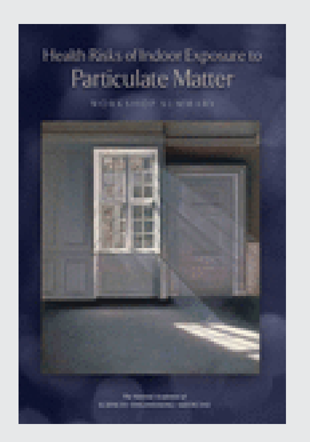

Health Risks of Indoor Exposure to Particulate Matter: Workshop Summary

DETAILS

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Health Risks of Indoor Exposure to Particulate Matter

WORKSHOP SUMMARY

David A. Butler, Guru Madhavan, and Joe Alper, *Rapporteurs*

Board on Population Health and Public Health Practice

Health and Medicine Division

The National Academies of
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PLANNING COMMITTEE ON THE HEALTH RISKS OF INDOOR EXPOSURE TO PARTICULATE MATTER WORKSHOP[1]

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[1] The National Academies of Sciences, Engineering, and Medicine's planning committees are solely responsible for organizing the workshop, identifying topics, and selecting speakers. The responsibility for the published workshop summary rests with the workshop rapporteurs and the institution.

Reviewers

This workshop summary has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published workshop summary as sound as possible and to ensure that the workshop summary meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the process. We wish to thank the following individuals for their review of this workshop summary:

George Gray, George Washington University
Petros Koutrakis, Harvard T.H. Chan School of Public Health
Barbara Turpin, University of North Carolina at Chapel Hill
Mark J. Utell, University of Rochester Medical Center
Lance Wallace, formerly U.S. Environmental Protection Agency and National Institute of Standards and Technology

Although the reviewers listed above have provided many constructive comments and suggestions, they did not see the final draft of the workshop summary before its release. The review of this workshop summary was overseen by **Linda McCauley,** Emory University. She was responsible for making certain that an independent examination of this workshop summary was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this workshop summary rests entirely with the rapporteurs and the institution.

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Acronyms and Abbreviations

3D	three-dimensional
AER	air exchange rate
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
EPA	U.S. Environmental Protection Agency
F_{inf}	infiltration factor
FPR	filter performance rating
HEPA	high-efficiency particulate air/arrestor
HVAC	heating, ventilating, and air conditioning
IAQ	indoor air quality
MERV	minimum efficiency reporting value
MPR	micro-particle performance rating
NAAQS	National Ambient Air Quality Standards
P	penetration factor
PM	particulate matter
$PM_{2.5}$	particles less than 2.5 micrometers in diameter (fine particles)

PM_{10}	particles 2.5 to 10 micrometers in diameter (coarse particles)
qPCR	qualitative polymerase chain reaction
RIOPA	Relationship of Indoor, Outdoor, and Personal Air (study)
SOA	secondary organic aerosol
SVOC	semivolatile organic compound
UFP	ultrafine particle, particle less than 0.1 micrometers in diameter
UV	ultraviolet

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Introduction[1]

The health effects of outdoor exposure to particulate matter (PM) are the subject of both research attention and regulatory action. Although much less studied to date, indoor exposure to PM is gaining attention as a potential source of adverse health effects. Indoor PM can originate from outdoor particles and also from various indoor sources, including heating, cooking, and smoking. Levels of indoor PM have the potential to exceed outdoor PM levels (Chen and Zhao, 2011).

The U.S. Environmental Protection Agency (EPA) defines PM as a mixture of extremely small particles and liquid droplets comprising a number of components, including "acids (such as nitrates and sulfates), organic chemicals, metals, soil or dust particles, and allergens (such as fragments of pollen and mold spores)" (EPA, 2003). When considering PM and health, it is appropriate to consider particulate matter as a class or category rather than as a single species, said William Nazaroff, the Daniel Tellep Distinguished Professor of civil and environmental engineering at the University of California, Berkeley. Sorting PM along one or more of its important attributes, he said, can assist in clarifying how sources and building parameters influence exposures and health consequences. Among the possible attributes useful for thinking about PM, he said, are its *size*, *source*, and *composition*.

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[1] The planning committee's role was limited to planning the workshop, and the workshop summary has been prepared by the workshop rapporteurs as a factual summary of what occurred at the workshop. Statements, recommendations, and opinions expressed are those of individual presenters and participants and are not necessarily endorsed or verified by the National Academies of Sciences, Engineering, and Medicine, and they should not be construed as reflecting any group consensus.

Nazaroff said that a size classification might consider three clusters: ultrafine particles (UFPs) that are less than 0.1 microns—or 100 nanometers—in diameter; fine particles that are less than 2.5 microns in diameter ($PM_{2.5}$); and coarse particles between 2.5 microns and 10 microns in diameter (PM_{10}). UFPs are found in greater quantities but have negligible influence on mass concentrations. Outdoors, $PM_{2.5}$ tends to be dominated by primary aerosols[2] (those that are emitted directly into the air, such as diesel soot) and the conversion of gaseous species to particulate matter in the atmosphere. In the latter case, the major air processes in the outdoor environment include sulfur oxides becoming particulate sulfate, nitrogen oxides becoming particulate nitrate, ammonia becoming ammonium in combining with nitrate and sulfate, and organic gases that become oxidized in the atmosphere into species with lower volatility and higher polarity. Coarse particles tend to be mechanically generated from such sources as crustal elements, tire and brake wear, and sea salt near the coasts (Masri et al., 2015).

Some of the evidence regarding the health effects of PM exposure derives from large-scale epidemiological studies, Nazaroff said in his introductory remarks. In the context of this workshop, he said, it is important to consider the effects of indoor PM—particularly $PM_{2.5}$—even though the majority of studies have focused on outdoor PM levels and their impacts. Understanding the major features and subtleties of indoor exposures to particles of outdoor origin can improve our understanding of the exposure–response relationship on which ambient air pollutant standards are based.

Other types of health risk studies also contribute to the overall state of knowledge. One important category, Nazaroff said, involves studying sources of PM. Examples include studies of the health risks of exposure to environmental tobacco smoke, cooking aerosols, and bioaerosols. Nazaroff said that most of the health-related exposure to PM is believed to occur through inhalation, and he added that the physiologic response to PM exposure is complex, nuanced, and involves much more than just the respiratory tract.

Nazaroff said that another broad theme to consider is the nature of indoor spaces and how these influence exposures and health risks associated with indoor PM. The spaces themselves are diverse along many dimensions, including the type of ventilation system, the density of occupancy, the types of indoor sources, the presence and quality of particle filtration, and the rates of particle deposition. In addition, individual behavior can play a predominant role in determining the ultimate exposure a person experiences, Nazaroff said. Consequently, indoor conditions that pose a negligible risk to one person can result in an adverse outcome for another.

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[2] An aerosol is a suspension of tiny particles or droplets in the air.

As a concluding note in his opening remarks, Nazaroff said that the features that might be considered for a rational public policy addressing indoor PM include public education, interventions targeting reduced exposures for vulnerable populations, and standards or guidelines for the design and operation of building factors that influence indoor PM levels and exposures.

EPA INDOOR ENVIRONMENTS DIVISION

EPA does not regulate indoor air. David Rowson, the director of the agency's Indoor Environments Division, explained that his division, which sponsored this workshop, is responsible for providing non-regulatory guidance, technical assistance, outreach, and education programs to protect the public from harmful exposure to indoor pollutants. This differs from EPA's outdoor programs, which work primarily, though not solely, in a regulatory capacity. The division's major priorities currently involve pollutants that present high public health risks and include radon, indoor environmental asthma triggers, secondhand smoke, mold, and moisture. The division is also involved with addressing exposure to formaldehyde, polychlorinated biphenyls, and other chemicals and biological contaminants found indoors. The division's non-regulatory activities focus on promoting voluntary interventions to reduce exposure to specific indoor pollutants of high concern. Rowson said that the division works to develop solutions that are holistic in nature and that are intended to address indoor air quality (IAQ) in homes, schools, and commercial buildings by focusing on their design, construction, operations, and maintenance. These holistic approaches include an important focus on PM.

"Providing information to the public on significant sources of indoor PM and how to reduce exposures is part of our ongoing work," Rowson said. However, given the growing body of literature related to indoor PM and because EPA was already aware that a number of indoor sources of PM present public health risks, his office commissioned the National Academies of Sciences, Engineering, and Medicine to hold a workshop examining the issue of indoor exposure to PM more comprehensively and considering both the health risks and possible intervention strategies. In particular, this workshop was held to address the following task:

> An ad hoc committee will convene a 1.5-day public workshop on the state of the science regarding the health risks of indoor exposure to particulate matter. The committee will plan and organize the workshop, select and invite speakers and discussants, and moderate the discussions. The workshop will feature invited presentations and discussions regarding the ailments that are most affected by particulate matter and the attributes of the exposures that are of greatest concern, exposure modifiers, vulner-

> able populations, exposure assessment, risk management, and gaps in the science. An individually authored summary of the presentations and discussions will be prepared by a designated rapporteur in accordance with institutional guidelines.

EPA requested that the discussion of the consequences of indoor exposure to PM give special attention to emerging health concerns and to the populations that it exercises responsibility for.

CONDUCT OF THE WORKSHOP

The workshop (see Appendix A for the agenda) was organized by an independent planning committee in accordance with the procedures of the National Academies of Sciences, Engineering, and Medicine. The planning committee members were Terry Brennan, Richard Corsi, Howard Kipen, William Nazaroff (Chair), and Tiina Reponen. The workshop took place in Washington, DC, on February 10–11, 2016 and was broadcast live over the Web.

About 60 people attended the workshop in person. The webcast analytics reported more than 400 unique viewers from 12 countries: Canada, Finland, France, India, Indonesia, Iran, Ireland, Mexico, Saudi Arabia, Sweden, the United Kingdom, and the United States (including 38 states and the District of Columbia). All workshop presentations were subsequently posted to the Web along with links to videos of the talks.[3]

ORGANIZATION OF THE SUMMARY

This publication summarizes the discussions that occurred throughout the workshop. It is divided into seven additional chapters plus supporting appendixes. Chapter 2 describes the major sources of indoor PM, while Chapter 3 explores the chemistry and dynamics of PM. Chapter 4 discusses issues related to exposure levels to indoor PM, and Chapter 5 describes some of the strategies for mitigating exposure to indoor PM. Chapter 6 recounts the discussion held among the workshop participants after the workshop's first day of presentations. Chapter 7 discusses some of the health risks associated with exposure to PM, and Chapter 8 takes up the issue of how to engage the public in matters related to the risks of exposure to indoor PM. The workshop agenda is provided in Appendix A. Appendixes B and C provide biographic information on the speakers and on the planning committee and staff.

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[3] See http://www.nationalacademies.org/hmd/Activities/PublicHealth/Health-Risks-Indoor-Exposure-ParticulateMatter/2016-FEB-10.aspx (accessed July 28, 2016).

In accordance with the policies of the National Academies of Sciences, Engineering, and Medicine, the workshop did not attempt to establish any conclusions or recommendations about needs and future directions, focusing instead on issues identified by individual speakers and workshop participants. In addition, the organizing committee's role was limited to planning the workshop. The workshop summary was drafted by rapporteur Joe Alper in collaboration with Academies staff members David A. Butler and Guru Madhavan as a factual summary of what occurred at the workshop.

2

Sources of Indoor Particulate Matter

In the workshop's first session, three panelists described some of the major sources of indoor PM. Brent Stephens of the Illinois Institute of Technology discussed outdoor air and non-combustion appliances as important source of indoor PM, Lynn M. Hildemann of Stanford University reviewed the indoor sources of airborne allergens and smoke, and Brandon E. Boor of Purdue University discussed the importance of particle resuspension as a source of indoor airborne PM. An open discussion moderated by William Nazaroff followed the three presentations.

INDOOR EXPOSURES TO OUTDOOR PARTICULATE MATTER[1]

The documented adverse health effects of exposure to outdoor PM include stroke, heart disease, lung cancer, and chronic and acute respiratory diseases, including asthma, reduced lung function, and mortality (EPA, 2009), said Brent Stephens as an introduction to his presentation. These effects, he added, are associated in varying degrees with the three broad classes of PM that Nazaroff described in his introductory remarks to the workshop—PM_{10}, $PM_{2.5}$, and UFPs—as well as with various chemical components of PM.

A substantial body of evidence shows that exposure to $PM_{2.5}$, both

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[1] This section is based on the presentation by Brent Stephens, assistant professor of civil, architectural, and environmental engineering at Illinois Institute of Technology, and the statements are not endorsed or verified by the National Academies of Sciences, Engineering, and Medicine.

short-term and long-term, is of particular concern with regard to adverse health effects (Shi et al., 2016). The strength of the underlying science varies, though: some of the links between PM and adverse health effects are well established, Stephens said, while suggestive evidence exists for others. A 2012 study by EPA researchers estimated that there were some 130,000 premature deaths per year of exposure that are attributable to elevated outdoor $PM_{2.5}$ levels (Fann et al., 2012). Most Americans, however, spend nearly 90 percent of their time indoors and about 70 percent of their day at home (Klepeis et al., 2001), so indoor exposure to PM is likely to be an important contributor to the adverse health effects caused by PM exposure. Indeed, Stephens said, outdoor PM enters into buildings at varying efficiencies, becoming indoor PM. Several studies have documented the extent to which human exposure to outdoor PM occurs indoors, including at home (Kearney et al., 2011; MacNeill et al., 2012, 2014; Meng et al., 2004; Wallace and Ott, 2011). Outdoor PM enters buildings by infiltrating through cracks and gaps in the building envelope as well as via natural ventilation and mechanical ventilation (Chen and Zhao, 2011). Mechanical ventilation is likely to be a bigger source of outdoor PM in commercial buildings than in homes. Important indoor sources of PM include combustion, candles, and cooking (Isaxon et al., 2015).

A 2011 review of 77 studies covering more than 4,000 homes found that the average ratio of indoor PM to outdoor PM—where the indoor PM includes contributions from both indoor and outdoor sources—is approximately 1.0 for $PM_{2.5}$ and approximately 0.8 for PM_{10} and UFPs (Chen and Zhao, 2011) (see Figure 2-1). “On average in most buildings, the indoor concentration of $PM_{2.5}$ is roughly the same as outdoors, but there is significant variability,” Stephens said. This same review also looked at the infiltration factor (F_{inf})—the ratio of indoor to outdoor PM considering outdoor sources only—and found a mean value from about 1,000 homes in the United States and 150 homes in Europe of 0.55 for $PM_{2.5}$ (see Figure 2-2). The mean infiltration factors for PM_{10} and UFPs were approximately 0.3, though again there was significant variability from home to home for all three classes of PM. In fact, studies of homes in Canada (Kearney et al., 2011, 2014) (see Figure 2-3) and the United States (Allen et al., 2012) (see Figure 2-4) have shown that the fraction of outdoor PM that infiltrates and persists as indoor PM can range from less than 10 percent to almost 100 percent, depending on the home, the season, and the location.

Several key factors drive this variability in infiltration factors (Allen et al., 2012; Chen et al., 2012; El Orch et al., 2014; MacNeill et al., 2012, 2014; Williams et al., 2003). Stephens mentioned that these include ventilation, either through infiltration, mechanical ventilation, or natural ventilation, and the magnitude of the air exchange rate (AER), which is driven in part by meteorological conditions. The airtightness and other characteristics of the

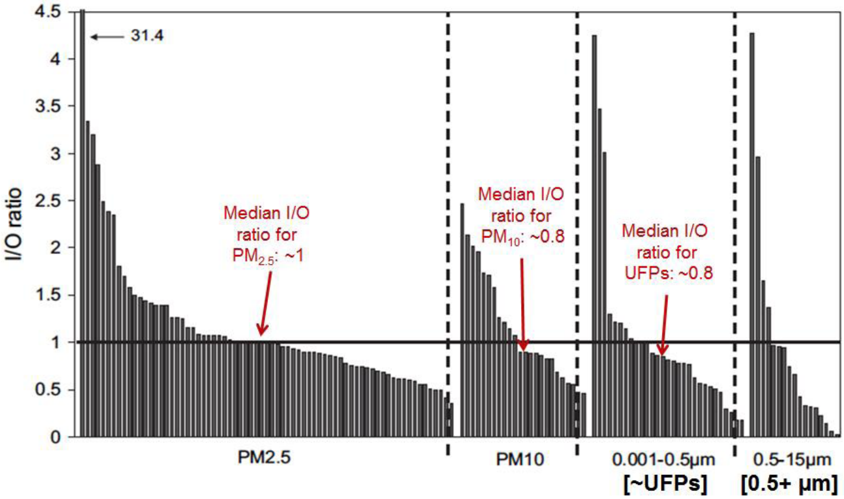

FIGURE 2-1 Experimental data distribution of indoor/outdoor (I/O) particle ratios from 77 studies.
SOURCES: Stephens slide 7, adapted from Chen and Zhao (2011) Figure 2; reprinted with permission from Elsevier.

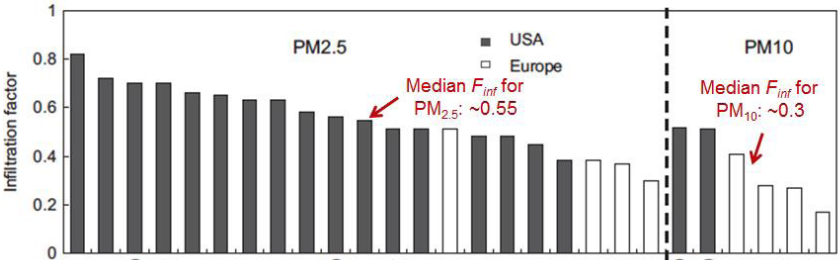

FIGURE 2-2 Experimental data distribution of $PM_{2.5}$ and PM_{10} infiltration factors (F_{inf}) for homes in the United States and Europe.
SOURCES: Stephens slide 8, adapted from Chen and Zhao (2011) Figures 3 and 4; reprinted with permission from Elsevier.

building, as well as the design and operation of the heating, ventilating, and air conditioning (HVAC) system, contribute to variability, too. Human behavior is an important contributor—some people open their windows more frequently than others, for example—and variability also depends on the sizes and even components of PM. Stephens said there is a need for more data to fully understand the relative importance of these drivers of infiltration factor variability.

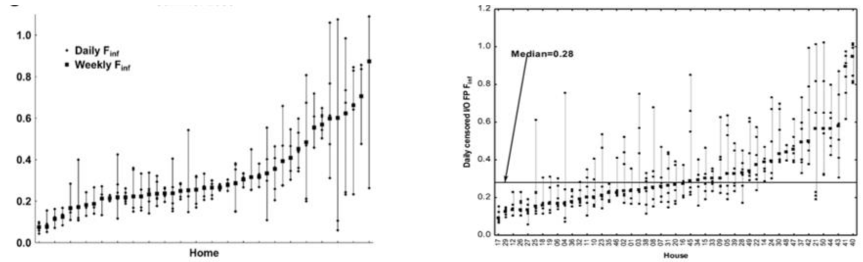

FIGURE 2-3 Infiltration factors for UFPs in Windsor, Ontario, in summer (left) and for $PM_{2.5}$ in Edmonton, Alberta, in winter (right).
SOURCES: Stephens slide 9, from Kearney et al. (2011) Figure 6c (left) and Kearney et al. (2014) Figure 2 (right). Left figure reprinted with permission from Elsevier.

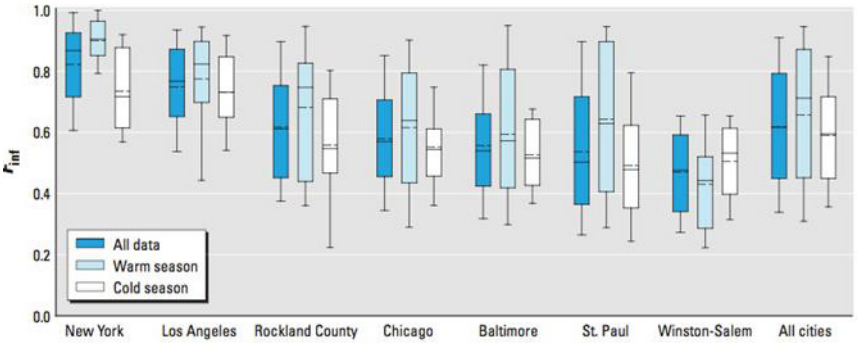

FIGURE 2-4 Two-week average infiltration factors for $PM_{2.5}$ in seven U.S. cities and overall.
SOURCE: Stephens slide 9, from Allen et al. (2012) Figure 1; reprinted with permission from *Environmental Health Perspectives*.

Stephens then addressed areas in which less is known about indoor exposures to outdoor PM, starting with how infiltration factor variability contributes to health effect estimates from epidemiology studies. One modeling study (Chen et al., 2012) constructed a PM_{10} exposure coefficient that tried to account for the likely variations in AERs across different U.S. regions based on housing characteristics, climate conditions, seasons, window opening behaviors, and HVAC runtime. This coefficient—which represents the change in total PM_{10} exposure per unit change in outdoor PM_{10} exposure—correlated reasonably well with estimates of the increase in short-term mortality associated with a given increase in the concentration of PM_{10} (PM_{10} mortality coefficients) derived from epidemiology studies, Stephens said. “If you try to account for the underlying indoor exposure to outdoor PM based on some key drivers of variability, you can explain many of the differences in mortality coefficients.”

A 2013 study by Hodas and colleagues took a similar approach in order to relate indoor levels of outdoor $PM_{2.5}$ with acute myocardial infarction based on a ranking of AERs derived from housing characteristics. These investigators found a higher odds ratio in homes with higher AERs, which, Stephens said, would have higher indoor levels of outdoor PM (Hodas et al., 2013). Another study (Sarnat et al., 2013) that examined the relationship between AERs, exposure to $PM_{2.5}$, and emergency department visits in Atlanta, Georgia, found that higher AERs were correlated to some extent with the relative risks of $PM_{2.5}$ exposure and emergency department visits.

What Stephens called the elephant in the room is the impact on AERs of how often people open their windows. “You could not ask a simpler question, but we do not have much data on this,” he said. Some investigators have conducted pilot studies (El Orch et al., 2014; Johnson and Long, 2004; Price and Sherman, 2006) in which they asked people how often they opened their windows, but Stephens said these data are limited and somewhat suspect. Nevertheless, his group and others have tried to use these data to model what the distributions of window opening might be and to estimate how AERs vary with open windows (Chen et al., 2012; El Orch et al., 2014; Johnson and Long, 2004; Marr et al., 2012). The rule of thumb from these analyses is that AERs are approximately two to four times higher when windows are open, but Stephens said that these exchange rates will depend on how open a window is, the difference between the indoor and outdoor temperatures, and meteorological driving conditions such as wind speed and direction.

More data are also needed to better understand the underlying mechanisms governing infiltration factors for outdoor particles, Stephens said. There are other factors that affect infiltration, such as the penetration factor (P), which describes how effective the building envelope is at preventing particle infiltration. When windows and doors are closed, and absent mechanical ventilation, the penetration factor multiplied by the AER equals the rate at which outdoor PM is delivered indoors. Particles are removed from indoor air by a combination of air exchange and a variety of loss mechanisms which include deposition to surfaces, phase changes, and control by filters and air cleaners. For conditions in which air exchange only occurs through infiltration, the particle infiltration factor equals the product of the AER and the penetration factor divided by the sum of the AER plus and the other loss mechanisms:

$$F_{\text{int}} = \frac{P \times AER}{AER + Loss}.$$

Modeling work (Liu and Nazaroff, 2001) has defined some of the physical parameters, such as particle size, that influence the penetration factor. Subsequent studies have measured the relationship between particle size and penetration (Rim et al., 2010; Stephens and Siegel, 2012) and have shown that mid-size particles, around 0.3 microns in diameter, tend to penetrate more efficiently than larger and smaller particles. Stephens cautioned, though, that these data are highly variable and that they come from fewer than 50 homes. In the case of $PM_{2.5}$, the penetration factor has been estimated in hundreds of homes but seldom, if ever, actually measured. He said that the technology for measuring particle penetration is challenging to use—one approach developed to measure UFP penetration, for example, takes 2 days to complete a measurement in an unoccupied house (Rim et al., 2010).

Other unknowns, Stephens said, include the associations between infiltration or penetration factors and building characteristics, though there are some data for the association between air conditioner usage, year of construction, and envelope tightness (Allen et al., 2012; MacNeill et al., 2012; Stephens and Siegel, 2012). His research group is currently trying to measure how the penetration factor changes after buildings undergo retrofitting. Little is known about how chemical transformations, such as evaporative losses, affect infiltration factors, and data are lacking concerning the spatial and temporal resolution of outdoor PM size distributions and outdoor size-resolved aerosol composition.

Summarizing research needs in the area of outdoor PM transport to indoors, Stephens said that there is a need for more integration between epidemiologists and exposure scientists, building scientists, and indoor air scientists. This would help address exposure misclassification and improve health effect estimates. He added that more data are needed on window opening frequencies and their impact on air exchange rates. And, more field measurements are needed for UFP and $PM_{2.5}$ penetration factors and how they are associated with building design characteristics.

Turning briefly to the subject of indoor sources of PM, Stephens said that there are several non-combustion sources that emit mostly UFPs, including vacuum cleaner bags, steam irons, laser printers, and desktop 3D printers. Recently, researchers found that semivolatile organic compounds (SVOCs) can be deposited on cooking pans and other surfaces, which when heated will produce UFPs (Wallace et al., 2015). While it is good to know the sources of indoor PM, it is more important to know the rates at which these various sources emit PM, and a number of investigators (Afshari et

TABLE 2-1 Selected Indoor UFP Emission Rates for Combustion and Non-Combustion Sources in Homes

UFP Emitting Device	Size Range (nm)	Emission Rate (#/min)	Reference
Flat iron with steam	20-1,000	6.0×10^{9}	Afshari et al. (2005)
Electric frying pan	10-400	$1.1\text{-}2.7\times10^{10}$	Buonnano et al. (2009)
3D printer w/PLA	10-100	$\sim2.0\times10^{10}$	Stephens et al. (2013)
Vacuum cleaner	20-1,000	3.5×10^{10}	Afshari et al. (2005)
Scented candles	20-1,000	8.8×10^{10}	Afshari et al. (2005)
Gas stove	20-1,000	1.3×10^{11}	Afshari et al. (2005)
3D printer w/ABS	10-100	$\sim1.9\times10^{11}$	Stephens et al. (2013)
Cigarette	20-1,000	3.8×10^{11}	Afshari et al. (2005)
Electric stove	20-1,000	6.8×10^{11}	Afshari et al. (2005)
Frying meat	20-1,000	8.3×10^{11}	Afshari et al. (2005)
Radiator	20-1,000	8.9×10^{11}	Afshari et al. (2005)
Desktop 3D printers	10-100	$\sim10^{8} - \sim10^{12}$	Azimi et al. (2016)
Laser printers	6-3,000	$4.3\times10^{9} - 3.3\times10^{12}$	He et al. (2010)
Cooking on a gas stove	10-400	$1.1\text{-}3.4\times10^{12}$	Buonnano et al. (2009)

NOTES: Highlighted items are combustion-related; all other items are non-combustion sources. PLA and ABS are thermoplastics used as 3D printer feedstock.
SOURCE: Stephens slide 21.

al., 2005; Buonanno et al., 2009; He et al., 2010) have measured emission rates (see Table 2-1). For example, Stephens and his colleagues recently measured the rate of PM and volatile organic compound emissions from desktop 3D printers and found UFP emission rates of between 10^{8} and 10^{12} particles per minute (Azimi et al., 2016).

In closing, Stephens said that researchers continue to find new sources of indoor PM and that it is essential to continue to gather emission rate data, including size-resolved emission rate data, for these and other sources. In the future, it will also be important for the field to continue to explore source control and strategies for mitigating exposure to indoor sources of PM.

INDOOR SOURCES OF AIRBORNE ALLERGENS AND SMOKE[2]

Combustion is a major source of indoor PM, Lynn Hildemann said, and the vast majority of combustion PM is submicron in size and includes a substantial number of UFPs. Combustion PM consists of a wide variety of organic compounds along with varying amounts of soot, depending on the combustion process and source. Hildemann noted that the physical and chemical characteristics of some sources of indoor PM—including cigarette smoke (Fernandez et al., 2015), incense burning (Wang et al., 2006), and wood combustion in stoves and fireplaces (Heringa et al., 2011)—have been well characterized.

The combustion and heating sources of indoor PM that need more study include cooking, natural gas stoves and ovens, and electronic cigarettes. The indoor PM emission rate from cooking, for example, depends greatly on the food being cooked, the cooking method (whether the food is being grilled, fried, baked, or sautéed and the type of cooking oil being used, for example), and the type of ventilation. Hildemann said that only a fraction of the people who have ventilation fans above their stoves actually turn them on in a consistent manner. She added that burning food can very quickly introduce large quantities of PM into the indoor environment. Natural gas stoves and ovens emit mainly UFPs, but how long they persist in indoor air is unclear, and their chemical composition is not well characterized (Minutolo et al., 2008).

Electronic cigarettes are a relatively new source of indoor PM, and it is clear from the literature, Hildemann said, that UFPs can form from the condensation of the organic chemicals in electronic cigarette emissions (Blair et al., 2015; Fernandez et al., 2015). The sizes and re-evaporation rates of these particles depend on the dilution conditions, she said. One shortcoming of available studies is that the measurements have been made under controlled laboratory conditions. "I don't think there is information out there that I yet trust that reflects what might be seen if you were indoors with someone smoking an electronic cigarette," Hildemann said.

Secondhand smoke can be a significant source of indoor PM in multiunit housing, she said. "If you live in an apartment or condominium and you have neighbors next door or underneath you who smoke, infiltration of secondhand smoke into your unit can be quite substantial," Hildemann said. She explained that secondhand smoke can infiltrate from outdoor areas, such balconies, patios, and open windows; through walls and ducts; and via ducts that can move air from one residence to the next. For example, in one study she and her colleagues collected PM from two units before,

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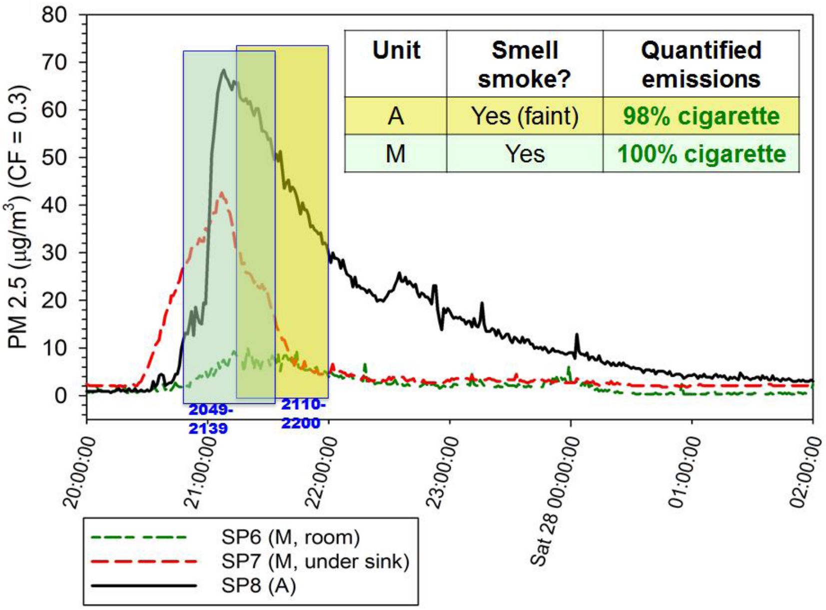
[2] This section is based on the presentation by Lynn Hildemann, a professor of civil and environmental engineering at Stanford University, and the statements are not endorsed or verified by the National Academies of Sciences, Engineering, and Medicine.

during, and after someone a floor below had smoked a cigarette (Dacunto et al., 2013), and they were able to demonstrate that 98 to 100 percent of the elevated $PM_{2.5}$ was from secondhand smoke (see Figure 2-5).

One area that needs more study, Hildemann said, is the relationship between exposure to combustion emissions and the proximity to the source. When indoor combustion is occurring under conditions of natural ventilation, PM will not disperse immediately throughout the indoor environment, she explained. The question is, How bad is it to be close to an active combustion source? One experiment found that exposure to PM within 1 meter of the source can be 10- to 20-fold higher under normal conditions than what the exposure would be in a well-mixed environment (Acevedo-Bolton et al., 2012). Moreover, while the average concentration indoors is lower with higher ventilation rates, the proximity enhancement is higher because ventilation decreases the well-mixed average concentration of PM but has a smaller effect on the cloud of emissions close to the combustion source.



Unit	Smell smoke?	Quantified emissions
A	Yes (faint)	98% cigarette
M	Yes	100% cigarette

FIGURE 2-5 Secondhand smoke intrusion into two units [A, M] above where a smoker was smoking as measured by 3 personal aerosol monitors [SP6, SP7, SP8; calibration factor (CF) = 0.3].
SOURCE: Hildemann slide 5, adapted from Dacunto et al. (2013) Figure 2; reprinted with permission from Elsevier.

The proximity effect is particularly important, Hildemann said, for short-duration sources, in cases where emissions consist mainly of large PM that quickly settles out of the air before it can be transported, and with UFP emissions, which are removed rapidly through coagulation. One implication of these physical phenomena, she said, is that standing close to a stove in use will result in higher exposures to stovetop PM emissions than would be the case for room-average conditions.

The indoor environment can also be a rich source of allergens, Hildemann said. Pets can be a significant source of shed skin flakes, or dander, which by itself can be an allergen because of its dog or cat saliva content. Dander also contains bacteria that can be allergenic. Various components of house dust, such as mold spores, bacteria, mite proteins, and cockroach proteins, can be allergenic, and dust is readily resuspended by vacuuming and other human activities. Damp surfaces can harbor molds and bacteria that can be resuspended, and, Hildemann noted, the levels of certain molds and fungi, such as those belonging to the genera *Aspergillus* and *Penicillium*, tend to be higher indoors than outdoors.

Compared to smoke particles, airborne allergens span a large range of sizes (see Figure 2-6). Mite allergen particles, for example, can come from mite feces or pieces of molted exoskeleton. What this size variation means as a practical matter, Hildemann explained, is that there will be a wide range of airborne residence times for indoor allergens, and there will be variability in terms of where these allergens deposit in human lungs. PM_{10}, she said, clears from the lungs in hours, whereas $PM_{2.5}$ and UFPs can take weeks to clear.

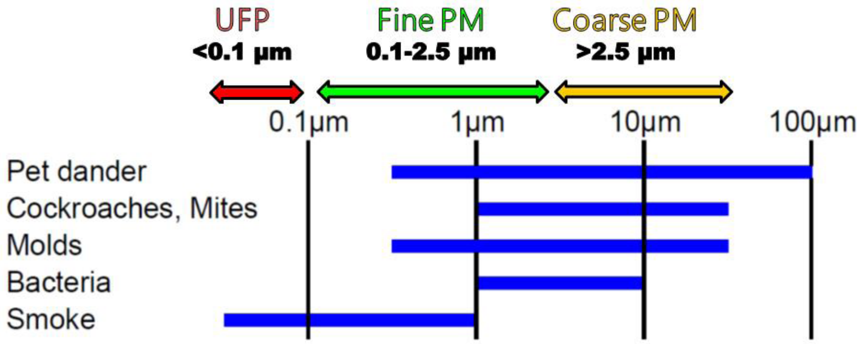


FIGURE 2-6 Sizes of different types of airborne allergens and PM from smoke.
SOURCE: Hildemann slide 10.

House dust is an important source of PM, Hildemann said, and vacuuming is good way to increase exposure to $PM_{2.5}$. Unpublished work from her laboratory found that $PM_{2.5}$ levels increase two- to five-fold during vacuuming, with the variation resulting largely from how well the exhaust filter fits in the filter frame.

Addressing areas that need further research, Hildemann said that little is known about the factors affecting the emission rates of bacteria and fungi from damp surfaces. Airflow, vibration, and material type are thought to play some role in determining the rate at which these organisms become airborne from damp surface, but the main challenge in learning more about these processes, she said, is that researchers are still not sure how to accurately estimate emission rates from damp surfaces. Additional studies would be useful to understanding how individual activity patterns and gender influence exposure to allergens.

As a final thought, Hildemann said she wondered what the impact of global climate change would be on indoor PM exposures. One concern she has is that more homes will be sealed tightly to reduce the cost of air conditioning, which would lower the AER and allow indoor PM emissions to build up to higher levels. Homes that are more tightly sealed will also have higher humidity levels, creating more hospitable conditions for molds, some bacteria, and mites.

PARTICLE RESUSPENSION IN INDOOR ENVIRONMENTS[3]

Every person is surrounded by a cloud of particles, Brandon Boor said, and the fundamental process for creating that cloud is resuspension. Particles resuspend when they detach from surfaces; are exposed to various removal forces, such as aerodynamic lift and drag, surface vibration forces, and electrostatic forces; and then become airborne. Human-induced particle resuspension, he said, is associated with various activity patterns and different types of movements—walking and crawling across a carpeted floor will resuspend particles, as will turning over in bed—and the concentration of resuspended particles is linked to the number of people in a room and how much they move around. Occupants can be exposed to resuspended particles as a result of resuspension they themselves cause or by resuspension induced by others in their workplace or home.

Particle resuspension from walking is an important indoor source of PM, with PM_{10} emission rates ranging from 1 to 10 milligrams per minute (Qian et al., 2014) (see Figure 2-7). To put that into perspective, Boor

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[3] This section is based on the presentation by Brandon E. Boor, assistant professor of civil engineering at Purdue University, and the statements are not endorsed or verified by the National Academies of Sciences, Engineering, and Medicine.

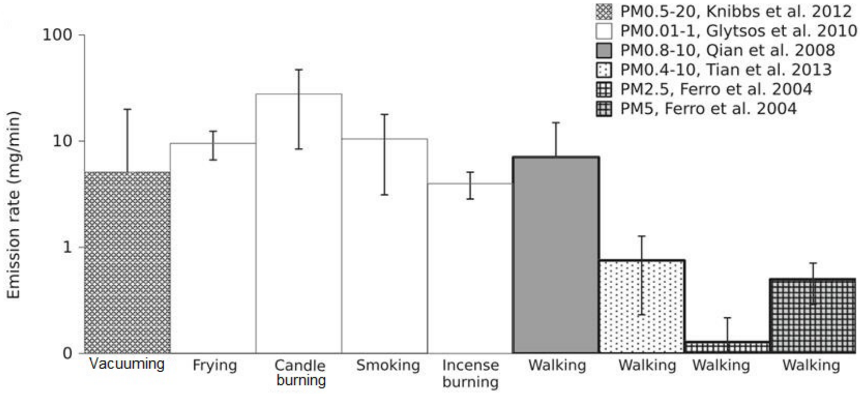

FIGURE 2-7 Emission rates of various sources of indoor PM from selected studies. SOURCES: Boor slide 4, from Qian et al. (2014) Figure 1 [references in original publication]; reprinted with permission from Elsevier.

estimated that, based on typical activity patterns, a typical person would resuspend 10 to 100 kilograms of dust (PM_{10}) over a lifetime. House dust, as Hildemann discussed, is a significant source of various allergens, but it is also a reservoir for many SVOCs, such as phthalates and organophosphates. One area of concern that Boor mentioned was the exposure of infants to PM in the near-floor environment as they crawl and play on carpeted surfaces.

Boor said that seminal studies on particle resuspension over the past 20 years, including work by Thatcher and Layton (1995) and Qian and Ferro (2008), have used a material-balance model to mechanistically evaluate particle resuspension from indoor surfaces. Resuspension rates and fractions can be determined by measuring the size-resolved concentration of particles in the air and on a surface as well as the frequency of movement. Resuspension is then linked to exposure through airborne particle transport processes and airflow patterns that create some concentration of PM in the breathing zone.

With regard to dust, Boor said that there are many studies in which various sources of household dust have been collected and analyzed for its microorganism content (Adams et al., 2015; Barberán et al., 2015) and SVOC content (Blanchard et al., 2014; Dodson et al., 2015; Weschler and Nazaroff, 2010). Some of these studies have calculated dust loads on indoor surfaces, which can range from light dust loads of less than 0.1 gram per square meter of surface from a mattress to as high as 100 grams per square meter from carpeting or ventilation ducts. Few studies, however, characterize the size distribution, either by number, volume, or mass fraction, of settled dust particles—something that Boor said needs to be addressed by future research to improve our mechanistic understanding of resuspension.

Collecting dust is not as simple as it sounds, Boor said. Dust often consists of fragile agglomerates of smaller particles that can fall apart during collection, which would shift the observed size distribution. Other aspects of research on dust are also challenging. "The structure of dust is complex and something we know little about," Boor said. Dust deposits, he added, can be compact or fluffy, depending at least in part on how they are deposited on a surface and how they are altered by compression or cleaning activities. They can also agglomerate in myriad ways to form a variety of shapes. Biological particles—such as single bacterial cells and aggregates of bacterial cells, pollen grains and fragments, fungal spores and fungal fragments, and abiotic particles (for example, mineral dust) with attached microbes—come in a spectrum of shapes and sizes (aerodynamic diameter), with complex surface features and varying electrostatic charge, Boor said.

Dust adhesion plays an important role in resuspension, yet most studies have been narrowly focused on spherical particles adhering to flat surfaces, and neither spherical particles nor flat surfaces reflect the indoor reality. "Indoors, we have non-spherical particles and complex surfaces such as fabric fibers, clothing, bedding material, and carpet fibers, and there are very few data on particle adhesion to different types of fabric fibers," Boor said. Fabric fibers, for example, come in intimate contact with the human body and accumulate moisture and skin lipids, which may affect particle adhesion over time. Particles may become embedded to varying degrees in different kinds of fibers, and little is known about the role that process would play in resuspension. The loosely bound fibers of a shirt or pillow cover also behave differently when exposed to movement, which may affect resuspension processes in ways that are still largely unknown.

There is a better understanding of how different human activities affect resuspension, Boor said. One study of walking, for example, used a mechanical foot in a small test chamber to measure resuspension from different types of flooring materials (Tian et al., 2014) and found that for particles greater than 1 micron, more particles come off of carpet than from hard flooring. Boor participated in a study that looked at the human-induced resuspension of mattress dust particles as a function of dust load, ventilation rates, and type and intensity of movement (Boor et al., 2015). Movement on a bed stirs up dust, he said, and the breathing zone concentration of dust particles remains elevated throughout the duration of the movement and decays slowly, leading to exposures that last beyond the period of movement—for example, as one falls asleep and lies still in bed. He and his colleagues also found that the resuspension rate increases with particle size, which he attributes to the increase in the magnitude of detachment forces, such as aerodynamic lift and drag and surface vibration, that accompanies an increase in particle size. The body mass of the volunteers who participated in study had little effect on resuspension rates, though the intensity of the movement, as characterized by surface vibrations, did have a large effect on the resuspension rate.

Another route of exposure to dust is dust becoming detached from clothing. One study found that as much as 25 percent of the particles deposited on a cleanroom suit detached while a volunteer was dancing to an Irish reel, which was considered a high-level of physical activity (McDonagh and Byrne, 2014a). Particle detachment was some 10-fold lower when the volunteer was engaged in a low-level physical activity (see Figure 2-8). Larger particles were displaced more than smaller particles (McDonagh and Byrne, 2014b).

As Boor had mentioned earlier, the effect of an infant crawling on the near-floor microenvironment is not well characterized, so in a recently completed study he and colleagues in Finland built a simplified mechanical crawling infant and used it to measure airborne particle concentrations as it scuttled across 12 area carpets borrowed from Helsinki residents. Boor also sent samples of the collected real-world dust that had been resuspended from these carpets to a microbiologist, Martin Täubel, for analysis using quantitative polymerase chain reaction (qPCR) and next-generation genome sequencing. Optical measurements showed large bursts of particles across the range of particle sizes (UFPs, $PM_{2.5}$, and PM_{10}) and indicated that the particles remained suspended in the air for a significant amount of time. The qPCR data revealed a large variation in the microbial concentra-

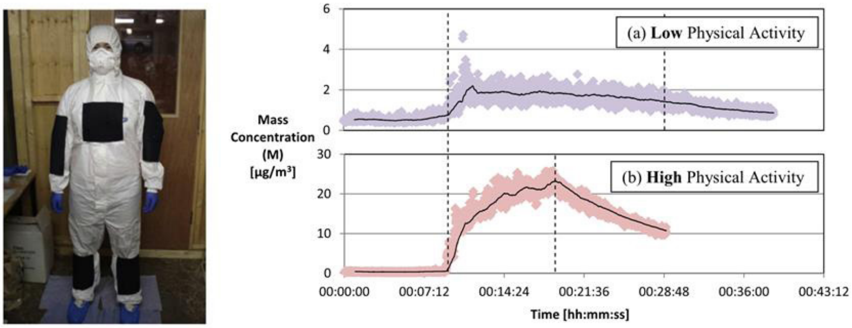

FIGURE 2-8 Mass concentration of airborne particles during resuspension due to low- and high-level physical activity as a function of time; and the suit used to collect the data.
SOURCES: Boor slide 22, from McDonagh and Byrne (2014a) Figures 1 and 2; reprinted with permission from Elsevier.

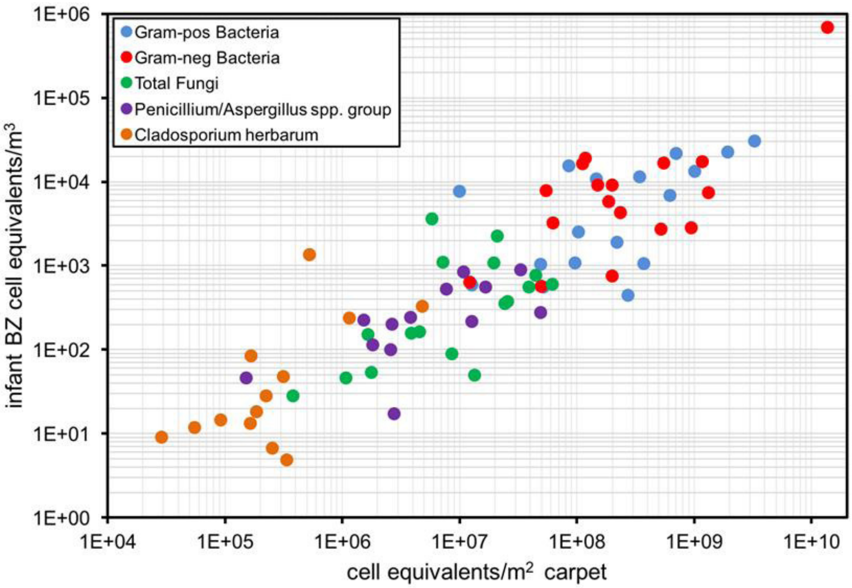

FIGURE 2-9 Concentrations of microorganisms in carpet dust resuspended in the infant breathing zone (BZ) by a mechanical crawler (qPCR data analyzed by M. Täubel).
SOURCE: Boor slide 26.

tions and composition in the infant breathing zone (see Figure 2-9). Boor proposed that there be more focus in characterizing this kind of cloud of particles and microbes around infants as they crawl.

While qPCR data are useful, it requires hours of dust collection on a filter to accumulate detectable amounts of microbial DNA. Another useful technique, which has been applied in Nazaroff's laboratory, is using laser-induced fluorescence to characterize bioaerosol concentrations and size distributions in real time. Boor and his colleagues in Finland used this technique to show that both crawling and walking triggered a burst of resuspended fluorescent particles from carpeting but that particle decay occurred more quickly in the infant breathing zone after crawling than in the adult breathing zone after walking. Boor mentioned some recent work using fluorescent and optical signatures to distinguish among bacteria, fungi, and pollen in real time (Hernandez et al., 2016) and said he thought it would be interesting to conduct that type of analysis on particles resuspended by human activity. He also proposed using high-speed imaging to follow the trajectories taken by individual dust particles as they are dislodged by human activity from various indoor surfaces—something that has been done with micrometer spherical glass beads (Kassab et al., 2013).

This type of work, Boor said, proves the importance of looking not just at resuspension, but also as the transport of particles to the breathing zone. As his work and that of others (Shalat et al., 2011) have shown, concentrations of PM are much greater near the floor than they are at the level of the typical stationary monitoring site used in indoor field measurements. Boor also cited the results of a modeling study showing that, while walking, shorter people will be exposed to more influenza virus particles in dust resuspended into their breathing zones than will taller people (Khare and Marr, 2015). What is needed to create a full, holistic picture of particle resuspension, Boor said in closing, are integrated measurements of particle resuspension to the breathing zone across all scales, from small-scale wind tunnel and chamber studies to full-scale controlled chamber studies and field measurements in offices and homes.

DISCUSSION

Nazaroff started the discussion by asking the panelists to offer their opinions on what they see as the biggest gaps in two areas: the gap between what is known and what needs to be known, and the gap between what experts in the field know and what they actually do in practice. Hildemann responded that she would like to see more attention paid to the roles that building design in general and ventilation in particular play in influencing indoor air quality. Stephens said he believes that more information is needed to understand how real-life exposures to PM relate to the epidemiology of health effects in order to better inform practice and regulation. Other priorities, he said, should be to develop approaches for reducing exposures to PM within the nation's large existing building stock and to create a labeling scheme for devices—he specifically mentioned desktop 3D printers—that would inform consumers what these devices are emitting into the indoor environment. "There are ways that government and industry consortia could help improve public knowledge," Stephens said.

Boor agreed that translating research results into useful information for the public is something the field needs to address, particularly with regard to helping parents limit exposure of infants to PM and to various gaseous species such as SVOCs. Barbara Turpin from the University of North Carolina singled out the need for better advice for the public on when to increase versus decrease ventilation in order to decrease PM exposure. Hildemann added that the same could be said of vacuuming, and she said that one question consumers could have is whether to vacuum more to reduce the resuspension of particles between vacuuming or to vacuum less because of the exposure to high concentrations of particles during vacuuming.

However, she said, the real solution would be to not have carpeting in the home because hardwood and tiled floors are more efficiently cleaned and the resuspension rates from walking on such flooring are much lower than from walking on carpeting. Boor said that he had examined the effect of vacuuming on particle resuspension in his mechanical infant crawling study and found that vacuuming prior to crawling had little effect on particle concentrations in the infant breathing zone.

Tiina Reponen from the University of Cincinnati, commenting on the work on bioaerosols that Hildemann and Boor had discussed, reiterated that bioaerosols are an important component of both indoor and outdoor PM. She then said that there are studies of bioaerosols emitted from damp surfaces showing that microbes are released more readily into dry air than into humid air and that increased airflow and vibration increase microbial release from surface. More importantly, she said, these studies have shown that small fragments of microbes are also released, so it is important to look for biological components in the smaller size fractions of PM as well as in the large fractions.

Howard Kipen from Rutgers University noted that while EPA regulates outdoor PM levels based on a substantial and sustained epidemiologic database linking outdoor PM levels with a wide range of adverse health effects, there needs to be work done to determine the health consequences of outdoor PM translated to indoor exposures, given that Americans spend 90 percent of their time indoors and that 50 percent of indoor PM comes from outdoor sources. “We need to do that to be able to decide whether the interventions we can demonstrate are going to protect health,” Kipen said. Charles Weschler from Rutgers University said he would argue that since the bulk of exposure to outdoor PM particles occurs indoors, more is known about the risk of indoor exposure to outdoor PM than is known about the risk of outdoor exposure to outdoor PM or indoor exposure to PM of indoor origin. Kipen replied that he agreed with Weschler but that that fact is not actualized in regulation.

Boor, also responding to Kipen’s remarks, said that one opportunity to get better data on indoor $PM_{2.5}$ and UFPs would be to explore the use of commercially available, relatively low-cost particle sensors on a broad scale. Today, he said, relatively inexpensive optical monitors can detect larger particles accurately, but work still remains to test the accuracy of devices in measuring $PM_{2.5}$ and UFPs and to develop portable devices that could be used to create sampling networks in multiple environments. “If we push in that direction,” he said, “we could build large-scale databases of size-resolved PM levels.”

Joe Hughes from IAQ Radio said that from his perspective one of the biggest gaps of knowledge concerns the value of mechanical systems cleaning. He noted that the information being used to advise consumers on whether to have their air ducts cleaned relies on a 1997 EPA report. Hughes also supported Boor's call to develop inexpensive ultrafine particle counters that could be deployed in the field. William Fisk from the Lawrence Berkeley National Laboratory remarked that panelists had not addressed three categories of indoor PM sources that need further study: the outdoor air as a source of allergens and inflammatory agents; the wetted surfaces in HVAC systems; and episodic outdoors sources such as wood combustion and wildfires.

An online participant asked the panelists if there were data on the contribution that cleaning product residues make to indoor PM and whether these residues alter the resuspension of other particles. Boor said he did not know of any studies looking at cleaning residues, and Hildemann said she thought that more work is needed to answer those questions. She did say that some proportion of the droplets produced by spray cleaning products do not reach a surface and that as the carrier solvents evaporate, they leave behind airborne particles of wax and other substances. She also explained that the enzymes in laundry detergents can be detected in active form in dryer lint after clothes have been washed and dried. As a result, in addition to dust coming off of clothing, there may also be some allergenic material in the form of active enzymes. Kipen added that one of the most interesting findings in occupational asthma epidemiology research over the past decade has been that people who do indoor cleaning for a living have increased rates of asthma. He noted, too, that there are suggestions that this finding extends to people who are non-occupational users of cleaning products. Stephens said that the challenge is going to be to develop a connection between knowledge of physics, chemistry, and biology and the epidemiology pointing to adverse health effects.

3

Particle Dynamics and Chemistry

The workshop's second session featured three presentations on the transport, fate, and transformation of indoor PM. The session moderator, Richard Corsi of The University of Texas at Austin, explained that the discussions in this session would serve as a link between the first session on sources and the following session on exposure. He noted that mitigation strategies can have a huge effect on particle dynamics—an idea relevant to the presentation of the first speaker, Jeffrey Siegel of the University of Toronto, who provided a building-science perspective on the dynamics of particle size and concentration indoors. After Siegel's presentation, Glenn Morrison of the Missouri University of Science and Technology discussed indoor chemistry and aerosols, and then Charles Weschler of Rutgers University described the composition of indoor PM and the influence of SVOC partitioning on that composition. An open discussion moderated by Corsi followed the three presentations.

A BUILDING SCIENCE PERSPECTIVE ON PARTICLE SIZE DYNAMICS AND INDOOR CONCENTRATION[1]

Jeffery Siegel focused on how a building influences particle size and the concentrations of PM indoors through its effects on particle sources and sinks and on how little is known about these effects. "Our knowledge of the

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[1] This section is based on the presentation by Jeffrey Siegel, a professor of civil engineering at the University of Toronto, and the statements are not endorsed or verified by the National Academies of Sciences, Engineering, and Medicine.

fundamental characteristics of buildings is insufficient to fully understand indoor aerosol exposure," Siegel said. The main sources of indoor PM, as discussed in the previous session, include combustion and heating processes, resuspension from indoor activities, secondary organic aerosols, and penetration from outdoors, and Siegel said that research on these sources has produced a significant body of literature on the size distribution and emission rate for these sources. Cooking on both gas and electric burners, for example, has been well studied as a source of indoor PM (Wallace et al., 2008). The four main sinks in a building are deposition, portable air cleaning, ventilation and leakage, and HVAC air cleaning, Siegel said, and these, too, have been the subject of extensive research. In related research, investigators have developed size-resolved filtration efficiency curves for many types of filters (Hanley et al., 1994; Stephens and Siegel, 2013).

There are four areas in which knowledge is emerging about how buildings influence PM levels: the impact of building surfaces, the effects of HVAC systems, the heterogeneity of indoor concentrations, and the impact of non-particle constituents. Buildings have many visible and unseen surfaces, both in terms of number and variety, and surfaces interact with indoor PM and aerosols in meaningful ways, Siegel said. Researchers have developed simple, idealized models of how particles are deposited on surfaces (Lai and Nazaroff, 2000), and they have extended that work to more realistic environments containing real building materials (Afshari and Reinhold, 2008). Investigators have also measured size-resolved PM deposition rates for specific idealized conditions (Thatcher et al., 2002). Siegel considers surface deposition to be an emerging area of knowledge because it remains difficult to predict how specific particles, such as $PM_{2.5}$, deposit onto a surface because of the order-of-magnitude variations for deposition rates, both modeled and measured, that have been reported in the literature. Improvements in modeling and measurements offer great promise for characterizing particulate matter accumulation on surfaces and its influence on resuspension. As Brandon Boor noted in the previous sessions, researchers have made progress in understanding the role that resuspension plays in determining indoor PM concentrations (Boor et al., 2013; Kassab et al., 2013; Mukai et al., 2009; Qian and Ferro, 2008). However, Siegel said, what is still not well characterized is the interaction between particles on a surface and the particles that then deposit on top of that initial layer and how the nature of specific materials affects resuspension.

Forced air HVAC systems are ubiquitous in the United States; they exist in nearly all commercial buildings and in 80 percent of residential buildings, creating possibilities for interactions between indoor PM and these systems, Siegel said. How the filters in a central forced system remove particles will be affected by how often the system runs and how much air goes through the filter. Leakage in such systems affects the efficiency of particle removal and dispersal, and there can be deposition on the surfaces within the HVAC system as well as resuspension from those surfaces. HVAC systems can serve as sources of particles or of precursors to particles, such as ozone, and they alter temperature, humidity, and indoor air mixing, which can in turn affect indoor chemistry and particle formation. "If we really want to understand indoor particles, we have to understand HVAC systems," Siegel said, "yet we are far behind in this area."

To illustrate how little is known about key fundamental parameters of HVAC systems, Siegel said that HVAC runtimes have been measured in only 213 homes, all from the southeastern United States and only over a few days to 1 week (Cetin and Novoselac, 2015; Stephens et al., 2011; Thornburg et al., 2004). He noted that runtimes play an important role in determining how much effective recirculation of air through a filter occurs. "If runtimes are short, it does not matter what type of filter is in place because air is not going through it," Siegel said. Runtimes matter less if the filter itself is not very good, which he said is the case in most homes. (In fact, runtimes can be quite short, and short runtimes compromise the ability to gain benefit from higher efficiency filters.) However, most of the models of runtimes and recirculation assume these to be much higher than those that actually take place in buildings.

Concerning the heterogeneity of indoor PM concentrations, Siegel said that most exposure estimates for indoor PM assume that the indoor air is mixed thoroughly because that makes the necessary calculations tractable. However, as Lynn Hildemann noted in her presentation, local concentrations near a particle source, such as a smoker or a stovetop, can be much higher than in a well-mixed environment. At the same time, the sinks in a building are also heterogeneous in terms of their effectiveness at removing PM from the air. In one experiment, for example, Siegel and a colleague put two different portable air cleaners at various places in a house, noting their distance from a particle source (Novoselac and Siegel, 2009), and found that both the location and the effectiveness of the particular device had a marked influence on indoor PM concentrations (see Figure 3-1). Proximity to a particle source also affects exposure, even at close distances, because the complicated fluid dynamics of air around a human body can affect how much is inhaled (Rim and Novoselac, 2009).

Having noted how little is known about HVAC systems, Siegel listed several other knowledge gaps that need to be filled. For example, ventilation dynamics (the AER, for example) can change dramatically over the course of a day (see Figure 3-2), but little is known about how such variations drive the levels of indoor PM. Sinks can also be dynamic, Siegel said, referring to the decreasing efficiencies of filters that occur over time (see Figure 3-3). Many HVAC filters in the United States use an electrostatic charge applied to the filter to remove particles, and this charge can decay

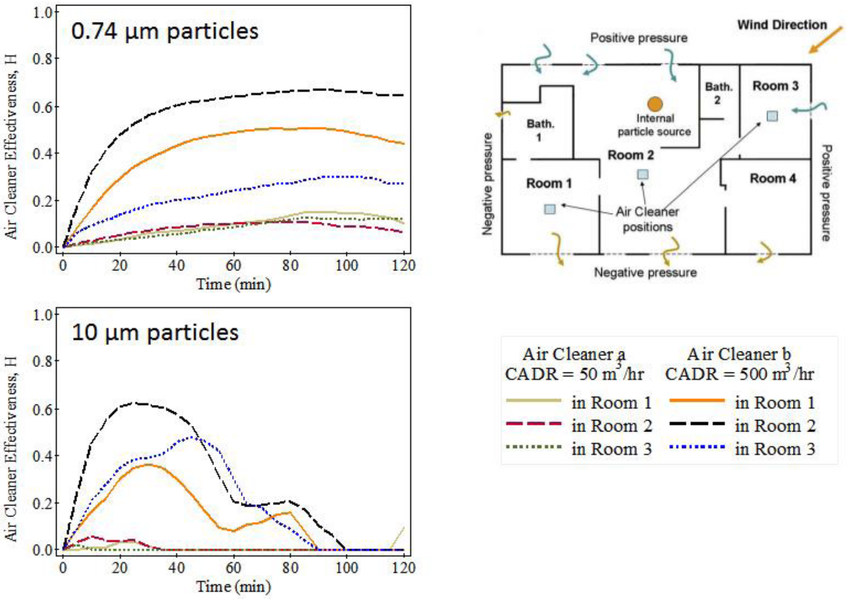

FIGURE 3-1 The location and effectiveness of portable air cleaners in removing indoor PM.

NOTE: CADR = clean air delivery rate.

SOURCES: Siegel slide 15, adapted from Novoselac and Siegel (2009) Figures 1 and 4; reprinted with permission from Elsevier.

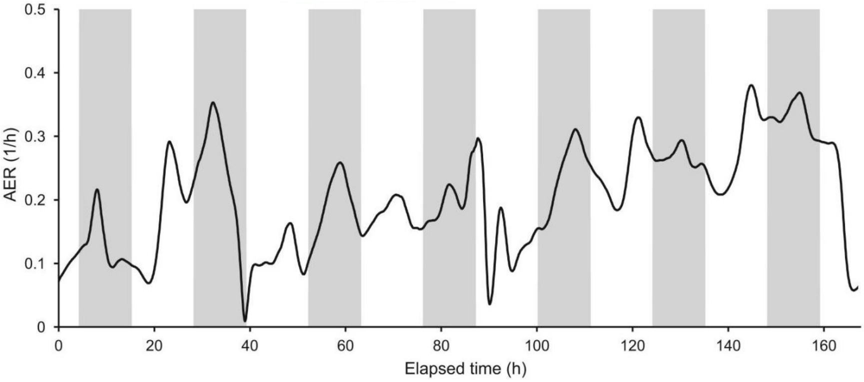

FIGURE 3-2 Air exchange rate (AER) in an unoccupied building over the course of 1 week.

SOURCES: Siegel slide 19, from Dias Carrilho et al. (2015) Figure 4; reprinted with permission from Elsevier.

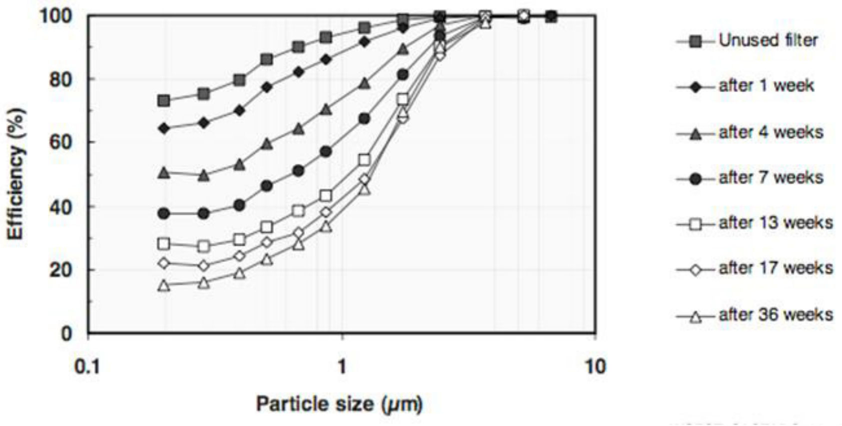

FIGURE 3-3 Decreasing efficiency of an air filter over time.
SOURCES: Siegel slide 20, from Lehtimäki et al. (2005). © 2005, ASHRAE (www.ashrae.org). Used with permission from ASHRAE (Investigation of mechanisms and operating environments that impact the filtration efficiency of charged air filtration media, RP-1189, 2005).

or be masked by particle deposition over time. "Even though this is well-identified as a problem, we do not understand what is causing this decay and why the decline is huge in some buildings and much less in other buildings," Siegel said. As an example of the type of research that is needed, he cited recent work looking at changes in filter efficiency and pressure drop as a function of what is being deposited on the filter and the particle structures that form there (Montgomery et al., 2015). "This kind of fundamental research that lets us understand how indoor PM sinks behave is important," Siegel added.

A final critical knowledge gap that Siegel addressed related to unseen surfaces and spaces, such as the space above drop ceilings and between walls and floors. The role that these spaces—which also include attics, crawl spaces, basements, and knee wall spaces—play as sources and sinks is largely unknown, Siegel said. Garages are perhaps the best studied of these unseen spaces as sources of indoor air pollution, but he said that he was aware of only one investigation of them that measured particle levels. "Even though we know these spaces can be important from an exposure perspective, they are largely unstudied," he said.

As one step toward filling these knowledge gaps, Siegel suggested that the field conduct what he called a "long-form building census" which would address the key building science parameters needed to understand and mitigate exposures to particles in buildings. Conducting such a census would not only generate knowledge but also create an opportunity for citizen science which might engage the people who work and live in buildings to pay more attention to their indoor environments.

INDOOR CHEMISTRY AND AEROSOLS[2]

Glenn Morrison began by noting that chemical transformations that take place in air, such as oxidation, photolysis, hydrolysis, oligomerization, and acid-base reactions, can influence aerosol levels and particulate formation. One well-studied atmospheric chemical reaction involves volatile organic compounds reacting with an oxidant, such as ozone, nitrate, or hydroxyl radical, to generate a variety of molecular products. The resulting sticky, polar molecules can serve as nuclei around which particles form, or else the polar molecules can condense onto existing particles. These particles can then agglomerate into larger masses. Together, the nuclei, condensed particles, and agglomerates are called secondary organic aerosols (SOAs). Sunlight is a major driver of this chemistry outdoors, but sunlight is less intense indoors, which potentially slows the process. Also, because of the short residence time indoors (hours or less) compared with outdoors (days), SOAs generated inside a building are "fresher" than their outdoor counterparts. Indoor surfaces play an important role in removing both SOAs and their precursors from indoor air, but they can also emit some of the precursors that eventually contribute to aerosol formation, and they can also serve as reaction sites, facilitating oxidative chemistry that can lead to SOA formation.

The indoor environment strongly influences precursor molecule levels, Morrison said. Important indoor sources of precursors include cleaning solvents, scented products, and foods. All three of these release large amounts of chemicals called terpenes, which are readily oxidized in air. Indoor oxidants levels are driven largely by outdoor ozone levels. Morrison said that there is a significant body of research showing that SOAs are generated indoors, and he cited a study showing that when an air freshener was introduced into a room with elevated ozone levels, there was a rapid increase in the concentration of submicron particles that persisted in the air for many hours (Sarwar and Corsi, 2007). A more recent study found that new particles with an average diameter of 100 nanometers can form indoors from paint solvents (Lazaridis et al., 2015).

The emerging science of indoor air chemistry is advancing on multiple

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[2] This section is based on the presentation by Glenn Morrison, a professor of civil, architectural, and environmental engineering at Missouri University of Science and Technology, and the statements are not endorsed or verified by the National Academies of Sciences, Engineering, and Medicine.

fronts, Morrison said. One advance is the ability to measure an increasing number of oxidized species, Morrison said, and as an example he cited a study in which the investigators were able to quantify levels of more than three dozen different compounds in aerosols formed by oxidation of solvents in household cleaners (Rossignol et al., 2013). Modeling is another area where progress is occurring, he said, with researchers adapting models developed for outdoor environments to account for the different surfaces and precursors found indoors. One such study (Carslaw et al., 2012) predicted that organic peroxides and nitrates would be the predominant compounds produced after a cleaning event but that the relative concentrations of different classes of chemicals produced in aerosols would vary depending on the amount of solvents released and the rate at which SOAs deposited on surfaces. "There is still a great deal of uncertainty in the ability to use models to be predictive of not just the aerosol mass concentration but also the composition," Morrison said. Recent experimental work has demonstrated that changing the indoor levels of ozone and terpenes, common constituents of cleaning products, has a significant impact on the composition of the PM that forms indoors (Khurshid et al., 2016). In particular, Morrison said, the level of $PM_{2.5}$-bound reactive oxygen species, which can irritate the lungs, can increase by more than four-fold when indoor levels of both ozone and terpenes are elevated.

Building operations can also influence aerosol chemistry. One recent study that Morrison cited found a strong influence of AER on peak SOA levels generated from select terpene compounds (Youssefi and Waring, 2015). "We still need to know about how buildings influence this chemistry," he said.

Several studies have shown that ozone can react with organic molecules deposited on surfaces to produce particles in the air above those surfaces (Sleiman et al., 2010; Waring et al., 2011). Morrison and a colleague found that this chemical reaction occurs much faster than would be expected if it were happening in the air (Shu and Morrison, 2011). What this might imply, Morrison said, is that many of the products of the chemistry that take place on surfaces can be transferred to aerosols and dust that can be resuspended and inhaled.

Room occupancy is an important factor in aerosol chemistry because skin contains chemicals that react readily with ozone. Human and animal bodies constantly shed skin in the indoor environment, and these skin cells and the skin oils can adhere to indoor surfaces. As a result, surfaces in occupied rooms are coated with chemicals waiting to react with airborne ozone. "That is one reason why our indoor environments are so reactive and why indoor ozone levels are lower than those outdoors," Morrison said. Another reason is that the humans in a room are also covered in these reactive compounds, and, in fact, research has shown that ozone levels fall when a human enters a test chamber designed to simulate an office environment (Fadeyi et al., 2013).

While the amount of sunlight indoors is much less than outdoors, it can still be sufficient to trigger chemical reactions, Morrison said. One study, for example, found that cooking produces nitrogen dioxide as a combustion byproduct and that the nitrogen dioxide sticks to surfaces, reacts with water in the air, and produces nitrous acid (Alvarez et al., 2014). Sunlight entering a room through a window can enhance this reaction, especially when surfaces are also coated with household cleaner residues. Nitrous acid is volatile, and when released from the surface into the air it will react with sunlight to produce hydroxyl radicals, one of the oxidants that can generate SOAs. As a result, in one study, the levels of hydroxyl radical near a window were of the same order of magnitude as is found outdoors. Morrison said that hydroxyl radical is indiscriminate, reacting with a wide range of volatile organic compounds and not just with terpenes.

Morrison emphasized that the development of sensitive instruments for monitoring outdoor air composition has created a great opportunity to better understand indoor chemistry. These instruments include high-resolution aerosol mass spectrometry for analyzing PM composition, fluorescence assay by gas expansion for detecting hydroxyl radicals, cavity ring-down spectroscopy for measuring nitrogen oxides, and direct analysis in real-time mass spectrometry for the real-time characterization of surface films. "Almost none of these instruments have been used indoors until very recently," Morrison said. One study using high-resolution aerosol mass spectrometry, for example, showed that there were hundreds—and perhaps thousands—of different compounds generated by oxidation chemistry (Romonosky et al., 2015). While it may not be possible to identify all of these compounds, Morrison suggested that this type of analysis can reveal the many factors that influence indoor chemistry.

Another area where Morrison said he expects progress to be made is in applying models of outdoor atmospheric chemistry to the indoor environment. Morrison said that the basic chemical reactions are well modeled, but researchers need to better account for the surface phenomena as well as building characteristics, occupancy, and human activity. Indoor surfaces, he reiterated, are coated with a film of organic material that can transfer material back and forth between aerosols and undergo chemical reactions. These reactions, in turn, are influenced by the acidity of the environment, which changes with human and animal activity. None of these processes are accounted for in outdoor models. Integrating building characteristics into models is challenging because of the sheer complexity and variety of building environments, Morrison added, and doing so successfully will require identifying those parameters of a building that are most important with respect to chemistry.

COMPOSITION OF INDOOR PM AND THE INFLUENCE OF SVOC PARTITIONING[3]

Given that buildings do a moderately good job keeping outdoor UFPs and PM_{10} from entering buildings, Charles Weschler said, the chemical constituents of these two classes of PM will be determined largely by chemical processes occurring indoors. Indoor UFPs are produced primarily via combustion, through gas-to-particle conversion, and via thermal desorption of SVOCs. The primary sources of indoor coarse particles include skin flakes, fibers, plastic wear particles, and soil and salt particles tracked indoors.

The chemical composition of $PM_{2.5}$, however, is determined by chemistry that occurs both indoors and outdoors. Weschler said that comparing the chemicals present in indoor and outdoor $PM_{2.5}$ shows indoor $PM_{2.5}$ that are rich in chemicals additives used in products that are part of the indoor environment, such as phthalate plasticizers, organophosphates, brominated flame retardants, and fluorinated surfactants. By weight, indoor $PM_{2.5}$ is approximately 50 percent organic carbon, with elemental carbon accounting for only 3 percent of the total particle mass. Sulfates and nitrates together account for nearly 30 percent of the weight, with ammonium ion and water together contributing about 15 percent at typical indoor relative humidities (see Figure 3-4). The total metal content in indoor PM is about 1 percent, with more than two-thirds of that being iron. Also present are zinc, vanadium, titanium, silver, copper, manganese, and chromium. Weschler explained that while small in amount, these metals may be relevant to human health given the evidence suggesting that water-soluble PM, which may be able to release those metals into the body, has a disproportionate effect on human health (Costa and Dreher, 1997).

Relative humidities above 25 percent have a measurable effect on the water content of $PM_{2.5}$. Depending on the composition of the particles—in particular, the water-soluble salts and oxidized organic compounds—$PM_{2.5}$ can be 10 to 40 percent water by weight when the relative humidity is between 50 and 70 percent. The water content of PM_{10}, with its lower soluble salt and oxidized organic content, is lower than that of $PM_{2.5}$. Water content is important, Weschler said, because it affects the partitioning of gases between air and particles and helps influence the chemical reactions that can occur on or within the particle, which also affects the particle composition (Lim et al., 2010). Weschler added that the water found in these particles is likely coated by an organic film (Gill et al., 1983) which can affect the transfer of gases into and out of the particle and partitioning.

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[3] This section is based on the presentation by Charles Weschler, an adjunct professor at Rutgers, the State University of New Jersey, and a visiting professor at the Technical University of Denmark and Tsinghua University, and the statements are not endorsed or verified by the National Academies of Sciences, Engineering, and Medicine.

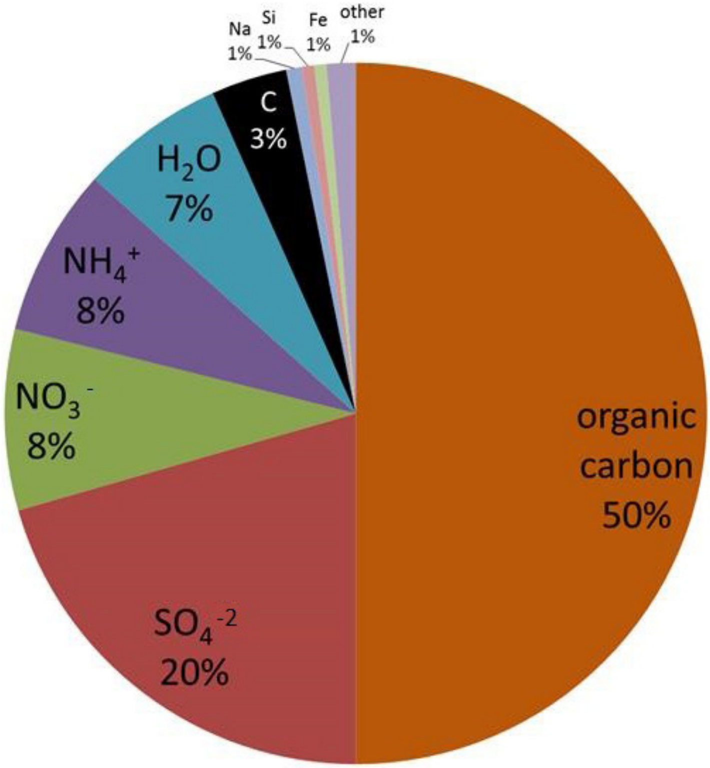

FIGURE 3-4 Typical chemical composition of indoor air by weight percent of $PM_{2.5}$.
SOURCE: Weschler slide 4.

The partitioning of SVOCs and various inorganic compounds between the gas phase and the surface of airborne particles plays an important role in determining the chemical composition of particles, Weschler said. In one of the first applications of aerosol mass spectrometry to the study of indoor PM, Michael Waring and his colleagues (Johnson et al., 2016) simultaneously sampled indoor and outdoor PM on the Drexel University campus. This analysis showed that hydrocarbon-like organic aerosols made up 19 percent of indoor PM, compared to 8 percent of outdoor PM (see Figure 3-5). A large part of this increase, Weschler said, arose from the partitioning that occurs because of the much higher concentrations of SVOCs found indoors compared to outdoors. "When an outdoor particle comes indoors, it will acquire phthalates, organophosphates, and perfluorinated surfactants from indoor air," Weschler explained. At the same time, the outdoor particles tend to lose polyaromatic hydrocarbons and ammonium nitrate when they move indoors. Data from the Relationship of Indoor, Outdoor, and Personal Air (RIOPA) study collected in Los Angeles, California; Houston, Texas; and Elizabeth, New Jersey, showed a similar increase in the organic content of indoor $PM_{2.5}$ compared to outdoor $PM_{2.5}$ (Polidori et al., 2006).

Increasing the level of SOAs affects SVOC partitioning in indoor environments by increasing both the concentration of airborne particles and the fraction of organic matter in the airborne particles, Weschler said. These increases, in turn, increase the proportion of SVOC in the particle phase versus the gas phase in a multiplicative fashion (Weschler and Nazaroff, 2008). In fact, he said, chamber experiments support this prediction (Benning et al., 2013; Chen and Hopke, 2009).

As Morrison pointed out, the occupants of a building influence the composition of indoor PM, and Weschler noted that humans shed their entire outer layer of skin every 2 to 4 weeks at a rate of 200,000 to 600,000 skin flakes per minute (30 to 90 milligrams of skin flakes per hour). Human skin is one of the very few sources of the chemical squalene in indoor environments. A 1973 study of size-fractionated indoor PM collected from a

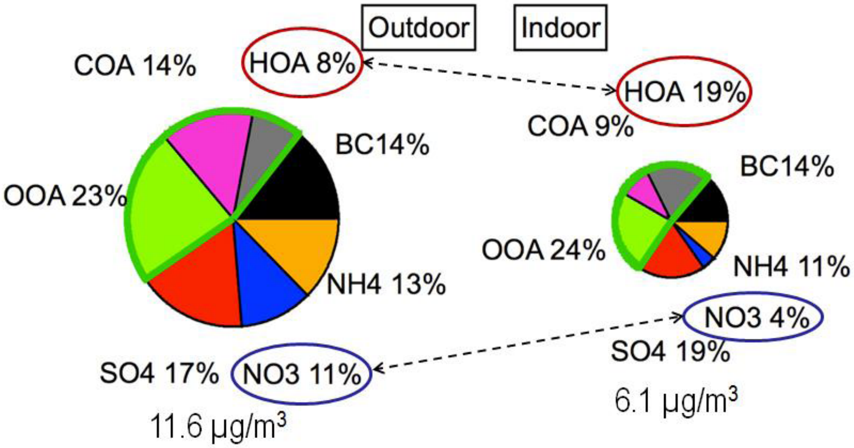

FIGURE 3-5 Aerosol mass spectrometry data showing the composition of indoor and outdoor PM.
NOTE: BC = black carbon; COA = cooking organic aerosol; HOA = hydrocarbon-like organic aerosol; OOA = oxygenated organic aerosol.
SOURCE: Weschler slide 10, from Johnson et al. (2016); reprinted with permission from John Wiley & Sons, Inc. © 2016.

house, a laboratory corridor, and the London Underground found that the squalene content was between 40 and 100 micrograms per unit gram of PM (Clark and Shirley, 1973). From this number, the investigators calculated that indoor PM is about 1 percent skin flakes by weight. Weschler said that other studies conducted since then have arrived at similar values.

Occupants contribute more than just skin cells to indoor PM, he added; they also shed bacteria and fungi along with their skin cells. One study of the microbial content of indoor PM in a classroom found that the amount of bacteria in indoor PM was 80 times higher and the amount of fungi 15 times higher when the room was occupied than when the classroom was empty (Hospodsky et al., 2015). The particle mass was also nine-fold higher in the occupied classroom. This study did not determine what fraction of the microbial PM content was viable.

Indoor PM particles include thousands of organic species. “The complexity is staggering,” Weschler said, adding that little work has been done to characterize the organic molecules found in indoor PM versus outdoor PM (Heald et al., 2010). Recently, investigators have shown that the composition of PM, both indoor and outdoor, influences the uptake of gases onto the particles and the subsequent chemistry that can occur within the particle (Morgan et al., 2015). Studies have also found that particles can exist in liquid, semi-solid, and glassy phases and that multiple phases can coexist in the same particle (Koop et al., 2011). This is important, Weschler said, because water and gas partitioning depends on the phase, as does the diffusion of molecules within the particle. For example, the amount of diffusion within a particle is up to 10 million times smaller in the semi-solid phase than in the liquid phase (Hodas et al., 2015), which, he pointed out, would affect particle chemistry. Weschler said that most of the modeling work on partitioning assumes that the organic content of PM is in the liquid phase, so if this is not the case, there will be large errors in the output of these models. What is not known, he said, is if this is a serious issue for indoor PM.

Weschler said that in his view more information is needed about the chemical form and oxidation state of the metals in PM, given the important effects these have on the chemical reactivity and bioavailability of metals. One study, for example, found that 25 percent of the iron in PM from urban and rural sites in Georgia was in the Fe(II) oxide state and that 15 percent of the iron was in soluble form (Oakes et al., 2012a,b). What remains to be characterized, he said, are the identities of the ions or molecules bound (coordinated) to the iron in these particles.

Another question Weschler said he would like to see addressed concerns the timescale over which SVOCs desorb from inhaled PM and the residence time of particles in the respiratory tract, which are important factors for the potential health effects of breathing PM. Those times, he explained, will depend on particle diameter and on the partition coefficient. His group has tried to model this process despite the various technical complications, he said. “We are fairly certain that some SVOCs in some particle size ranges make it to the alveoli, while for other SVOCs and in other size ranges, the SVOCs desorb fairly high in the respiratory tract.” Experimental studies, he added, have proved to be even more challenging than the modeling efforts.

Weschler also questioned the role that reactive oxygen species associated with PM might play in triggering oxidative stress. It is known that inhaling PM enriched in certain transition metals will induce oxidative stress, so it might be the case that having reactive oxygen species present on PM would increase the potential for harm. Studies have shown that reactive oxygen species are present in indoor air (Khurshid et al., 2016) and that they can remain active in air for many hours, with a decay half-life of 6 to 7 hours (Chen et al., 2011).

In summary, Weschler said, indoor PM is enriched in synthetic organic chemicals such as plasticizers and flame retardants, metals, and microbes from occupants, and as PM is transported from outdoors to indoors, the chemical content can change substantially. “We need to know more about the actual molecular nature of the chemicals present in indoor PM, both in terms of the transition metal complexes and the organic species,” he said. “I think a large number of people are unaware of the holes in our knowledge when it comes to the chemical composition of indoor PM.”

DISCUSSION

Corsi launched the discussion by asking the panelists to comment on the importance of unseen spaces to the topics they discussed. Siegel said that those spaces are very important and, based on energy conservation studies, are well connected to the rest of the building. As such, he said, he would like to see more research to identify how much PM is in those spaces, both airborne and deposited, and how that changes the distribution of particle size and concentration coming in from outdoors. Morrison agreed that little is known about the chemistry that occurs in interstitial spaces and said he thought that the first place to start with regard to addressing that deficit would be to collect samples using many of the new technologies used to collect outdoor PM. “Just deploying those technologies indoors will lead to a great deal of discovery,” he said. Weschler gave an example of what can be learned from studying the PM in interstitial spaces. When he worked at Bell Laboratories, he said, he and his colleagues sampled the PM that was coming from the spaces under the raised floors in telephone data centers. They found that PM was “grossly enriched” in phthalate esters, which presumably came from the plasticizers present in the PVC insulation surrounding communication cables running through the space under the floor.

Brent Stephens, noting that calculations of SVOC partitioning use the total suspended particle mass as a measure of particle concentrations, asked Weschler if the resulting estimates would be improved if the calculations accounted for the size distribution of the particles. Weschler replied that the estimates for partitioning that use total suspended particle mass are crude and provide only order of magnitude–type results. "You would certainly refine those estimates by looking at the fraction of organic matter in different size ranges," Weschler said.

An online participant said that she had seen significant spikes in indoor PM levels associated with humidifiers, boiling water, and sometimes even showering. She asked if anyone had studied particle emissions from water. The answer, Weschler said, is yes, and those particles, sometimes referred to as "gray dust," emerge from water-soluble salts when aerosolized water droplets evaporate. That is why it is important, he added, to use deionized water in ultrasonic humidifiers. However, Gediminas Mainelis from Rutgers University said that his group has observed that particles of unknown composition form when even the purest water is aerosolized. Morrison said that certain types of evaporative coolers also produce high particulate loads for the same reason. Siegel added that HVAC systems often generate a water aerosol for the purpose of humidification or air cleaning, but the extent to which this produces indoor PM has not been explored.

Another online participant proposed tapping into the data collected by Internet-enabled home thermostats on temperature and HVAC runtimes. Siegel said he thought this was a "great idea," particularly if those data could be combined with information about the buildings associated with those thermostats. Privacy issues could be a concern, he said, but he expressed confidence that issue is resolvable.

Vito Ilacqua from EPA asked the panelists to suggest which parameters of the indoor environment would be most important to have more data on in order to better understand indoor PM behavior. Siegel said that acquiring data on the amount of surface area in different types of buildings, the nature of interstitial spaces, and HVAC operation parameters would be easy and inexpensive to do and simply requires making that a priority and doing it. More work is needed on advanced instrumentation to better characterize indoor PM composition, he added. Siegel also said that there are many inexpensive and easy steps that could be taken today to protect people in buildings from PM exposure without having to wait for better characterized buildings and particles. Offering one specific example of such a step, he said, "It is a no-brainer for certain people in certain indoor environments to be using better filtration or activated carbon filtration."

Morrison agreed with Siegel that the presumption from a chemistry perspective is that indoor exposure to SOA is not good. "That is an assumption right now, and we do not know for sure what the direct health effects are," he said, "but if we make that assumption, it is relatively straightforward to remove ozone from indoor air, which is the main driver of SOA levels." Morrison added that, given the difficulty in changing behaviors that lead to elevated exposures to indoor PM, it will be important to integrate mechanisms to remove the main drivers of indoor PM exposure into building design.

Lynn Hildemann asked the panelists to comment on the possible effects that humidity might play in the indoor environment. Morrison replied that there are cases where the moisture content of the air influences the chemistry on particles. Less is known, he added, about the influence of humidity on ozone uptake at the particle surface. Siegel noted that every HVAC system with an operating cooling coil has water-saturated air at some point. "High humidity is a reality in many buildings much of the time," said Siegel.

David Young from INLOGIX asked for the panelists' thoughts on the challenges of conducting health investigations in residences with HVAC systems equipped with ultraviolet (UV) light systems. Morrison said that while UV lights can potentially deactivate certain microorganisms, they can also produce high levels of ozone. Given what is known about ozone as a lung irritant and its ability to generate the type of reaction products—which he described in his presentation—Morrison said that he is not in favor of anything that releases ozone into the home environment. Siegel added that UV lights also contribute to the degradation of certain components and insulating materials in HVAC systems. Corsi said that he has found UV light systems in many animal shelters and has measured high ozone levels in kennels in those shelters. Mainelis added that handheld hair dryers produce high levels of ozone—as much as 10 parts per billion above the background level—within the breathing zone of the user. Morrison said that hairdryers and many other unregulated devices produce ozone unintentionally.

4

Characterizing Indoor Exposure Levels

The workshop's third session focused on exposure levels from indoor PM, including approaches for measuring exposure and some of the factors that determine exposure levels. Barbara Turpin of the University of North Carolina Gillings School of Global Public Health discussed how characterizing indoor air can provide insights into the sources of indoor PM and the transformations that these particles can undergo. Roy Harrison of the University of Birmingham addressed some of the determinants of and exposure to indoor PM. Gary Adamkiewicz of the Harvard T.H. Chan School of Public Health reviewed the socioeconomic factors that can influence indoor PM exposures. An open discussion moderated by Terry Brennan followed the three presentations.

PM$_{2.5}$ EXPOSURE CHARACTERIZATION PROVIDES INSIGHTS INTO SOURCES AND TRANSFORMATIONS[1]

As had been discussed in earlier workshop sessions, Barbara Turpin said, indoor PM$_{2.5}$ concentrations represent a balance between sources and sinks, and the sources include indoor emissions of particles and outdoor-to-indoor transport of particles. The sinks include the deposition of particles on indoor surfaces, filtration by HVAC systems, and exfiltration of

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[1] This section is based on the presentation by Barbara Turpin, a professor of environmental sciences and engineering at the University of North Carolina Gillings School of Global Public Health, and the statements are not endorsed or verified by the National Academies of Sciences, Engineering, and Medicine.

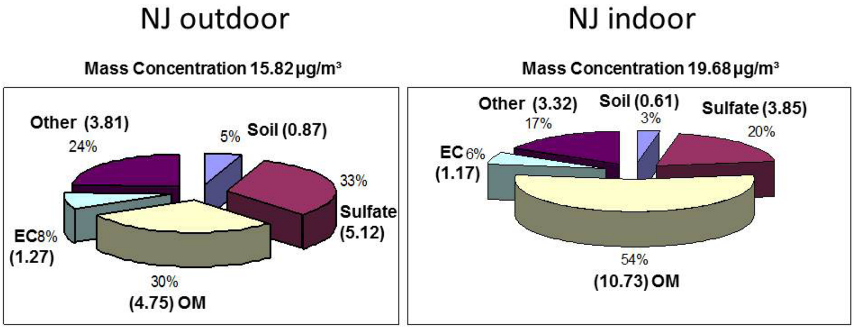

FIGURE 4-1 Indoor and outdoor $PM_{2.5}$ concentrations and compositions from homes in Elizabeth, New Jersey.
NOTE: EC = elemental carbon; OM = organic matter.
SOURCE: Turpin slide 3, Reprinted by permission from Macmillan Publishers Ltd.: *Journal of Exposure Science and Environmental Epidemiology* (Polidori et al., 2006), adapted from Figure 3.

particles. Chemistry and partitioning also affect indoor $PM_{2.5}$ concentration because of the changes that particles may undergo when moving from the temperature and humidity conditions outdoors to different conditions indoors.

Data from the RIOPA study, which was undertaken to evaluate the contribution of outdoor sources of air pollutants to indoor concentrations and personal exposures (Weisel et al., 2005), found that the mass of organic matter in indoor household $PM_{2.5}$ was more than twice the organic matter in $PM_{2.5}$ collected outside of the same house at the same time (see Figure 4-1), while the masses of sulfates, elemental carbon, and soil material were lower indoors. The additional organic matter in indoor PM has to be coming from an indoor source, Turpin said, either emitted as PM or produced via a phase change or a chemical reaction. She and her colleagues measured the amount of particulate organic matter indoors versus outdoors and calculated that, on average, 71 to 76 percent of the organic carbon in indoor $PM_{2.5}$ comes from indoor sources, with a lower bound estimate of 41 percent (Polidori et al., 2006).

Data from another study using an unoccupied home near Fresno, California, showed that it is difficult to get particulate nitrate from outdoors to indoors (Lunden et al., 2003), a finding that Turpin said makes sense because nitrate is semivolatile and exists in equilibrium with the gaseous nitric acid. When a nitrate-bearing particle and the equilibrium-associated nitric acid gas moves from outdoors to indoors, Turpin explained, the nitric acid is scrubbed from the air, either because it cannot pass through the building envelope or because it sticks to interior walls once it has made it inside the building. Once the nitric acid is removed, the ammonium nitrate has to re-equilibrate and it does so by turning into gaseous nitric acid. Calculations using data collected in southern California show that at a typical indoor air exchange rate, only approximately 12 percent of the outdoor particulate nitrate is found indoors.

The degree to which the components of outdoor $PM_{2.5}$ penetrate and persist indoors vary broadly, from 4 percent for soil components to 78 percent for sulfate (Lunden et al., 2008; Meng et al., 2007; Polidori et al., 2006). The observed differences are a function of the size distribution of the diverse aerosol components within $PM_{2.5}$ and changes in the gas–particle partitioning of the components as the aerosol encounters indoor conditions. "The fraction of outdoor PM that you find in indoor air varies significantly depending on the PM species," Turpin said. "In addition, the composition of that PM changes when you bring outdoor PM indoors." She also noted that the composition of indoor PM of indoor origin is mostly organic (see Figure 4-2).

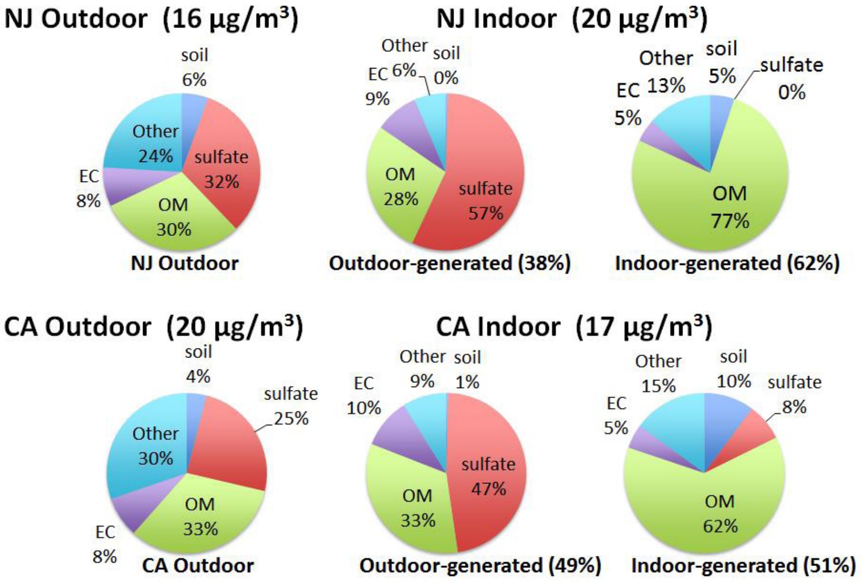

FIGURE 4-2 Indoor-generated sources contributed the majority of $PM_{2.5}$ in households in New Jersey (62% of the total) and in California (51% of the total). Chemically, indoor generation was found predominantly to be organic matter (77% in New Jersey and 62% in California).
NOTE: EC = elemental carbon; OM = organic matter.
SOURCE: Turpin slide 9.

It is also possible to use a mass balance model to calculate the fraction of indoor $PM_{2.5}$ that are of outdoor origin. This calculation entails accounting for the species-resolved size distribution, for whether the windows in the home were open or closed, and for what the losses from air conditioning and filtration would be as well as taking into account measured variations in AERs and the day-to-day particle composition (Hodas et al., 2014). For elemental carbon and sulfate, the agreement between calculated and measured values was good, Turpin said, but it was not good for organic carbon (see Figure 4-3). That latter result was not surprising, she said, given that there is so much organic carbon generated indoors and that these modeled values exclude indoor sources.

Turpin and her colleagues have used this model to take outdoor $PM_{2.5}$ measurements and predict what would happen to these particles when they transited indoors (see Figure 4-4). For a home near a major roadway in the northeastern United States, at an AER that is typical of low-income homes (0.90 per hour), the fraction of outdoor $PM_{2.5}$ that makes it indoors and remains suspended was estimated to be 62 percent, while in a southwestern suburban home that is not near a roadway and has an AER typical of a median-income home (0.45 per hour), that fraction would be 36 percent.

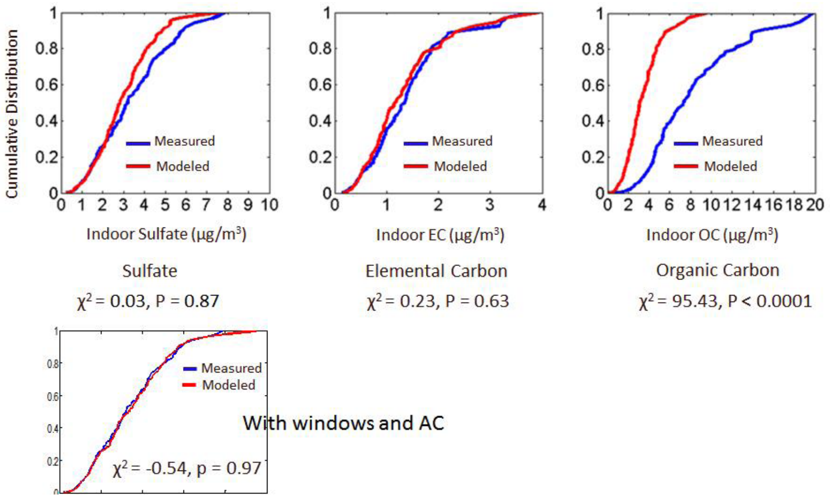

FIGURE 4-3 Comparison of the cumulative probability of indoor concentrations of indoor sulfate, elemental carbon (EC), and organic carbon (OC) between a mass-balance model assuming no indoor sources and RIOPA measurements.
SOURCE: Turpin slide 11, from Hodas et al. (2014) Figure 1; reprinted with permission from Elsevier.

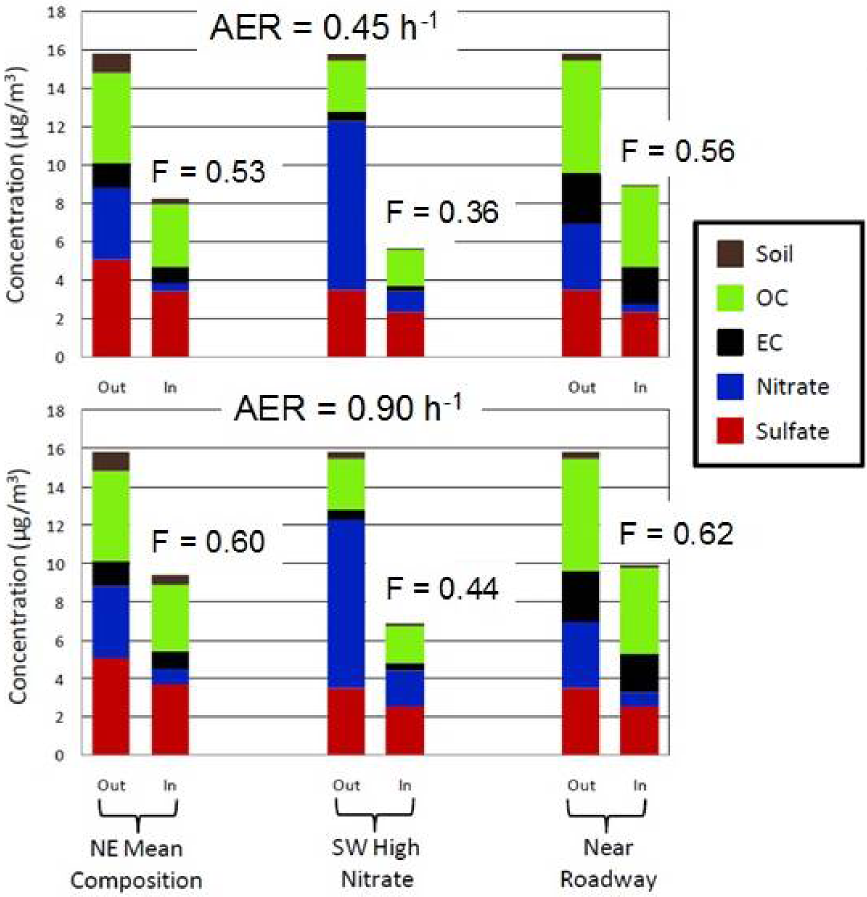

FIGURE 4-4 Infiltration factors (F) representing the indoor proportion of outdoor particles, effectively determining the indoor PM concentration in the absence of indoor sources.

The infiltration factors reported here were calculated from a model that considers the particle size-dependence of the infiltration factor, the various particle size distributions of different chemical components of outdoor $PM_{2.5}$ and the air exchange rate for a typical [AER = 0.45 h^{-1}] and low-income [AER = 0.90 h^{-1}] U.S. residence.
NOTE: AER = air exchange rate; EC = elemental carbon; NE = Northeast; SW = Southwest.
SOURCE: Turpin slide 12; reprinted by permission from Macmillan Publishers Ltd.: *Journal of Exposure Science and Environmental Epidemiology* (Hodas et al., 2012), adapted from Figure 3.

Turpin's conclusion from this study is that there is "quite a bit of geographic and seasonal variability in the fraction of outdoor PM that makes it indoors."

As an aside, Turpin noted that there is also large variability in the health effect estimates for outdoor $PM_{2.5}$, and she cited studies (Bell et al., 2009; Peng et al., 2009) showing that the increase in respiratory hospital admissions per 10 microgram per m^3 increase in $PM_{2.5}$ was smaller in the southwestern United States than in the Northeast. "Some of that difference could be because the composition of aerosol is different in the southwest than in the northeast," Turpin said, "but some could be from exposure error given that we are not measuring $PM_{2.5}$ levels indoors where people are spending most of their time and the fraction of PM that gets indoors is different in different places." In fact, a study conducted in China that accounted for the fraction of outdoor PM that becomes indoor PM produced larger effect estimates, less inter-city heterogeneity, and a better fit between daily mortality figures and model prediction (Chen et al., 2013).

To support the idea that gas-particle partitioning changes as particles move from outdoors to indoors, Turpin used gas and particle phase polycyclic aromatic hydrocarbon (PAH) measurements from the RIOPA study. A significant amount of variability in the PAH gas-particle partitioning was associated with changes in temperature going from indoors to outdoors, which would affect the volatility of these compounds (Naumova et al., 2003). Subsequent modeling studies for a more complex mixture of organic compounds yielded similar results which correlated geographic differences in temperature gradients, air conditioning and heating use, and indoor organic matter emissions to indoor organic PM composition (Hodas and Turpin, 2014).

More recently, Turpin and her colleagues have been measuring levels of oxidized volatile organic compounds in both outdoor and indoor air. Measurements from 13 homes show the indoor levels of water-soluble organic compounds, which are presumed to be oxidized, are more than an order of magnitude higher than the outdoor levels. Turpin and her colleagues are currently working to determine the identity of those compounds. Exposures to oxidized volatile organic compounds are poorly characterized, and Turpin predicted that these compounds participate in further chemistry on indoor surfaces in damp homes (for example, via hydrolysis, oxidation, acid-catalyzed, or nucleophilic chemistry on walls, skin and wet aerosol particles).

SOME DETERMINANTS OF INDOOR PM CONCENTRATIONS AND EXPOSURE[2]

Over a decade ago, Roy Harrison and his colleagues measured the flow of air pollutants from a busy road in London into an empty office and found substantial wind-dependent penetration of pollutants indoors, particularly $PM_{2.5}$ (Riain et al., 2003). As Harrison told the workshop audience, a detailed analysis of similar data from an empty office at the University of Westminster showed that there was a lag of approximately 20 minutes between changes in the outdoor $PM_{2.5}$ levels and indoor levels. Measurements of PM_{10} and PM less than 1 micron in diameter (PM_1) in an occupied house found substantial reductions of both PM_{10} and PM_1 indoors compared to roadside measurements, except when the occupants were cooking or when someone entered the house (see Figure 4-5).

When the analysis focused on particle number instead of particle mass, the results showed similar spikes for indoor-emitted PM reflecting human activity. After accounting for the spikes, there was good correlation between indoor and outdoor particle number levels, though there was a much bigger attenuation of the indoor concentrations for particle number than there is for particle mass. “We see a substantial reduction in indoor particle numbers compared to outdoors when we look solely at the penetration of outdoor particles to the indoor environment,” Harrison said.

In another study, Harrison and his colleagues measured particle size distributions both in an unoccupied, sealed walkway with little ventilation above a busy highway and from the nearby roadside. When they plotted the ratio of indoor to outdoor numbers by particle size, the results, as Harrison recounted, were surprising in that there was a rapid decline in indoor-to-outdoor ratio at larger diameters (see Figure 4-6). He said that he would not expect such a large drop-off if the buildings were better ventilated, and he did not expect these results to be typical of all buildings.

Harrison then discussed the results of a study conducted in Bologna, Italy (Zauli Sajani et al., 2015) in which outdoor air was pumped into two unoccupied rooms, one near a heavily trafficked location, the other in a residential neighborhood, to look specifically at particle sinks (see Figure 4-7). This study found that there was a more substantial loss of UFPs than of $PM_{2.5}$ when moving from outdoors to indoors. An analysis of the chemical composition of the particles showed that approximately 95 percent of the nitrate was lost moving from outdoors to indoors, with much smaller losses of sulfate and organic carbon. Measurements showed there was rel-

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[2] This section is based on the presentation by Roy Harrison, the Queen Elizabeth II Birmingham Centenary Professor of Environmental Health at the University of Birmingham, and the statements are not endorsed or verified by the National Academies of Sciences, Engineering, and Medicine.

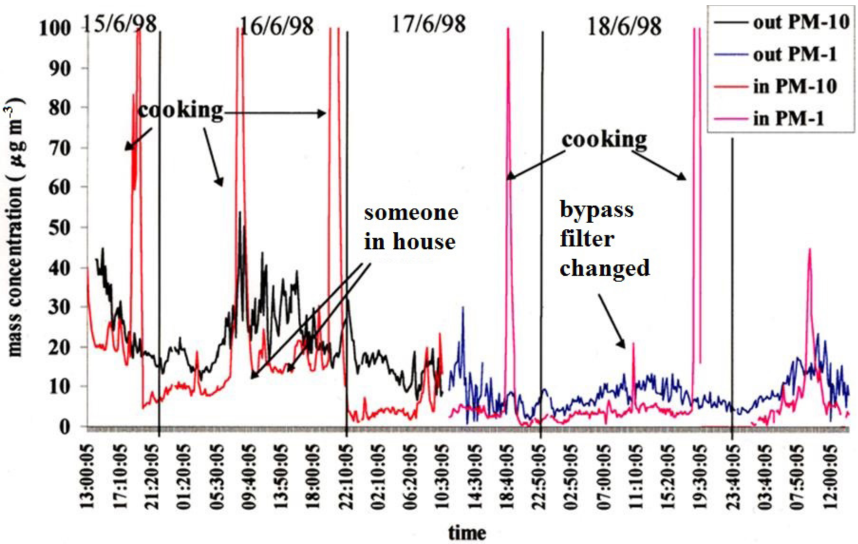

FIGURE 4-5 Indoor and outdoor PM_{10} and PM_1 mass concentration measurements at the roadside and inside a house as a function of time.
SOURCES: Harrison slide 5; underlying research discussed in Jones et al., 2000.

atively little loss between outdoors and indoors for $PM_{2.5}$ mass, but there was a substantial loss of ultrafine particle numbers, which Harrison noted was especially pronounced for rooms near road traffic.

There are many possible explanations for the heavy loss of UFPs, Harrison said. One is that their deposition velocities are higher than for larger particles. Modeling results suggest that coagulation of particles in the 30- to 50-nanometer range is likely to be rapid and that it may be a factor when the concentration of particles is high. Evaporation of UFPs is a possible third mechanism, one Harrison believes to be important because the walls of the unoccupied room were likely to serve as a sink for the SVOCs that dominate the composition of traffic-generated UFPs.

Another study, also conducted in Bologna, measured indoor and outdoor PM at the front and back of two buildings—one on a heavily trafficked street and a second on a low-traffic residential street—during hot and cold seasons (Zauli Sajani et al., 2016). During the summer, there was little difference in the $PM_{2.5}$ levels at analogous measurement locations. In winter, however, there was a significant difference between outdoors and indoors at both the front and rear measurement locations, which Harrison believes arose because outdoor $PM_{2.5}$ in the winter is likely to have a higher nitrate content than outdoor $PM_{2.5}$ in summer. The data from

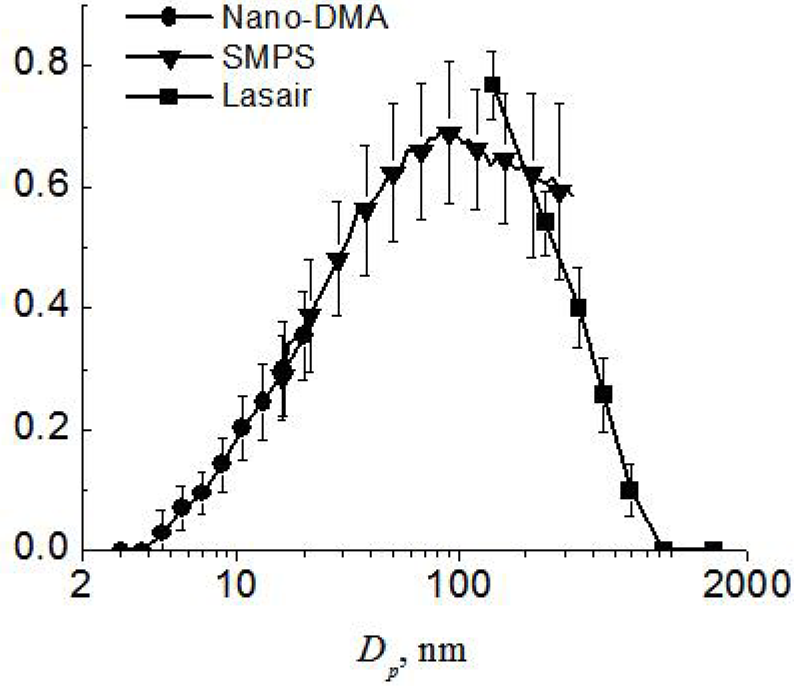

FIGURE 4-6 Indoor-to-outdoor particle concentration ratio in Birmingham City Centre (UK) offices by particle size, as characterized by Nano-DMA, SMPS, and Lasair measuring systems.
SOURCE: Harrison slide 11.

this study also showed a substantial loss of smaller particles when moving from outdoors to indoors, particularly for particles collected at the front of the building. A study conducted in Prague named cooking and cleaning materials as the largest contributors to indoor-generated PM. Incense burning, vacuuming, and smoking were other important sources of indoor PM identified in this study, Harrison said.

Harrison then addressed the subject of exposure and, in particular, the difference between measurements of personal exposure to PM versus the results from static indoor monitoring. Data from one study showed that personal exposure to carbon monoxide and nitrogen dioxide was well reflected by a static room monitor, but the personal measurement for PM_{10} was always higher than that determined from the static measurement (Kim et al., 2002). Harrison said that the larger personal exposure levels likely resulted from a “personal cloud” of shed skin cells and dust from clothing.

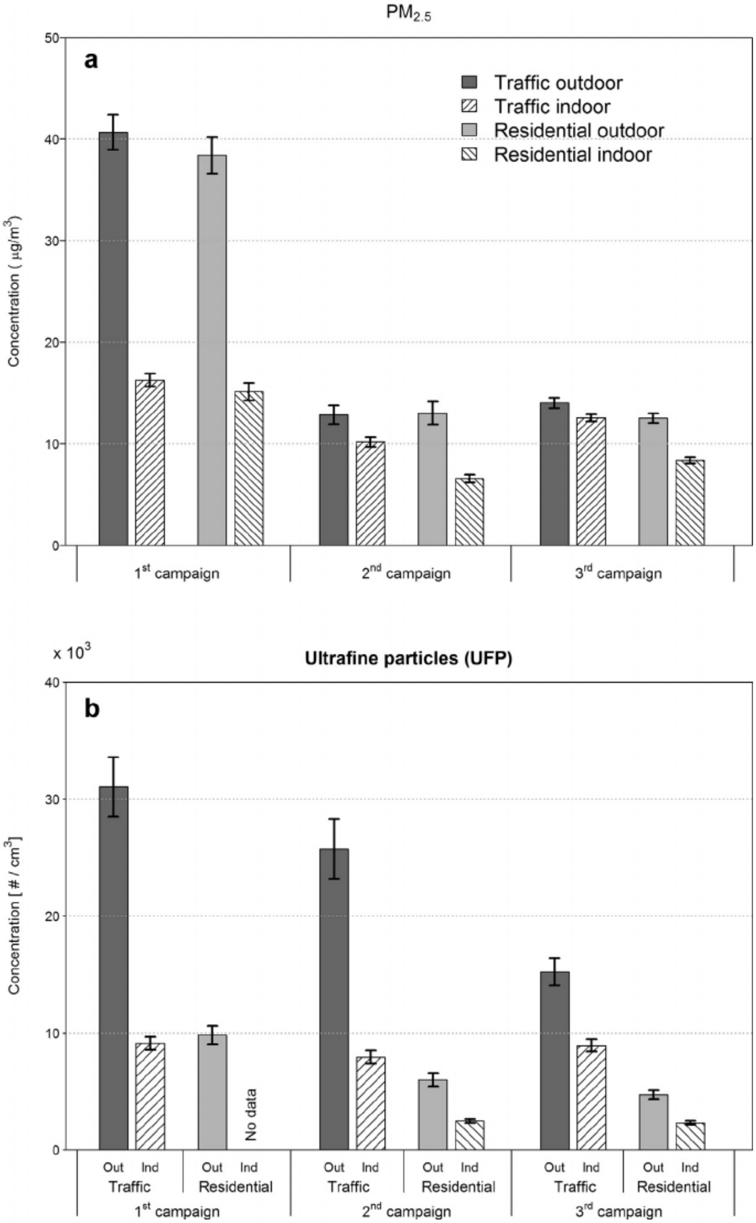

FIGURE 4-7 Average value and standard error indoor and outdoor (a) $PM_{2.5}$ and (b) UFP levels in Bologna, Italy, during three monitoring periods.
SOURCES: Harrison slide 13, from Zauli Sajani et al. (2015) Figure 1; reprinted with permission from Elsevier.

While the difference between the personal measurements and the static room monitor for $PM_{2.5}$ was smaller, Harrison said that the exposures to these particles can also be significantly higher than would be reflected by measured indoor concentrations because of this personal cloud effect.

Reflecting on the meaning of these findings with respect to health risk, Harrison said that they point to a number of unresolved issues, starting with the differential toxicity of particles from various sources or of those with different compositions and sizes. He wondered if particles from indoor origins such as cooking and resuspended house dust are as toxic as the outdoor pollutant mixtures measured in most epidemiological studies and if the elemental carbon component of diesel particles is comparable in toxicity to the organic component, which is largely from lubricating oil. He also wondered if the fact that buildings are very protective for UFPs, SVOCs, and nitrates matters in terms of health risk and what the determinants and significance of the personal cloud of particles is for health.

SOCIOECONOMIC DETERMINANTS OF INDOOR PM EXPOSURE[3]

Gary Adamkiewicz began his presentation by stressing two points: there are potential disparities in the exposure of individuals and communities to high levels of PM, and there are many instances where people are exposed to high levels of indoor pollutants known to cause adverse health effects, yet these issues have been largely ignored by policymakers. As an example, he cited cooking and ventilation and said that there are certainly disparities with regard to the type, age, and condition of ventilation equipment installed in kitchens. He observed, though, that even if everyone in the United States had the same stove and ventilation equipment, there would still be disparities as a result of differences in the homes people live in. His research has focused on public and low-income housing, where an open kitchen and living room often form one primary living space. In such homes, a family's exposures to PM generated during cooking is likely to be higher than in a middle- or upper-class home with a separate kitchen. But even if everyone American lived in the same type of home, he added, there would be disparities in exposures due to different levels of outdoor PM. "All of this is to say that we need to take a multilevel view of the determinants of exposure to indoor pollutants," Adamkiewicz said. "We have to look at how a household embeds within a building that embeds within a neighborhood."

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[3] This section is based on the presentation by Gary Adamkiewicz, an assistant professor of environmental health and exposure disparities at the Harvard T.H. Chan School of Public Health, and the statements are not endorsed or verified by the National Academies of Sciences, Engineering, and Medicine.

TABLE 4-1 Drivers of Exposure Disparities in Indoor Environments

Sources	Indoor Sources	• Cooking appliances • Tobacco smoke • Cleaning products	• Air fresheners • Personal care products • Furnishings	• Pesticides • Pollutant reservoirs • Water sources
Settings	Outdoor Sources	• Traffic • Industrial activity	• Residential activity • Contaminated soil	
Structure	Physical Structure	• Age of structure • Size of living space • Heating systems	• Mechanical ventilation • Size/design of structure • Single family versus multifamily • Leakage and/or air exchange	
Behavior	Source Use Patterns	• Cooking appliance use • Cooking practices	• Smoking behavior • Consumer product usage • Personal care product usage	
	Activity Patterns	• Time spent at home	• Interaction with sources • Influences on air exchange	

SOURCE: Adapted from Adamkiewicz slide 4.

There are so many drivers of disparities—including different sources of indoor PM, the settings in which people are exposed, the structures in which they live and work, and individual behaviors and activity patterns (see Table 4-1)—that eliminating or at least reducing the disparities can seem intractable, Adamkiewicz said. Nonetheless, he continued, it is possible to approach them mechanistically and to identify the most important ones that can be addressed using what is already known about buildings and sources. One issue that he identified, though, is that these drivers are not considered in most studies of exposure. For example, the multifamily dwellings that house low-income families often have many deferred maintenance issues, including ventilation systems that do not function properly, so standard assumptions about AERs may not apply to those residences. There are many instances, too, where stoves are used not only for cooking but also as a source of supplemental heat in low-income households, which would potentially increase exposures to nitrogen oxides and PM beyond what might be included in typical models of indoor exposure. Adamkiewicz presented data for some of these housing-related variables (see Table 4-2).

Leakage and AER are two variables that are important to exposure and that differ by socioeconomic status (Chan et al., 2005). Data from single-family homes show, for example, that low-income homes have higher normalized rates of leakage, which would be expected to decrease PM concentrations because of the important influence of indoor sources. However, low-income homes are typically much smaller than middle- and upper-class homes, and the smaller volume of low-income homes would be expected to increase indoor PM concentrations, Adamkiewicz explained. "We need a framework to understand how these different factors work together mechanistically," he said, referring to the fact that multiple determinants of indoor air quality can add up in complex ways that affect exposures and cumulative risk. He also emphasized the importance of considering PM originating from both indoor and outdoor sources.

In a modeling study, Adamkiewicz and colleagues examined how various inputs might affect indoor air quality (Adamkiewicz et al., 2011). They started by taking 10 years of Boston outdoor air quality data, varied AERs, sources, and ambient concentrations, and then took the ensemble of results and divided the individual elements into quartiles of $PM_{2.5}$ exposure level (see Figure 4-8). As expected, Adamkiewicz said, they found that many factors contributed to indoor PM levels, with air exchange and smoking having the biggest effects. The most important finding, he said, was that there were many more indoor factors than the outdoor pollution level that affected indoor PM levels. "Even at very high outdoor air pollution levels and high air exchange rates, the biggest impacts were from indoor factors," he said.

Time-activity patterns are another variable that can map onto socioeconomic status (see Figure 4-9), which Adamkiewicz said points to the importance of understanding the make-up of a community and how its members conduct their daily activities when thinking about exposure disparities. A community with a large number of low-income seniors, for example, would likely have relatively high exposures to indoor PM. "If you think about the chain of events leading to health effects that we should care about, these are important microenvironments to focus on," Adamkiewicz said.

Numerous studies have shown that smoking, which is linked to socioeconomic status, can be a major contributor to indoor $PM_{2.5}$ (Frey et al., 2014; Russo et al., 2015). Adamkiewicz and colleagues, for example, looked at $PM_{2.5}$ and nicotine levels in common areas in multifamily housing in Boston and found differences related to resident characteristics, smoking policy, and season (Arku et al., 2015). The highest levels of $PM_{2.5}$ and nicotine were found in winter, in units housing the elderly and disabled, and in buildings without smoke-free policies, suggesting that even elderly nonsmokers may be exposed to elevated levels of $PM_{2.5}$ produced by smokers.

TABLE 4-2 Representative Housing Variables Associated with Indoor Environmental Exposures by Household Income (data from the American Housing Survey, 1999)

	Income Category	
Housing Variable	< \$30 K/Year (n = 25,647)	\$30 < \$60 K/Year (n = 25,840)
Built before 1980 (%)	71.56	65.72
Area of peeling paint larger than 8 × 11 in (%)	3.11	2.04
Any inside water leaks in past 12 mo (%)	9.14	8.67
Neighborhood with heavy street noise or traffic (%)	28.19	25.42
Industry or factory within half block (%)	6.90	5.50
Unit uncomfortably cold for ≥ 24 h (%)	10.70	9.67
Evidence of rodents in unit (%)	17.77	16.81
Mean floor area of unit (ft^2)	1,524.00	1,762.00
Mean occupant density (no./1000 ft^2)	2.78	2.59
Homes with cracks in floor, wall, or ceiling (%)	7.13	5.10
Homes with holes in floor (%)	1.85	1.03

SOURCE: Adapted from Adamkiewicz et al. (2011) Table 1; reprinted with permission from The Sheridan Press.

Adamkiewicz noted that in most federally subsidized public housing, units are divided typically into family housing and elderly/disabled housing.

The importance of smoking as a contributor to indoor PM$_{2.5}$ was also demonstrated in the Centers for Disease Control and Prevention (CDC) Green Housing Study (Coombs et al., 2016). For families enrolled in the Cincinnati study site, the investigators found that indoor levels of PM$_{2.5}$ were not markedly lower in the renovated units than in control units. A closer examination of the data showed that the green units happened to have had a higher prevalence of smokers and use of air fresheners in the home, which, Adamkiewicz said, sends an important message. “It is not just about the buildings, but it is about the activity in the buildings, and fixing buildings is not necessarily going to lower exposures,” he said.

As an example of the type of analysis he would like to see more of, Adamkiewicz cited an effort that used American Housing Survey and census data, combined with data on activities and smoking prevalence, to model indoor PM$_{2.5}$ concentrations (Chahine et al., 2011). Among the results of this effort were predictions that the highest levels of exposure would occur in the South and Midwest, among rural populations, and in

$60 < $100 K/Year (n = 24,000)	≥ $100 K/Year (n = 22,842)	Associated Exposure and Hazards
57.77	48.63	Lead paint; structural integrity
1.41	0.99	Lead paint
8.24	7.98	Mold and moisture; structural integrity
21.95	16.69	Outdoor air sources—mobile
3.54	1.74	Outdoor air sources—stationary
7.33	6.71	Supplemental heating; comfort
16.98	16.26	Allergen exposure; pesticide exposure
2,098.00	2,853.00	Exposure to indoor air pollutants
2.31	1.82	Indoor source strength—various
3.88	3.31	Allergen exposure (pests)
0.58	0.37	Allergen exposure (pests)

low-income households. While there are many caveats concerning the use of this model, Adamkiewicz said that it does provide the ability to try various what-if scenarios and start to develop an understanding of how exposures may vary at a population level.

As a final example of research on the role that smoking plays in determining indoor PM levels, Adamkiewicz described a study he and his colleagues have been conducting using real-time data from in-unit public housing sites (Russo et al., 2015). These data were collected from apartments, adjoining hallways, and outdoors. In this study, which compares $PM_{2.5}$ levels in a smoker's apartment with $PM_{2.5}$ levels in an adjacent unoccupied apartment, the smokers record every smoking event so that the investigators can see the real-time effect that those events have on the air quality in the neighboring apartment (see Figure 4-10). Such measurements showed that the levels of $PM_{2.5}$ in a neighboring apartment rise significantly during and after recorded smoking events.

Adamkiewicz said that there are many studies that, like this one, measure indoor and personal levels of $PM_{2.5}$ but that do not have disparities as a primary or even a recognized focus of the research. However, embed-

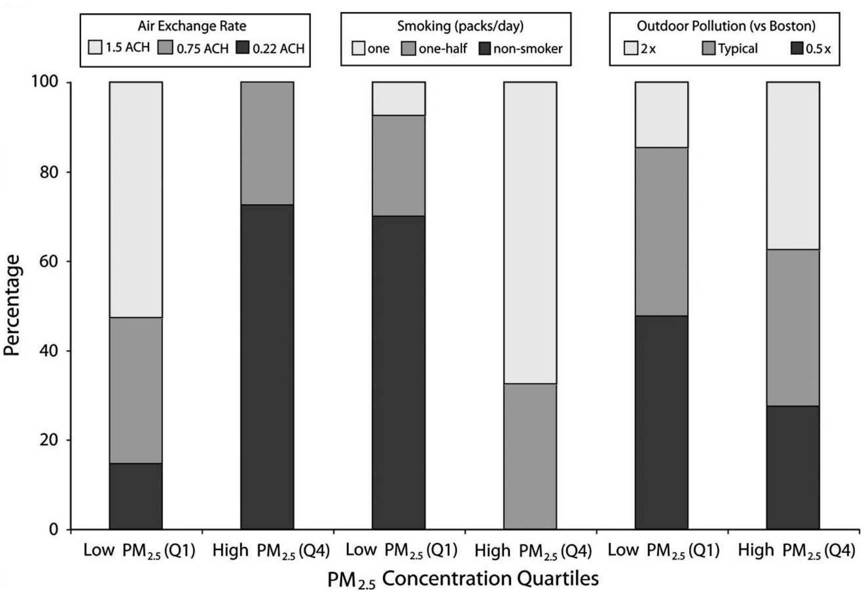

FIGURE 4-8 Estimated contribution of indoor $PM_{2.5}$ between the lowest (Q1) and highest (Q4) quartile for categories of AER, smoking, and outdoor air pollution.
NOTE: ACH = air changes per hour.
SOURCE: Adamkiewicz et al. (2011) Figure 2b; reprinted with permission from The Sheridan Press.

ded in many of these studies are data relevant to the issue that can be mined with some effort to provide insights on disparities. He also said that addressing the disparities that lead to increased levels of exposure is going to require thinking not just about places, but about people, places, and policies together. As an example, Adamkiewicz cited a green housing intervention that he and his colleagues studied (Colton et al., 2014; Russo et al., 2015) that combined better ventilation and a tighter building shell with mandatory smoke-free policies. The interventions resulted in reductions in $PM_{2.5}$ and nitrogen dioxide levels as well as a 47 percent reduction in respiratory symptoms. This study also found that within a small geographic area there was significant between-household variability in $PM_{2.5}$ levels that depended on household behaviors and building age and design.

As a concluding thought, Adamkiewicz said he would like to see more work aimed at understanding how household activities affect indoor PM levels and how exposure disparities are related to conditions or activities

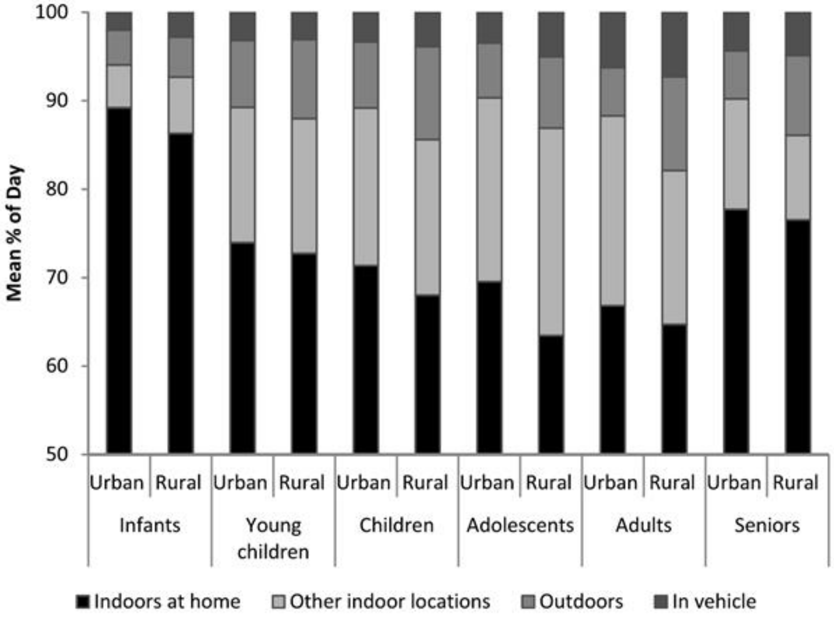

FIGURE 4-9 Time spent in various microenvironments as a function of age and home location.
SOURCES: Adamkiewicz slide 11, from Matz et al. (2015) Figure 1; reprinted from *Environmental Health*, published by BioMed Central.

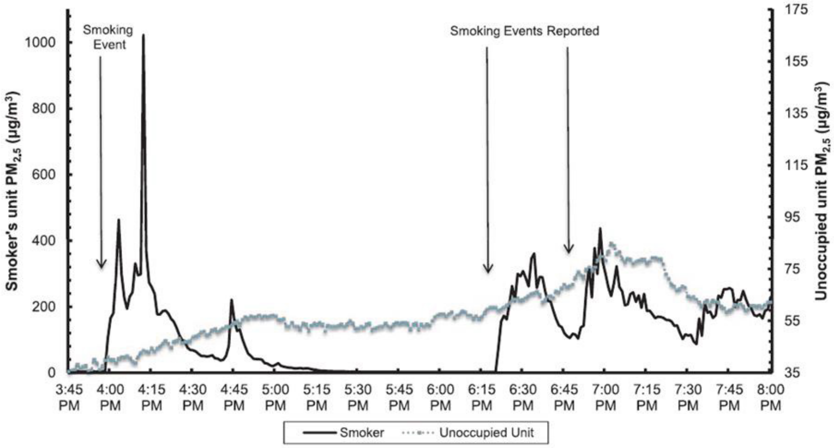

FIGURE 4-10 Real-time $PM_{2.5}$ levels in a smoker's housing unit and adjacent unoccupied unit.
SOURCES: Adamkiewicz slide 18, from Russo et al. (2015) Figure 2; reprinted with permission from Oxford University Press.

that can be mitigated. There are needs, he said, to better understand the links among energy, housing, and health; to recognize the importance of subpopulations—rural versus urban, the elderly, and those in managed or public housing, for example; and to take environmental justice into account when designing studies to assess exposure to indoor PM. He added that he believes a proposal from the U.S. Department of Housing and Urban Development calling for all public housing in the United States to be smoke-free[4] would be the biggest indoor $PM_{2.5}$ intervention possible.

DISCUSSION

Richard Corsi asked Adamkiewicz if any comparisons are being made between new conventional housing and new green housing because, he said, in his mind it is not a fair comparison to pit new green housing against existing housing. Adamkiewicz acknowledged Corsi's point and said that the only counter to that question is whether all new public housing should be green. "I feel that green new construction is not going to be the answer for all public housing in the United States, but that there are things we can learn about the effect of green elements," he said.

William Nazaroff asked the panelists to comment on the somewhat conflicting evidence he had heard in the day's presentations about whether increasing ventilation was good or bad. Harrison responded that there is no simple answer to this question given that good ventilation will increase the amount of outdoor PM that gets indoors but will also decrease the amount of indoor PM that remains in the house when there are significant indoor sources of PM. Turpin added that ventilation itself will not address concerns about indoor PM and PM precursors. The better answer, she said, is to reduce indoor and outdoor emissions of PM. Jeffrey Siegel commented that not all ventilation is equal and that the benefits of ventilation depend on the pathway it takes in a building and whether a ventilation system takes advantage of opportunities to mitigate PM levels. "I think it is more a question of how we do ventilation rather than assessing whether ventilation is good or bad," Siegel said.

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[4] Docket FR 5597-P-02 *Instituting Smoke-Free Public Housing*, 180 FR 71762 (November 17, 2015).

5

Exposure Mitigation

After considering various issues regarding exposure to PM, the workshop next explored several approaches to mitigating exposure as a means of reducing risk from exposure to indoor PM. William Fisk of the Lawrence Berkeley National Laboratory addressed the use of filtration to remove airborne PM. Sergey Grinshpun of the University of Cincinnati College of Medicine described several methods of controlling viable bioaerosol particles in indoor air. Brett Singer of Lawrence Berkeley National Laboratory then discussed the challenges of mitigating PM exposure in low-socioeconomic households. An open discussion moderated by Tiina Reponen followed the three presentations.

INDOOR PARTICLE MITIGATION WITH FILTRATION[1]

Filtration can be effective in reducing indoor levels of PM, William Fisk said, but current filtration practices are relatively ineffective even though the cost of doing better using existing technology is not prohibitive. Indeed, Fisk said, the filtration of incoming outdoor air and recirculated indoor air should be the first approach taken to mitigate individual exposure to PM. He added that there are also techniques, such as using ion generators and increasing air movement, to enhance particle deposition on indoor surfaces.

Many particle filtration technologies exist today, with the use of fibrous

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[1] This section is based on the presentation by William Fisk, a senior scientist at Lawrence Berkeley National Laboratory, and the statements are not endorsed or verified by the National Academies of Sciences, Engineering, and Medicine.

filters or stretched membranes predominating. Other technologies include electrostatic devices that charge particles and collect them on charged and grounded plates, combination technologies such as ion generation and filtration through fibrous materials, and combining a tight building envelope with exhaust ventilation. While Fisk limited his remarks to fibrous filtration, he said that these other technologies have potential for wider use.

Several factors determine the performance of a filter: its rate of particle removal, its energy use, the cost of filtration, the filter's reliability, and inadvertent pollutant production. The factors that affect particle removal include the rate and duration of air flow, the particle removal efficiency as a function of particle size, and the location of the filter relative to pollutant sources and to the location of a building's occupants. Factors affecting energy and cost include airflow resistance, pressure drop, fan and motor efficiency, and the particle-holding capacity as it relates to the filter's lifetime. Fisk noted that there are three systems used in the United States to rate filters:

1. Minimum efficiency reporting value (MERV), developed the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), which rates filters on their minimum efficiency within a set of particle size bins
2. Micro-Particle Performance Rating (MPR), developed by 3M, which rates performance on removal of PM in the 0.3- to 1-micron size range
3. Home Depot's Filter Performance Rating system (FPR), which uses a scale of 1 to 10 and a color code to rate filters based on large particle removal, small particle removal, and particle-holding capacity.

Fisk said that while filtration can be highly effective, the effectiveness of filtration systems varies widely. One recent informative study of particle filtration in nine southern California classrooms (Polidori et al., 2013) resulted in the data displayed in Figure 5-1. This study compared filtration in a baseline scenario, in which the HVAC system fitted with a MERV 7 filter runs continuously, to several other filtration alternatives. Adding a standalone filtration unit with a MERV 16 filter produced a large increase in removal effectiveness, Fisk said, though adding a MERV 16 filter in the HVAC system itself was even more effective. None of the configurations tested were able to maintain the indoor concentration of PM_{10} below 60 percent of the outdoor air PM_{10} concentration, probably because of high indoor PM_{10} generation rates in classrooms. Many of the configurations were quite effective at reducing the indoor concentration of $PM_{2.5}$ and UFPs relative to the baseline filtration system.

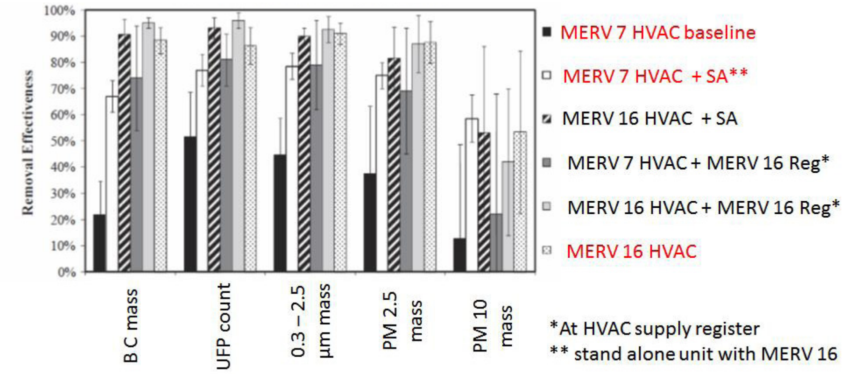

FIGURE 5-1 Particle removal effectiveness (%) as a function of filter efficiency.
NOTE: Bars indicate data averaged at all schools and in all classrooms sampled by the authors; vertical lines represent standard deviations for each bar.
SOURCES: Fisk slide 6, from Polidori et al. (2013) Figure 3; reprinted with permission from John Wiley & Sons, Inc.

One limit to the impact that filtration currently has on reducing PM exposure, Fisk said, is that the current ASHRAE standards for both residences and commercial building only require MERV 6 filters except in areas of the country that are not in compliance with $PM_{2.5}$ regulations (in which case the standard for commercial buildings is MERV 11 filters). However, MERV 6 filters remove less than 20 percent of the particles of most sizes (see Figure 5-2). “So the filters that we commonly use have a low efficiency for particles in the most interesting size range,” Fisk said. In homes, this deficiency is compounded by the fact that HVAC systems run intermittently. Given that approximately 55 percent of homes have filters with a rating of MERV 6 or lower (El Orch et al., 2014), which will remove about 7 percent of $PM_{2.5}$ (Azimi et al., 2014), and that the HVAC in a typical home runs approximately 20 percent of the time (Cetin and Novoselac, 2015) with an air flow rate of approximately 4.4 air exchanges per hour (Jump et al., 1996; Stephens et al., 2011), Fisk calculated that the total removal rate is less than 10 percent of the indoor particle load per hour. “Those filters are not bringing us much benefit, but that is what we use today,” he said.

Most filters sold today contain embedded charged fibers, which can increase particle removal efficiency but only for a limited time (Raynor and Chae, 2004). Studies in several settings have shown that PM in cigarette smoke and diesel exhaust can quickly reduce the efficiency of charged fiber

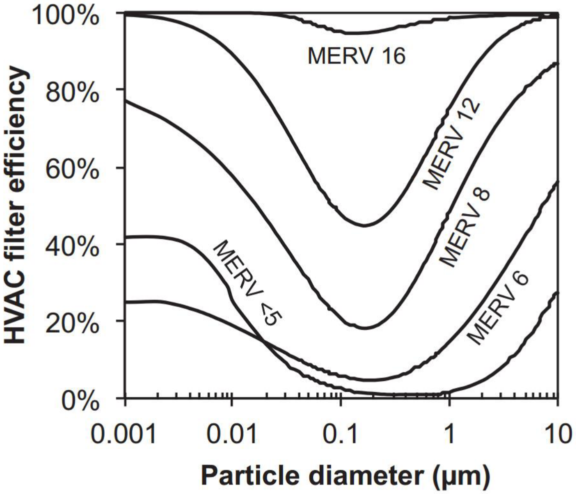

FIGURE 5-2 Particle removal efficiency by filters of different MERV ratings. SOURCES: Fisk slide 8, from El Orch et al. (2014) Figure 4; reprinted with permission from Elsevier.

filters (Lehtimäki and Heinonen, 1994; Raynor and Chae, 2004). "We do not fully understand the physics behind this phenomenon," Fisk said.

A growing trend, he said, is to add "nanofibers," a term the filtration industry uses for fibers with diameters of less than 0.5 microns (as compared with diameters of a few microns in the most common filters). Experimental data suggest that these nanofiber filters can produce a higher ratio of particle removal efficiency to air pressure drop (Ahn et al., 2006; Leung et al., 2009; Wang et al., 2008).

Fisk explained that the energy used to remove particles with filters varies dramatically depending on the system being used. His recent research showed, for example, that a standalone high-efficiency filter can remove particles for a fraction of the cost per gram compared to an HVAC system (Fisk and Chan, 2016) (see Table 5-1).

Fisk then discussed the common belief that better filters will substantially increase energy costs because they will increase airflow resistance. "For many situations," he said, "the data do not bear that out" (Walker et al., 2013), and while better filters do cost more, he said he would argue that the increase in costs is not so high as to be prohibitive. Deeper filters with more pleating can reduce airflow resistance, which minimizes the effects on the energy consumed by the HVAC system fan, he explained. Calculations also show that for a system in a commercial building that has multiple

TABLE 5-1 Characteristics of Continuously Operating HVAC and High-Efficiency Standalone Filters

	HVAC + Low ε Filter	HVAC with High ε Filter	Standalone with High ε Filter
Flow rate (h^{-1})	4.3	4.3	1
House volume (m^3)	433	433	433
Watt per $m^3\ s^{-1}$	1090*	1090*	600*
$PM_{2.5}$ removal efficiency	0.12*	0.27*	0.9
Time	1 year	1 year	1 year
Electricity price	\$0.132/kWh	\$0.132/kWh	\$0.132/kWh
Home $PM_{2.5}$	20 $\mu g\ m^{-3}$	20 $\mu g\ m^{-3}$	20 $\mu g\ m^{-3}$
PM removed (g)	39	88	68
Electricity cost (\$)	\$650	\$650	\$83
\$ Elec. per gr. PM removed	\$16.7	\$7.4	\$1.2

$$\text{Electricity Cost of operating a filtration system} = \textit{flowrate} \times \left(\frac{\textit{Power}}{\textit{Flow}}\right) \times \ (\text{time}) \times \left(\frac{\$}{\textit{energy}}\right)$$

$$\text{Particle Mass Removed} = \textit{flowrate} \times \textit{efficiency} \times \textit{time} \times \textit{concentration}$$

NOTE: Data marked with "*" are derived from Fisk and Chan, 2016.
SOURCE: Fisk slide 13.

filters and occupants, the increased life-cycle costs of a MERV 13 versus MERV 8 filter works out to at most \$3 per person per month (Montgomery et al., 2012).

In 2013, Fisk reviewed the health benefits of filtration (Fisk, 2013) and came to two main conclusions. The first was that filtration has only a minor benefit with regard to reducing allergy and asthma outcomes. There is some evidence of benefit in homes with large sources of allergens, but only a fraction of health outcomes improved. The second conclusion was that the greatest potential comes from using better filtration to reduce indoor concentrations of outdoor PM, thus reducing the morbidity and mortality associated with outdoor air PM. "The health benefits are predicted to far exceed the costs for those interventions," Fisk said. Other conclusions he drew in his review included

- Systems that delivered filtered air to the breathing zone when individuals are sleeping appear to be more effective in reducing allergy and asthma symptoms;

- Evidence of health benefits from filtration in homes, offices, and schools in subjects without allergies and asthma is limited; and
- The reductions in markers of future adverse coronary events with filtration support modeled health benefits of using filtration to reduce particles from outdoor air.

Fisk concluded his presentation with a list of issues and challenges relating to filtration, which included

- Quantifying, demonstrating, and communicating benefits to motivate the use of better filters;
- Improving filtration effectiveness while reducing costs;
- Increasing minimum filtration efficiency requirements in standards;
- Limited expected effectiveness for locally resuspended coarse particles, such as some allergens;
- Pollutant generation by some electronic air cleaners;
- Soiled filters may emit pollutants and diminish perceived air quality;
- Many expensive and ineffective products are sold; and
- Empirical validation of predicted health benefits.

One of Fisk's concerns relates to the trend of increasing the use of natural ventilation in commercial buildings, which will increase exposure to outdoor particles and ozone. He said that it will be important to identify approaches for mitigating those exposures in naturally ventilated commercial buildings. Fisk said he also believes that there is a need to better understand the relative health risks of outdoor PM versus PM that is generated indoors and also how filtration can be a tool to differentially affect exposures and risks.

METHODS AND APPROACHES FOR CONTROLLING EXPOSURE TO BIOLOGICAL AEROSOLS[2]

One of the measurables that is specific to biological particles, Sergey Grinshpun said, is the percentage of airborne organisms that are viable. Viability is measured by counting colonies of microorganisms from collected particles that grow on agar plates. Other ways of analyzing biological materials include looking at antigens and allergens, quantifying molecules specific to the cell wall or membranes, and assessing the presence of fungal toxins, also known as mycotoxins. Biological particles appear in a wide

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[2] This section is based on the presentation by Sergey Grinshpun, a professor of environmental health at the University of Cincinnati College of Medicine, and the statements are not endorsed or verified by the National Academies of Sciences, Engineering, and Medicine.

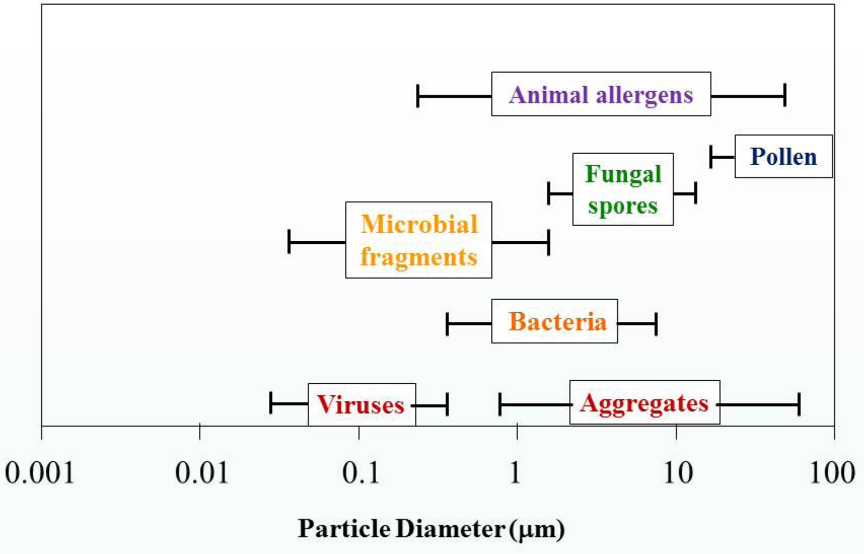

FIGURE 5-3 Size ranges for different types of bioaerosol particles.
SOURCE: Grinshpun slide 4.

range of sizes (see Figure 5-3). Viruses range in size from approximately 20 to 400 nanometers, the bacterial and fungal size range is approximately 0.5 to almost 10 micrometers, and pollen occupies the high end, from >10 to >100 micrometers in diameter. Air purification may not be an important issue for pollen because pollen grains settle out of the air rapidly.

Grinshpun said that there are two main approaches to mitigating exposure to biological particles. The first is to reduce the overall PM burden from all sources via, for example, filtration or electrostatic precipitation. While Fisk had already discussed filtration, Grinshpun pointed out that every type of filter has a characteristic particle size for which its removal efficiency is lowest. For the typical devices used for indoor air filtration, this size ranges between <0.1 and 1 micrometer, which corresponds to the sizes of larger viruses and many bacteria. Electrostatic precipitators have been found to be good at removing bacterial aerosol particles (Mainelis et al., 2002). While these precipitators are inexpensive and quiet to operate, they are not commonly used against bioaerosols.

Ozone generation devices are available but Grinshpun questioned their utility for removing indoor PM or reducing the viability of microorganisms in indoor air. Grinshpun and his colleagues have shown that commercially available ozone generators do not remove particles but instead create new ones (Grinshpun et al., 2010). Ion emission devices work by generating ions that attach to particles, causing the particles to migrate toward and stick to indoor surfaces. Grinshpun and his colleagues evaluated this method in a test chamber and found that it does have the potential for removing particles, albeit with lower efficiency than filtration. The main problem is that most ion emitters also emit ozone, which, as Glenn Morrison had noted in his presentation, can trigger the generation of UFPs.

A number of different methods, including heat, UV light, and cold plasma, have been used to inactivate microorganisms. "With these methods, we do not care about concentration, we just want to kill viable microorganisms," Grinshpun explained. He noted that some commercially available air cleaners use ion emission, ozone generation, and photocatalytic oxidation to inactivate microorganisms. The efficiency of these methods varies, he said.

Thermal inactivation has potential as a means of inactivating microorganisms, even stress-resistant bacterial spores such as anthrax spores. In one experiment, Grinshpun and his colleagues showed that only 0.1 percent of anthrax surrogate spores remained viable after passing through a thermal inactivation device at 315°C (Grinshpun et al., 2010). The major limitation to this technique, Grinshpun said, is being able to process enough air through such a device. A group of investigators in South Korea performed a study similar to what Grinshpun and his colleagues did with the anthrax surrogate spores (Jung et al., 2009) and showed that short-term exposure to high temperature changes the physical structure of aerosolized fungal spores. Whether this change is responsible for the ultimate inactivation of the spores is still unclear, Grinshpun said, "but the bottom line is that it is quite efficient." Viruses, he added, are readily inactivated at air temperatures as low as 60°C.

The ability of UV irradiation to inactivate viable microorganisms has been well studied, though not in aerosols. One study (Peccia et al., 2001) found that the rate of inactivation of aerosolized bacteria using UV light depended on the humidity. Other experiments have shown that the combination of UV light and heat is more effective at inactivating bacteria in indoor air environments and at lower temperatures than when heat alone is used. The one caveat to the use of UV light, Grinshpun said, is that UV lamps can generate ozone. Recently, Grinshpun and his colleagues have been studying the use of atmospheric-pressure cold plasma to inactive viable microorganisms, and they found that this method causes viruses to fragment (Wu et al., 2015). They have not yet studied the effects of cold plasma on other types of bioaerosol particles.

Viable microorganisms, Grinshpun said, can also be inactivated after they have been collected on filters. Biocidal chemicals, such as iodine (Eninger et al., 2008), have been shown to be effective at inactivating microorganisms on filters, as have microwave and infrared irradiation (Lee et al., 2009; Ratnesar-Shumate et al., 2008; Zhang et al., 2010). Alumina nanofibers with a positive surface charge have been shown to strongly retain virus particles, which are often naturally negatively charged (Li et al., 2009).

As a final note, Grinshpun mentioned that filtering respirators can reduce exposure to biological aerosols (Eninger et al., 2008; Grinshpun et al., 2007) and are generally as effective as stationary air filters. Protection may not be efficient, however, because of leakage between the respirator and the user's face. Grinshpun also expressed caution about the use of so-called antimicrobial respirator filters, given that the risks of inhaling biocidal agents or having them come in prolonged contact with skin are not known.

MITIGATING PARTICLE EXPOSURE IN LOW-SOCIOECONOMIC HOUSEHOLDS[3]

Low socioeconomic status is often equated with low income, Brett Singer noted, but it also is correlated with low education and, more importantly, low status and low access to information, all of which are important when it comes to thinking about changing behavior or practice. "When we talk about these fixes," he said, "something that will work for a family that has it all together might not work for a family that is struggling just to get through the day."

There are physical, economic, and sociological challenges to reducing PM in low-socioeconomic homes, Singer said (see Table 5-2), many of which Gary Adamkiewicz addressed in his earlier presentation. Singer pointed out two items in particular. "When we talk about low-cost remedies, what is low-cost for me is going to be different from what is low-cost to a family of four living on $30,000 a year that has no credit or very costly credit," he said. "There's also limited or no choice in their housing. They cannot move or readily change it." He also pointed to the importance of low status, which often translates into a limited ability to demand repairs. "They do not complain because they are worried about being thrown out and they have no alternative place to live," he said.

While the typical way to think about mitigation is to parse it into source control, ventilation, and filtration, Singer said he uses a different mental model, one that includes reducing PM from outdoor sources, reducing indoor sources, and accelerating the removal rate of indoor PM. The first step, he said is to reduce PM from the outdoors, given that a large

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[3] This section is based on the presentation by Brett Singer, a staff scientist in the Indoor Environment Group at Lawrence Berkeley National Laboratory, and the statements are not endorsed or verified by the National Academies of Sciences, Engineering, and Medicine.

TABLE 5-2 Challenges to Reducing PM in Low-Socioeconomic Homes

Physical Challenges

- Smaller spaces, higher density, and occupied more
- Housing units in closer proximity; more exchange of air between units
- More mechanical equipment problems related to age, quality, and lack of servicing
- Closer to outdoor sources such as roadways, industry and ports
- Leakier buildings leads to more exposure to outdoor pollutants
- More smoking, mold, pests, and dust
- More use of odorants; may include candles, incense, and others
- Lack of thermal control leads to a need to open windows

Economic Challenges

- Limited or negative disposable income
- No credit or very costly credit
- Limited or no choice in housing

Sociological Challenges

- Limited status to demand repairs
- Language and digital divide limit access to knowledge
- Complicated co-habitation arrangements
- Cultural norms may limit source control options

SOURCES: Singer slides 6 and 7.

fraction of indoor PM originates outdoors (Allen et al., 2012; Meng et al., 2004). In a series of experiments conducted in a moderately tight, empty house located some 300 meters downwind of Interstate 80 in Sacramento, California, Singer and his colleagues studied the effects of a number of different combinations of ventilation and filtration on $PM_{2.5}$ levels (see Figure 5-4) and UFP levels inside the house. They found that a relatively tight shell was very effective in reducing $PM_{2.5}$ and UFP infiltration but was less effective in keeping out carbon black particles. Levels fluctuate, however, and the research observed times during the day when the indoor level of carbon particles was higher than that outdoors.

Indoor PM levels were further reduced by filtration, Singer said, either when a MERV 16 filter was used to filter the air supply coming into the house or when a MERV 13 or better filter was used with a recirculating HVAC system. “You can get very effective outdoor particle reductions with a recirculating system,” Singer said. He noted that a simulation analysis using measured parameters conducted by Brent Stephens and his colleagues (Zhao et al., 2015) found that protecting the indoors from outdoor particles by sealing the envelope provides the biggest impact on reducing in-home exposure to outdoor PM, while filtration does more for reducing levels of indoor PM generated indoors. However, filtration was predicted to have a significant impact on indoor PM in old homes with significant infiltration of outdoor PM.

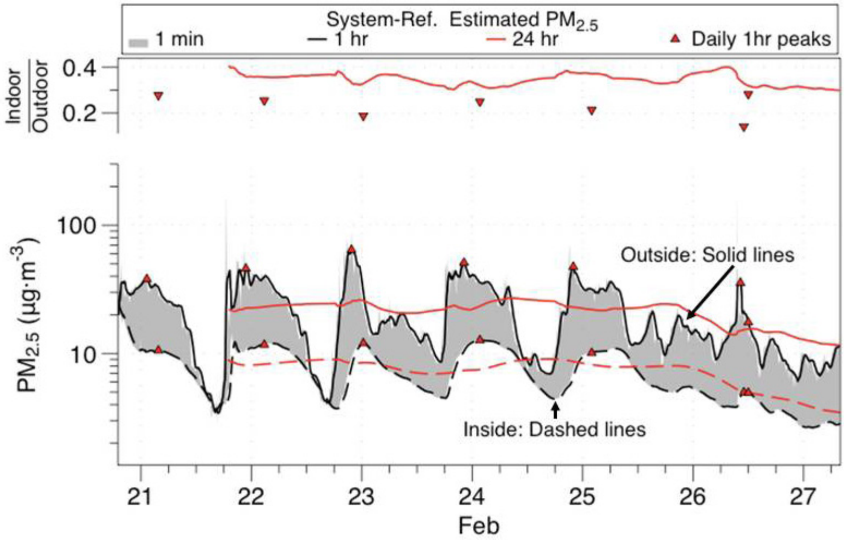

FIGURE 5-4 The effect of air sealing on $PM_{2.5}$ infiltration.
SOURCE: Singer slide 10; from Singer et al., 2016.

Singer said that the air tightness of homes has improved over the years (Chan et al., 2013) and that retrofitting measures do reduce air infiltration in existing homes. Weatherization assistance programs, he said, are achieving median reductions in PM levels of 30 percent for single-family homes and 28 percent for multifamily homes.

Indoor sources of $PM_{2.5}$ and UFPs vary greatly by home and according to the time of day (Wallace et al., 2003). If there is habitual smoking in the house, that will typically be the most importance source, Singer said. He noted that efforts to get smokers to stop smoking indoors have been successful, particularly in low-socioeconomic homes, and that when smokers stop smoking indoors, it does produce meaningful reductions in indoor levels of $PM_{2.5}$ (Semple et al., 2015; Wilson et al., 2012; Zhang et al., 2012). Portable filters placed in children's bedrooms reduce PM levels in the homes of smokers and non-smokers alike (Batterman et al., 2012), though the researchers who conducted this study found that filter use waned over time.

Cooking is an important PM source in most homes, as are candles and incense in homes where these are used frequently. As had already been discussed, hot surfaces, resuspension, and cleaning can be important indoor sources of PM. With regard to cooking, range hoods can be effective at removing PM from indoor air, but only if they are used and only if they are installed correctly. Some range hoods, for example, simply run air through a charcoal filter and recirculate it back into the home. Singer said that he and his colleagues at Lawrence Berkeley National Laboratory are working with the voluntary consensus standards organization ASTM International to develop a standard method of testing the efficiency with which range hoods capture cooking pollutants. As part of that work, he has found that the capture efficiency for cooking on the back burner is typically greater than 70 percent but that the efficiency is highly variable for cooking on the front burner (Delp and Singer, 2012). These measurements were made under controlled conditions in the laboratory, Singer cautioned, and the results were far worse when he went into the field and tested hoods in homes (Singer et al., 2012). A study using self-reports found that one-third of those responding to the survey used their hoods infrequently and that 10 percent reported they never used their hoods (Mullen and Singer, 2012). Some 20 percent of homes surveyed in California did not have an exhaust fan over their stoves.

With regard to costs, Singer said a quiet, energy-efficient, standalone high-efficiency particulate air/arrestance (HEPA) filter unit may cost $400 to $500 to cover 500 square feet of living space, with a less efficient, noisier unit costing perhaps half as much. The filters for the low-end units range from $20 to $30 and those for the high-efficiency units from $80 to $100. Low-income households are not likely to spend their limited funds on a filtering device, Singer said. Central HVAC filters are less expensive, but Singer said the landlord of a low-income housing unit is likely to think twice about spending $20 to $30 on a MERV 13 filter for every unit. A basic, noisy range hood can cost less than $50, but a quiet range hood with sufficient power to efficiently remove PM can cost $200 to $300.

The best control, then, starts with a good building, Singer said in summary: one with an airtight envelope, a vented range hood that is also quiet (so that it will be used), a central forced air HVAC system with an efficient blower and a 2- to 5-inch filter slot, robust venting of combustion appliances, and limited use of carpeting, except perhaps in the case of housing for the elderly where slipping on uncarpeted surfaces can be hazardous. Singer also suggested a number of actions that individuals can take to reduce their exposure to PM, including closing windows to reduce the levels of outdoor PM, particularly when pollution is bad or likely to be bad; restricting smoking and burning candles and incense; using a range hood and cooking on back burners; using a HEPA vacuum cleaner and ventilating when cleaning; and investing in good filters and using filtration. As a final thought, he said that PM is just one element of the indoor environment and rather than worry about which elements of green housing are most important, the key point is that providing good housing for people will provide a great deal of benefits in many areas beyond reducing PM.

DISCUSSION

Tiina Reponen started the discussion by asking the three session speakers to list the key questions that need answering with regard to mitigating exposure to PM. Fisk responded that there is a need to identify appropriate techniques to deal with airborne allergens or particles that are inflammatory so as to help reduce the effects that these have on respiratory difficulties, including asthma. Fisk also said he thought that while filtration is predicted to produce large reductions in mortality and morbidity, empirical data are needed to support those predictions even though acquiring such data will be challenging. He did note that there are some data in the asthma mitigation literature indicating that a broad combination of approaches is more effective at improving health than any single approach. Also, a subset of studies that looked at the effects of using filtration systems to ventilate the breathing zone of asthmatic individuals when they were sleeping found that these systems produced more benefits more consistently than whole-house measures (Fisk, 2013).

Grinshpun said that given the rapidly growing U.S. and European markets for air purifiers, he would like to see more research to identify the various byproducts produced by some of the methods for removing bioaerosols from circulation and to determine the optimal condition under which a given method is most efficient at reducing exposure without doing any harm. He said in response to a question about ozone production from ion generators that no device that emits ozone should be deployed and that he has tested ion generators that do not emit any measurable ozone. However, he added, filter-based air purifiers are generally more efficient than ion generators at removing indoor PM. Singer said that one of the big questions for him is how to better communicate what is already known to the public about the effectiveness of and issues associated with various mitigation strategies so that the public, including building professionals, can make use of information on how to best mitigate exposure to PM.

Grinshpun, responding to a question about the mechanism by which cold plasma inactivates viruses, said that the mechanism is still not well understood. With regard to thermal inactivation, he said that mechanical disintegration of microorganisms may occur at 600 to 700°C, which is where 100 percent inactivation has been observed, but the mechanism by which lower temperatures produce moderate levels of inactivation is still not adequately characterized.

When asked about the difficulty of retrofitting an HVAC system to take deeper MERV 13 or MERV 16 filters, Fisk said that manufacturers are now making filters with higher than MERV 7 efficiency that fit in standard 1-inch filter slots and that there are systems that can be installed over the return grill instead of in the furnace system that are not hard to install. “In many cases, you do not need to retrofit," he said, "but having said that, a home owner or renter in a low-income environment is not likely to have the resources to make even modest improvements their highest priority." Singer said that adding more efficient filters to some older HVAC systems could increase the pressure drop significantly, raising a legitimate concern about whether a retrofit on an existing system is a good idea. With regard to retrofitting kitchen exhaust hoods, Richard Corsi commented that many range hoods, at least in Texas where he lives, get vented into attics, which can lead to a buildup of chemically reactive unsaturated fatty acids on surfaces in that space.

Terry Brennan said that while tightening the building envelope can produce large reductions in the transport of outdoor PM to the indoors, that would also lead to increases in the levels of indoor PM from indoor sources. Singer replied that the judicious use of indoor ventilation and reducing the production of indoor PM through education have to go hand-in-hand with envelope tightening. He also responded to a question about air quality in net-zero energy homes by noting that such homes also need to make judicious use of effective ventilation. The one criticism Singer had of some of these homes is that they may forgo range hoods in the mistaken belief that cooking on electric stoves does not produce UFPs, which in fact it does. A possible solution, he said, would be to use high-efficiency filters in the forced-air HVAC systems that are installed in at least some of these homes.

6

Discussion and Summary of Day 1

To conclude the workshop's first day, William Nazaroff moderated a discussion among the workshop participants. He opened the discussion by summarizing the key messages he had heard, starting with what he said he thought was a clear picture of the degree to which buildings protect their inhabitants from outdoor PM—which he said was not very good for $PM_{2.5}$, better for UFPs, and better still for PM_{10} and larger particles. Buildings are also good, he said, for providing protection against outdoor nitrate but not as good for organic carbon, particularly given the evidence that indoor sources are the predominant contributors to the organic carbon content of indoor PM.

The second key message Nazaroff said he heard concerned the lack of data available to understand the nuances of what is a richly complex system; that lack suggested a potential for using information technology and the "Internet of things" to address the data deficit. Another important message, he said, was the significant variability that exists with regard to how the features of individual buildings and the activities taking place in buildings affect indoor PM levels and their associated health effects. "We are dealing with 100 million dwellings in the United States, tens of millions of commercial spaces, and each one has its own attributes even if the governing principles are common," Nazaroff said. Similarly, he said, the variability of how people behave in the indoor environment has an important influence, creating a huge challenge to understanding exposure and mitigation but also an opportunity for progress through research.

Bob Thompson of EPA commented on the importance of distilling what is known about indoor PM, mitigation approaches, and possible health effects into a form that will help the program officers in EPA's Office of Research to make decisions about where future resources will go, given how tight the research budget is today. "The more we can turn this information into language [that] helps them clearly see its value, the better off we will be from EPA's perspective," Thompson said. He also noted the importance of putting terms such as "high cost" and "low cost" into a context of how much value a given expense brings to the people who will be spending money on these mitigations.

Steven Welty of Green Clean Air said that Hong Kong has an indoor air quality rating system that participating buildings post, and he wondered if there is a way to distill what is known about indoor air quality to create such a rating system for use in U.S. commercial buildings or even homes. Brett Singer said that while this is an interesting idea, it is important to remember that indoor air quality will vary significantly over time, depending on how a building is operated and what the people inside it are doing. What could be done, though, is to rate a building's robustness in providing good indoor air quality based on its HVAC system, how it is operated, the type of filtration and ventilation installed, and other features that are known to contribute to improved indoor air quality.

Richard Corsi remarked that an understudied area concerns the chemistry occurring in the breathing zone, where organic compounds in a person's breath can react with ozone. Barbara Turpin commented that consumer products had not been discussed much, and she said she worried that consumers place too much trust in the idea that a device is safe if used as directed. William Hallman from Rutgers University asked if there were any data on particle emissions from gas and electric clothes dryers. Nazaroff responded there has been one paper published on UFPs produced by clothes dryers (Wallace, 2005), and based on the results of that paper his group looked for but could not find evidence that dryers in the homes they studied contributed to the UFP burden in those homes. Nazaroff noted that Lynn Hildemann had said that laundry detergent enzymes are present in dryer lint. Jeffrey Siegel added that there is emerging evidence that dryers can transfer SVOCs deposited on clothing into the air. He also said that a dryer vent produces a high-volume flow rate of air, and in buildings with tight envelopes, that can create potentially serious problems in terms of depressurization and pulling contaminants into the indoor environment from particle-generating appliances.

Terry Brennan commented on the importance of intervening when a building is being designed or completely gutted and rebuilt, noting that he often goes into new buildings with horrible problems that could have been easily avoided during design and construction. He said that one approach to improve conditions in multifamily buildings could be to encourage mortgage companies and banks to require PM-reducing interventions when owners refinance mortgages, which, he said, occurs every 10 to 15 years. Another opportunity to intervene is when building owners retrofit HVAC systems.

Glenn Morrison wondered if it would be more cost-effective as a nation to spend money, perhaps via tax rebates, to retrofit buildings to remove indoor PM than on making incremental reductions in outdoor PM levels. William Fisk replied there have been a number of cost–benefit analyses for the health benefits that would accrue from improving filtration systems in buildings and the numbers look promising from a societal perspective. What he has not seen, he said, is a comparison of the cost effectiveness of improving health through traditional outdoor PM mitigation approaches versus approaches that can be implemented in buildings.

7

Potential Health Concerns

While the first day's presentations and discussions focused on the physical science and engineering aspects of indoor PM, the second day's presentations turned to what William Nazaroff called the "So what?" and "What now?" topics—the associated health risks of exposure to indoor PM and risk communication. In the first of the day's two sessions, Ryan Allen of Simon Fraser University discussed the effect of indoor PM on cardiovascular health, David Rich from the University of Rochester Medical Center presented emerging evidence linking ambient PM and adverse birth outcomes, and Marc Weisskopf of the Harvard T.H. Chan School of Public Health addressed the role that PM may play in neurological and psychiatric disorders. An open discussion moderated by Howard Kipen of Rutgers University followed the three presentations.

INDOOR PM AND CARDIOVASCULAR HEALTH[1]

Ryan Allen began his presentation by noting that he was not going to cover household air pollution from solid fuel combustion, which, he indicated, is "arguably the most important environmental risk factor globally" but isn't generally an issue in high-income countries. After reiterating that a significant percentage of indoor PM originates outdoors (Allen et al., 2012), he stated that, in his view, the line between indoor and outdoor PM

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[1] This section is based on the presentation by Ryan Allen, an associate professor on the faculty of health sciences at Simon Fraser University, and the statements are not endorsed or verified by the National Academies of Sciences, Engineering, and Medicine.

is not as distinct as some might think. He said that while much of the early research on PM and health focused on respiratory health, there have been a growing number of studies over the past 15 years on the cardiovascular effects of PM exposure (Bai et al., 2007; Brook et al., 2010; Crouse et al., 2012; Koulova and Frishman, 2014; Kunzli and Tager, 2005; Simkhovich et al., 2008; Sun et al., 2010). An important conclusion from these studies, Allen said, is that exposure to PM has a causal effect on cardiovascular health, not just a statistical association. In 2010, he noted, the American Heart Association issued a statement declaring, "It is the opinion of the writing group that the overall evidence is consistent with a causal relationship between $PM_{2.5}$ exposure and cardiovascular morbidity and mortality" (Brook et al., 2010, p. 2365). He noted that the evidence backing this statement came almost entirely from studies using outdoor measurements and models.

The accumulated evidence also supports the finding that adverse cardiovascular effects occur at the lowest levels that individuals encounter (Crouse et al., 2012), said Allen, noting that "The evidence seems to suggest the absence of a threshold or a safe exposure level." In fact, he added, the data seem to suggest that the relationship between PM exposure and cardiovascular health outcomes is linear or even supralinear, where the dose–response curve is steepest at the low end of the exposure distribution. If this finding holds, the implication would be that there would be a health benefit from further reductions in PM exposures.

Taken together, Allen said, these data show that exposure to ambient PM is an important public health risk factor (see Figure 7-1) and that the public health impacts from PM are driven largely by its effects on cardiovascular and circulatory diseases. "We still tend to think of PM as a respiratory pollutant or toxicant, but in terms of its public health impacts it is the cardiovascular and circulatory effects of PM that are driving the public health burden," he said.

Research suggests that there are three interrelated mechanisms linking PM exposure with cardiovascular health (see Figure 7-2). The first, Allen explained, involves an inflammatory response in the lungs to PM inhalation which leads to the release of cytokines and other biomolecules into the circulatory system. The second mechanism involves the activation of the autonomic nervous system, which in turn affects blood vessels, heart rhythm, heart variability, and other physiological systems. The third mechanism involves direct transport of the smaller particles into the bloodstream, where they interact with blood vessels and various blood cells.

The methods for investigating the role of indoor PM on cardiovascular health include in vitro and epidemiologic studies. Epidemiologic studies, Allen said, have some important limitations, given the lack of good models for predicting indoor PM levels. "In most cases, we have to actually measure

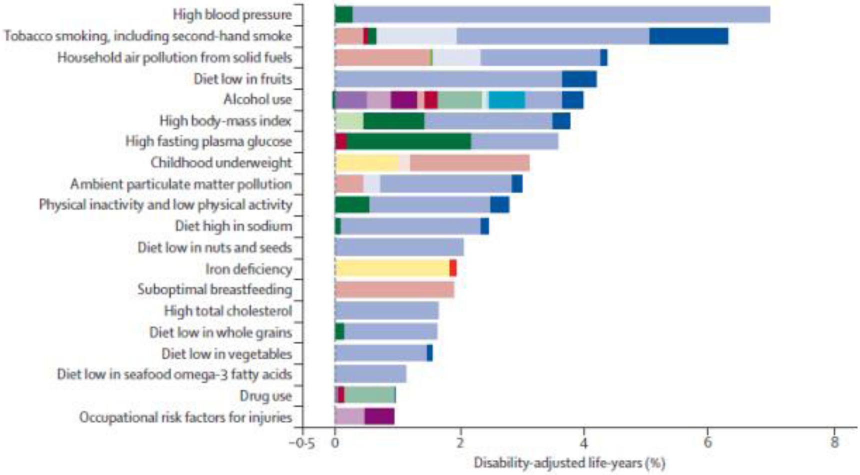

FIGURE 7-1 Global public health burdens attributable to 20 leading risk factors in 2010. The pink bar (far left) represents the contribution of respiratory infections; the light blue bar, chronic lung diseases; the medium blue bar, cardiovascular and circulatory diseases; and the dark blue bar (far right), cancer.
SOURCE: Allen slide 7, adapted from Lim et al. (2012) Figure 2C; reprinted with permission from Elsevier.

indoor PM," he said, "and because these measurements are time-consuming and expensive, we end up studying relatively small populations that may be non-representative, creating challenges extrapolating our results to the broader general population." The time and money constraints also lead to studies being restricted to examining short-term effects, on the order of days and weeks, rather than the years over which chronic disorders develop. The other main limitation of these studies is that they look at relatively subtle subclinical effects, such as changes in markers of inflammation and blood vessel function, rather than the clinically relevant outcomes of heart attack and stroke, among others.

As an illustration of the type of in vitro studies researchers perform, Allen described one study in which researchers collected PM samples inside and outside of homes in Boston, dosed rat lung macrophages with the particles, and then measured the release of cytokines from these immune system cells (Long et al., 2001). The results showed that there was a larger inflammatory response to indoor PM than to outdoor PM. Allen stressed that he did not want to overemphasize these data and that he was just using them as an example of the tools that investigators are bringing to bear on the challenge of understanding how indoor and outdoor PM affect inflammation and other relevant health indicators.

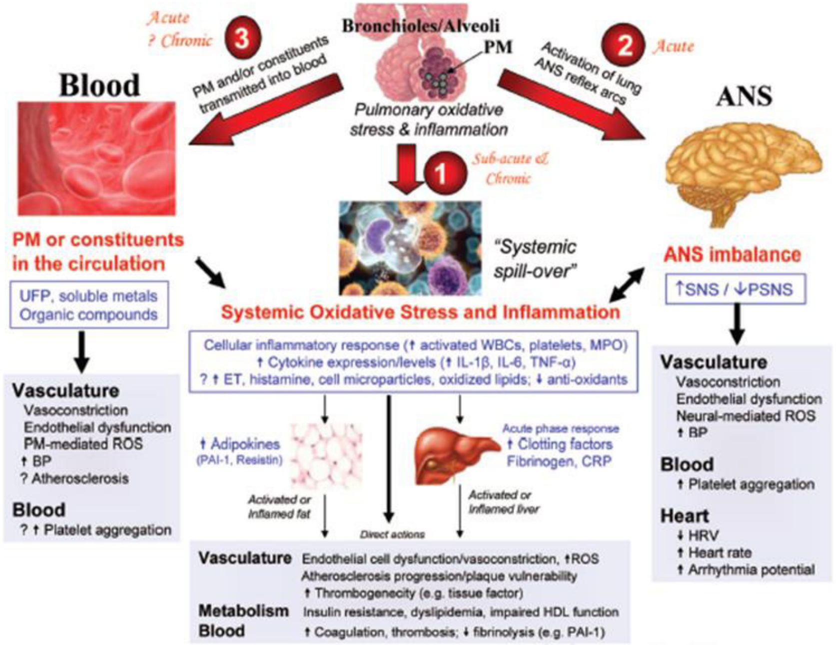

FIGURE 7-2 Biological pathways linking PM exposure with cardiovascular diseases. A question mark (?) indicates a pathway/mechanism with weak or mixed evidence or a mechanism of likely yet primarily theoretical existence based on the literature. [Abbreviations defined in source publication.]
SOURCE: Allen slide 9, from Brook et al. (2010) Figure 3; reprinted with permission from Wolters Kluwer Health, Inc.

Allen then discussed some of the intervention studies that have been conducted. These studies use an air filter to reduce indoor PM levels, which, he explained, allows researchers to isolate the effects of PM from the polluting gases that may also be in the environment. In one study, Allen and his colleagues divided the residents of a wood smoke–affected community in the central part of British Columbia into two groups. Each participant was observed for two consecutive 7-day periods, during which time portable HEPA filters were operated in the participants' living rooms and bedrooms. HEPA filters were operated normally during one 7-day period and without the internal filters in place (which was called "placebo filtration") during the other period, thus blinding participants to the filters' status. The order of filtration or non-filtration was random. Health measurements were made again after another week. The data showed that the use of portable HEPA filtration for 7 days, which reduced $PM_{2.5}$ levels from 11 micrograms per cubic meter to 5 micrograms per cubic meter, was associated with improved blood vessel function and decreased systemic inflammation (Allen et al., 2011).

In a second study using the same design, Allen and his colleagues studied the differential effects of two different sources of PM: traffic emissions and residential wood combustion (Kajbafzadeh et al., 2015). Using previously developed spatial models, he and his colleagues were able to identify parts of Vancouver affected by traffic-related air pollution but not by wood smoke, and vice versa. The data from this study revealed an association between indoor $PM_{2.5}$ and the blood levels of an inflammatory protein, but only in the group exposed to traffic-generated PM. “The take-home message,” Allen said, “is that indoor PM and its relation to health outcomes depends on where the $PM_{2.5}$ is coming from, and this one small study suggests that particles produced by traffic may have some greater impacts than wood smoke particles on inflammation.”

Other intervention studies have shown that air filtration improves blood vessel function (Brauner et al., 2008; Karottki et al., 2013), reduces blood pressure (Padro-Martinez et al., 2015; Weichenthal et al., 2013), and reduces inflammatory and thrombogenic biomarkers (Chen et al., 2015). Allen also noted that one study in Massachusetts found results that were surprising and inconsistent in that filtration increased levels of a cytokine related to inflammation but also decreased blood pressure (Padro-Martinez et al., 2015). Allen said that the only cohort study of which he is aware, which looked at long-term exposure to indoor PM, found that long-term exposure to incense at home was associated with an increased risk of cardiovascular mortality (Pan et al., 2014).

In summary, Allen said, PM is an established cardiovascular risk factor, and the global public health burden of PM is primarily a result of its cardiovascular effects. Although the data are not entirely consistent, human studies have found links between indoor PM levels and increased systemic inflammation, blood vessel dysfunction, and increased blood pressure. The study of indoor PM, he said, presents an important epidemiologic research challenge, and more research is needed to better characterize the relative toxicity of PM generated indoors and outdoors, of PM from specific indoor and outdoor sources, and of $PM_{2.5}$ versus UFP. Other knowledge gaps, he said in closing, concern the role that bioaerosols play in generating the cardiovascular effects of exposure to indoor PM and the relationship between long-term exposure and actual clinical outcomes such as heart attack and stroke.

AMBIENT PM AND ADVERSE BIRTH OUTCOMES[2]

The first indication that ambient PM levels might have an impact on adverse birth outcomes, David Rich said, came from a 1995 study in China. In this study (Xu et al., 1995), the investigators used the Beijing birth registry to identify all of the mothers living in one of two urban districts and data collected from ambient monitors in the city to calculate an estimated average pollutant concentration for the first, second, and third trimester and over the course of the entire pregnancy. These data showed that the mean pollutant concentration, as reflected by sulfur dioxide and total suspended particulate levels, in the 7 days before birth was correlated with a risk of preterm birth. The data from this study also revealed a significant increase in the risk of having a baby with low birth weight when average pollution levels rose during the third trimester (Wang et al., 1997). This type of study, using existing datasets of birth outcomes, birth registry data, and pollution levels, has been conducted in numerous locations around the world to evaluate whether air pollution exposure during pregnancy is associated with preterm birth, fetal growth restriction, and pregnancy complications, Rich said.

Another type of study, which Rich called a "natural experiment," takes advantage of one-time events such as large sporting events, industrial facility closures, or government policies that drops ambient pollution levels for a defined time period and thus becomes a community-wide or region-wide intervention. One such study was conducted in the Utah Valley when a steel mill there closed for some 13 months, leading to a dramatic reduction levels of PM_{10} and other pollutants (Parker et al., 2008). The data from this study showed that the preterm birth rate in the Utah Valley dropped significantly during the period of the steel mill closure, whereas the preterm birth rate outside of the Utah Valley remained constant (see Figure 7-3). The finding that a drop in pollutant levels produced a beneficial health effect presents a powerful complement to studies showing an increase in pollutant levels produces a negative health effect, Rich said. "If this relationship is truly causal, we should see the effects in both directions," he explained.

Rich was involved in another natural experiment which looked at differences in birth weight associated with the 2008 Beijing Olympics, when the Chinese government mandated that, to improve air quality during the event, industries were shut down for 47 days, cars were only to be driven every other day, and several other pollution restrictions were put in place. This resulted in $PM_{2.5}$ levels dropping 40 percent, though they remained markedly higher than U.S. levels. The study by Rich and his colleagues

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[2] This section is based on the presentation by David Rich, an associate professor of public health sciences at the University of Rochester Medical Center, and the statements are not endorsed or verified by the National Academies of Sciences, Engineering, and Medicine.

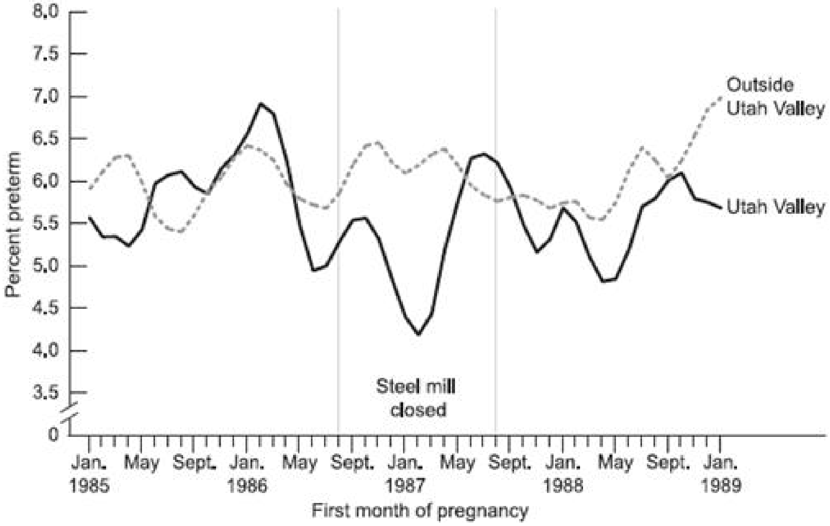

FIGURE 7-3 Preterm birth rate in and outside the Utah Valley before, during, and after the Utah Valley Steel Mill temporary close-down.
SOURCE: Rich slide 4, from Parker et al. (2008) Figure 1; reprinted with permission from Wolters Kluwer Health, Inc.

found an increase in birth weight for babies whose 8th month of gestation was during the Beijing Olympic Games period and its substantially lower air pollution levels (Rich et al., 2015). A separate analysis examining a longer study period and more pregnancies than just immediately before, during, and after the Beijing Olympic Games found that increases in 8th-month $PM_{2.5}$, nitrogen dioxide, sulfur dioxide, and carbon monoxide levels were associated with decreased birth weight, which provided complementary evidence of a late-pregnancy air pollution effect on birth weight.

A review of 12 studies examining the connection between fetal growth and air pollution identified a number of methodological issues, Rich said (Woodruff et al., 2009). The authors of this review noted that the limitations to these studies included confounding by socioeconomic status and maternal characteristics, inconsistent reporting of when during a pregnancy the exposures occurred, and a limited examination of exposures and outcomes. The authors recommended increasing the use of natural experiments, accounting for the socioeconomic indicators in the regions being studied, using alternate outcome measures other than those in birth registries, and measuring alternate surrogates of exposure.

One outcome from this review was that an international group of investigators, including Rich, each ran the same analyses on their datasets and found that the data, though not in total agreement, were consistent with the hypothesis that having a low-birthweight baby was associated with elevated exposures to PM_{10} during pregnancy (Parker et al., 2011). A more recent meta-analysis of these same studies' data found that this relationship held for both $PM_{2.5}$ and PM_{10} at a low but statistically significant level (Dadvand et al., 2013). "There is some evidence that air pollution causes or could cause fetal growth restriction, though the data are not consistent across the world and we do not yet fully understand mechanisms," Rich said.

Rich then described a study in which researchers in Spain examined the relationship between nitrogen dioxide levels and markers of fetal development measured from ultrasound images. This analysis found that first-trimester exposure to nitrogen dioxide levels correlated with measures of fetal head size (Iñiguez et al., 2016). "The timing is not the same, but this study again suggests that exposure to elevated levels of air pollution during pregnancy can have an effect on fetal growth," Rich said. One possible explanation for these findings could be that air pollution has an effect on the placenta that in turn affects fetal growth. To explore that possibility, a group of researchers looked at markers of placental growth and function and found that elevated levels of PM_{10} and nitrogen dioxide in the second trimester and during the entire pregnancy were associated with adverse changes in these markers (van den Hooven et al., 2012).

Pregnancy complications may also increase in frequency with elevated exposures to air pollutants. One study in southern California cited by Rich found an association between local traffic-generated air pollution—as measured by $PM_{2.5}$ and nitrogen dioxide levels—and preeclampsia (Wu et al., 2009). Another study in New Jersey found that $PM_{2.5}$, nitrogen dioxide, sulfur dioxide, and carbon monoxide levels were all correlated with an increased risk of stillbirth (Faiz et al., 2013).

Up to this point the studies that Rich discussed all dealt with ambient, or outdoor, PM, but he said that it should also be possible to study the effects of indoor PM exposure on birth outcomes. Pregnancy cohort studies, longitudinal panel studies that look at biomarkers throughout pregnancy, and intervention studies involving indoor air pollution could be used to study the effects of indoor PM on pregnancy outcomes, he suggested. Such studies would require identifying internal dose markers of individual exposures to indoor pollution and mechanistic biomarkers that could be measured throughout pregnancy. Rich suggested that researchers would need to determine when to make biomarker and pollutant measures, as well as whom to study and where such studies should be done.

To illustrate how researchers are addressing these issues, Rich cited a study now under way in Mexico City that enrolled non-smoking women ages 18 and older who would agree to visit the hospital for testing every 4 weeks for assessment (O'Neill et al., 2013). The 800 women in this study filled out extensive questionnaires that generated data on demographics, time, and activity in order to estimate pollution exposure, food intake, and GPS coordinates for home and work locations. Clinical data collected included ultrasound images, a glucose tolerance test at 22 weeks of pregnancy, and blood, urine, and other samples for biomarker measurements. At birth, the infant's characteristics, gestational age, and the baby's saliva were collected, along with a blood sample from the mother and the umbilical cord. Data collection is now complete, and analysis is under way to determine if exposure to certain pollutants at different time points during pregnancy is associated with the clinical outcome of preterm birth and with increases in levels of markers of inflammation, said Rich.

The final study Rich discussed was conducted by Ryan Allen and Enkhjargal Gombojav in Ulaanbaatar, Mongolia. It examined whether removing indoor PM using a portable HEPA filtration unit would prevent preterm birth. The researchers enrolled 465 women and collected data on preterm birth, birth weight, and maternal blood pressure. They also collected hair, whole blood, and blood spot samples for biomarker analysis. Data collection for this study was completed in December 2015, Rich said, and analysis is under way.

NEUROLOGICAL AND PSYCHIATRIC DISORDERS[3]

Researchers have begun studying the effects of air pollutants and PM on neurological and psychiatric disorders, Marc Weisskopf said, because of data showing that PM exposure has established consequences for cardiovascular diseases. "Frankly, there is a great deal of interaction between the vascular system and the brain, and many vascular risk factors are associated with cognition, dementia, and late-onset depression," he said. He added that studies have shown that $PM_{2.5}$ and UFPs can reach the brain, either via the nose and olfactory nerve (Oberdorster et al., 2004) or via the lungs and systemic circulation (Peters et al., 2006). The route through the olfactory system is perhaps the most relevant, Weisskopf said, because the olfactory nerve connects directly to important centers in the brain involved in emotional regulation and memory as well as to the limbic system. Crossing from the systemic circulation into the brain involves direct transport or damage to the blood–brain barrier (Calderón-Garcidueñas et al., 2008).

There is evidence that whichever route PM takes into the brain (see Figure 7-4), it alters neurotransmitter levels (Sirivelu et al., 2006) and trig-

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[3] This section is based on the presentation by Marc Weisskopf, an associate professor of environmental health and occupational epidemiology at the Harvard T.H. Chan School of Public Health, and the statements are not endorsed or verified by the National Academies of Sciences, Engineering, and Medicine.

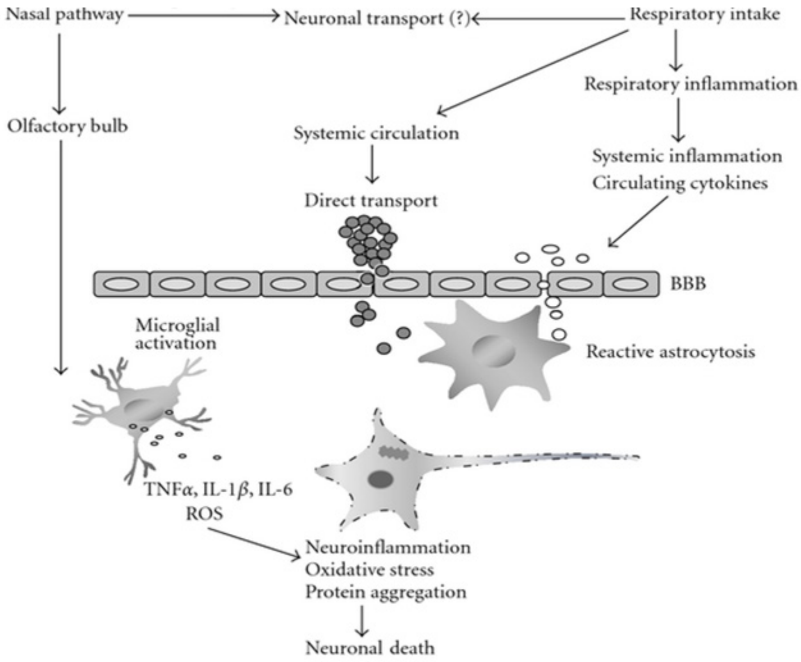

FIGURE 7-4 Effects of PM exposure on the central nervous system.
NOTE: BBB = blood-brain barrier; ROS = reactive oxygen species.
SOURCE: Weisskopf slide 4, adapted from Genc et al. (2012) Figure 1.

gers oxidative stress, inflammation, and other biochemical changes (Block and Calderón-Garcidueñas, 2009; Campbell et al., 2005; Kleinman et al., 2008), all of which can lead to neuronal degradation (Veronesi et al., 2005). All of these suggested negative consequences of particular exposure are evident in both human disorders and models of multiple neurodegenerative and psychiatric disorders, Weisskopf said. As an example, he cited one study in mice showing dramatic increases in the size of lateral ventricles—the space where cerebrospinal fluid circulates in the brain—with exposure to inhaled UFPs (Allen et al., 2015).

Experimental evidence suggesting involvement of the maternal inflammatory system in promoting autism-like behavior in mice (Choi et al., 2016), prompting researchers to look for a possible link between maternal PM exposure during pregnancy and autism. Using data from monitoring networks, meteorological readings, and a set of geographic information system–based predictors, Weisskopf and his colleagues created a time and space model of average predicted PM_{10} and $PM_{2.5}$ levels from 1988 to 2007 (Yanosky et al., 2014). They then used this model to analyze data from the

Nurses' Health Study II to estimate maternal exposure to PM_{10} and $PM_{2.5}$ for 9 months before pregnancy, during pregnancy, and for 9 months after pregnancy and to identify those women who had children diagnosed with autism. Compared with a matched set of women who did not give birth to children who developed autism, there was an increased risk of autism in mothers who had higher $PM_{2.5}$ exposure during any of those time periods, and particularly during the third trimester (Raz et al., 2015; Weisskopf et al., 2015). Weisskopf noted that several other groups have made similar observations (Becerra et al., 2013; Kalkbrenner et al., 2015; Talbott et al., 2015; Volk et al., 2013). "It's becoming quite consistent to see this association between higher perinatal exposure to PM and increased risk of autism in many different settings," Weiskopf said.

He and his colleagues have also been examining a potential link between PM exposure and anxiety. Data from the Nurses' Health Study I showed that 15 percent of the nurses in this study had elevated anxiety symptoms. The researchers observed an association between elevated anxiety and $PM_{2.5}$ exposure—but not PM_{10} exposure—within the month preceding the time at which the nurses filled out their questionnaires (Power et al., 2015). Weisskopf said that his team's most recent analysis suggests that "very recent or maybe even daily exposure might affect anxiety levels."

Other work from Weisskopf and his colleagues and other research teams in both the United States and Europe have revealed what Weisskopf called reasonably consistent results linking $PM_{2.5}$ and UFP exposure to changes in cognitive function, including the development of dementia, Parkinson's disease, and Alzheimer's disease (Kioumourtzoglou et al., 2016; Power et al., 2011). He added that a group in Spain has started looking at the connection between PM and other pollutant levels near schools and cognitive function in children.

Finally, Weisskopf addressed some potential methodological issues that may confound the link between personal air pollutant exposure and neurological and behavioral disorders. One issue, which is common to epidemiologic studies, is that there may be others factor such as personal behavior that are related to both exposure and effect. That may be less of a concern with the aforementioned studies because the extensive work modeling ambient air pollution levels show that the inputs are largely independent of personal behaviors and many other factors that could also be related to disease. However, that independence is not likely to be true for indoor exposures to PM because personal behaviors are an important determinant of exposure. "That does not mean you cannot do these studies," Weisskopf said, "but it raises concerns about bias issues that we have to pay attention to." He suggested that one approach to dealing with this potential bias that could be applicable to studies of short-term cognitive function and perhaps anxiety would be to assess performance on various cognitive tasks in a controlled office environment in which exposure levels could be adjusted.

DISCUSSION

To start the discussion, Howard Kipen commented that, in his opinion, the real challenge for the research community will be to identify which analyses will be useful to the regulating community in helping determine whether particular adverse health effects stem from indoor exposures or outdoor exposures. Rich said that the question becomes one of numbers with regard to how many people must be studied in order to have adequate statistical power to link outcomes with indoor PM exposure. He also said that an inexpensive validated marker of different indoor PM sources would be needed. Allen remarked that the epidemiologic studies that Weisskopf and Rich described are, in a sense, already addressing indoor PM given that people spend the majority of their time indoors. "So even when we see a signal from ambient PM, that has real relevance to what is happening inside people's homes and in their workplaces," he said.

This challenge, Allen said, is largely an exposure assessment issue, and he said he wants data with which to develop a time-and-space model for indoor PM in the same way that such models have been developed for outdoor PM. His group has tried to do that using property tax records to see if there were variables such as the age of the home and location that would allow them to predict PM infiltration. "It showed some promise, but it was not good enough to use in an epidemiologic analysis," he said. "Maybe we can explore other data sources that will help us understand residences, what is going on inside residences, and the infiltration of outdoor pollution indoors."

Weisskopf agreed with Allen's idea but said that he thought it would be difficult to find variables that will be good indoor predictors at the individual level. He added that he believes that intervention studies, where PM is removed from the indoor environment, could make possible the kind of analysis Kipen would like to see for short-term effects. For larger prospective cohort studies, he suggested doing smaller validation studies to see if there are simple questions that could be asked of study subjects that could probe the link between indoor activities and indoor air particulate levels. He mentioned the study on incense burning that Allen had described as an example. William Fisk thought it would be difficult to study a large enough population to get statistically meaningful data to link indoor PM exposures to long-term health issues. Barbara Turpin said there have been questionnaire-based studies in which 24- or 48-hour average PM levels were measured at the same time, but for the most part there is not a strong association between indoor PM levels and particular activities and sources in the home. Finding such associations will require real-time PM measurements or a chronic exposure situation where an activity happens frequently every day.

Joseph Hughes from the IAQ Training Institute said that researchers at the Carnegie Mellon University Robotics Institute have developed an under-$200 device called Speck that measures and records $PM_{2.5}$ levels in real time and uploads data to the Web. Rich mentioned that researchers at Clarkson University are trying to use some of these low-cost sensors to measure PM both indoors and outdoors. Weisskopf then asked if there is a filtration system that records how much PM is removed from circulated air and if such data could be used to calculate exposure levels. William Nazaroff replied that there are well-developed models for estimating indoor exposure in a mechanically ventilated building that could provide useful estimates for exposure at work, but this would still leave exposures at home to be determined. He added that he is optimistic that collaborations among members of the International Society of Environmental Epidemiology, the International Society of Exposure Science, and the International Society of Indoor Air Quality and Climate would provide a better mechanistic understanding of how to take outdoor PM levels and provide estimates of indoor exposures.

Arnold Schwartz from the Milken Institute of Public Health at the George Washington University asked Weisskopf if there were any correlations between pollution and olfactory nerve dysfunction. Weisskopf replied that there is evidence relevant to that question in occupational exposure settings and said that he and his research team are in the process of accumulating a large enough dataset to look at the effect of ambient air pollution exposures on olfactory nerve dysfunction. Schwartz then asked Rich if there is a correlation between inflammatory markers in placental tissue and in blood and if there are morphological changes within the placenta corresponding with those inflammatory markers. Rich replied that he is not aware of studies that have looked specifically at whether inflammation in the mother affects the placenta in a way that affects the fetus. He said he is optimistic that such studies would be performed soon. Weisskopf added that this is an important question for his work on autism because it points to something happening during the pregnancy period that is not tied to transport of particles to the fetal brain. “I think there is a maternal component we should be examining,” Weisskopf said. Schwartz also asked Allen if there are markers of indoor pollution that provide a linkage with atherosclerosis. Allen said he was unaware of any research explicitly looking at that link. He added, though, that inflammation is known to play an important role in the development of atherosclerosis, so it would make sense mechanistically that such a link might exist.

Paula Olsiewski from the Alfred P. Sloan Foundation asked if the panelists knew of anybody who is studying the effect of PM on the human microbiome. Kipen said his group is conducting some pilot studies toward that end but not in the indoor air context. Rich said he has reviewed a few grants proposals in that area but has not yet seen any research in the literature.

Fisk said that there should be an explicit notice in the workshop summary that allergy and asthma were not addressed in this session on health concerns. Kipen, who was on the workshop planning committee, acknowledged the importance of allergy and asthma but said that the decision had been made to focus on lesser-known and emerging health concerns in the time available. Rich agreed that there is a large body of work on allergy and asthma and said that in his mind there are fewer questions about whether there is a relationship between those outcomes and PM exposure.

An online workshop participant asked if the neurological health effects of PM exposure are thought to be caused by the irritant effect or by the chemical composition of the particles, and Weisskopf replied that he would guess that the answer is both. The irritant effect could trigger the inflammatory cascade and activation of microglial cells that prune the connections between nerve cells, he said, and if there were metal ions in the particles, such as lead, they could certainly have direct adverse effects on nerve cells.

Lynn Hildemann said she is intrigued with idea of trying to identify which PM sources have more or less effect on human health, and she asked the panelists if studies of occupations could provide any relevant information. For example, she said, a study of cooks might provide a good first estimate of how important exposure to cooking emissions is in terms of impacts on human health. Rich said that would be a good approach for something such as birth outcomes where there is a defined event—birth—with a well-defined date. "I think that is the kind of innovative, novel idea to try to take first-pass stabs at whether or not these sources could have important impacts," Rich said. Weisskopf noted that such studies are the foundation of classic occupational epidemiology. In fact, he said, he is doing just such a study in Denmark, where there are records tracking health outcomes and occupations for the entire population. What remains to be done, he said, is working with industrial hygienists and occupational epidemiologists to make measurements of indoor pollutant levels in various occupational settings.

Kipen asked if it should be possible to add a reasonable set of questions to the annual Nurses' Health Study that could be used to provide a retrospective analysis of residential exposures. Rich responded that such an approach could be a relatively inexpensive way to get preliminary data to look at long-term exposures, but he said that it would not be very useful for acute effects. Weisskopf said that the Nurses' Health Study III is in the process of recruitment and that it focuses specifically on younger women and includes questions on reproductive outcomes. "What we need to know," he said, is, "What are the questions to ask about the home environment? Which ones are the biggest drivers of changes in indoor particulate matter?" Developing those questions, he said, will require going into various types of homes, performing detailed assessments, analyzing the data to determine those factors that predict PM levels and account for the most variance, and then deciding if those factors can be captured in a reasonably simple question.

Allen added that it would be important to capture exposure variability. "If everybody is exposed to the same level, you cannot do an epidemiologic study," he said. "You need the exposure contrast." He also commented that questionnaires are only going to be able to capture information on the major sources of PM and said that there might not be sufficient variability in a specific population. "If everybody is cooking roughly the same amount in a week, it is going to be more difficult to see associations with health just because the exposure variability within the population will not be there," he said.

Laura Kolb from EPA asked the panel to offers their views on the scope of indoor PM as a public health issue. Weisskopf replied that if there is a link between PM exposure and anxiety, then this is a significant public health problem. "I think environmental exposures have been underappreciated in that realm, and the fact is, particulate matter is ubiquitous," he said. "If it even has a subtle effect, across the population, I think, it could be quite large. If you are knocking down IQ (intelligence quotient) by even a few points or having a bad day in the office because of particulate matter, that is a big impact on productivity." He noted, though, that there is the important question of how much exposure people are getting indoors over the course of the entire day.

Allen said he agreed completely with Weisskopf, both in terms of potential impact and the importance of determining indoor exposures, and he said that, at least for outdoor exposures, there does not appear to be a threshold in terms of dose–response level. "Any exposure seems to carry some health risk," he said. In the context of cardiovascular disease, he said that because these are prevalent outcomes, increasing the risk by 5 or 10 percent adds a significant number of additional cases. The bottom line, he said, is, "We do not know, but the potential is there for this to be a significant public health issue."

Rich agreed, adding that reproductive health outcomes were also a public health issue internationally. The issue with air pollutants such as PM is that everyone breathes, and so every pregnant woman is exposed to PM. "I think the absolute risk for some of these outcomes could be substantial simply because of the complete exposure everyone has," Rich said.

8

Interventions and Risk Communication

The workshop's final session featured three presentations on risk communication. George Gray of Milken Institute School of Public Health at the George Washington University discussed the challenge of communicating the risk of indoor PM exposure. William Hallman of Rutgers University talked about the lessons learned from communicating about other health risks. Lee Ann Kahlor spoke about what could be learned from a benchmark study to gauge public understanding and information seeking related to indoor PM risk. An open discussion moderated by William Nazaroff concluded the workshop.

THE CHALLENGE OF COMMUNICATING INDOOR PM RISK[1]

Two important unanswered questions regarding indoor PM are what to tell people about the associated risks and how to tell them, George Gray said. "This is particularly important because persuasion is the only thing we can do, as there are no regulatory avenues into the indoor environment," he explained. "What we have to do is help people understand the risks and make decisions." This challenge is compounded, he added, by the lack of data definitely linking indoor PM exposures to specific health risks.

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[1] This section is based on the presentation by George Gray, a professor of environmental and occupational health at Milken Institute School of Public Health at the George Washington University, and the statements are not endorsed or verified by the National Academies of Sciences, Engineering, and Medicine.

One of the first things the scientific community needs to understand with regard to explaining risk, Gray said, is how the public feels about risk because that attitude plays an important role in the way the public receives information (IOM, 2001). Attitude is shaped by a number of factors, including the magnitude of the risk, whether the risk outcome is fatal or not fatal, if the risk arises from a voluntary or involuntary behavior, if it is controllable or uncontrollable, if it is manmade or natural, whether it is observable or not, and if there is any benefit associated with the risk (see Figure 8-1). These factors, Gray said, have been identified over the past 20 years or so from research in the field of cognitive psychology (Fischhoff et al., 1993; Slovic et al., 2004). As an example of how benefits can affect decisions about risk, he observed that people choose to drive even though they know it is inherently risky because there is a tangible benefit.

Gray believes that getting the public to grasp the risk of indoor PM exposure is going to be difficult because many of the most important sources are familiar, voluntary, and linked to benefits. Cooking, for example, is something that people do every day, and it produces food they enjoy eating. Burning candles or incense is voluntary and makes the house smell good or may be part of a cultural or religious experience that is important to an individual.

There are, however, perception factors that might help with communicating risk. Children, for example, could be at risk as could a developing fetus, and those risks are controllable, sometimes through relatively simple and even inexpensive actions. Some of the important sources of adverse exposures are already areas of at least some concern among the public, such as secondhand tobacco smoke and outdoor PM. A 20-year-old study (Slovic et al., 1995) found that 80 percent of the Canadian public—as well as 80 percent of toxicologists—said that indoor air quality posed a slight, moderate, or high risk, suggesting that the public (at least in Canada) is aware that there may be a health risk associated with exposure to indoor pollutants.

Among the other challenges that the scientific community will face in conveying the risk of indoor PM to the public is the need to understand the magnitude of the risk before deciding how much to communicate about it, Gray said. "Is this something that everybody needs to know about?" he asked, noting the limited bandwidth that people have for thinking about risks and taking action to mitigate them. He suggested that comparing a risk to the risk associated with environmental tobacco smoke might be an approach that would get the public's attention, while comparing the risk of indoor PM exposure to the risks of cooking on a gas stove would lead the public to downplay the risks of indoor PM exposure.

It will be important too, Gray said, to communicate the relative contributions of different sources, particularly indoor versus outdoor, and how much of the exposure to these sources is under the individual's control.

Fatal	↔	Not Fatal
Global Impact	↔	Not Global Impact
Involuntary	↔	Voluntary
Uncontrollable	↔	Controllable
Unfair	↔	Fair
Catastrophic	↔	Individuals
Future Generations	↔	Only Current Generation
Increasing	↔	Decreasing
Not Easily Reduced	↔	Easily Reduced
Observable	↔	Not Observable
Known to Exposed	↔	Unknown to Exposed
Immediate Effect	↔	Delayed Effect
Old Risk	↔	New Risk
Known to Science	↔	Unknown to Science
Man-Made	↔	Natural
Children at Risk	↔	Only Adults at Risk
Untrustworthy Institutions	↔	Trustworthy Institutions
Media Focus	↔	Media Neglect
Identifiable Victims	↔	Statistical Victims
No Benefit to Me	↔	Benefits Me

FIGURE 8-1 Risk perception factors influencing public concern.
SOURCES: Gray slides 4, 5, and 6.

"One of the things that people want to know if you are going to talk to them about risk is, What can I do?" he said. "Don't just tell me to be scared—tell me that there is something I can do." He added that mitigation approaches that require changes in personal behavior are hard to sell, either because people benefit from those behaviors or do not feel the risk is big enough to warrant changing those behaviors. Another challenge, Gray said, will involve sorting out the risk tradeoffs, such as ventilation versus energy use, and explaining those to the public in a way that does not cause them to take actions that actually increase risk.

There are examples of success from which the indoor PM field can learn and borrow. Indoor radon is a close analog, Gray said, and it is an area where effective risk communication has over time changed perception and the actions that the public takes to mitigate that risk. One difference is that radon exposure has no known benefits associated with it. Secondhand smoke is an area in which there has been substantial behavioral change over the past 20 years, and there are similarities to indoor PM with regard to the risk to children and the voluntary nature of the activity. There is, however, a different level of awareness, concern, and dread associated with tobacco smoke, Gray said. The public has become more aware of the risks associated with indoor pesticide use, and risk communication there has focused on how to minimize the risks from exposure, particularly to children. Indoor pesticide use is voluntary and does have benefits, making it analogous to indoor PM, but it also comes with the connotation that, by default, synthetic pesticides are bad. There may also be lessons that can be applied from the evidence presented in various studies of indoor air quality in the developing world relating largely to indoor activities such as cooking with wood and other forms of biomass.

In closing, Gray said that if the field is to effectively communicate the risk of indoor PM, it will need the research disciplines represented at this workshop to produce data on the magnitude of the risks from exposure to indoor PM. But success will also depend on developing a better understanding of how the public thinks and feels about these risks, he said. "Maybe we can borrow information from similar situations to help guide us think about how we can be effective in communicating this information if and when we decide it is the thing to do."

EMPOWERING PEOPLE TO REDUCE INDOOR PM EXPOSURES[2]

Risk communication is integral to the risk analysis process, William Hallman said, and it also involves more than just determining what to tell people. “It is also about asking the right questions, which requires being very clear about our particular goals,” he explained. Citing a 1989 report from the National Research Council, Hallman listed three essential goals for risk communication: education, advocacy or persuasion, and fostering partnerships for decision making. All three of these goals, he added, are implicit outcomes with regard to indoor PM.

Education aims to provide information and context so that people can choose what they believe is the right action to take in the face of risk. Advocacy or persuasion, in contrast, tries to change beliefs, attitudes, and behaviors in order to convince people to adopt a particular position: to take or not take an action. The goal of fostering partnerships, Hallman said, is to collect and discuss information with stakeholders in a way that leads to better collective decisions. He stressed the importance of involving stakeholders, manufacturers, and regulators early in this process to get their perspectives on how to deal with the issues related to indoor PM. Hallman added that simply alarming people is ethically problematic. “We have to tell them not just what the problem is, but what to do about the problem,” he said.

Interventions, Hallman said, can be focused on changing technology, behavior, policy, or regulations. With regard to technology, it is important to determine who has the responsibility and resources to make the necessary technology choices, an issue that was raised in earlier discussions concerning disadvantaged communities and individuals. One solution for these communities—where the ability to get property owners to make changes to HVAC systems is limited, for example—might be to provide incentives or tax rebates for the purchase of portable HEPA filtration units.

The invisibility of PM matters, Hallman said, and it represents a key issue in communicating the risk of indoor PM exposure. One approach to discussing the risks, he said, is to use how people feel when other impose risks on them. “You can harness strong feelings to try to get fairly rapid changes in policies and regulations, and that is exactly what happened with secondhand smoke,” he said. In contrast, when individuals are responsible for their own exposures, it is easy to ignore them, particularly when the problem is invisible. Radon is the prototypical example of the latter, and Hallman described the work that he and his colleagues did with EPA in the

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[2] This section is based on the presentation by William Hallman, a professor and the chair of the Department of Human Ecology at Rutgers, the State University of New Jersey, and the statements are not endorsed or verified by the National Academies of Sciences, Engineering, and Medicine.

early 1990s trying without much success to persuade people to spend $7 on a carbon canister to test their homes for radon.

When a threat is invisible, people look for proxy indicators, such as smoke detectors and carbon monoxide detectors. In the area of food safety, which Hallman has studied, people use their sense of smell and taste as indicators, or else they look for visual indicators, such as mold. The problem with this particular mental model of food spoilage is that the bacteria that cause spoilage are not necessarily pathogenic. Hallman has found that the public perceives that a clean-looking home is a germ-free home (Hallman, 2008) and that the presence of mold, dust, filth, and bad smells are good indicators of germs being present. "People are using proxies of things they can see to represent things they cannot see," Hallman said, "so one question we need to ask is what are the proxies that people will use or are using for indoor PM," given that PM may have no taste or smell.

Hallman noted that while the size of PM is an important concern to the scientific community, he believes that this will be of little concern to the public and that it is not the place to start a communication effort. He also said that the lack of a feedback loop matters and that it can be difficult for people to make the link between an invisible cause and a later, visible effect. He again used food safety as an example. People do not recognize the symptoms of foodborne illness, and few people believe they have made themselves or other sick because the most common mental model is that eating contaminated food will make one sick immediately. "As a result, they do not connect their poor food safety practices with ultimate illness," Hallman said. "I suspect we have a similar issue here, although we need the research to show that."

Hallman said if there was one key message he wanted to convey at this workshop, it was that mental models matter. While it is important to know what people know about an issue and what they want to know about an issue, it is more important to know how they think about an issue. Certainly, he said, answering the questions that people are most interested in makes it more likely they will be willing to hear more of the information the scientific community wants to convey. "But I would also argue as a psychologist," he said, "that it is important to understand how people think about an issue, how they construct a 'big picture' or world view about an issue." In that context, Hallman said, the scientific community needs to realize how much most Americans overestimate their knowledge and understanding of science and technology. "Only 20 percent of Americans rate their understanding of science as poor, but ask them any science question and most will get it wrong." In fact, Hallman added, Americans often exhibit false fluency, where they may have the right vocabulary but not the right constructs. The lesson here, he said, is that when conducting social science research, people in the field needs to be careful to ask the right questions phrased in a way that will yield both qualitative and quantitative data on how people think about indoor PM, not just the facts they know about it.

The issue with mental models, Hallman said, is that people try to make sense of the world by creating meaning based on whatever information they have available and filling any gaps with misinformation or by inventing information. This is a particular problem in the world of the Internet and social media, he said. "A quick search on indoor PM issues suggests there is already bad information available on indoor PM." Hallman also explained that people use analogies and metaphors to organize their mental models, and he recounted some work that he did for CDC on how the public thinks the immune system works. Without any prompting, the most common explanation people gave used a military metaphor with "good guy" blood cells engaging in a war against "bad guy" germs or cancer. Then, when asked how vaccines work, the most common answer was that a vaccine adds more troops to the germ fighters. "It is like the cavalry riding in, which makes absolute sense, except that it is absolutely wrong," Hallman said, adding that his response as a risk communicator was to stick with the military metaphor but explain that vaccination helps the germ fighters recognize the enemy and respond more quickly to them. "We need to identify the metaphors we can use that will get into people's heads relatively quickly rather than trying to give them a lecture on $PM_{2.5}$," he said.

Acknowledging that he lacked data because no mental modeling research appears to exist regarding indoor $PM_{2.5}$, Hallman said that his guess is that the mental models the public might use to understand indoor PM would include the following:

- "Bad air" triggers asthma attacks, and since nobody in my family has asthma, I do not have a problem.
- "Air pollution" is "outside," and I keep my windows closed, so I do not have a problem.
- "Air pollution" is caused by cars, factories, and power plants that produce "smoke."
- Sources of "indoor air pollution" have to do with combustion and smoke, and because nobody in my house smokes, I do not have a problem.
- Combustion is associated with open flames and not electricity, and I have an electric stove, so I do not have a problem.
- My cooking produces pleasant aromas, not harmful PM, so I do not have a problem.
- Candles produce small flames and so are not a significant source of PM, so I do not have a problem.

- Water "washes things" and is clean, so my water is not a source of PM.
- Air "fresheners" clean the air, so I do not have a problem.
- "Particulate matter" means "dust," and I vacuum twice per week, so I do not have a problem.
- Why is a filter rated 16 better than a filter rated 1? Isn't being number 1 the best?

Hallman also noted the importance of advertising claims to the formation of mental models and the need to look at the information being passed to consumers through advertisements for air cleaning products and services. He said that a quick search yields bad information associated with these products, so the field will need to think about how to counter this misinformation and do so in a way that provides useful holistic advice. Simply warning people does not work, Hallman said, but telling them what to do and helping them do it by providing practical, effective, and affordable advice can work. Consistency and dependability will be key to avoiding the problem that the field of nutrition now has—i.e., as a result of ever-changing dietary recommendations, many Americans lack trust in nutritional advice. Hallman stressed the need to engage stakeholders—including partner organizations involved in science, health, and engineering, as well as appliance manufacturers and professionals in the building trades—to develop consistent, credible messages for consumers.

Hallman concluded his presentation with a list of what people will likely want to know about indoor PM:

- What causes indoor air pollution?
- Am I affected, how will I know, and who else is vulnerable?
- What are the immediate and long-term consequences?
- Does this explain my health issues?
- Can I do anything about it? Do I know what to do? Do I have what I need? Can I do it by myself? Where should I start?
- Who is responsible for the problem, and can it be prevented?
- Who will solve the problem, how long will it take, how effective will the solution be, who will pay for it, and how expensive will it be?
- How will I know that the problem has been solved, and can I trust that it has been solved?

Hallman said that not having all of the answers to these questions does not preclude engaging in risk communication today, particularly given that this conversation about exposure to particulate matter in indoor air is already occurring. His prescription for communicating information in the face of uncertainty is to acknowledge that uncertainty and say, "This is what we know and do not know now. This is why it matters, this is what we are doing to become more certain, and this is what you can do while we continue to work on this particular problem."

WHAT COULD BE LEARNED FROM A BENCHMARK STUDY[3]

In the workshop's final presentation, Lee Ann Kahlor discussed the desirability of gathering baseline data to jump start a risk communication research agenda focused on PM. Such data are needed, she said, because little is known about how the public perceives indoor environmental issues broadly and the issues of PM in particular. "We need a current snapshot of PM risk, knowledge, and attitudes but also data to give us direction about how to make information more compelling, especially to audiences that are uniquely vulnerable," Kahlor said.

Communication, she continued, is about telling compelling stories to a variety of audiences that need to hear those stories. When thinking about stories and audiences, the research community must remind itself often that it is a privileged group and that while only 29 percent of adults 25 years of age and older have a 4-year college degree, the other 71 percent can make important decisions about their health and their family's health on a moment's notice when necessary. It is also important to remember that 43 percent of Americans live in rental housing, and therefore are limited in the actions they can take, and that 15 percent live in poverty, which means they cannot afford most of the remediation approaches described at this workshop.

Each of the many audiences for information on PM needs to be reached uniquely, in ways that respond to its members' resources and values and that take into account the competing threats to their health, safety, and quality of life, Kahlor said. Mass communications research can identify the psychological and social psychological factors unique to each audience, and crafting narratives with these factors in mind will help develop a version of the story that resonates in important ways with that unique audience. This kind of research can also identify which of the many information channels that exist are best suited for conveying stories to specific audiences to achieve a desired effect, which can be a change in attitude, knowledge, or behavior. Kahlor said that one aspect of developing a strategic communication plan is understanding what the information source says and with what intention. "So we as information creators want to be very honest about

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[3] This section is based on the presentation by Lee Ann Kahlor, associate professor in the Stan Richards School of Advertising at The University of Texas at Austin, and the statements are not endorsed or verified by the National Academies of Sciences, Engineering, and Medicine.

our intention," Kahlor said. "Why do we think we have this story to tell, and why do we think it going to resonate with our audience?" Being self-conscious about intentions is critical, she said.

From the presentations she had heard, Kahlor said she had developed a list of research questions that could be part of a baseline study. These included the following:

- Who is vulnerable to PM risks?
- What information do they have about PM risks, and what more do they want to know?
- What risk messages about PM would be compelling for what audiences?
- Who would be credible sources for messages about PM?
- What partnerships would be useful in getting messages out?

To answer these questions, Kahlor recommended using a risk-information-seeking framework, one that focuses on people helping themselves to information outside of a formal education setting. She noted that people do not simply absorb the information that the scientific community generates, but rather, they must be engaged in such a way that they process the information and make it meaningful in a way that makes sense personally. "We need to think about what motivates people to seek information," Kahlor said. Such motivations might include social norms in terms of what others in their social circle and community expect them to know about topic; a sense of risk; existing knowledge that provides a mental model through which new information flows; how much knowledge people think they need; beliefs about seeking information and whether useful information exists for them to use; and beliefs about the ability to get and process information. Kahlor has organized these motivations in a model she calls the Planned Risk Information Seeking Model (Kahlor, 2010), illustrated in Figure 8-2. One motivation not included in this model, she said, is avoidance, which refers to actively avoiding information. Avoidance can be driven by both negative affect and a desire to maintain hope and feel happy.

Communicating risk is a complicated task, Kahlor said, because it is affected by the fact that understanding is difficult when the audience lacks a knowledge of basic science. "You are not just explaining your science, you are explaining all of science so that you can provide some scaffolding with which to process your information," she explained. In that context, it is important to decide what a person really needs to know in order to hear a message and to make meaning from it. Other concepts of interest include vulnerability indicators, such as age, life stage, overall health, community, and place; trusted sources for health risk information; comparative social,

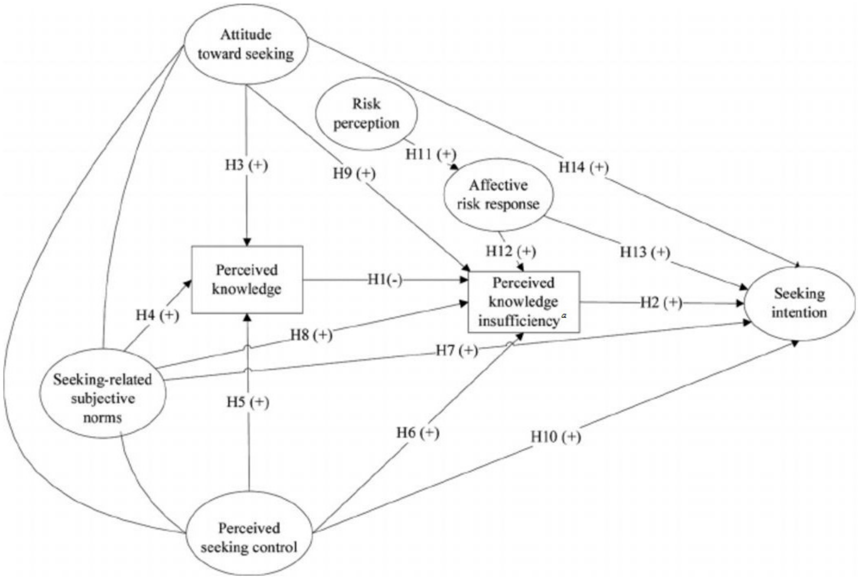

FIGURE 8-2 The Planned Risk Information Seeking Model. [Abbreviations defined in source publication.]
SOURCE: Kahlor slide 13, adapted from Figure 1 in Kahlor (2010). From PRISM: A Planned Risk Information Seeking Model, Kahlor, *Health Communication*, 2010, Taylor & Francis, reprinted by permission of the publisher (Taylor & Francis Ltd., http://www.tandfonline.com).

economic, safety, and health risks in the environment; and existing risky behaviors.

Kahlor said that in her opinion the best approach for getting data to explore these questions and concepts would be to start with a survey that produces generalizable data from a cross-section of Americans, with a special effort to include vulnerable communities in the sample. For example, because children are vulnerable and parents are natural information seekers when it comes to their children, the survey might include a subset of parents of children up to age 12. Residents of disadvantaged communities, identified by zip code or county, and the elderly could both be oversampled in order to provide a sense of some of the challenges associated with getting information into those communities.

To get a sense of how long it would take to conduct such a survey and how much it would cost, Kahlor contacted a private company that conducts probability-based online surveys for academia, government, and nonprofit organizations. A 15-minute survey of 2,500 individuals, including 500 parents of children up to age 12 and 500 residents of designated disadvantaged communities—as a starting point—would take 2 months and cost $65,000. This sum, she noted, did not include conducting the survey in Spanish or sampling elderly and retired persons, which she thought would be a good idea.

Kahlor observed that the data from this survey would provide information on the social norms that would help or hinder getting information out to audiences. It would also reveal patterns in perceived risk and related worry and existing knowledge versus how much knowledge individuals think they need. The data would help researchers understand beliefs about the information available and attitudes toward that information, the ability to get and process information, and whether such information will be accessible. The data would also identify trusted sources for conveying information and the preferred channels for receiving information. It will be important to distribute the data through multiple channels in order to reach as many disciplines as possible, and this will require presenting the data in multiple venues, including journals and conferences.

In summary, Kahlor said, once the data are available to illuminate who the audiences for information on PM are and what information they need, the challenge will be to focus on the stories that need to be told and on tailoring those stories in ways that are meaningful to these audiences. Partnerships will be critical to delivering those stories in a way that resonate with place, time, and most critically, the people themselves.

DISCUSSION

To start off the final discussion, William Nazaroff asked the panelists if their messages to the workshop would change if the audiences for information were expanded beyond the general public to include architects, members of the building trades, manufacturers of mitigation equipment, professional associations, health care providers, and policy makers. Kahlor said she thought the answer would be no, that stories would just be tailored for each of these unique audiences. Gray added that, given the influence that standards can have on the design of buildings and the products that go into them, the standards community should be included as an important audience. Hallman disagreed, however, saying that he believes talking to these other audiences requires different conversations, not different messages, and directing those conversations requires answering different questions.

William Fisk asked if, given the invisibility of particles, communication should revolve around sources and approaches to mitigation and the tangible actions that people can take. Gray said he thought that was a good idea, but added that there will still be the need to get people to care about why they need to make an investment in time and money or change some aspect of their behavior. That, Gray said, is why the big challenge is making the invisible visible, at least in a mental model. Howard Kipen asked if getting hard data on the health effects of exposure to indoor PM—as opposed to extrapolating from outdoor PM data—would help address this challenge, and Hallman said that the answer was yes, that those data for indoor PM are essential.

Brett Singer asked the panelists to comment on whether the precautionary principle—the idea that knowing that something could be harmful would warrant action if there is an easy way to reduce risk—would be a useful framework in the absence of hard data. Kahlor responded that the precautionary principle can be helpful, but the danger is that the media will convert uncertainty into certainty. The argument, she said, has to be put forward with care so that it gets to the intended audience in the right form. Hallman suggested that this was the approach the field was taking today. "I think the assumption around the room is that exposure to PM is not a good thing at any level and we should try to reduce it," he said. "Unfortunately, in the United States we do not regulate on the precautionary principle very often, and when we do it is called government overreach." As a result, he said, the goal should be to reduce exposures but not based on the precautionary principle.

Gray noted that relying on the precautionary principle could have the effect of increasing disparities because people with resources would be more likely to take action than those whose resources are limited. Hallman agreed with Gray's assessment and said an additional complication is that those without the resources to take action are often left feeling guilty about not being able to protect their children and their families.

Brent Stephens asked about the challenge of communicating the type of relative risks that were discussed in the prior session, and Hallman responded that people often have a difficult time with very large and very small numbers. The shorthand that the technical community uses to communicate within its members serves to alienate the public, he said, and so trying to get the public to think like scientists and understand scientific language and concepts will not work.

With regard to changing personal behavior, Marc Weisskopf asked whether the message that PM could be influencing an individual's energy level might be a good secondary message, given that this is an effect that people would experience every day and that does not take years to develop. Kahlor replied by reiterating the need to picture what people would do with that kind of information, and Weisskopf acknowledged that concern but countered that there may be easy and inexpensive actions—using the kitchen hood or opening the apartment windows at the appropriate time—that would provide some benefit. "It would seem that people would act on something if it was more likely to affect something they experience every day," he said. Gray cautioned that it is important that the message be credible and that the subsequent action needs to produce a meaningful benefit that will not be overwhelmed by all of the other things going on in someone's life. "That would hurt credibility," he said.

Hallman cautioned that once people are convinced that indoor PM is a problem and learn there are multiple sources, they will pick and choose which ones to address. One lesson from nutrition research, he said, is that people form an indulgence mental model in which somehow the apple in their pocket cancels out the big breakfast they ate. With PM, people could run their kitchen fans and then feel better about burning candles, he suggested.

In response to an online question about how to improve compliance for air cleaner and range hood use, Hallman said that the answer is to make them automatic, to make "on" the default condition and to make them quiet. Vito Ilacqua from EPA agreed with Hallman and suggested that the way to get such automatic systems into homes would be to start with the early adopters, the people willing to pay a higher price to get a market started. As an analogy, Ilacqua noted that thermostats were a luxury item at one time but are now standard in every home and apartment. Hallman said that the idea had potential and suggested linking automatic systems to the "Internet of things" that could provide remote sensor readings of airborne PM to provide the necessary input. "These things are possible, and they are not necessarily all that expensive," Hallman said. "With research dollars, it could happen."

Along those same lines, Barbara Turpin asked if outfitting homes with PM monitors that display real-time PM levels would change people's behaviors, similar to the way that cars are now outfitted with fuel economy readouts. Gray and Hallman both said they thought that was a good idea, and Hallman added that providing people with social norm data could also help motivate behavior change, though it could also create anxiety.

Paula Olsiewski wondered if it was possible to frame the interventions discussed at this workshop in terms of creating a healthier home. Kahlor said she thought that could be a useful framework because it is general and not tied to a specific risk factor. The key will be the rest of the message—what an individual can do to create that healthier home. Gray agreed with the importance of the "What next?" part of that message and added that some of those what-next steps will be things that some stakeholders who hold a different point of view will not want to have happen. Hallman added that there is a science of science communication and methods for testing these kinds of messages before putting them out to the world, and he said that this is the kind of research needed once the baseline data are available. "We need programmatic research in this area and not just a couple of studies," he said. He noted, too, that EPA was the initial leader in the federal government on risk communication.

Richard Corsi remarked that when he gives talks to the general public about indoor PM, members of the public pay attention when he talks about candles, and they then inquire where they can get more information. Corsi said that the EPA and California Air Resources Board websites have good information on them about indoor PM, and he asked the panelists if those sources of information are important and if the public perceives the importance of getting that kind of information. Kahlor said that when experts direct individuals to websites, they can be good sources of information, but in some settings, such as a doctor's office, a well-designed pamphlet could be a more useful information source. Hallman added that when people want health-related information, they typically go to the Internet these days, and so it would behoove the experts to check what Wikipedia and WebMD have to say about indoor PM to make sure they are providing good information. Most members of the public, he said, are not likely to think of going to the EPA website as their first source of information. He also suggested that this community could create a website with an intuitive name that would naturally draw people to good information.

Gediminas Mainelis asked if the panelists had any thoughts about how to communicate information in a way that will not lead to people altering their behavior in a way that negates any improvements that might make, such as putting ionizers and filters in their homes and then smoking inside. Hallman said risk homeostasis theory (Wilde, 1998) addresses this kind of behavior. David Rowson from EPA then asked the panelists for ideas on how to conduct non-regulatory risk communication around an issue that involves promoting, encouraging, and suggesting behavior change rather than requiring it and enforcing compliance. Hallman replied that the argument can be framed in terms of a gain—health will improve if indoor PM levels are reduced—or a loss and that social norms can be used to encourage positive behaviors. He added, though, that it is important to be realistic about what risk communication alone can accomplish. "The idea that we are going to encourage 90 percent of the public to do something based on the information we provide is unrealistic, which is why regulations are needed," he said. Offering an example that he said was relevant to indoor PM, he noted that getting New Jersey homeowners to test for radon only happened when stakeholders insisted that radon tests be done before people could get mortgages.

To end the discussion, Terry Brennan noted that when he was building single-family residences in the 1980s, he would violate manufacturer's warranties by wiring thermostats into the range hood so that they would turn on automatically when someone was cooking, and he installed high-efficiency filters in the HVAC systems. "That was easy for me to do as the builder because I had control over what went into the building, and it was an easy sell to the homeowner." Since then, he said, he has worked with builders who put up 5,000 houses per year. Making changes at that scale would represent an important step, but doing so would require making changes in standards, which he said is an uphill process, given that for every group involved in the discussions that wants change there is another group that does not. The key in that case, Hallman said, is to convince the policy makers that the public wants these changes, which is where the data from the study Kahlor proposed could help.

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Appendix A

Workshop Agenda

Workshop on the Health Risks of Indoor Exposure to Particulate Matter

500 Fifth Street NW, Washington, DC 20001

WEDNESDAY, FEBRUARY 10, 2016

8:30 a.m. **Welcome, Workshop Goals, and Introductions**
William Nazaroff, Ph.D., Chair

8:40 a.m. **Sponsor Remarks**
David Rowson, M.S.
U.S. Environmental Protection Agency

9:00 a.m. **SESSION I: SOURCES OF INDOOR PARTICULATE MATTER**
Moderated by: William Nazaroff, Ph.D.

Outdoor Air and Appliances as Sources of Indoor Particulate Matter
Brent Stephens, Ph.D.
Assistant Professor of Architectural Engineering,
Illinois Institute of Technology

Indoor Sources of Airborne Allergens and Smoke
Lynn M. Hildemann, Ph.D.
Professor of Civil and Environmental Engineering,
Stanford University

Surrounded by a Cloud of Dust: Particle Resuspension in Indoor Environments
Brandon E. Boor, Ph.D.
Assistant Professor of Civil Engineering, Purdue University

10:30 a.m. **Break**

10:45 a.m. **SESSION II: PARTICLE DYNAMICS AND CHEMISTRY**
Moderated by: Richard Corsi, Ph.D., P.E.

Indoor Chemistry and Aerosols
Glenn Morrison, Ph.D.
Professor of Civil, Architectural, and Environmental Engineering, Missouri University of Science and Technology

Dynamics of Particle Size and Concentration Indoors: A Building Science Perspective
Jeffrey Siegel, Ph.D.
Professor of Civil Engineering, University of Toronto

Composition of Indoor PM, Including the Influence of SVOC Partitioning
Charles Weschler, Ph.D.
Adjunct Professor, Rutgers University; Visiting Professor, Technical University of Denmark and Tsinghua University

12:15 p.m. **Lunch**

1:15 p.m. **SESSION III: EXPOSURE LEVELS AND CHARACTERIZATION**
Moderated by: Terry Brennan, M.S.

Fine PM Exposure Characterization Provides Insights into Sources and Transformations
Barbara Turpin, Ph.D.
Professor of Environmental Sciences and Engineering, University of North Carolina Gillings School of Global Public Health

Some Determinants of Indoor Concentrations and Exposures to Particulate Matter
Roy Harrison, Ph.D., D.Sc. (*presenting via web conference*)
Queen Elizabeth II Birmingham Centenary Professor of Environmental Health, University of Birmingham

Socioeconomic Determinants of Indoor PM Exposure: Understanding Sources, Structures and Settings
Gary Adamkiewicz, Ph.D., M.P.H.
Assistant Professor of Environmental Health and Exposure Disparities, Harvard T.H. Chan School of Public Health

2:45 p.m. **Break**

3:00 p.m. **SESSION IV: EXPOSURE MITIGATION**
Moderated by: Tiina Reponen, Ph.D.

Indoor Particle Mitigation with Filtration
William Fisk, M.S.
Senior Scientist, Indoor Environment Group, Lawrence Berkeley National Laboratory

Methods and Approaches for Controlling Exposure to Biological Aerosols
Sergey A. Grinshpun, Ph.D.
Professor of Environmental Health, University of Cincinnati College of Medicine

Indoor PM Exposure Mitigation in Low-Socioeconomic Status Households
Brett C. Singer, Ph.D.
Staff Scientist, Residential Building Systems, Indoor Environment Group, Lawrence Berkeley National Laboratory

4:30 p.m. **General Discussion and Summary**

THURSDAY, FEBRUARY 11, 2016

8:30 a.m. **Welcome**
William Nazaroff, Ph.D., Chair

8:35 a.m. **SESSION V: IDENTIFIED AND EMERGING HEALTH CONCERNS**
Moderated by: Howard Kipen, M.D., M.P.H.

Indoor Particulate Matter Air Pollution and Cardiovascular Health
Ryan Allen, Ph.D. (*presenting via web conference*)
Associate Professor, Faculty of Health Sciences, Simon Fraser University

Ambient Particulate Matter (PM) Air Pollution and Adverse Birth Outcomes: Targets for Studies on Health Effects of Indoor PM
David Rich, Sc.D., M.P.H.
Associate Professor of Public Health Sciences, University of Rochester Medical Center

Particulate Matter Air Pollution: Neurological and Psychiatric Disorders
Marc Weisskopf, Ph.D., Sc.D.
Associate Professor of Environmental and Occupational Epidemiology, Harvard T.H. Chan School of Public Health

10:05 a.m. **Break**

10:20 a.m. **SESSION VI: INTERVENTIONS AND RISK COMMUNICATION**
Moderated by: William Nazaroff, Ph.D.

The Challenge of Communicating Indoor PM Risk
George Gray, Ph.D.
Professor of Environmental and Occupational Health, Milken Institute School of Public Health at the George Washington University

Empowering People to Reduce Indoor Exposures to Particulate Matter: What Can We Learn from Communicating About Other Health Risks?
William K. Hallman, Ph.D.
Professor and Chair, Department of Human Ecology, Rutgers University

Public Understanding and Information Seeking Related to Indoor PM Risk: The Need for a Benchmark Study
Lee Ann Kahlor, Ph.D.
Associate Professor, Stan Richards School of Advertising, The University of Texas at Austin

11:50 a.m. **Closing Remarks**
William Nazaroff, Ph.D., Chair

12:00 p.m. **Adjourn**

Appendix B

Biographical Information: Workshop Speakers

Gary Adamkiewicz, Ph.D., M.P.H., is an assistant professor of environmental health and exposure disparities at the Harvard T.H. Chan School of Public Health, where much of his work focuses on the connections between housing and health and on understanding disparities in environmental exposure. His research has included studies of indoor environmental conditions within the homes of children with asthma and studies that aim to understand the factors that contribute to specific exposures such as pesticides and other chemicals, allergens, secondhand smoke, particulate matter, and other combustion by-products. He has worked with national, state, and local agencies on projects that aim to reduce the burden of disease from indoor environmental issues. Dr. Adamkiewicz is a member of the Science Advisory Committee for the National Center for Healthy Housing and has served on the U.S. Environmental Protection Agency's Environmental Justice Technical Guidance Review Panel, under the auspices of the agency's Science Advisory Board. He has also served as an advisor to the World Health Organization's effort to establish indoor air quality guidelines. He also serves as the Healthy Cities Program Leader at the Harvard Center for Health and the Global Environment. In 2012 the *American Journal of Public Health* awarded Dr. Adamkiewicz a Paper of the Year honor for his work on housing as an environmental justice issue. Dr. Adamkiewicz holds a Ph.D. in chemical engineering from the Massachusetts Institute of Technology and an M.P.H. from Harvard.

Ryan Allen, Ph.D., is an associate professor of environmental health in the Faculty of Health Sciences at Simon Fraser University. He holds a master's degree in environmental engineering and a Ph.D. in environmental health sciences, both from the University of Washington in Seattle. Dr. Allen completed a postdoctoral training in environmental epidemiology as part of the U.S. Environmental Protection Agency–funded MESA Air study, which focused on the link between long-term air pollution exposure and the progression of subclinical cardiovascular disease. Dr. Allen's current research focuses include air pollution exposure assessment methods, the cardiovascular effects of air pollution, the evaluation of interventions to reduce air pollution exposures and health effects, and the impacts of early-life air pollution exposure on childhood growth and development. In 2010 Dr. Allen was awarded the Joan M. Daisey Outstanding Young Scientist Award by the International Society of Exposure Science.

Brandon E. Boor, Ph.D., is an assistant professor of civil engineering and environmental and ecological engineering (by courtesy) at Purdue University. He leads the Indoor Aerosol and Exposure Laboratory at Purdue and is a member of the Center for High Performance Buildings at the Ray W. Herrick Laboratories. Dr. Boor's research focuses on characterizing the dynamics of airborne particles in buildings and human exposure to indoor and urban air pollutants. He has previously worked with research groups at the University of Helsinki, Finnish Institute of Occupational Health, and VTT Technical Research Centre in Finland as well as the National Institute of Standards and Technology in Maryland. He has received various fellowships, including a National Science Foundation Graduate Research Fellowship, U.S. Environmental Protection Agency STAR Fellowship, ASHRAE Grant-In-Aid, and a Fulbright doctoral grant to Finland. Dr. Boor received his Ph.D. from the Department of Civil, Architectural, and Environmental Engineering at The University of Texas (UT) at Austin. He also holds an M.S.E. in environmental and water resources engineering from UT Austin and a B.S. in mechanical engineering from York College of Pennsylvania. While at UT Austin, Dr. Boor participated in the interdisciplinary National Science Foundation Integrative Graduate Education and Research Traineeship program in indoor environmental science and engineering.

William Fisk, M.S., is a senior scientist at the Lawrence Berkeley National Laboratory. His research focuses primarily on energy efficient methods of maintaining and improving ventilation and indoor environmental quality (IEQ) in commercial buildings and on quantifying the impacts of building ventilation and IEQ on health and performance. He has more than 30 years of experience in research on the interrelated issues of building energy performance, ventilation, IEQ, and occupant health and performance. Mr. Fisk is a fellow of ASHRAE and a member of the Academy of Indoor Air

Sciences, and he serves as an associate editor of the journal *Indoor Air*. He is an author of approximately 115 refereed archival journal articles or book chapters. He has B.S. and M.S. degrees in mechanical engineering. Mr. Fisk was a member of the Institute of Medicine Committee on Damp Indoor Spaces and Health and the Committee on the Assessment of Asthma and Indoor Air Quality.

George Gray, Ph.D., is a professor of environmental and occupational health at the Milken Institute School of Public Health at the George Washington University. Dr. Gray's primary research interests are risk characterization, risk communication, and the role of science in policy making. Particular areas of emphasis include the role of risk analysis in sustainability decisions, characterizing the risks of sparsely tested chemicals, and improving the use of scientific information in regulatory decisions. Earlier, he served as assistant administrator for the Office of Research and Development at the U.S. Environmental Protection Agency (EPA) and as the agency science advisor, promoting scientific excellence in EPA research, advocating for the continuing evolution of the agency's approach to analysis, and encouraging programs that provide academic research to support EPA's mission. His areas of focus included nanotechnology, ecosystem research, the influence of toxicology advances on testing and risk assessment, and sustainability. Dr. Gray has his M.S. in toxicology and Ph.D. from the University of Rochester School of Medicine and Dentistry.

Sergey A. Grinshpun, Ph.D., is a professor in the Department of Environmental Health and the director of the Center for Health-Related Aerosol Studies at the University of Cincinnati College of Medicine. He has been involved in experimental and theoretical research on aerosol sampling, analysis, real-time detection, and characterization. At the University of Cincinnati since 1991, he has been engaged in the laboratory and field studies of aerosol transport in indoor and outdoor environments, aerosol exposure assessment, and the development and evaluation of respiratory protection and indoor air purification techniques with a focus on biological aerosols. He is also extensively engaged in the bio-defense and counter-terrorism research. Dr. Grinshpun's program has been supported by government agencies and international organizations as well as major industries. He has served on panels convened by the National Academies of Sciences, Engineering, and Medicine; the Council of Canadian Academies; and several federal agencies. He has also served on the editorial boards of eight scientific journals. Dr. Grinshpun received his M.S. degree in physics in 1982 and Ph.D. degree in thermophysics (aerosol science) in 1987 from Odessa University in Ukraine.

William K. Hallman, Ph.D., is a professor in and the chair of the Department of Human Ecology and the former director of the Food Policy Institute at Rutgers, the State University of New Jersey. He holds a B.S. (biology, psychology) from Juniata College and a Ph.D. in experimental psychology from the University of South Carolina. He is a member of the graduate faculties of psychology, nutritional sciences, and planning and public policy at Rutgers. An expert in risk perception and risk communication, he has written extensively on food safety, food security, and public perceptions of controversial issues concerning food, technology, health, and the environment. Dr. Hallman has served as a member of several National Academies' committees focused on food safety and as the chair of the Risk Communication Advisory Committee of the U.S. Food and Drug Administration, and he recently co-authored a handbook on risk communication applied to food safety for the Food and Agriculture Organization of the United Nations and the World Health Organization. He currently serves on the executive committee of the Risk Communication Specialty Group of the Society for Risk Communication and as a member of the National Academies' ad hoc Committee on the Science of Science Communication.

Roy Harrison, Ph.D., D.Sc., is the Queen Elizabeth II Birmingham Centenary Professor of Environmental Health at the University of Birmingham's School of Geography, Earth, and Environmental Sciences. Dr. Harrison started his academic career as a chemist and then undertook postdoctoral work at Imperial College in the Department of Civil Engineering, working on air pollution by heavy metals. He moved to the University of Birmingham in 1991 to take up the newly created post of Queen Elizabeth II Birmingham Centenary Professor of Environmental Health, becoming the director of the Institute of Public and Environmental Health and the head of the Division of Environmental Health and Risk Management. He has served as the chair of the Quality of Urban Air Review Group for the Department of Environment and of the Airborne Particles Expert Group for the Department of Environment, Transport and the Regions, and he was subsequently a member of the Department for Environment, Food & Rural Affairs (DEFRA) Science Advisory Council. He is a member of the Department of Health Committee on the Medical Effects of Air Pollutants, the DEFRA Air Quality Expert Group, and the Department of Health Committee on Toxicity. He has advised the World Health Organization on both the 2005 update of the *Air Quality Guidelines* and the 2010 *Guidelines for Indoor Air Quality*. He has both his Ph.D. and D.Sc. from the University of Birmingham.

Lynn M. Hildemann, Ph.D., is a professor of civil and environmental engineering at Stanford University, where she has also served as an associate department chair, chaired the University Committee on Judicial Affairs, and been elected (twice) to the University Faculty Senate. Her current research areas include indoor sources of particulate matter, the factors affecting their dispersion within and between rooms, and assessment of human exposure to particulate toxins and airborne allergens indoors. She has served on advisory committees for the Bay Area Air Quality Management District and the California Air Resources Board and as an associate editor for *Environmental Science & Technology* and *Aerosol Science and Technology*. She is currently on the advisory board for *Environmental Science & Technology*. Her honors include Young Investigator Awards from the National Science Foundation and the Office of Naval Research, the Kenneth T. Whitby Award from the American Association for Aerosol Research, and Stanford's Gores Award for Teaching Excellence (2013); she also was a co-recipient of *Atmospheric Environment*'s Haagen-Smit Outstanding Paper Award (2001). Professor Hildemann received her M.S. and Ph.D. degrees in environmental engineering science from the California Institute of Technology.

Lee Ann Kahlor, Ph.D., is an associate professor in the Stan Richards School of Advertising at The University of Texas at Austin. Her primary research interest is in health and environmental risk communication with an emphasis on information seeking and processing. A secondary interest is in cultural and racial norms related to health behaviors and message processing. Her work has been funded by the National Science Foundation, the Alfred P. Sloan Foundation, the State of Texas, and the St. David's Center for Health Promotion and Disease Prevention Research. She has won awards from the International Communication Association and the Association for Education in Journalism and Mass Communication for her research on science communication and television viewing, and recently, she was awarded her college's highest honor for undergraduate teaching. She is also her school's minority liaison, working extensively with students from disadvantaged backgrounds. Prior to entering academia Dr. Kahlor worked in journalism as a freelance writer and as communication officer for a Robert Wood Johnson Foundation program office. Dr. Kahlor earned an M.A. in journalism from Marquette University and a Ph.D. in mass communication from University of Wisconsin–Madison.

Glenn Morrison, Ph.D., is a professor of civil, architectural, and environmental engineering at Missouri University of Science and Technology (S&T). He joined Missouri S&T in 2001 and has been a professor since 2013. He is currently the president of the International Society of Indoor Air Quality and Climate (ISIAQ) and an associate editor for *Indoor Air*. Dr. Morrison teaches courses in environmental engineering and studies air pollution, primarily in indoor environments. His research interests include indoor air pollution, human exposure to air pollution, building science, indoor air and surface chemistry. He received his B.S. in chemical engineering from the University of California, San Diego, in 1988 and worked for 6 years as a chemical engineer for Catalytica. He received his M.S. and Ph.D. in environmental engineering from the University of California, Berkeley, and then studied atmospheric chemistry at the National Oceanic and Atmospheric Administration (NOAA) in Boulder, Colorado, before joining Missouri S&T.

David Rich, Sc.D., M.P.H., is an associate professor in the Department of Public Health Sciences and in the Department of Environmental Medicine, and the associate director of the Center for Energy and Environment at the University of Rochester Medical Center. Dr. Rich's research interests focus on the cardiovascular, respiratory, and reproductive health effects of exposures to environmental agents such as ambient air pollution, phthalates, bisphenol A, and perchlorate as well as controlled exposures to ozone and ultrafine particles. He is an environmental epidemiologist whose research is directed at understanding not only if specific environmental agents impact health, but also by what mechanism and in what potentially susceptible subgroup of the population. He also examines the utility of different methodological approaches to address these environmental epidemiology research questions. He received his Sc.D. in epidemiology and environmental health from Harvard T.H. Chan School of Public Health and his M.P.H. in epidemiology and quantitative methods from the Rutgers University (formerly University of Medicine and Dentistry of New Jersey) School of Public Health.

David Rowson, M.S., is the director of the Indoor Environments Division at the U.S. Environmental Protection Agency (EPA). During his approximately 30-year career at EPA, Mr. Rowson has led several important public health initiatives, including initiatives on radon, healthy schools, and asthma and international programs on indoor air. Mr. Rowson is an alumnus of the University of Virginia where he earned his undergraduate and graduate degrees in environmental sciences and meteorology. He also worked in state-level water pollution control programs prior to joining EPA.

Jeffrey Siegel, Ph.D., is a professor of civil engineering at the University of Toronto and a member of the university's Building Engineering Research Group. His research interests including healthy and sustainable buildings, ventilation and indoor air quality in residential and commercial buildings, control of indoor particulate matter, secondary impacts of control technologies and strategies, aerosol dynamics in indoor environments, and HVAC systems. Dr. Siegel is an active member of the International Society of Indoor Air Quality and Climate, ASHRAE, and other organizations. He teaches courses in indoor air quality, sustainable buildings, and sustainable energy systems. Prior to his position at the University of Toronto, Dr. Siegel was an associate professor at The University of Texas. He holds an M.S. and Ph.D. in mechanical engineering from the University of California, Berkeley.

Brett C. Singer, Ph.D., is a staff scientist and the group leader of indoor environment in the Energy Analysis and Environmental Impacts Division of Lawrence Berkeley National Laboratory. He is also a principal investigator in the Whole Building Systems Group in the Building Technologies and Urban Systems Division. Dr. Singer conceives and leads research projects related to air pollutant emissions and physical-chemical processes in both outdoor and indoor environments, aiming to understand real-world processes and systems that affect air pollutant exposures. The recent focus of Dr. Singer's work has been indoor environmental quality and risk reduction in high performance homes, with the goal of accelerating adoption of indoor air quality, comfort, durability and sustainability measures into new homes and retrofits of existing homes. Key focus areas of this work are low-energy systems for filtration, smart ventilation, and mitigation approaches to indoor pollutant sources including cooking. Dr. Singer co-developed the population impact assessment modeling framework (PIAMF). He holds a Ph.D. in civil and environmental engineering from the University of California, Berkeley.

Brent Stephens, Ph.D., is an assistant professor of architectural engineering at Illinois Institute of Technology (IIT). He is an expert in the fate and transport of indoor pollutants, building energy and environmental measurements, HVAC filtration, human exposure assessment, building energy simulation, and energy efficient building design. Dr. Stephens runs the Built Environment Research Group at IIT, which consists of undergraduate students, graduate students, and postdoctoral researchers conducting research on energy efficiency and indoor air quality in buildings. His recent research projects include improving and applying methods to measure the infiltration of outdoor particulate matter and reactive gases into homes; measuring gas and particle emissions from desktop three-dimensional printers and evaluating emission control devices; measuring the in-situ particle removal efficiency of HVAC filters in real environments; developing a suite of inexpensive, open source devices based on the Arduino platform for measuring and recording long-term indoor environmental and building operational data; and characterizing the energy and air quality impacts of higher-efficiency HVAC filters in central residential air-conditioning systems. Dr.

Stephens holds a Ph.D. in civil engineering and an M.S.E. in environmental and water resources engineering from The University of Texas at Austin.

Barbara Turpin, Ph.D., is a professor of environmental sciences and engineering at the University of North Carolina Gillings School of Global Public Health. Dr. Turpin's research is focused on revealing fundamental processes needed to accurately predict human exposures and the effects of airborne particles from precursor emissions. She is best known for her work on the formation of organic particulate matter through aqueous chemistry (for example, in clouds), organic sampling artifacts, and modification of the ambient air pollution mix with outdoor-to-indoor transport. Her work seeks to facilitate communication among atmospheric, exposure, and health scientists with the ultimate goal of effective public health protection. She is an associate editor of *Environmental Science and Technology* and a fellow of the American Geophysical Union, American Association for Aerosol Science, and American Association for the Advancement of Science. Dr. Turpin earned a B.S. in engineering and applied science with a focus in mechanical/environmental engineering research from the California Institute of Technology and a Ph.D. in environmental science and engineering from the Oregon Health & Science University.

Marc G. Weisskopf, Ph.D., Sc.D., is an associate professor of environmental and occupational epidemiology at Harvard's T.H. Chan School of Public Health. His research is focused on how environmental factors affect the nervous system as well as the epidemiology of neurologic disorders. Current areas of work include how environmental exposures relate to autism spectrum disorders; mental health; cognitive function/Alzheimer's disease; Parkinson's disease; and amyotrophic lateral sclerosis (ALS). Some examples of his current work include exploring how exposure to toxicants (for example, lead, manganese, and air pollution) affect cognitive function and psychiatric symptoms, how air pollution and other toxicants relate to autism spectrum disorder, and how formaldehyde and lead exposure relate to the development of ALS. Dr. Weisskopf received his Ph.D. in neuroscience from the University of California, San Francisco (1994), and his Sc.D. in epidemiology from the Harvard School of Public Health in 2006. He joined the school's faculty in 2007 and is a faculty member of both the Department of Environmental Health and the Department of Epidemiology.

Charles Weschler, Ph.D., is an adjunct professor in the Environmental and Occupational Health Sciences Institute (EOHSI) at Rutgers, the State University of New Jersey, and a visiting professor at the Technical University of Denmark and Tsinghua University (China). His research areas include chemicals present in indoor air, their sources and their fate; factors that influence the concentrations, transport, and surface accumulations of indoor pollutants; human exposure to these pollutants, including the contribution of indoor pollutant exposures to total pollutant exposures and the consequent health effects; chemical reactions among indoor pollutants, with an emphasis on ozone-initiated chemistry, the production of secondary organic aerosols and ozone reactions with skin oils; semi-volatile organic compounds (SVOCs); and gas/particle and gas/surface partitioning of SVOCs indoors. He served as a researcher at Bell Laboratories and its successor institutions before accepting positions at EOHSI and the International Centre for Indoor Environment and Energy, Technical University of Denmark. Dr. Weschler has served as a member of several National Academies' committees and from 1999 to 2005 was a member of the U.S. Environmental Protection Agency's Science Advisory Board. He is an elected member of the International Academy of Indoor Air Sciences and has received the Pettenkofer Award, its highest honor. Dr. Weschler earned his Ph.D. in chemistry from the University of Chicago.

Appendix C

Biographical Information: Planning Committee and Staff

PLANNING COMMITTEE

William Nazaroff, Ph.D. (*Chair*), is the Daniel Tellep Distinguished Professor of Engineering in the Department of Civil and Environmental Engineering at the University of California, Berkeley. Dr. Nazaroff's research focuses on the physics and chemistry of air pollutants in proximity to people, especially in indoor environments. His research also involves the domain of exposure science, stressing the development and application of methods to better understand mechanistically the relationship between emission sources and human exposure to pollutants. Dr. Nazaroff is the editor-in-chief of the journal *Indoor Air*. He is the former president of the Academy of Fellows in the International Society of Indoor Air Quality and Climate, and also served as president of the American Association for Aerosol Research. Dr. Nazaroff received his master's in electrical engineering and computer science from the University of California, Berkeley, and holds a Ph.D. in environmental engineering sciences from California Institute of Technology. He is co-author of *Environmental Engineering Science* and has served on the National Academies' Committee on the Effect of Climate Change on Indoor Air Quality and Public Health (2011) and the Committee on Air Quality in Passenger Cabins of Commercial Aircraft (2001).

Terry Brennan, M.S., is a building scientist, educator, and the president of the consulting firm Camroden Associates, Inc. He has studied buildings since the 1970s. Mr. Brennan has provided research, training, curriculum development, and program support for the U.S. Environmental Protection Agency, building owners and managers, individual homeowners, and several state health departments. He is a member of ASHRAE 62.2 committee on ventilation for low-rise residential buildings and the ASTM E06 Committee on the Performance of Buildings, and he chairs the Air Barrier Association of America Whole Building Testing Committee (ASTM WK35913 Collaboration New Standard—Whole Building Enclosure Air Tightness Compliance). Mr. Brennan served as a consultant to the National Academies' Committee on Damp Indoor Spaces and Health and presented testimony to the Committee on the Effect of Climate Change on Indoor Air Quality and Public Health. He holds a master's degree in environmental studies from Antioch–New England Graduate School.

Richard Corsi, Ph.D., P.E., is the chair and ECH Bantel Professor of Practice in the Department of Civil, Architectural, and Environmental Engineering at The University of Texas (UT) at Austin. Dr. Corsi's general areas of expertise include the sources, fate, human exposure to, and control of indoor air pollution. His research foci are on homogeneous and heterogeneous chemistry that occur indoors, the novel use of building materials to sequester indoor chemistry, and links between building energy use and indoor air quality. He has been honored as a Distinguished Alumnus of Humboldt State University and of the College of Engineering at the University of California, Davis, and he has been elected to the UT Academy of Distinguished Teachers. His work has been featured in the media, from the CBC (Canada) television series The Nature of Things, to *The Economist*, *Business Week*, and *National Geographic*. Dr. Corsi received his M.S. and Ph.D. degrees in civil engineering from the University of California, Davis.

Howard Kipen, M.D., M.P.H., is a professor in the Environmental & Occupational Health Department of the Rutgers School of Public Health. He is also the director of the Clinical Research and Occupational Medicine Division of the Environmental & Occupational Health Sciences Institute at Rutgers University. Dr. Kipen's research focuses on clinical and epidemiological studies of the health effects of ambient air pollution. He received his M.D. from the University of California, San Francisco, and holds an M.P.H. from Columbia University. He is the chair of NASA Human Research Program's Advanced Environmental Health/Advanced Food Technology Standing Review Panel; a governor's appointee of the Public Employees Occupational Safety and Health Review Commission, New Jersey Department of Labor; and a member of the Public Health Scientific Advisory Board, New Jersey Department of Environmental Protection. He has served on several committees of the National Academies of Sciences, Engineering, and Medicine.

Tiina Reponen, Ph.D., is a professor in the Department of Environmental Health at the University of Cincinnati, College of Medicine. Dr. Reponen is also director of the National Institute for Occupation Safety and Health–funded University of Cincinnati Education and Research Center, which includes graduate programs related to occupational health from three colleges: medicine, nursing, and applied science and engineering. She is also a visiting professor at the University of Eastern Finland and a recipient of Finland Distinguished Professor award. Dr. Reponen is an editor for the journal *Aerosol Science and Technology*, an associate editor for *Indoor Air*, and a member of the editorial advisory board of *Science of the Total Environment*. Dr. Reponen received both her M.S. and her Ph.D. from the University of Kuopio, Finland. She has served on the board of directors of the American Association of Aerosol Research and the International Society of Indoor Air Quality, of which she is a fellow.

NATIONAL ACADEMIES OF SCIENCES, ENGINEERING, AND MEDICINE STAFF

David A. Butler, Ph.D., is a scholar in and the director of the Medical Follow-up Agency in the Health and Medicine Division of the National Academies of Sciences, Engineering, and Medicine. He received his B.S. and M.S. in engineering from the University of Rochester and his Ph.D. in public policy analysis from Carnegie Mellon University. Before joining the Academies, Dr. Butler served as an analyst for the U.S. Congress Office of Technology Assessment, was a research associate in the Department of Environmental Health of the Harvard School of Public Health, and performed research at Harvard's Kennedy School of Government. He has directed several Academies studies on environmental health and risk assessment topics, including ones that produced *Climate Change, the Indoor Environment, and Health*; *Damp Indoor Spaces and Health; Clearing the Air: Asthma and Indoor Air Exposures*; and the series *Characterizing the Exposure of Veterans to Agent Orange and Other Herbicides Used in Vietnam*. Dr. Butler was also a co-editor of *Systems Engineering to Improve Traumatic Brain Injury Care in the Military Health System*. He was awarded the Cecil Award, the highest distinction for a staff member of the Institute of Medicine.

Guru Madhavan, Ph.D., is a senior program officer with the Board on Population Health and Public Health Practice of the National Academies of Sciences, Engineering, and Medicine. He is a co-developer of SMART Vaccines—a novel multi-stakeholder software tool to help prioritize new vaccine development. Dr. Madhavan received his M.S. and Ph.D. in biomedical engineering and an M.B.A. from the State University of New

York. He has worked in the medical device industry as a research scientist developing cardiac surgical catheters for ablation therapy and has been a strategic consultant for technology startup firms and nonprofit organizations. Dr. Madhavan is a vice-president of IEEE-USA and was a founding member of the Global Young Academy. Among numerous honors, he has been named as a distinguished young scientist by the World Economic Forum. Dr. Madhavan has also received the Innovator Award and the Cecil Award from the presidents of the National Academies of Sciences, Engineering, and Medicine.

Anna Martin, B.A., is a senior program assistant in the Board on Population Health and Public Health Practice of the National Academies of Sciences, Engineering, and Medicine. She has worked on three consensus studies at the Academies: Community Based Solutions to Promote Health Equity in the United States; the Public Health Impact of Raising the Minimum Age for Purchasing Tobacco Products; and the Assessment of Agent-Based Models to Inform Tobacco Product Regulation. She also staffs the Roundtable on the Promotion of Health Equity and the Elimination of Health Disparities. Prior to joining the Academies, Ms. Martin worked at the National Museum of Women in the Arts. She received a B.A. in art history and studio art from McDaniel College.

Rose Marie Martinez, Sc.D., is the senior director of the Board on Population Health and Public Health Practice in the Health and Medicine Division of the National Academies of Sciences, Engineering, and Medicine. Under her leadership, the board has examined such topics as the safety of childhood vaccines, pandemic influenza preparedness, the revival of civilian immunization against smallpox, the health effect of environmental exposures, the capacity of governmental public health to respond to health crises, systems for evaluating and ensuring drug safety post-marketing, the soundness and ethical conduct of clinical trials to reduce mother-to-child transmission of HIV/AIDS, and chronic disease prevention. Prior to joining the Academies, Dr. Martinez was a senior health researcher at Mathematica Policy Research, where she conducted research on the impact of health system change on the public health infrastructure, access to care for vulnerable populations, managed care, and the health care workforce. Dr. Martinez is a former assistant director for health financing and policy with the U.S. General Accounting Office, where she directed evaluations and policy analysis in the area of national and public health issues. Her experience also includes directing research studies for the Regional Health Ministry of Madrid, Spain. Dr. Martinez received her Sc.D. from the Johns Hopkins University School of Hygiene and Public Health. She is also a recipient of the Cecil Award.