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MAY/JUNE 2015

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Infiltration of Outdoor Pollutants

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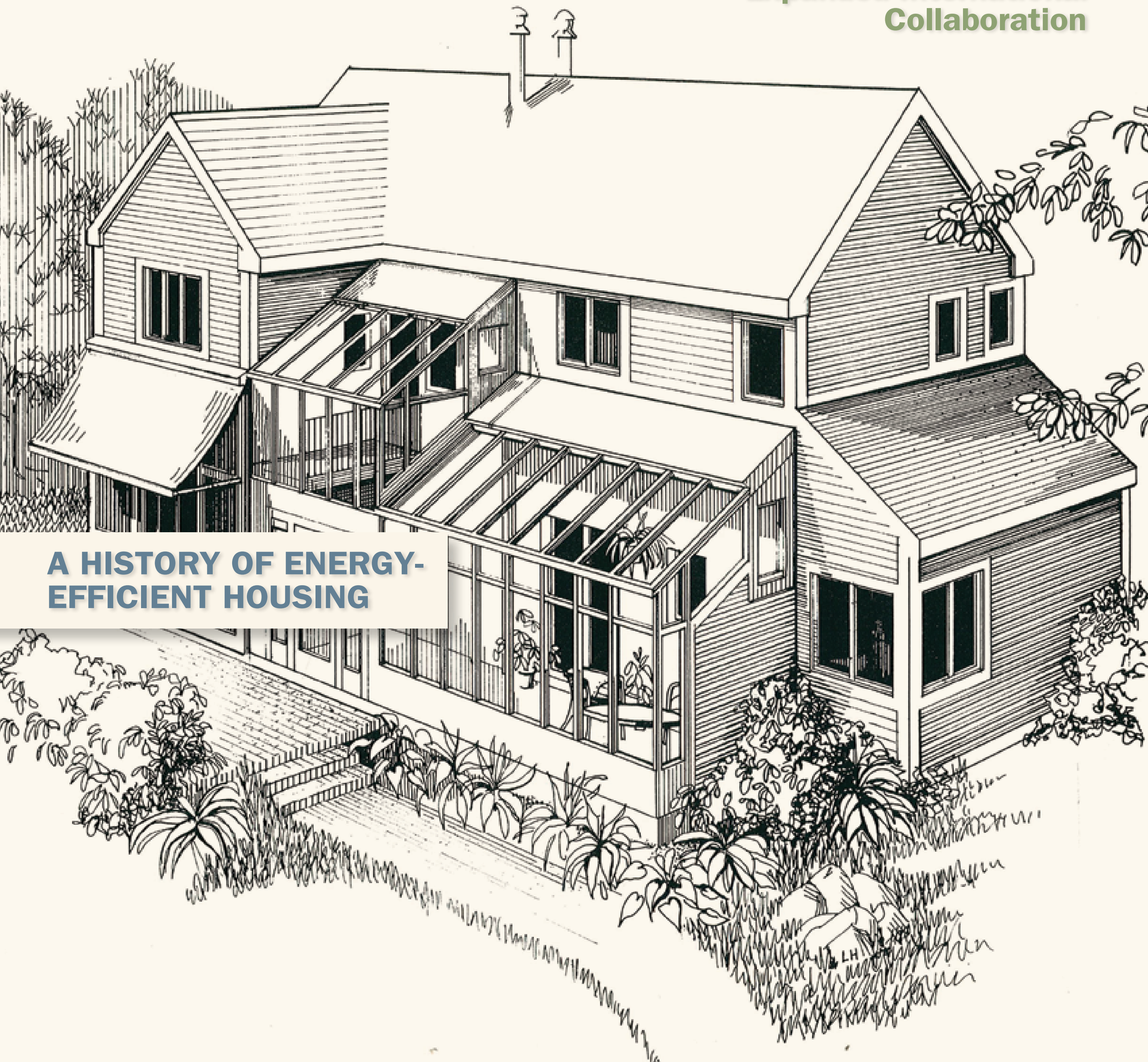


A HISTORY OF ENERGY-EFFICIENT HOUSING

INFILTRATION of Outdoor Pollutants

How building airtightness and pollutant characteristics affect the transport of outdoor air pollution into the indoor environment

by Brent Stephens
Figures by Brent Stephens

Outdoor air pollution is a complex mixture of thousands of solid, liquid, and gaseous constituents. EPA sets National Ambient Air Quality Standards (NAAQS) for just six "criteria" pollutants in the outdoor environment that are known for their adverse effects on human health. These six pollutants are carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), ozone (O_3), lead (Pb), and particulate matter (PM), which includes two subsets of PM—the mass of particles less than 2.5 micrometers in diameter ($PM_{2.5}$) and the mass of particles less than 10 micrometers in diameter (PM_{10}). These regulations are designed to protect public health, including the health of sensitive populations, such as asthmatics, children, and the elderly. But what do they have to do with home energy performance and the readers of *Home Energy*?

First, while concentrations of these criteria pollutants are heavily regulated outdoors in the United States and other countries, they also infiltrate the indoor environments where we spend most of our time. Of particular interest is the infiltration of these pollutants in homes, where the average person spends nearly 70% of his or her time. For comparison, we spend only about 8% of our time outdoors. Therefore, much of our cumulative exposure to criteria pollutants of outdoor origin actually occurs indoors, particularly at home. Second, there is an inextricable link between home energy performance—chiefly in terms of envelope airtightness—and the infiltration of outdoor pollutants. In this article, I will describe how both building airtightness and fundamental pollutant characteristics affect the transport of these criteria outdoor air pollutants into indoor residential environments.

Simplifying the Criteria Pollutants

The six criteria pollutants listed above can be grouped into three simple categories based on their physical and chemical behaviors: (1) nonreactive gases, (2) reactive gases, and (3) PM. Nonreactive gases are just that—gases that *do not react* meaningfully with indoor surfaces or other airborne compounds present in the indoor environment. Examples of nonreactive gases include CO and a wide variety of volatile organic compounds (VOCs), such as benzene and styrene, and aldehydes, such as formaldehyde. VOCs and aldehydes do have the ability to adsorb onto materials and later desorb into the indoor environment, but this phenomenon only affects their time-varying concentrations, not their longer-term average concentrations.

Reactive gases are gases that *do react* with building surfaces or other compounds rapidly enough to cause measurable reductions in their concentration indoors. Examples of reactive gases include SO_2, NO_2, O_3, and many others. These pollutants can react with surfaces and other compounds once they are in the indoor environment. They can also react with materials within the building enclosure prior to entering the indoor environment. The rates at which these compounds react vary widely depending on pollutant characteristics and material type. For example, O_3, which is a major driver of indoor chemistry, typically reacts more rapidly with most building surfaces than NO_2. Ozone is also more likely to react with porous materials, such as brick or stone, than with nonporous materials, such as aluminum or glass.

PM is a different class of pollutant altogether. Airborne particles are mixtures of solids and liquids suspended in air. Airborne particles exist in a wide variety of sizes, from only a few nanometers to tens of micrometers. Their size, shape, and density greatly affect the rate at which particles deposit onto surfaces indoors or are captured inside building enclosure assemblies. These same characteristics also determine where in our respiratory system particles are most likely to deposit, which in turn influences their impact on our health. PM can also be classified based on its chemical or biological constituents. Common chemical constituents of PM include black carbon, sulfate, nitrate, organic carbon, and metals such as the criteria pollutant Pb. Biological constituents of PM include a huge array of bacteria, fungi, and viruses.

Indoor Concentrations of Outdoor Pollutants

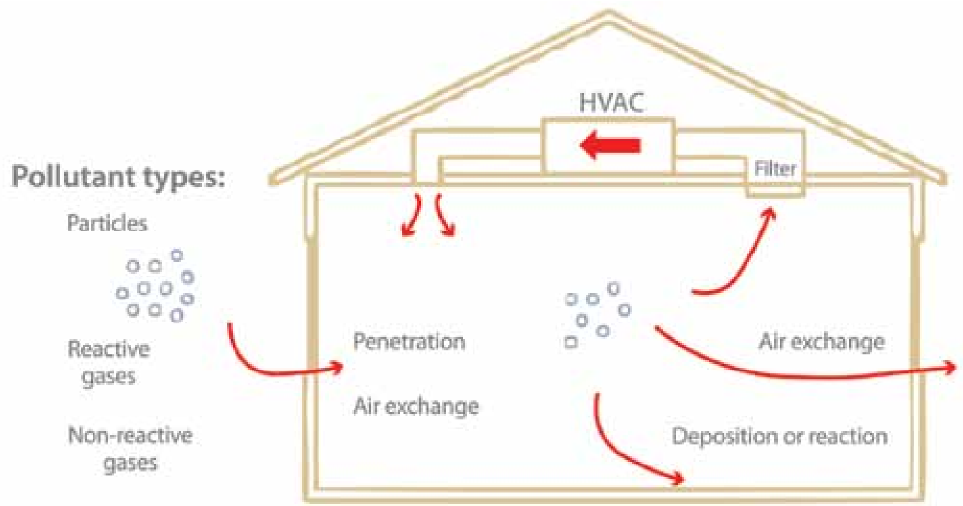
Three basic mechanisms govern how outdoor pollutants are transported indoors. These mechanisms are (1) air exchange rate, (2) envelope penetration factor, and (3) indoor loss rate, including reaction (of reactive gases), deposition (of particles), or removal by filtration or air cleaners (of gases or particles, depending on filter type). These basic mechanisms, along with a simple equation of time-averaged indoor concentrations of outdoor origin, are shown in Figure 1.

Air Exchange Rate

The first mechanism is straightforward and is common to all pollutants. The air exchange rate is a measure of the rate of turnover of indoor air with outdoor air, or ACH. In buildings operating under infiltration alone—that is, when windows are closed and mechanical ventilation systems are not intentionally providing outdoor air—air exchange rates are driven by a combination of envelope airtightness, indoor and outdoor temperature differences, and wind speed and direction. As we have worked to air seal and tighten building envelopes over the last few decades, the median air exchange rate across U.S. single-family homes has decreased by about 10%, from 0.50 ACH in the 1990s (Murray and Burmaster, 1995) to ACH 0.44 now (Persily, Musser, and Emmerich, 2010). A recent study of 108 new homes in California revealed a median air exchange rate of only ACH 0.26 (Offermann, 2009).

While actual air exchange rates—which will vary on the scale of minutes or hours—are not perfectly predicted by airtightness metrics from blower door tests alone (such as CFM_{50}, ACH_{50}, or ELA), they are highly correlated with those metrics. (See "Reader Questions Cost-Effectiveness of Weather Stripping" *HE* Jan/Feb '13, p. 3.) Actual air exchange rates will be lower in homes with tight envelopes under the same temperature and wind driving forces. Low air exchange rates have competing effects on indoor

Basic Mechanisms Governing Indoor Concentrations of Outdoor Pollutants



$$\frac{C_{indoor}}{C_{outdoor}} = \frac{\text{Penetration} \times \text{Air Exchange Rate}}{\text{Air Exchange Rate} + \text{Deposition} + \text{Reaction} + \text{Filtration}}$$

Figure 1. The indoor proportion of outdoor pollutants in a home ($C_{indoor}/C_{outdoor}$), including particles, reactive gases, and nonreactive gases, is governed by mechanisms such as the air exchange rate, envelope penetration factor, and indoor loss rate. These mechanisms vary according to building characteristics, such as airtightness, as well as fundamental pollutant characteristics.

pollutant concentrations. Low air exchange rates will transport outdoor pollutants indoors at a slower rate, but will also dilute indoor-generated pollutants at a slower rate, leading to a shift in the balance of indoor and outdoor sources.

Envelope Penetration Factor

The next key parameter governing indoor proportions of outdoor pollutants is the envelope penetration factor. The penetration factor is a number between 0 and 1 that describes what fraction of a pollutant is removed—reacted away (for reactive gases) or deposited or captured (for particles)—by the envelope during outdoor air infiltration. Think of this parameter as a filtration efficiency of sorts; a penetration factor of 1 means that 100% of the outdoor pollutant will penetrate through the building envelope without any reaction with, or deposition to, materials inside the assembly. In other words, the envelope would offer no protection or incidental filtration. A penetration factor of 0 means that none of the outdoor pollutant penetrates through the building envelope, meaning that the envelope offers complete protection. (It is a perfect filter). Lower penetration factors are thus desirable in homes in order to reduce indoor exposure to outdoor pollutants. The penetration factor is a difficult parameter to measure accurately, so there is not much data for many pollutants across a wide variety of homes. (This is something we are actively working on in our research group at the Illinois Institute of Technology in Chicago.) See "Is That House an Air Filter?" *HE* Jan/Feb '13, p. 32.

However, we do know that nonreactive pollutants will have a penetration factor of 1; there is no potential for reaction. Penetration factors for reactive gases will vary between 0 and 1, depending on their reactivity with materials inside building envelopes and the likelihood of outdoor air coming in contact with these materials during infiltration. Similarly, penetration factors for particles will also vary between 0 and 1, depending on particle size, particle density, and envelope leak characteristics. For just four of the criteria pollutants introduced here, typical values of penetration factors found in the literature are as follows: 1.0 for CO and NO_2 (Nazaroff and Cass, 1986; Fabian, Adamkiewicz, and Levy, 2012); 0.8 for O_3 (Stephens, Gall, and Siegel, 2012); and 0.72 for $PM_{2.5}$ (Williams et al., 2003). These are only typical values used in previous work—these values can also vary widely from home to home, although measurements are still very limited.

Indoor Loss Rate

The last key parameter governing indoor proportions of outdoor pollutants is the indoor loss rate once the pollutant has transported indoors. This can be expressed by an indoor loss rate constant in the same units as ACH. For reactive gases such as NO_2 and O_3, this includes reactions with surfaces and other indoor compounds, such as reactive VOCs. For PM, this largely involves deposition to surfaces, which is highly dependent on particle size. The use of particulate air filters in central HVAC systems or portable air cleaners can also increase the indoor loss rate and reduce indoor concentrations of PM. This is also true for both reactive and nonreactive gases when using air cleaners that incorporate activated carbon or other types of gas phase filtration. In the absence of higher-efficiency filtration or portable air cleaners, typical indoor loss rates for the same four criteria pollutants are as follows: 0 per hour for the nonreactive gas CO (Nazaroff and Cass, 1986), 0.7 per hour for $PM_{2.5}$ (Wallace et al., 2013), 0.87 for NO_2 (Fabian, Adamkiewicz, and Levy, 2012), and 2.8 per hour for O_3 (Weschler, 2000). Again, indoor loss rates will vary widely from home to home based on material surfaces, surface area to volume ratios, air speeds, the presence of other reactive compounds, the use of higher-efficiency filtration or air cleaners, and even temperature and relative humidity. I will consider only these typical values in this article to explore typical indoor concentration profiles of these criteria outdoor pollutants.

Profiles of Indoor Pollutants of Outdoor Origin

Using these typical values of penetration factors and indoor loss rate constants for four of the six criteria outdoor pollutants (CO, NO_2, O_3, and $PM_{2.5}$) along with a typical air exchange rate of 0.4 per hour, Figures 2–5 demonstrate a hypothetical 24-hour profile of indoor concentrations of these outdoor pollutants. The outdoor pollutant concentrations are real data obtained from an EPA air quality monitoring site in Chicago, Illinois, for an arbitrary day of September 9, 2013. The air exchange rate is held constant at 0.4 per hour for simplicity, although it would more realistically vary by the hour based on changes in indoor/outdoor temperature differences and wind speeds throughout the day.

Indoor CO concentrations (in units of ppm) will closely track outdoor CO concentrations because there are no reaction losses within the building envelope or indoors (Figure 2). Indoor

Example Profile of Indoor and Outdoor CO Concentrations

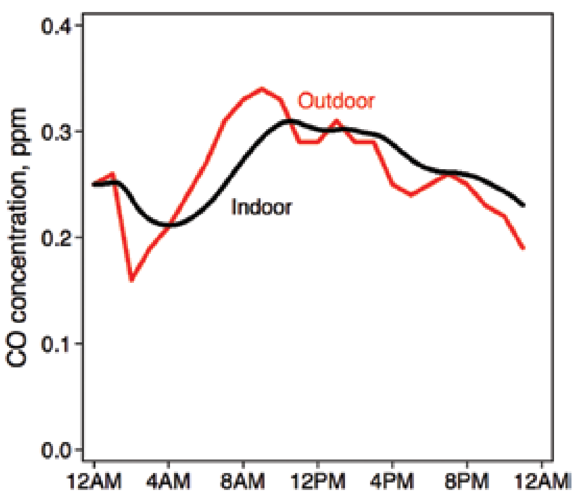


Figure 2. Indoor concentrations of outdoor CO will closely track with outdoor CO concentrations since CO is a nonreactive gas.

Example Profile of Indoor and Outdoor NO_2 Concentrations

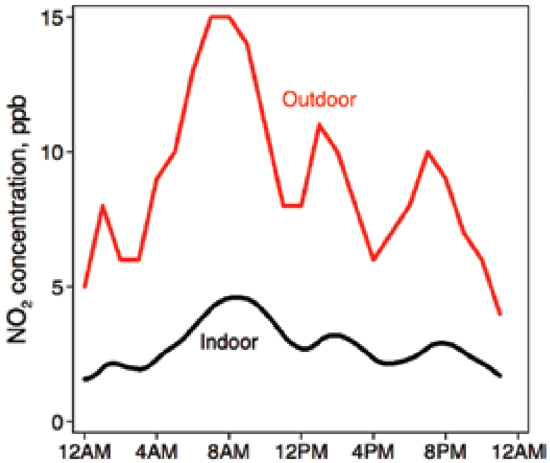


Figure 3. An example profile of indoor NO_2 of outdoor origin (a reactive gas) relative to outdoor NO_2 in a typical home.

Example Profile of Indoor and Outdoor O_3 Concentrations

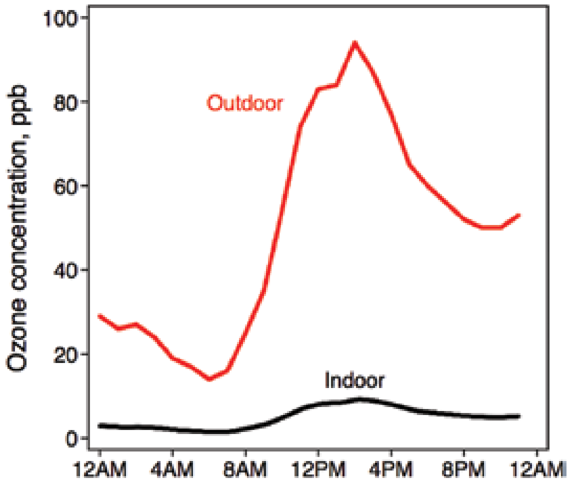


Figure 4. An example profile of indoor O_3 of outdoor origin (another reactive gas) shows the correlation between indoor and outdoor concentrations.

Example Profile of Indoor and Outdoor $PM_{2.5}$ Concentrations

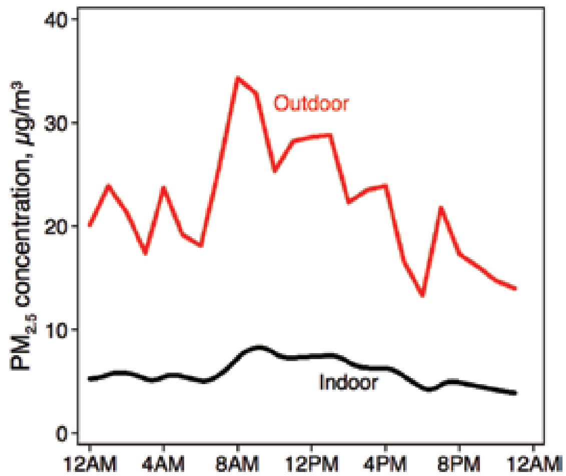


Figure 5. An example profile of indoor $PM_{2.5}$ of outdoor origin in a typical home.

concentrations of other nonreactive gases and VOCs of outdoor origin would follow a similar trend. On the other hand, indoor concentrations of both NO_2 and O_3 (in units of ppb, or parts per billion) are substantially lower than outdoor concentrations because of reactions both within the building envelope and with indoor surfaces (Figures 3 and 4). Indoor-outdoor concentration ratios for O_3 are lower than those for NO_2 because O_3 is more reactive with both envelope and indoor materials (that is, the penetration factor is lower and the indoor loss rate is higher). Similarly, indoor $PM_{2.5}$ concentrations (in units of µg/m3, or micrograms per cubic meter) are also highly buffered by a combination of losses in the building envelope and through indoor deposition (Figure 5). This would also be true for Pb or other PM constituents, depending on the underlying particle size distribution of outdoor PM constituents.

The average indoor-outdoor concentration ratio of each pollutant over this example 24-hour period in the modeled home is shown in Figure 6. Based on these fundamental characteristics, the indoor-outdoor ratio of CO would be approximately 1, or 100% of outdoor levels. The indoor-outdoor ratio of the two reactive gases would be 0.32 for NO_2 and 0.1 for O_3, or only 32% and 10% of outdoor levels, respectively. Similarly, the indoor-outdoor ratio of $PM_{2.5}$ would be 0.27, or 27% of outdoor levels. However, even though indoor concentrations of reactive gases and PM would be lower than outdoor concentrations, remember that the average person spends nearly 70% of his or her time inside the home and only 8% outdoors (a ratio of about 16.5 hours to 2 hours during a typical 24-hour day). Therefore, the ratio of indoor-to-outdoor exposure in this home would be approximately 2.8:1 for NO_2, 2.3:1 for $PM_{2.5}$, and 0.9:1 for O_3. These findings demonstrate that indoor exposure to outdoor pollutants can easily dominate (or at least be comparable to) outdoor exposure!

Concentration Ratio for Four Criteria Pollutants

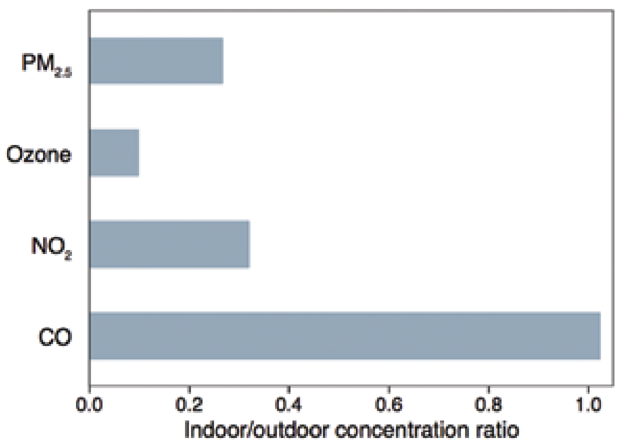


Figure 6. The indoor-outdoor ratio of reactive gases (NO_2 and O_3) and particulate matter ($PM_{2.5}$) of outdoor origin is lower than the nonreactive CO.

Average NO_2 Concentrations

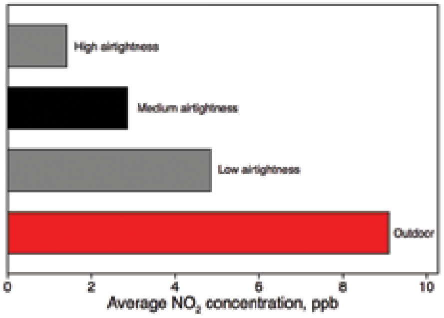


Figure 7. Average NO_2 concentrations over the 24-hour period outdoors and indoors under three airtightness scenarios.

Average O_3 Concentrations

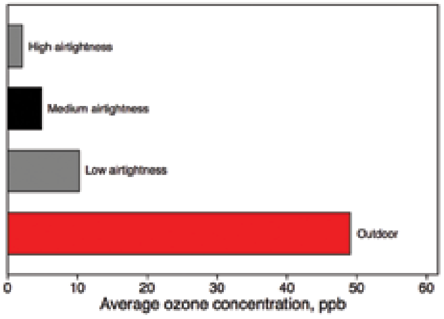


Figure 8. Average O_3 concentrations over the 24-hour period outdoors and Indoors under three airtightness scenarios.

Average $PM_{2.5}$ Concentrations

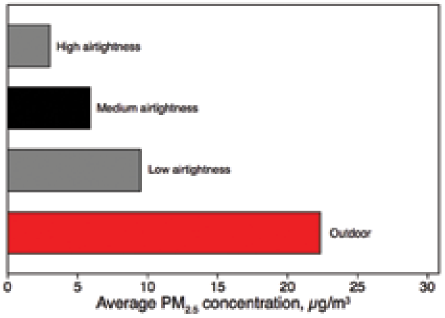


Figure 9. Average $PM_{2.5}$ concentrations over the 24-hour period outdoors and indoors under three airtightness scenarios.

Impacts of Airtightness

Because envelope airtightness plays an important role in governing air exchange rates, airtightness will also influence the rate of supply of outdoor air pollutants. The impact of airtightness on the nonreactive gas CO is negligible—it will affect only the lag times between changes in outdoor and indoor concentrations. But the impact of airtightness is substantial for the two reactive gases and PM (Figures 7–9). For example, when the average outdoor NO_2 concentration is 9 ppb over this 24-hour period, the average indoor NO_2 concentration would be 4.9 ppb, 2.9 ppb, and 1.4 ppb in the house under low, medium, and high airtightness scenarios, assuming 1.0 ACH, 0.4 ACH, and 0.16 ACH, respectively (Figure 7).

Clearly, decisions made for the purposes of improving home energy performance, such as envelope air sealing, will directly affect indoor concentrations of pollutants of both indoor and outdoor origin. Increasing envelope airtightness will tend to reduce infiltration of the outdoor criteria pollutants described here, but will also tend to increase concentrations of indoor-generated pollutants. The addition of mechanical ventilation systems to tight homes complicates this relationship, but also offers an opportunity to dictate where the source of ventilation air is located, and to introduce gas or particle filtration, if needed, to reduce indoor exposure to outdoor pollutants while simultaneously diluting indoor-generated pollutants.

Brent Stephens *is an assistant professor in the Department of Civil, Architectural and Environmental Engineering and directs the Environment Research Group (http://built-envi.com) at the Illinois Institute of Technology, Chicago, Illinois.*

To view a companion article, "Infiltration of Outdoor Pollutants: Field Notes," go to www.homeenergy.org. In this article, Don Fugler describes the work of a Pittsburgh-based initiative called Reducing Outdoor Contaminants in Indoor Spaces, or ROCIS, led by Linda Wigington and Norm Anderson. He asks several building scientists to describe their approaches to minimizing outdoor pollutant penetration for five hypothetical houses.

>> learn more

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