perspect.*, **113**, 499–503.

Liu, D. and Nazaroff, W.W. (2001) Modeling pollutant penetration across building envelopes, *Atmos. Environ.*, **35**, 4451–4462.

Liu, D.-L. and Nazaroff, W.W. (2003) Particle penetration through building cracks, *Aerosol Sci. Technol.*, **37**, 565–573.

Long, C.M., Suh, H.H., Catalano, P.J. and Koutrakis, P. (2001) Using time- and size-resolved particulate data to quantify indoor penetration and deposition behavior, *Environ. Sci. Technol.*, **35**, 2089–2099.

Lunden, M.M., Thatcher, T.L., Hering, S.V. and Brown, N.J. (2003) Use of time- and chemically resolved particulate data to characterize the infiltration of outdoor PM2.5 into a residence in the San Joaquin Valley, *Environ. Sci. Technol.*, **37**, 4724–4732.

McAuley, T.R., Fisher, R., Zhou, X., Jaques, P.A. and Ferro, A.R. (2010) Relationships of outdoor and indoor ultrafine particles at residences downwind of a major international border crossing in Buffalo, NY, *Indoor Air*, **20**, 298–308.

Meng, Q.Y., Turpin, B.J., Korn, L., Weisel, C.P., Morandi, M., Colome, S., Zhang, J.J., Stock, T., Spektor, D., Winer, A., Zhang, L., Lee, J.H., Giovanetti, R., Cui, W., Kwon, J., Alimokhtari, S., Shendell, D., Jones, J., Farrar, C. and Maberti, S. (2005) Influence of ambient (outdoor) sources on residential indoor and personal PM2.5 concentrations: analyses of RIOPA data, *J. Expo. Anal. Environ. Epidemiol.*, **15**, 17–28.

Meng, Q.Y., Spector, D., Colome, S. and Turpin, B. (2009) Determinants of indoor and personal exposure to PM2.5 of indoor and outdoor origin during the RIOPA study, *Atmos. Environ.*, **43**, 5750–5758.

Miller, K.A., Siscovick, D.S., Sheppard, L., Shepherd, K., Sullivan, J.H., Anderson, G.L. and Kaufman, J.D. (2007) Long-term exposure to air pollution and incidence of cardiovascular events in women, *N. Engl. J. Med.*, **356**, 447–458.

Mosley, R.B., Greenwell, D.J., Sparks, L.E., Guo, Z., Tucker, W.G., Fortmann, R. and Whitfield, C. (2001) Penetration of ambient fine particles into the indoor environment, *Aerosol Sci. Technol.*, **34**, 127–136.

Penttinen, P., Timonen, K.L., Tiittanen, P., Mirme, A., Ruuskanen, J. and Pekkanen, J. (2001) Ultrafine particles in urban air and respiratory health among adult asthmatics, *Eur. Respir. J.*, **17**, 428–435.

Persily, A., Musser, A. and Emmerich, S.J. (2010) Modeled infiltration rate distributions for U.S. housing, *Indoor Air*, **20**, 473–485.

Pope, C.A. and Dockery, D.W. (2006) Health effects of fine particulate air pollution: lines that connect, *J. Air Waste Manag. Assoc.*, **56**, 709–742.

Pope, C.A., Burnett, R.T., Thun, M.J., Calle, E.E., Krewski, D., Ito, K. and Thurston, G.D. (2002) Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution, *JAMA*, **287**, 1132–1141.

Rhodes, J.D., Stephens, B. and Webber, M.E. (2011) Using energy audits to investigate the impacts of common air-conditioning design and installation issues on peak power demand and energy consumption in Austin, Texas, *Energ. Buildings*, **43**, 3271–3278.

Rim, D., Wallace, L. and Persily, A. (2010) Infiltration of outdoor ultrafine particles into a test house, *Environ. Sci. Technol.*, **44**, 5908–5913.

Sacks, J.D., Stanek, L.W., Luben, T.J., Johns, D.O., Buckley, B.J., Brown, J.S. and Ross, M. (2010) Particulate matter–induced health effects: who is susceptible? *Environ. Health Perspect.*, **119**, 446–454.

Sherman, M. (1995) The use of blower-door data, *Indoor Air*, **5**, 215–224.

Sioutas, C., Delfino, R.J. and Singh, M. (2005) Exposure assessment for atmospheric ultrafine particles (UFPs) and implications in epidemiologic research, *Environ. Health Perspect.*, **113**, 947–955.

Stephens, B. and Siegel, J.A. (2012) Comparison of test methods for determining the particle removal efficiency of filters in residential and light-commercial central HVAC systems, *Aerosol Sci. Technol.*, **46**, 504–513.

Stephens, B., Siegel, J.A. and Novoselac, A. (2011) Operational characteristics of residential and light-commercial air-conditioning systems in a hot and humid climate zone, *Build. Environ.*, **46**, 1972–1983.

Stölzel, M., Breitner, S., Cyrys, J., Pitz, M., Wölke, G., Kreyling, W., Heinrich, J., Wichmann, H.-E. and Peters, A. (2007) Daily mortality and particulate matter in different size classes in Erfurt, Germany, *J. Expos. Sci. Environ. Epidemiol.*, **17**, 458–467.

TCAD (2011) Travis central appraisal district [WWW Document]. *Travis Central Appraisal District*. Available at: http://www.traviscad.org/property_search.html (accessed 20 July 2011).

Thatcher, T. (2002) Effects of room furnishings and air speed on particle deposition rates indoors, *Atmos. Environ.*, **36**, 1811–1819.

Thatcher, T.L. and Layton, D.W. (1995) Deposition, resuspension, and penetration of particles within a residence, *Atmos. Environ.*, **29**, 1487–1497.

Thatcher, T.L., Lunden, M.M., Revzan, K.L., Sextro, R.G. and Brown, N.J. (2003) A concentration rebound method for measuring particle penetration and deposition in the indoor environment, *Aerosol Sci. Technol.*, **37**, 847–864.

Thornburg, J., Ensor, D.S., Rodes, C.E., Lawless, P.A., Sparks, L.E. and Mosley, R.B. (2001) Penetration of particles into buildings and associated physical factors. Part I: model development and computer simulations, *Aerosol Sci. Technol.*, **34**, 284–296.

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

US Census Bureau (2011) *American FactFinder: Selected Housing Characteristics from 2010*, Travis County, TX, American Community Survey [WWW Document]. Available at: http://factfinder2.census.gov/faces/nav/jsf/pages/index.xhtml (accessed 17 November 2011).

Vette, A., Rea, A., Lawless, P., Rodes, C., Evans, G., Highsmith, V.R. and Sheldon, L. (2001) Characterization of indoor-outdoor aerosol concentration relationships during the Fresno PM exposure studies, *Aerosol Sci. Technol.*, **34**, 118–126.

Wallace, L.A., Wheeler, A.J., Kearney, J., Van Ryswyk, K., You, H., Kulka, R.H., Rasmussen, P.E., Brook, J.R. and Xu, X. (2010) Validation of continuous particle monitors for personal, indoor, and outdoor exposures, *J. Expos. Sci. Environ. Epidemiol.*, **21**, 49–64.

Weichenthal, S., Dufresne, A. and Infante-Rivard, C. (2007) Indoor ultrafine particles and childhood asthma: exploring a potential public health concern, *Indoor Air*, **17**, 81–91.

Wheeler, A.J., Wallace, L.A., Kearney, J., Van Ryswyk, K., You, H., Kulka, R., Brook, J.R. and Xu, X. (2011) Personal, indoor, and outdoor concentrations of fine and ultrafine particles using continuous monitors in multiple residences, *Aerosol Sci. Technol.*, **45**, 1078–1089.

Williams, R., Suggs, J., Rea, A., Sheldon, L., Rodes, C. and Thornburg, J. (2003) The Research Triangle Park particulate matter panel study: modeling ambient source contribution to personal and residential PM mass concentrations, *Atmos. Environ.*, **37**, 5365–5378.

Wilson, W.E., Mar, T.F. and Koenig, J.Q. (2007) Influence of exposure error and effect modification by socioeconomic status on the association of acute cardiovascular mortality with particulate matter in Phoenix, *J. Expo. Sci. Environ. Epidemiol.*, **17**, S11–S19.

Wu, J., Lurmann, F., Winer, A., Lu, R., Turco, R. and Funk, T. (2005) Development of an individual exposure model for application to the Southern California children's health study, *Atmos. Environ.*, **39**, 259–273.

Zhang, Q. and Zhu, Y. (2012) Characterizing ultrafine particles and other air pollutants at five schools in South Texas, *Indoor Air*, **22**, 33–42.

Zhu, Y., Hinds, W., Krudysz, M., Kuhn, T., Froines, J. and Sioutas, C. (2005) Penetration of freeway ultrafine particles into indoor environments, *J. Aerosol Sci.*, **36**, 303–322.