Protecting Commercial Buildings from Outdoor Pollutants:
School, Office, and Multifamily Buildings

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Tom spent over 30 years working at the intersection of research and policy addressing public health, pollution, and buildings. While at the Research Division of the California Air Resources Board (CARB) from 1985 to 2009, he designed and managed research contracts on human activity patterns, indoor and personal air exposure monitoring, air cleaning, emissions testing, and building ventilation. He produced guidelines on indoor combustion pollutants and air cleaning devices, and helped update California's air quality and building ventilation standards. Tom also served as a technical advisor to national, state, and local agencies and NGOs on various IAQ issues and green building programs for homes, schools, and offices. Since 2010 Tom has served as the principal scientist at Healthy Building Research, where he co-authored a research roadmap for indoor environmental quality in net zero energy buildings and retrofits for California's energy program through 2030. The scope of his consulting work also includes climate change adaptation to extreme heat, resilient buildings and communities, training and communication, and policy and regulation.

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Executive Summary

This paper provides a broad framework for understanding sources, pathways, and mitigation approaches in protecting commercial buildings from outdoor pollutants. It complements the ROCIS white paper on homes, "Protecting Homes from Outdoor Pollutants". The outdoor pollutants to be considered include outdoor pollutants that enter buildings via air, water, and/or soil media, for both the U.S. and Canada. The paper focuses on three types of commercial buildings: schools, large office buildings, and mid- and high-rise multifamily buildings.

Both indoor and outdoor environments are important in determining the type, amount, and duration of pollutant exposures we experience. People spend about 90% of their time indoors, where they are exposed to a mix of indoor and outdoor pollutants. Much, if not most, of our cumulative pollutant exposure, our body's dose, and our health risk for some outdoor pollutants occurs in indoor environments. Indoor environmental quality (IEQ), which includes the quality of air, acoustics, thermal conditions, and lighting, can have a very large impact on human health, performance, and economic productivity.

The poor quality of outdoor air, water, and soil is a growing public health concern. Existing health risks from emission sources, such as motor vehicles, freight transport, and industrial activities, continue to persist. New environmental pollution stressors, such as fracking and climate change, are growing dramatically. The types of outdoor pollutants that pose health concerns in indoor spaces span a wide variety—particles, gases, semivolatile organic compounds (SVOCs), and biological pollutants. Their sources also vary widely—industrial activities, motor vehicles, regional air pollution, agriculture, and nearby commercial, construction, and maintenance activities.

Monitoring outdoor pollutants of concern in buildings is not usually warranted due to the cost, time, and effort required and the difficulty in interpreting the results. Exceptions would be when there is a need to evaluate a mitigation measure, meet a regulatory requirement, or track indoor levels of extremely hazardous pollutants. Some pollutant sources can be identified by visually inspecting a building and its neighborhood, contacting state and local governments, and consulting maps and databases on the Internet. Some indoor pollutants can be monitored easily, at low cost (about $200 or less), and at least a semi-quantitative level. Monitoring of air pressures can also be measured easily in order to assess potential IEQ problems and monitor the performance of air filters and air pressure control of pollutant infiltration. Liability concerns from disclosing monitoring results have been raised, but the evidence to date indicates that exposure to liability is minimized by monitoring IEQ proactively, especially if best practices for managing IEQ are followed as well.

Some community groups have employed more expensive monitoring methods to test the outdoor and indoor air, water, and soil in their neighborhoods. Numerous low cost, small, portable sensors for real-time monitoring of indoor and outdoor air pollutants are being developed, and some should be available in the near-term for public use.

Several basic strategies can be used to mitigate pollutant entry in commercial buildings, each strategy with its own limitations, advantages, and disadvantages. The appropriate

strategies will depend on the pollutants, their pathways into the building, the occupants, and cost considerations. Some strategies involve avoiding nearby sources by increasing setbacks of buildings from nearby pollutant sources, locating air intakes away from nearby sources, sealing air leaks, and keeping air intakes and air filters clean. Other strategies use active removal of pollutants by filtering or cleaning air, treating potable water, reducing soil track-in, and cleaning indoor surfaces. Air pressure is used to control intrusion of soil gases and air pollutants from adjoining spaces and below-grade foundations. Water treatment is used to remove radon and VOCs from drinking water.

When considering mitigation strategies, the interactions of building systems and the durability of the strategies must be considered. Systems interactions can cause moisture condensation, depressurization of sewage vents, and inadequate air flow to air filters and building spaces. The effectiveness of a strategy may decline over time, e.g., the rapid drop in the use of portable air cleaners reported in an asthma intervention study. A mix of strategies may often be the optimal solution, e.g., improved air sealing of the building enclosure along with improved air filtration enhances pollutant removal while also saving substantial amounts of energy and reducing cleaning costs.

In terms of IEQ improvements, data on the effectiveness of many of these mitigation strategies are limited or absent for commercial buildings. Control of soil gas (vapor) intrusion by subslab depressurization and air sealing is well documented and widely used in commercial and residential applications. The effectiveness of air filters in central air systems and portable air cleaners in reducing indoor PM is fairly well documented, but the data on the health impacts are limited and the results mixed. The effectiveness of houseplants and living walls in removing indoor air pollutants has not been well demonstrated. Other strategies such as building setback, air intake location, and reducing ventilation during high pollution periods are widely used and considered best practice, but documentation of their effectiveness is limited.

In conclusion, ample opportunities are available for reducing the infiltration and intrusion of outdoor pollutants into buildings and thereby reducing the health impacts, especially for vulnerable populations. Several mitigation strategies are well characterized and commonly used, while other strategies have little or no test data on their effectiveness in commercial buildings. Some of these strategies, such as air sealing and commissioning of buildings to reduce infiltration and duct leakage, can be cost effective based on energy savings alone. Affordable monitoring methods are available for some outdoor pollutants, and low-cost portable sensor technology should be available soon for widespread use by the public.

Several research, development, and demonstration needs are identified. In addition, the following generic, interrelated actions are recommended:

- Build the evidence base for mitigation measure effectiveness and co-benefits.
- Build a better toolbox for the monitoring of exposure, health, and biomarkers.
- Implement and improve best practices for IEQ by addressing outdoor air pollution.
- Stress awareness and training of the public, building operators, and decision-makers at all levels.
- Take a seat at the table in all forums related to buildings and their occupants.

Introduction

The purpose of this paper is to provide a broad framework for understanding sources, pathways, and mitigation approaches in protecting commercial buildings from outdoor pollutants. This paper complements the ROCIS white paper on homes, "Protecting Homes from Outdoor Pollutants". The outdoor pollutants to be considered include outdoor pollutants that enter buildings via air, water, and/or soil media.

We will focus on school buildings because children are one of the subpopulations most vulnerable to the health impacts of environmental pollution. Large office buildings (including large public buildings) and multifamily buildings (mid- and high-rise size with central air systems) will also be addressed. Unlike most small residential buildings, these three types of commercial buildings usually have mechanical ventilation systems that supply outdoor air, filter the outdoor and recirculated air, and receive some kind of routine maintenance program.

First, we examine the background on why indoor and outdoor pollution are important for human health and performance. Then we summarize the variety of outdoor pollutants that present health concerns, and list related indoor and outdoor sources of those pollutants. The paper then discusses the pathways of pollutant entry into buildings, available pollutant detection methods, and pollutant sensor development. The next sections describe mitigation strategies and what has been successful at reducing outdoor entry or indoor concentrations of these pollutants. Actual examples and data will be shown from several case studies. Recommendations for implementing some of these mitigation strategies are also discussed.

Additional information resources are listed in Appendix A, including best practice guidelines and standards. Presentations on this paper and the residential white paper at project meetings are available from the project sponsor. The public health framework for this project is discussed in the ROCIS paper entitled "Public Health Basis for ROCIS".

Why is indoor environmental quality important?

Indoor environmental quality (IEQ) is a major factor in the health, safety, and productivity of people. IEQ includes aspects of air quality, thermal comfort, acoustic quality, and lighting quality. This paper will focus on the air quality aspects of IEQ, but also address multimedia exposures to pollutants in the soil and water.

The indoor environment is where we spend most of our lives, breathe most of our air, and can be most affected in terms of health and productivity. Adults and school age children in the U.S. and Canada spend on average almost 90% of their time indoors, based on large survey studies in the 1980's and 1990's.[1] A recent nationwide survey of activity patterns in Canada found little change from the previous survey. Some vulnerable groups, such as

[1] (Jenkins et al. 1992)(T. Phillips, Jenkins, and Mulberg 1991) (Klepeis et al. 2001)(Leech et al. 2002) (Matz et al. 2014)

young children, the elderly, and chronic disease patients can spend even more of their time indoors.[2]

Pollutants that are emitted indoors, such as allergens, volatile organic compounds (VOC), combustion pollutants, soil and sewer gases, and volatile pollutants in potable water can build up quickly indoors. Pollutants that concentrate in indoor surface dust (house dust), such as heavy metals and semivolatile organic compounds (SVOCs), can also build up indoors over time. Consequently, indoor pollutant exposures can correlate closely with personal exposure levels (the pollutant concentrations measured on a person as they move throughout the day) and the resultant health risks. Furthermore, indoor exposures can dominate the cumulative exposures to pollutants that mainly come from outdoor air, e.g.:

- Personal exposures of 16 Danish workers to airborne black carbon (BC, a diesel soot indicator) over seven days were highest in concentration during transportation activities with short durations, as shown in Figure 1.[3] But the cumulative exposure, based on concentration and activity duration (shown by the size of boxes in the chart), was much greater for the sum of all indoor activities than for transportation activities, especially for homemakers.

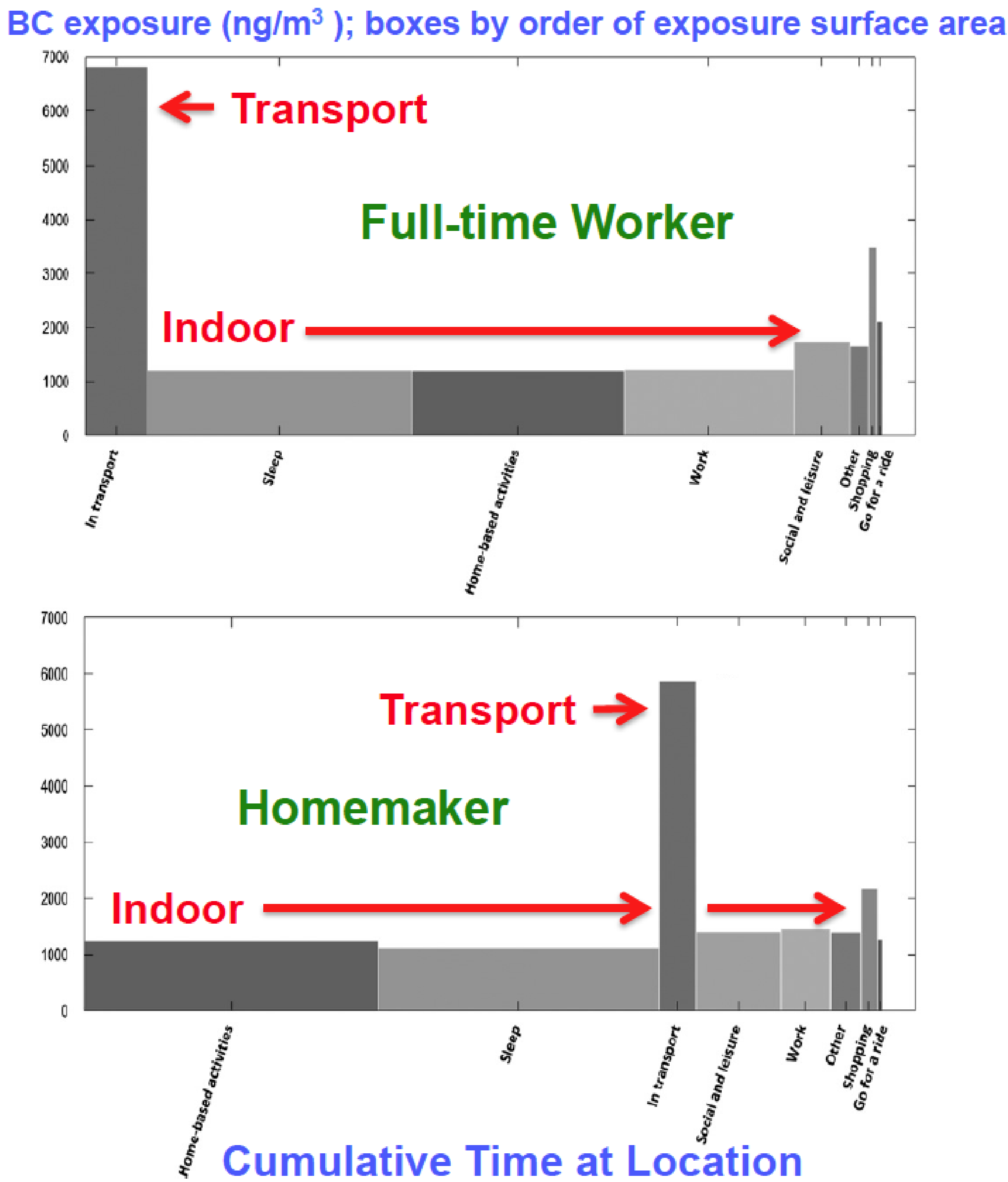
- The time fraction spent indoors by 59 Irish office workers, on weekdays over 28 months, averaged over 92%.[4] When personal exposures to PM_{10} and physical activity levels were factored in, the inhaled dose of PM_{10} was largely from exposure in the workplace and at home, although the main PM sources were outdoors.

Indoor pollutant exposures are also important because the toxicity of indoor pollutants, alone and as a mixture, can be much different than that of outdoor pollutants.[5] Many common allergens are primarily emitted from indoor sources. Thousands of man-made chemicals are introduced into the indoor environment every year, but we have little or no toxicity data for many of them. Many chemicals were grandfathered in long ago without any health and safety review. To avoid the known or potential health risks from indoor pollutant exposures, avoiding or reducing the source of the indoor pollutant is generally the most effective and reliable strategy.

IEQ can also have a huge economic impact. A review of human health and human impacts of IEQ in schools and other commercial buildings was conducted recently by the Lawrence Berkeley National Laboratory (LNBL).[6] The reviewers found that student and worker performance can be improved by up to 10 percent through improved IEQ. Significant

[2] (Van Ryswyk et al. 2014)(Matz et al. 2014)
[3] (Dons et al. 2011)
[4] (McCreddin et al. 2013)
[5] (NRC 2004)(Matsumura et al. 2010)(Carlin et al. 2013)(Hasheminassab et al. 2014)(Rager et al. 2011)
[6] (LBNL 2014)

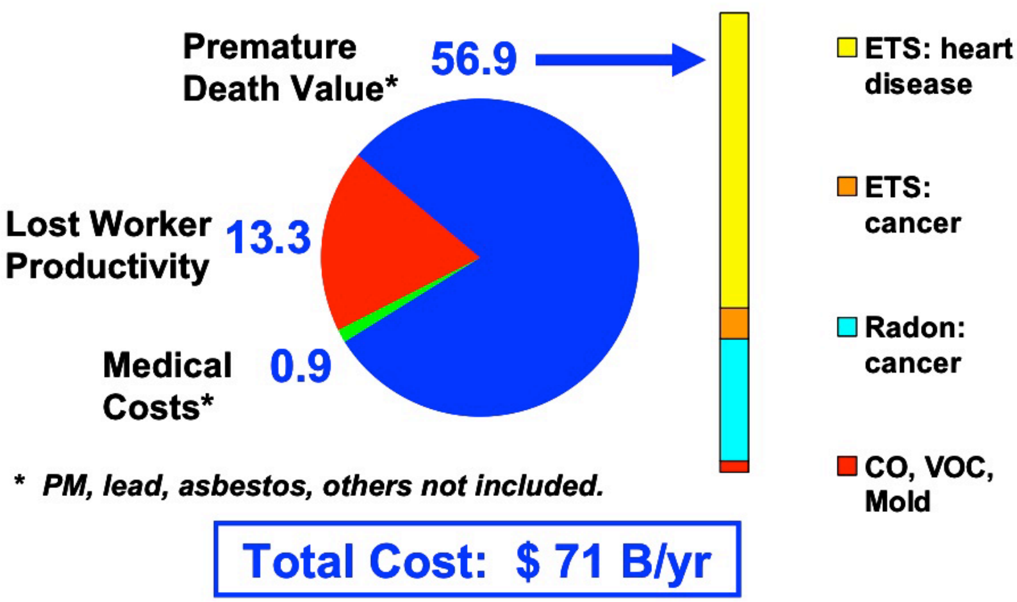
Figure 1: Personal black carbon (BC) exposures, activity type, and duration in Danish workers



Source: modified from (Dons et al. 2011) increases in academic task performance and student test scores were associated with increased ventilation rates and comfortably cooler temperatures, respectively. Improved performance of office tasks by office workers was associated with improved thermal conditions, increased ventilation rates, the removal of pollutant sources, and perceived indoor air quality. Modeling studies of cost-benefit analyses for IEQ improvement through building design, operation, and maintenance of office buildings suggested that financial benefits might often exceed the improvement costs by a factor of 10 or more.

The California Air Resources Board (CARB) estimated conservatively in 2008 that indoor air pollution in California resulted in $13 billion per year in lost productivity of office workers and teachers, $0.9 billion in direct medical costs, and $57 billion in premature death valuation, for a total of over $70 billion per year (Figure 2). The estimates were based on only the handful of air pollutants for which good exposure and toxicity data were available; PM, asbestos, and lead were not included. Liability costs for IEQ problems in schools and commercial buildings, e.g., sick building syndrome, mold problems, can also be substantial but were not included in these estimates.

Figure 2: Estimated costs of health and worker impacts of indoor air pollution in California ($ billion per year, in 2007 $)



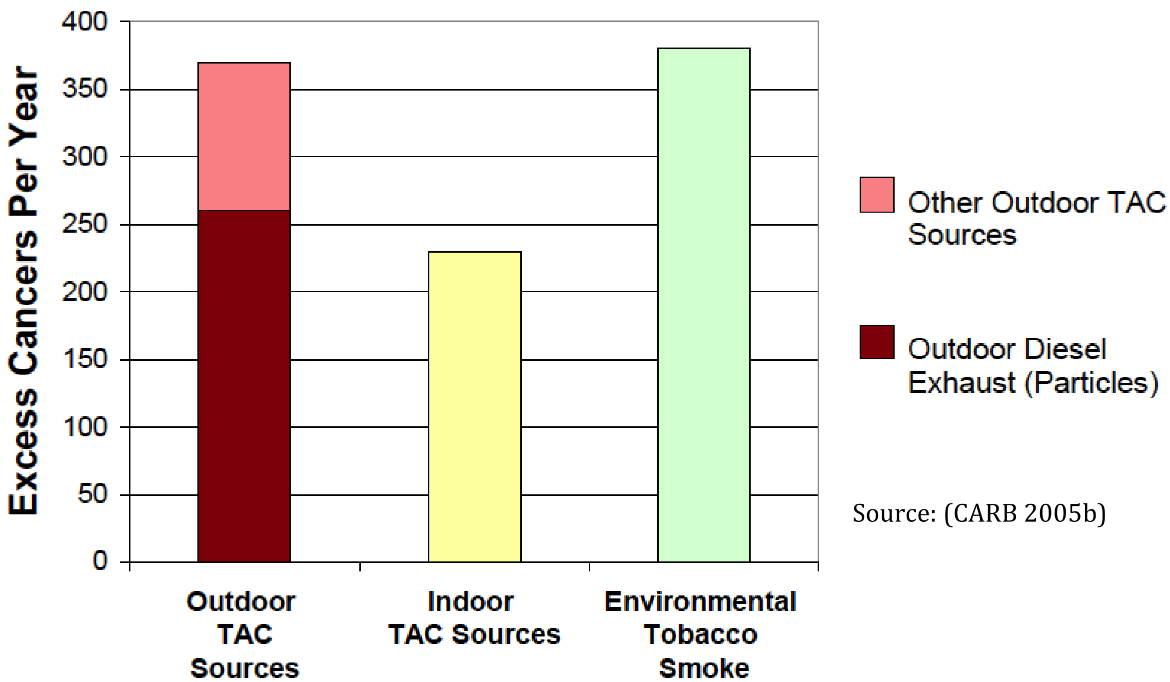
Sources: (Philllips 2008), (CARB 2005b)

Why is outdoor pollution important to building occupants?

The primary purpose of a building is to give us a shelter that is safe, healthful, and comfortable. Outdoor air is the source of "fresh air" used to dilute and remove indoor air pollutants and excess moisture. Building standards for commercial buildings incorporate ventilation standards, usually based on the industry standard ASHRAE 62.1, for the flow rates and basic filtration levels of outdoor air.[7] These design standards assume that the outdoor air quality does not exceed the federal air quality standards, and that basic air filtration will provide adequate air quality. One of the key steps in best practices for IEQ design, according to heating, cooling, and ventilation engineering association, is to control the sources of outdoor air pollution before the pollutants enter the building.[8]

In many parts of the U.S. and Canada, especially during certain times of the year, the outdoor air contains unhealthy levels of regulated air pollutants such as PM_{10} (particulate material, or particles, 10 microns and smaller in diameter), $PM_{2.5}$ (particles 2.5 microns and smaller in diameter), nitrogen oxides (NO_x), and ozone. This increases the chance that outdoor pollutants will enter the buildings, especially if open windows and doors ventilate the building. These elevated levels of indoor pollutants are associated with significant health risks. For example, the estimated cancer risks from outdoor and indoor exposure to diesel particle emissions in California are comparable to those from environmental tobacco smoke or other indoor toxic air contaminants, as shown in Figure 3.

Figure 3: Estimate of potential cancer burden from toxic air contaminants (TAC) in California, by source



Source: (CARB 2005b)

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[7] (ASHRAE 2013)
[8] (Apte et al 2008)

In addition to air pollutants, pollutants in the water or soil can also enter a building and create health hazards. VOCs such as benzene, methane, and trihalomethanes (THM) from industrial operations, leaks, spills, or water disinfection can enter buildings via well water, municipal water, or off-gassing from soil beneath buildings. Hydraulic fracturing (fracking) operations to extract natural gas and oil have been linked to contamination of residential water supplies with toxic and flammable organic compounds and to the contamination of soil with toxic metals and radioactive elements.[9]

Leakage from underground storage tanks for gasoline is a widespread problem – the current backlog of cleanup for leaking underground tanks in the U.S. is over 75,000 tanks.[10] A recent federal study indicates that the 156,000 underground gasoline tanks in the U.S. are susceptible to corrosion of the sump pump, tanks, and pipes from ethanol-gasoline blends.[11]

Toxic and odorous gases from leaking sewage pipes and vents can enter buildings too. The current sewage systems in the U.S. are deteriorating rapidly, and concrete sewage pipes may be susceptible to bacterial degradation.[12]

Soil contaminated with pesticides, heavy metals, or SVOCs such as polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs) can be tracked or blown into commercial buildings and remain there for decades. Elevated levels of lead and arsenic in the indoor surface dust were found in a statewide study of K-12 schools in California.[13] In California alone, there are 381 sites undergoing voluntary cleanup of hazardous wastes, including 50 school sites.[14] Of the over 13,000 hazardous waste sites in California that have completed or are undergoing cleanup, over 5,000 sites (over 40%) could have environmental contamination that affected indoor environments, as shown in Table 1.[15]

Table 1: Potential indoor contamination sources at waste cleanup sites

Environmental Media Type	Number of Current and Past Sites	% of Total Sites
Soil	4,019	30.9
Soil vapor	940	7.2
Indoor air	271	2.1
Contaminated surface/ structure	89	0.7
Well water for drinking	80	0.6
Total	**5,399**	**41.5**

Source: (DTSC 2014) Advanced search, Potential Media Affected, Current and past cleanup sites totaling 13,006 sites. Some double counting of media affecting IEQ may occur.

9 (Vengosh et al. 2014)
10 (EPA 2014a)
11 (NIST 2014)
12 (Ling et al. 2014)
13 (CARB 2004a)
14 (DTSC 2014a)
15 (DTSC 2014b)

Why the growing concern about outdoor air pollutant sources?

In Canada and the U.S. the outdoor air quality and emission of toxic air pollutants in many cities has improved markedly in last several decades due to the improvement in emission control programs for vehicles, industrial sources, and consumer products, along with the decline of manufacturing industry.[16] However, over 142 million people lived in U.S. areas in 2012 that did not meet one or more national air quality standards for criteria air pollutants.[17]

A growing body of epidemiology, exposure, and toxicology studies points to outdoor pollution sources, especially vehicle traffic and other combustion sources, as major risk factors for respiratory and cardiovascular health effects.[18] A large fraction of outdoor pollutants and their chemical reaction products become part of the indoor air mixture in homes, schools, and offices.[19] Outdoor air pollutants are routinely monitored in regional monitoring networks, but elevated concentrations or "hot spots" often occur at the neighborhood level and usually go undetected. For example, recent studies of public schools in selected major U.S. and Canadian cities have reported that public school students may be exposed to elevated levels of vehicle emissions and noise due to their close proximity to major roadways. Nearly 12% of U.S. schools were less than 100 meters from medium or heavy traffic, and 16% of the Canadian schools were within 75 meters of major roadways.[20] [21] An estimated 6.4 million children in 2006 attended public or private U.S. schools that were within 250 meters of a major roadway; minority and underprivileged children were disproportionately affected.[22]

Several metropolitan areas have assessed the outdoor pollution levels, health risks, and sources. For example, a recent assessment of toxic air pollutants and their outdoor sources in the southwest Pennsylvania region, the PRETA report, used monitoring and modeling to estimate cancer and non-cancer health risks.[23] This assessment found that the region as a whole, and especially certain locations within the region, have elevated cancer risks from pollutants such as benzene, chlorinated hydrocarbons, formaldehyde, and diesel particulate matter. Increased cancer risks were associated with diesel PM (on road and off road), coke ovens and nearby industrial sources, vehicle traffic, and small nonpoint sources. Figure 4 shows how the modeled lifetime cancer risks exceed the EPA target of one per million persons across the region by a factor of about 25, and that some locations exceed the target by a factor of 500 or more.

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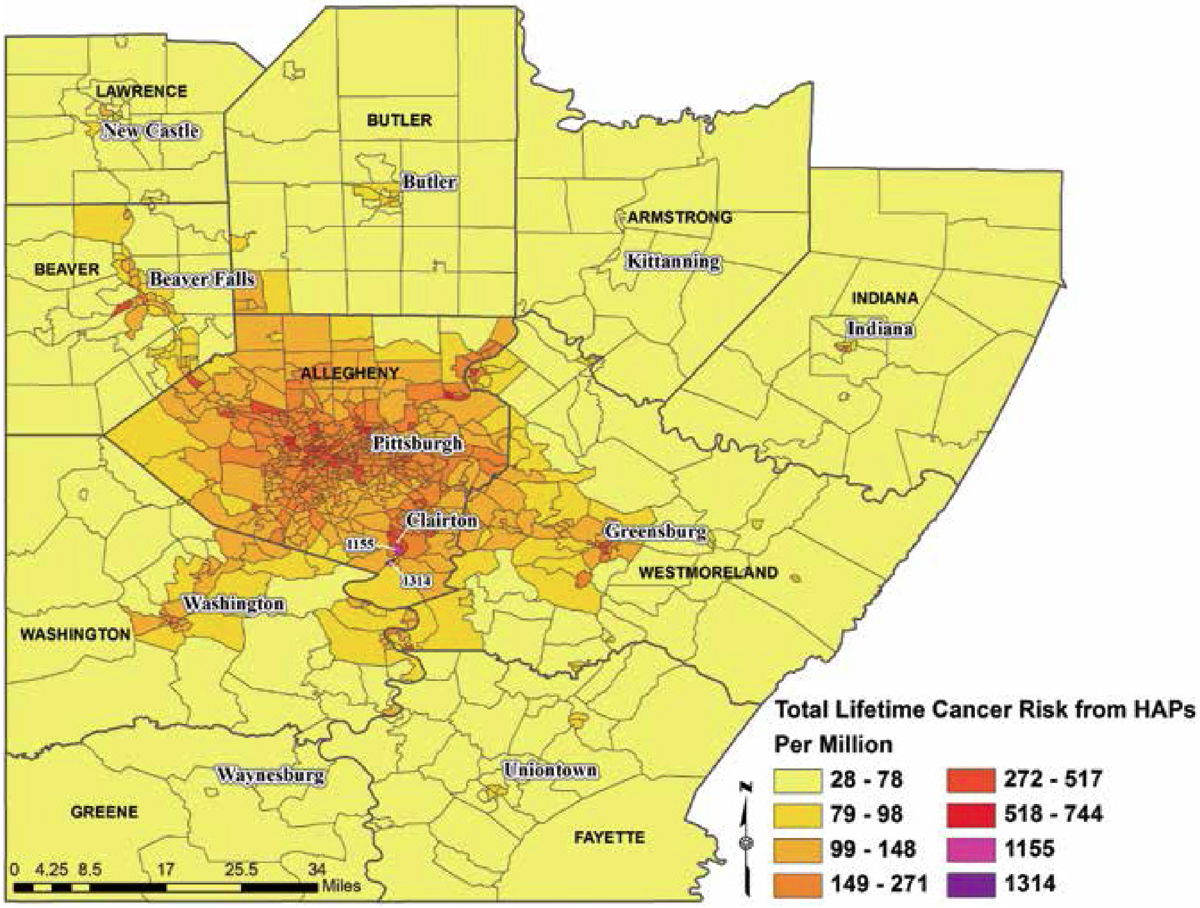
[16] (Brauer et al. 2011) (Voiland 2014) (EPA 2014e) (NASA 2014)
[17] (EPA Air and Radiation 2014)
[18] (J. H. Curran et al. 2013)(J. Curran 2014)
[19] (Noullett, Jackson, and Brauer 2010) (Wichmann et al. 2010)(J Wu et al. 2005)(Jun Wu et al. 2009) (Wolkoff 2013) (MacNeill et al. 2012) (Banerjee and Annesi-Maesano 2012)(Weschler 2006) (Chen, Zhao, and Weschler 2012)
[20] (Appatova et al. 2008)
[21] (Amram et al. 2011)
[22] (Kingsley et al. 2014)
[23] (Michanowicz et al. 2013)

Figure 4: Total lifetime cancer risk from all hazardous air pollutants (HAPs) within the Pittsburgh Regional Environmental Threats Analysis Report (PRETA) region, as predicted by the 2005 National Air Toxic Assessment



Source: (Michanowicz et al. 2013)

Current trends in the U.S. and Canada suggest that exposures to outdoor air pollutants in the indoor environment will increase in the near future.[24] As population increases in urban areas, pollutant emissions from vehicle, commercial, and industrial activities will increase. Population density and human proximity to these emission sources will also increase as infill and transit-oriented development increase.[25] [26] Rail and road accidents with hazardous materials and refinery accidents can cause emergency situations where protecting the building from outdoor pollutants is critical for the short term. In addition, terrorist incidents can release toxic materials in populated areas near or in buildings. Wildfires are expected to continue increasing in frequency and duration, especially in the western states.

[24] (Levin and Phillips 2013)
[25] (Hricko 2014)
[26] (Marshall, Brauer, and Frank 2009)

Another growing concern is that of pollutant emissions from fossil fuel extraction, cargo shipping, and transport of fuels and chemicals by road, rail, and water. For example, extraction and shipping of coal in the U.S. has increased by 115% from 2006 to 2011, through ports on the east, west, and Gulf coast.[27] Coal transport by rail produces significant amounts of diesel emissions and toxic coal dust.[28].

As another example, hydraulic fracturing (fracking) operations to extract oil and gas have increased dramatically in recent years and can pollute the local air, water, and soil and, especially in rural areas, where pollutant monitoring is usually lacking.[29] [30] Fracking emissions of hydrocarbons have also been linked to regional exceedances of the national ozone standard and have even made it difficult to meet the ozone standard in the wintertime when ozone formation is usually minimal.[31] Tar sand oil extraction has triggered air quality (NO_2 and SO_2) and water quality exceedances and widespread mercury contamination in Canada.[32] [33] It has also raised many air quality, odor, and health concerns about transportation and refinery emissions in the U.S. and Canada. Railroad emissions and the potential for spills of hazardous materials are also increasing drastically in many communities. For example, oil car shipments in the U.S. from 2008 to 2014 are estimated to increase by 68 times, and oil car shipments from Canada to the U.S. increased by 20 fold from 2011 to 2013.[34]

In addition, wood burning and biomass electrical generation are still an outdoor air quality problem in some regions. In 2012 EPA adopted more stringent standards for toxic air pollution emissions, including mercury and particle pollution, from biomass and other fossil fuel boilers.[35] Emission limits on wood burning have become more common in western states, and EPA is proposing to tighten emission limits on new wood burning stoves. Agricultural burning also has major impacts on outdoor air quality in some regions.

Climate change is projected to have a major impact on outdoor and indoor air quality in the U.S. and Canada in the near future. A warming climate will exacerbate air outdoor air pollution as a result of increases in outdoor ozone formation, stagnant weather conditions, pollen and mold spore production, and wildfires.[36] [37] More frequent, longer, and hotter heat waves are expected to lead to higher peak ozone and PM concentrations.[38]

Climate action plans usually include measures to reduce air infiltration through the building envelope and ductwork, but the retrofit of existing buildings in the U.S. and

[27] (Platts 2014)
[28] (Sierra Club 2013)
[29] (Institute of Medicine 2013)
[30] (D. Brown et al. 2014)
[31] (Moore et al. 2014)
[32] (Alberta Environment and Sustainable Resource Development 2014)
[33] (Munro 2013)
[34] (P. Brown et al. 2014)
[35] (EPA 2012a)
[36] (Moore et al. 2014)(Institute of Medicine 2011)(Horton et al. 2014) (Dawson 2014)
[37] (USGCRP 2014)
[38] (Voiland 2014)

Canada is proceeding very slowly. Another common measure is ventilation, i.e., the use of open doors and windows to cool buildings, or a hybrid or mixed-mode approach using both natural and mechanical ventilation. Increased natural ventilation could increase indoor-outdoor air exchange without necessarily protecting IEQ. For further information on trends that are expected to affect IEQ by 2030, see the report by Levin and Phillips (2013).[39]

Which pollutants and sources are of concern in commercial buildings?

Table 2 lists the types of solid- and gas-phase pollutants that this paper will cover, and the outdoor and indoor sources of the pollutants. The fourth column lists the potential interior sources of these pollutants. Some of these pollutants have both indoor and outdoor sources, e.g., particulate matter (PM), carbon monoxide (CO), NO_X, polycyclic aromatic hydrocarbons (PAHs), formaldehyde, lead, asbestos. The pollutant classes listed below have some overlap: some pollutants will fall into more than one category, reflecting what is found in published research data and guidelines from authorities.

Most of the pollutants listed are airborne, but some such as heavy metals, SVOCs, and asbestos, can also be introduced to the building through dust transport on footwear and clothing. Some pollutant gases such as radon and VOCs can also enter the building through well water, which releases the pollutants into the indoor air when aerated and or heated. Most of these pollutants enter the body via the inhalation route of exposure, but some can enter through skin (dermal exposure) or hand-to-mouth contact (ingestion).

The health effects of these pollutants vary widely, from respiratory irritation to asthma causation and exacerbation, from cancer to developmental toxicity, from increased heart disease to fatal poisoning. Some of these pollutants have synergistic health effects of multiple pollutant exposures, such as radon plus smoking and ozone plus cat allergen, but the vast majority of pollutants have not been studied as part of a mixture that would be common in indoor air and drinking water.[40]

What are the major health risks and the pollutants of concern in commercial buildings? The prevalence and severity of the health risks from indoor pollution in commercial buildings have not been assessed on a wide scale. Depending on regional pollution variations and the population at risk, one or more outdoor pollutants could be a major health concern, e.g., pesticides from nearby agriculture, wildfire smoke, traffic emissions, soil contamination, drinking water contamination, industrial emissions.

Thermal conditions are another indoor stressor that can exacerbate other indoor health hazards and human performance impacts. Thermal conditions indoors and outdoors have a significant public health impact and are expected to worsen with climate change, so this issue will be discussed as it relates to mitigation strategies and co-benefits.

[39] (Levin and Phillips 2013)
[40] (Mortimer et al. 2000) (Scientific Committee on Health and Environmental Risks 2007) (Rider et al. 2013) (Murphy et al. 2012)

Table 2: Pollutants of concern – sources and consumer monitors

Pollutant Type	Examples	Outdoor Sources	Indoor Sources	Consumer Monitors?
Particles and fibers of chemical, industrial, combustion, or geological origin	PM_{10}, $PM_{2.5}$, ultrafine PM, black carbon, road dust, diesel exhaust, wood smoke, asbestos, respirable silica	Soil and dust, vehicles, trains, industrial activity, fracking, wood smoke, wild fires, cooking, asphalt paving	Smoking, cooking, combustion appliances, re-suspended dust, crafts, renovations, candles, skin and hair from occupants and pets, clothes dryers, ozone reaction products	In Part: Emerging low-cost particle counters good for detecting relative amounts
Biological pollutants	Mold, pollen, viruses, bacteria, skin flakes, dust mite feces, cockroaches, rodent and mice urine, bat feces, microbial VOCs	Plants, soil, decay, agricultural activity, municipal composting, standing water	Mold or bacterial growth, interior plants, food preparation or storage, allergens from pets, rodents, roaches, dust mites	In Part: Common dust allergen testing is available; Emerging low-cost particle counters good for detecting relative amounts.
Heavy metals	Lead, arsenic, mercury, arsenic, etc.	Soil and dust, industrial activity, smelters, leaded gasoline, leaded paint, emissions, mining activity, coal burning, pesticides	Leaded paint, craft activities (e.g. stained glass), hunting or fishing equipment, mercury spills	Yes: Inexpensive tests are available
Semivolatile organic compounds (SVOCs)	Phthalates, preservatives, flame retardants, PCBs, PAHs	Pesticides, contaminated soil, industrial activity, combustion, asphalt sealant	Pesticides, flooring, toys, cosmetics, furniture, consumer products, caulk additives, light ballasts, sealants, smoking, cooking, fossil fuel heating appliances	No
Volatile organic compounds (VOCs)	Benzene, toluene, decane, styrene, limonene, trihalomethanes, etc.	Vehicle emissions, fuel storage, industrial activity, combustion, construction, oil and gas fields, sewer gas, asphalt sealant	Building materials, furniture, clothes, cleaning products, personal care products, attached spaces, well water, municipal water	In Part: Rudimentary Total VOC sensors in some applications, but health linkage is not clear
Aldehydes	Formaldehyde, acetaldehyde	Power plants, incinerators, vehicle emissions	Furniture, building materials, ozone chemistry, consumer products	In Part: Formaldehyde samplers are available

Table 2, *continued*

Pollutant Type	Examples	Outdoor Sources	Indoor Sources	Consumer Monitors?
Other chemical pollutants	Hydrogen sulfide (H_2S), pesticides	Oil and gas wells, farm and landscape treatments	Consumer products, pesticides	In Part: H_2S sensors are available
Odors	Sewer gas, sour gas, restaurant or food preparation (e.g. allium, peppers, decomposition, meat grilling)	Industrial activity, oil and gas wells, vehicle emissions, farming, natural decomposition, swamp emissions, waste storage	Mold and bacterial growth, cooking, consumer products (especially scented)	Yes: Sense of smell; H_2S sensors
Explosive gases	Methane	Natural gas leakage, coal mines, natural decomposition, animal sources, soil sources	Natural gas leakage, stored compressed gases, decomposition	Yes: Alarms are available
Ozone	Photochemical smog	Vehicle emissions, industrial activity, fracking	Ozone generators, electrical appliances, printers	In Part: Some ozone badges may be adequate
Carbon monoxide (CO)		Vehicle emissions, combustion, coal mines, natural decomposition in soils	Malfunctioning combustion appliances, cigarettes, combustion in attached space	Yes: Most inexpensive alarms are relatively insensitive, but good monitors are available
Carbon dioxide (CO_2)		Combustion, vehicle emissions, organic material decomposition	Human and pet emissions, combustion (e.g. cigarettes)	Yes
Nitrogen compounds	NO_2, NO	Vehicle emissions, industrial activity	Combustion sources (e.g. gas stoves, unvented gas appliances, cigarettes)	No
Radioactive particles and gases	Radon, thoron, depleted uranium dust	Naturally occurring soil sources, well water, industrial waste, fracking sediments	Exposed soil or bedrock	In Part: Radon sensors are available

This paper does not describe the health impacts of different pollutants in detail. An extensive summary of the health effects, indoor and outdoor sources, and exposure levels, for indoor air pollutants is available in the peer-reviewed report by the California Air Resources Board (CARB) from 2005.[41] In addition, the information sources in Appendix A provide more information on IEQ and health for those interested.

In terms of outdoor pollutants and their health effects, some progress is being made in understanding which pollutants should be measured. Recent studies suggest that for urban air pollution, nitrogen oxides (NO_x) may be a better surrogate for outdoor pollution from traffic and other combustion sources.[42] In a study of emergency hospitalization for asthma and wheeze, increased indoor-outdoor air exchange rate (AER) was associated with increased levels of outdoor levels of NO_x, CO, and higher levels of $PM_{2.5}$, but not ozone; the results were significant or near-significant statistical levels.[43] For natural gas and oil extraction, certain VOCs may be good source signatures or indicators.[44] [45] A large U.S. study reported that residential outdoor NO_2 was associated with an increased frequency of symptoms of right heart failure, a common cause of mortality and morbidity from heart and lung disease.[46]

In order to determine which outdoor pollutants may be of concern in a given area, several complementary approaches can be taken. National and state maps of major sources of air, water, and soil pollution are available on the Internet. Local public health, air quality, and water quality officials may also be helpful in providing monitoring data and identifying such sources, particularly from local traffic, industrial, and waste emissions, that might affect a building or neighborhood. The type and history of symptoms in building occupants can help narrow down which pollutants are likely suspects that may be present in the building. Occupational safety and health agencies can also be very helpful at conducting visual inspections of workplaces, often at no cost and no potential fine, to identify potential problems and solutions.

[41] (CARB 2005b)
[42] (Prill, Hales, and Blake 2003)
[43] (Sarnat et al. 2013)
[44] (Gilman et al. 2013)
[45] (Macey et al. 2014)
[46] (Leary et al. 2014)

What methods of pollutant detection are available for building occupants, owners, and operators?

Monitoring of indoor pollutants is generally not warranted unless a specific question (a testable hypothesis) must be answered or long-term surveillance is required, e.g.:

- For regulated indoor pollutants, such as radon or asbestos, what are the indoor concentrations and will remediation be required?
- What is the IEQ before and after an action is taken to solve an IEQ problem?
- What are levels of indoor and outdoor pollutant levels or personal exposures where a known source of a hazardous pollutant that cannot be controlled and whose presence is known or should reasonably be known?
- What are IEQ conditions relative to recommended targets or worker health and safety standards?

Some indoor pollutants can be measured easily, at an affordable cost (a few hundred dollars), and at least at a semi-quantitative level. Examples include carbon monoxide (CO) alarms and monitors, passive monitors for various gases, and low cost PM counters. In such cases, routine monitoring may be warranted as a means of establishing baseline conditions, tracking deviations from performance targets, and locating potential sources within or near a building. For situations where the source cannot be identified, the use of more expensive monitors may be warranted, e.g., real-time monitors for CO, radon, or ultrafine PM (particles with diameters of 0.1 micron or less).[47]

However, it can be difficult and expensive to detect many air pollutants of concern, especially for organic pollutants that require special laboratory analysis. It often takes a trained diagnostician to identify which pollutants and environmental factors, if any, should be measured, and to determine where the pollutants are coming from and how they are entering building. Commercial air testing companies are able to sample and analyze air and surface pollution and ventilation in commercial buildings, but costs are high. Unless an IEQ diagnostics expert can narrow down the range of pollutants that should be tested, the exploratory costs for sampling the suspected pollutants of concern would run into thousands of dollars in technician time and analysis. Even having a technician sample the indoor and outdoor air for a single pollutant for a day typically costs hundreds of dollars. Using these commercial services is therefore not an obvious or affordable choice for building owners or occupants unless a source of a hazardous pollutant is clearly present and source control, ventilation, filtration, and pressurization solutions have already been attempted.

[47] (Keady and Mainquist 2000)

Building operators may be able to afford more expensive pollutant monitoring packages for criteria pollutants, VOCs, and thermal conditions (on the order of $10,000 - $20,000), especially if the monitoring system can be used in several buildings or shared with other building owners. A basic inspection to monitor indoor PM counts, CO, CO_2, temperature, and humidity for a few days should only cost on the order of $1,000. Schools have successfully used portable, real-time monitor packages themselves to diagnose IEQ problems and to conduct preventive maintenance, e.g.:

- School districts in Clovis, CA and Everett, WA used EPA's Indoor Air Quality (IAQ) Tools for Schools program and a rapid complaint response approach using a portable indoor air monitoring kit.[48] Additional staff were not needed to implement the program. This program quickly paid for itself by reducing complaints by up to 60%, and by reducing the cost for environmental consultants. It has also greatly improved the credibility of the school maintenance program with school staff and parents.

- Washington State University conducted a demonstration study to use an IEQ monitor package and share the data online.[49]

Very few low-cost, accurate methods of pollutant detection are available on the market, but the field of low-cost pollutant sensors is evolving rapidly. The last column in Table 2 identifies some indoor pollutants that can be measured with an affordable, consumer-grade device. An affordable device for owners or renters of multifamily housing units is one that that costs about $200 or less. The affordable monitoring devices currently available are as follows:

- Particle phase: common dust allergens, heavy metals (e.g., lead)
- Organic gases: total VOCs, formaldehyde, CO, CO_2, explosive gases
- Inorganic gases: hydrogen sulfide, ozone, radon

For these consumer-affordable detection methods, it can be worthwhile to the building owner or tenant to purchase the sampler, alarm, or sensor that allows them to monitor building conditions. Having a record of pollutant variation from continuous, real-time measurements can provide valuable information as to the pollutant source and the relative need for mitigation methods. Web-based aggregation of data can also be used for multiple buildings to make tracking IEQ more efficient and to expedite response times for IEQ problems. Homeowner associations and local agencies may be able to justify and afford more expensive and accurate monitoring package for measuring pollutant levels, ventilation airflow rates, and room air pressures.

Community groups across the U.S. have conducted their own surveys and pollutant testing of outdoor air, water, and soil in their neighborhoods. For example, costs for the "Bucket Brigade" training and one year of community monitoring start at several thousand

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[48] (CARB 2005b)
[49] (Prill, Hales, and Blake 2003)

dollars.[50] A recent multi-state study of unconventional gas extraction sites (fracking) used the Bucket Brigade approach to monitor several VOCs and hydrogen sulfide; Pennsylvania was one the study areas.[51]

Another example is the “ground-truthing” work by a collaborative of community groups in Los Angeles, California.[52] Volunteers mapped local pollutant sources and, with the help of the local air district and university researchers, measured outdoor PM at the local level. They found several sources of air toxics emissions that were not in government data bases, were not where government maps indicated, and/or were near sensitive areas where vulnerable populations were located. They also found that outdoor PM levels exceeded state standards about half of the time, and six schools were closer than the recommended distance of 500 feet from a major freeway. This report formed the basis for the Clean Up Green Up initiative, which will establish pilot Green Zones to reduce and prevent pollution and support economic revitalization in three heavily polluted areas.[53] A major benefit of community monitoring of indoor and outdoor environments is the long-term engagement of community members who can act on the monitoring results.

In addition, surveillance monitoring of IEQ over the long term can provide useful information for assessing health risks, pollutant sources, and prevention effectiveness. For example, schools and daycare facilities in France are required to monitor indoor formaldehyde, benzene, and CO_2 every seven years; current plans are to use passive monitors for gaseous pollutants.[54]

Affordable methods for monitoring indoor PM counters are emerging. The developments in low-cost, portable sensors are discussed in the next section of this paper. Currently available particle counters could be used in some cases to indicate when outdoor airflows should be reduced. For example, a $PM_{2.5}$ monitor was proposed for a Beijing office building to control outdoor air ventilation during extreme pollution episodes. The outdoor air supply to the HVAC system could be reduced, in tandem with more efficient air filtration.[55] A modeling study concluded that this approach could keep indoor $PM_{2.5}$ below federal air quality standards. This approach is relatively new, so a standard design and commissioning specification has not been developed yet. Some ventilation experts believe that the robustness of IAQ sensors does not appear to be adequate for controlling HVAC systems over the lifetime of a HVAC system, at least for residential applications.[56]

Liability from disclosing monitoring results. On a final note regarding IEQ monitoring, the potential liability for IEQ problems identified by monitoring may discourage some building owners from assessing or monitoring IEQ, but it should not. If best practices in IEQ

[50] (Global Community Monitor 2014)
[51] (Macey et al. 2014)
[52] (Los Angeles Collaborative for Environmental Health and Justice 2010)
[53] (Clean Up Green Up Los Angeles 2014)
[54] (OQAI 2010) (Michelot et al. 2013)
[55] (NIBS 2014)
[56] (I Walker, Sherman, and Less 2014)

management have been followed, the monitoring is warranted, and it is done properly, exposure to liability should be negligible. In fact, we are not aware of any cases where a building owner was sued after following best practices in managing IEQ and monitoring IEQ. To the contrary, a building owner who takes a proactive rather than reactive approach demonstrates due diligence, thereby reducing their exposure to liability. Building owners who "manage what they measure" reportedly have far lower exposure to liability than those who only address issues after they cause harm, real or perceived.[57] Monitoring results and best practices, especially if verified by a third party, may also provide a market advantage in selling or renting a building. One caveat: monitoring of regulated indoor pollutants such as radon and asbestos could result in liabilities if the regulatory requirements for measurement methods, quality assurance, and documentation are not followed.

The liability of school districts for indoor air quality conditions was reviewed by the Environmental Law Institute in 2005.[58] The review found that the lion's share of litigation in the U.S. involved insurance companies, and many cases involved mold problems (which is generally outside the scope of this paper). Published court decisions were rare, and out-of-court settlements were usually confidential. State liability laws for schools varied widely in how they treated immunity, negligence, damage caps, and other legal issues. The review concluded that litigation and administrative remedies such as workers' compensation impose significant burdens on all sides in terms of time and resources, and can take a heavy emotional toll as well. These burdens should actually provide a strong incentive to proactively manage IEQ in buildings instead, which is what many school districts have done.

We are aware of examples where school districts did not respond quickly to complaints or have a proactive, transparent approach.[59] These school districts had to respond to third party IEQ testing by a so-called "expert", deal with prolonged public controversy, and perhaps respond to litigation. Any potential savings from failing to respond promptly to resolve IEQ complaints were probably exceeded by the eventual administrative, legal, and consulting costs. In addition, the loss of credibility with employees and parents of students could have long-term impacts on student, teacher, and community morale.

Insurance companies can become involved proactively to prevent IEQ problems and reduce potential liability. Most insurance policies for general liability exclude environmental pollution, but special environmental pollution policies are available.[60] Some insurance companies also provide services to proactively identify IEQ, ventilation, and/or energy efficiency issues and recommend possible solutions if needed, as part of their risk or loss

[57] (Healthy Buildings International 2014)
[58] (Environmental Law Institute 2005)
[59] (CDPH 1999) (Simpson and Caskey 2014).
[60] (O'Neal-Coble 2002)(Mills, Deering, and Vine 1998) (Mills, Deering, and Vine 1998) (EMC Insurance Companies 2010)(XL Insurance International 2014)

management service. Self-insured building owners and employers could employ the same strategies.

In California, employers are required to measure a specific IEQ parameter annually — outdoor air ventilation flows in HVAC systems.[61] They are also required to inspect and maintain HVAC systems to ensure that design ventilation requirements are met on an annual basis. The inspection and maintenance must be documented and provided on request to employees or state occupational health and safety officials. If serious IEQ problems or complaints arise, an employer could be fined and be liable if they did not comply with this regulation.

What about new low-cost technologies and approaches for IEQ monitoring?

Several low cost, small, portable sensors for measuring real-time air pollution are being developed around the world, for both outdoor and indoor applications. The European Union's EUNetAir program recently reviewed the literature and summarized current projects around the world that use such sensors to monitor indoor, outdoor, exhaled breath, and personal exposures.[62] The sensors have been mounted on lampposts, cellphones, bikes, motor vehicles, trains, and unmanned aircraft; indoor applications have been limited to date. Pollutant sensors have also been combined with sensors that measure location, meteorology, noise, and/or traffic conditions. Sensor data have been collected via the Internet and then mapped and analyzed. Some projects involve community-based participation such as citizen observation, participatory, and crowdsourcing projects.[63]

Several sensors have been developed by the EU projects to monitor gaseous pollutant concentrations, mainly ozone, NO_2, sulfur dioxide (SO_2), VOCs, and CO.[64] The sensors employ different detection principles (resistive sensors, electrochemical sensors, infrared radiation absorption sensors, and photoionization detector sensors). Research is still underway for sensors to capture dust (PM) concentrations. Laboratory testing of these various sensors has been generally successful, but field-testing is scarce and not so promising.[65] The EU report also identifies key research needs such as sensor accuracy, interpreting and managing the data, and using the sensors for education and outreach. For more information on EU project updates, reports, research needs, and presentations, see project websites listed in the summary report, e.g., the EuNetAir[66] and Citizen Observatories projects.[67]

The EPA is also funding research and demonstration projects on low-cost, portable sensors, leak detectors, passive monitors, fence line monitors, satellite measurements, and citizen

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[61] (CDIR 1987)
[62] (Castell et al. 2013)
[63] (European Union 2014)
[64] *Ibid*.
[65] *Ibid*. (Schütze 2013)(Borrego, Ginja, and Costa 2014)
[66] (EuNetAir 2014)
[67] (European Union 2014)

science; it has published a draft roadmap for new monitoring technology development.[68] Research to date has compared the performance of several sensors on the market and has deployed sensors in "citizen science" projects.[69] Most of the research to date has been focused on laboratory testing, but field-testing is underway. The EPA has recently issued a request for research proposals on how communities can effectively use low cost, portable air pollutant sensors.[70] EPA has provided information on how to select and use low cost, portable monitors for citizen science and has plans to issue informal guidance on how to interpret 1-minute monitor readings.[71] For more information on air pollutant sensor technology, funding resources, development and research needs, see EPA's website documents such as the 2014 state-of-the-science report and the EPA Air Sensor Project workshop series.[72]

Monitoring methods are also available for detecting accidental or intentional releases of hazardous compounds in or near buildings. There is no standard package of monitoring equipment or system currently available for chemical, biological, and radiological weapons, but the technology is rapidly evolving.[73]

Another approach to identifying areas with significant outdoor pollutant sources is mapping. The EPA has mapped the U.S. for areas of high radon potential and some states have conducted more detailed mapping in high radon areas.[74] The EPA and other groups provide online maps and locators for industrial facilities, hazardous waste sites, and air toxics risk (cancer and non-cancer) across the U.S.[75] Major metropolitan areas in the U.S. and Canada provide real time and time series mapping of ozone and PM through EPA's AirNow program.[76] This program also provides comparisons of counties in terms of air quality and several health concerns, as well as links for school air quality warning systems and mapping of smoke plumes from wildfires. The EPA has recently released the Environmental Justice Screening Tool, a web-based mapping tool for identifying various sources of outdoor pollutants and the vulnerable populations nearby.[77] NASA provides mapping of outdoor PM and NO_2 from satellite measurements.[78]

Regional groups have used modeling and mapping to identify and address "hot spots" of outdoor air pollution. San Francisco has mapped outdoor $PM_{2.5}$ and noise at the neighborhood level using models to address emissions from roadways and construction activities.[79] In those areas with high $PM_{2.5}$ areas, new multifamily homes are required to

[68] (EPA 2013a)
[69] (Williams 2014)(EPA 2014g)
[70] (EPA 2014f)
[71] (EPA 2014f)(Leven 2014)
[72] (EPA July 7 2014b)
[73] (New York Police Department 2014)(A Persily et al. 2007)
[74] (CDPH 2014)
[75] (EPA 2014a).(EPA 2014b) (EPA 2014d)
[76] (EPA 2014i)
[77] (EPA 2014h)
[78] (NASA 2014)
[79] (Cohn 2014)

install whole house ventilation with enhanced air cleaning and provide maintenance for five years. In southwest Pennsylvania, researchers have used models and measurements to map outdoor air toxics at the census tract level and to estimate the contributions of different emission sources to air concentrations and health risks.[80] High school students in Queens, New York built their own PM sensors and used them to map emission sources in their neighborhood; the sensors cost about $120 to build.[81]

One important monitoring method that was not mentioned yet is air pressure. The measurement of air pressure in a building, although it is not a pollutant *per se*, can also be very useful in minimizing exposures to outdoor pollutants in commercial buildings. A simple example is that of a pressure gauge or sensor at the HVAC air filter. This method allows the building operator or occupants to closely monitor when the air filter is starting to clog up and need replacement. Another example would be pressure sensors to continuously monitor the effectiveness of infiltration control measures such as sub-slab depressurization, positive pressurization, and exhaust ventilation in attached garages, range hoods, and fume hoods (these measures are discussed later in the paper). Airflow measurements of exhaust fans and central fans are also essential in verifying the proper performance of HVAC systems and should be done periodically. A wireless sensor package to monitor air pressures, HVAC operation, CO_2, and thermal conditions is being developed by groups at the Illinois Institute of Technology and Boise State University.[82] Sensors for noise, which is a major environmental stressor, can also be incorporated into sensor packages and be used to help concurrently assess traffic and other emission sources.

In summary, emerging technologies should produce accurate, reliable, and affordable sensors and monitors for indoor and outdoor air in the near- to mid-term, at least for the gaseous pollutants and air pressure. The related issues of data management, quality control, and data interpretation will also take some time to work out. After that, these technologies will become not only valuable research tools but also essential tools for building owners, tenants, and managers of buildings, communities, and educators. The widespread use of such tools could revolutionize how we manage, measure, and value IEQ.

How do outdoor pollutants enter commercial buildings?

In addition to identifying the source of a pollutant, it is also important to identify the pathway by which the pollutant enters a building. There are several pathways for pollutants found in the outdoor environment to enter commercial buildings and become part of the indoor pollution mix. The air pathway is usually the largest source of indoor pollution. Gaseous pollutants can also be carried into a building by municipal, well, or ground water. Solid or semivolatile materials can enter through dust that is tracked in on shoes or shed from clothing or pets. The various pathways are described in more detail below.

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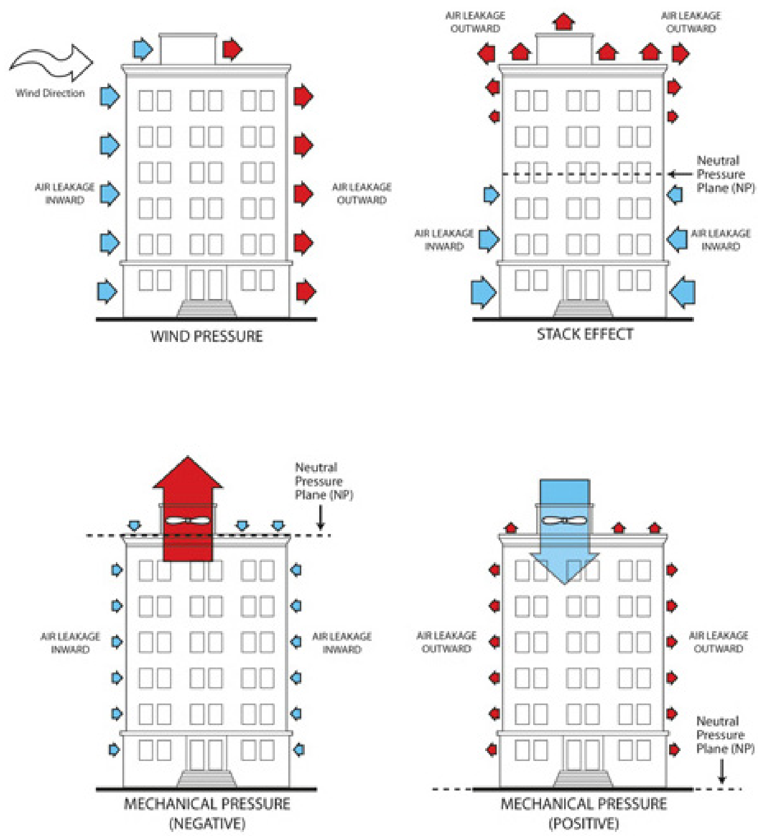
[80] (Michanowicz et al. 2013)
[81] (EPA 2014c)(Newtown Creek Alliance 2014)
[82] (Stephens et al. 2014)(Loo 2014)

1. **Outdoor air infiltration:** Usually outdoor air is the "clean" air with which the building is ventilated, but it can become a threat when it contains a high load of pollution. There are three main mechanisms for outdoor air to enter or infiltrate the building, as discussed below. The effects of natural (passive) and mechanical (fan-assisted) ventilation are illustrated in Figure 5.

Figure 5: Wind pressure, stack effect, and mechanical ventilation pressure on building air leakage



Source: (Canada Mortgage and Housing Corporation 2007)

Mechanical ventilation. The most common mechanism for moving outdoor air into a commercial building is intentional air movement across the building envelope by mechanical ventilation. The large majority of commercial buildings rely on central heating, ventilating, and air conditioning (HVAC) systems, which use mechanical fans and ductwork to supply "thermally conditioned" air to the occupied spaces. Dedicated air intakes with air filters and exhaust vents are usually part of an HVAC system.

Mechanical ventilation includes air-handling (central fan) units for HVAC systems, bathroom and kitchen exhaust fans, laboratory exhaust fans, heat recovery ventilators (HRVs), and heating systems with power vents. Some buildings also use an economizer, an energy efficiency measure that uses a mechanical fan to bring in 100% outdoor air to the HVAC system when outdoor temperatures and humidity are suitable for cooling purposes.

Ideally, HVAC systems are designed to maintain a slight positive (outward) pressure on the building envelope to prevent infiltration of dust and fumes, allow exterior doors to open properly, and to provide sufficient air flow to exhaust fans for bathrooms, laboratory hoods, and range hoods. In reality, seldom are buildings ever operated at a slight positive pressure; they normally operate at a slight negative pressure, especially in cooler weather when stack effects can dominate.[83] It is only in recent years that some facilities have been designed and tested to have tight enclosures that could allow the building to be run at a slight positive pressure without prohibitive operational costs. On the other hand, buildings that include a restaurant with large exhaust fans may be more likely to be depressurized – restaurants have large exhaust fans that create flow imbalances due to dirty HVAC filters, lack of mechanical make-up air, or leaking ductwork.[84]

Unintentional air leakage from the HVAC system operation is another mechanism by which outdoor air may enter the building envelope. Leakage in the HVAC ductwork is very common. A building with ductwork that leaks to the outside will have higher air change rates when the air handler fan is operating and producing high pressure across the leaks, much like a water hose leak under high pressure. In addition, a building with substantial duct leakage will not be able to balance air pressure between different spaces in the building. This can create a vacuum or depressurization in a space.

That depressurization can be sufficient to "suck" or pull in outdoor air from that part of the building envelope or from adjoining interior spaces. The air pulled in may come from outside locations with pollutant sources such as smoking areas, attached garages, dumpsters, chemical storage areas, restaurants, hair or nail salons, and high moisture areas. Depending on pressures induced by the wind, temperature and HVAC operation, the type and amount of pressurization can vary widely within a building.

Natural ventilation, i.e., ventilation produced by passive (non-mechanical) air movement through windows, doors, and air leaks in the building envelope is the third mechanism. Windows and doors can be opened during mild weather to provide indoor-outdoor air exchange while providing thermal comfort, although some commercial buildings have non-operable windows and automatic door closers. Every building has air leaks, but some buildings are much worse than

[83] (Turner 2014)
[84] (Cummings et al. 1995)

others.[85] For air to move through a leak, there must also be a pressure difference across these openings.

Natural ventilation is driven by the combined effects of indoor-outdoor temperature differences and wind pressure (see Figure 5). Temperature differences between indoor and outdoor air can create a “stack effect” during cold weather due to the buoyancy of warm indoor air. This can result in outward pressure in the upper stories of a building, and inward (negative) pressure on the lower stories, especially in very tall buildings. The reverse can happen during hot weather, so that the air enters from the top of a cooler building and increases outward (positive) pressure in the lower stories. The neutral pressure plane is the vertical location in a building where the indoor-outdoor pressure difference is essentially zero. Of course, temperature differences can vary throughout the day, week, and season.

Wind produces more pressure on the upwind side of the building, driving air through building envelope leaks and open windows and doors. It can also increase negative pressure (depressurization) on the upper part of the building due to increased wind speed over the building top, especially in tall buildings. This same effect (the Bernoulli Effect) helps airplane wings produce lift forces.

Wind speed can vary widely in velocity and direction across the day, week, and season as well. In cold weather, temperature-driven stack pressure is a more persistent and significant cause of air movement than wind.[86] Wind pressures can be the dominant infiltration driver in milder weather, e.g., strong winds can overwhelm stack effects in naturally ventilated office buildings during mild weather.[87] Due to the variable forces from wind, temperature, and ventilation systems throughout the building, pressures can vary widely within a very tall building.

Natural ventilation is most effective when the location and orientation of building openings and the width of building interiors are designed to take advantage of prevailing winds, cross ventilation, building depressurization, and the buoyancy of indoor air. Natural ventilation can also be enhanced by the placement of passive exhaust vents in the roof, cooling towers, and windcatchers. However, most commercial buildings are not engineered to provide adequate natural ventilation under local weather conditions, although LEED and CHPS allow credits in natural ventilation if prescriptive or modeling requirements are met.

A significant fraction of commercial buildings in the U.S. and Canada are designed or operated to rely on natural ventilation. In a large statewide survey of California

[85] (S. J. Emmerich and Persily 2011)
[86] (Reardon 2008)
[87] (J.W. Axley 2001)

K-12 public schools with portable classrooms, 5% of the portable classrooms and 23% of the traditional classrooms lacked any air conditioning and would have probably relied on natural ventilation for cooling and ventilation.[88] In a field study of 156 K-12 schools in Washington, 10% of the portable classrooms had no mechanical ventilation system.[89] In both studies, a large percentage of the portable classrooms also turned off the HVAC system frequently because of its excessive noise.

Natural ventilation is most likely to be used as the primary ventilation method in older commercial buildings that are located in mild climates, especially if they have sea breezes throughout most of the year. There is also a trend for low-energy and low-carbon building programs to increase the use of natural ventilation, alone or along with mechanical ventilation (hybrid or mixed-mode ventilation), in order to make commercial buildings more sustainable or regenerative in terms of natural resources. Hybrid ventilation systems that are designed to optimize natural ventilation and mechanical ventilation for energy efficiency are more common in Europe, where there is an active demonstration research and demonstration program.[90]

As with any building system, commissioning (performance verification) is essential for efficient and safe operation of hybrid and other ventilation systems.[91] The Collaborative for High Performance Schools (CHPS), a voluntary certification system for sustainable schools in 13 states, allows a rating credit for natural ventilation. To qualify, the building must be engineered to meet ventilation and thermal comfort standards and include a low-noise roof exhaust fan as a backup.[92]

Because it depends on the variable forces of nature, natural ventilation can be very sporadic. Natural ventilation is not suitable for conditions when outdoor air pollution, hot or cold weather, outdoor noise, and perhaps security are concerns. Window opening on the lower floors of office buildings has been associated with increased indoor levels of traffic VOCs (benzene, toluene, ethylbenzene, and xylene, or BTEX).[93] Baffled vents for outdoor air transfer can be used to reduce outdoor noise impacts on occupants and keep rain and pests from entering the building. Some commercial buildings have both mechanical systems and windows that occupants can control. Such buildings have to be managed carefully to avoid building depressurization problems and excess energy use from over-ventilation.

Other disadvantages of natural ventilation are that the outdoor air is not filtered. When windows and doors are open, which can be frequent in schools (see above),

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[88] (Whitmore et al. 2003)
[89] (Prill, Hales, and Blake 2003) (Axley 2001)
[90] (Venticool 2013)
[91] (Lomas, Cook, and Short 2008)
[92] (Collaborative for HIgh Performance Schools (CHPS) 2014).
[93] (Mandin et al. 2014)

the indoor PM, diesel soot, ozone, and NO_2 levels may increase due to an increased air exchange rate and also because deposition on ductwork and air filter surfaces are avoided. Fortunately, there are cost effective options for new or retrofit HVAC systems for portable classrooms that are low-noise and energy efficient, so that teachers do not have to turn off the HVAC to be heard and open the windows to ventilate the room.[94]

2. **Attached spaces:** Air can enter from spaces attached to a building that are not specifically outdoors (or recognized as such). For instance, in an apartment in a multifamily building, air pollutants from smoking, incense burning, and cooking may enter from adjacent apartments or restaurants. This air is not from the "outside," but it does enter from outside the building envelope of the dwelling unit. This air may enter via a ventilation system, but often times it enters via leaks in the interior structure or ductwork. Other common examples of attached spaces of concern include attached garages (containing vehicle emissions and stored chemicals), loading docks, dry cleaners and other commercial activities, attics vented to the outside, and vented crawl spaces. [95] [96]

3. **Soil gas:** Soil gas is actually a subset of outdoor air. It includes all gases that travel through the soil and enter the building in the below-grade sections of the foundation. For all structural types, utility penetrations through floors, foundations, and walls are a key route of entry. The most common routes of vapor intrusion include: seams between construction materials (including expansion and other joints); utility penetrations and sumps; elevator shafts; and cracks.[97] Soil gas entry rates are determined, as described above regarding outdoor air leakage, by the combination of foundation leakage areas and the pressures across the leaks. Radon is one notable soil gas, but others include pesticides, water vapor, and VOCs from leaking underground storage tanks. Crawlspaces, especially dirt floor crawlspaces in heating climates, are a known source of elevated indoor radon levels.

4. **Cleaning and track-in:** Pollutants that are found in outside soil and dust are tracked into buildings on shoes, feet, clothing, and pets. Airborne pollutants from outdoors can deposit on surfaces and become part of surface or house dust. The surface dust (house dust) exposure is secondary in terms of inhalation exposures but is very important for children's total exposures to heavy metals, SVOCs, and other pollutants that concentrate in house dust. House dust has been identified as a major source of lead in house dust for inner-city neighborhoods.[98] Pesticides from outdoor applications have been found in floor dust in homes and schools.[99] [100]

[94] (Apte et al 2008)
[95] (Storm et al. 2013)
[96] (Ma et al. 2009)
[97] (EPA 2008)
[98] (Roberts 1992)
[99] (Colt et al. 2004)
[100] (CARB 2004a)

Similarly, dioxins and furans found in house dust have been associated with nearby cement kilns and major freight routes and roadways.[101] As it is relatively easy to minimize this pathway, it should be included in any remediation strategy where surface soil and dust are sources.

5. **Water:** Some pollutants enter via potable water, either from the municipal water source, well water, or spring water. Overland flooding can also bring in a host of contamination to affected buildings. Municipal water is an often-noted source for organochlorine compounds such as THMs.[102] Well water is more likely than other water sources to carry radon and VOCS from contaminated sites. These various waterborne pollutants are emitted into air during normal use such as baths, showers, cooking, and clothes washing. Once the water is aerated by a faucet or spray nozzle, the pollutant can become airborne and inhaled, especially if the water is hot.[103] Some waterborne pollutants, such as uranium, radium, arsenic, and THMs also enter the body through ingestion (drinking) or skin absorption.[104]

6. **Sewer gas:** Sewer gas can enter buildings from dry drain traps, leaks in sewer gas vent lines, broken sewer water lines, or re-entrainment from sewer vents on roofs. Sewer gas is a complex mixture of toxic and nontoxic gases produced and collected in sewage systems by the decomposition of organic household or industrial wastes, typical components of sewage. Sewer gases may include hydrogen sulfide, ammonia, methane, carbon dioxide, sulfur dioxide, and nitrogen oxides. Hydrogen sulfide has a strong rotten egg odor. Sewer gas can also contain high concentrations of tetrachloroethylene (PCE).[105] Sewer gas from sewage leaks can also be drawn into buildings that have excessive depressurization.[106]

How can we mitigate pollutant entry in commercial buildings?

There are several basic strategies to preventing or reducing pollutant entry, and these are discussed below. The limitations of these approaches are also discussed.

Controlling the pollutant source before it enters the building is usually the most effective and reliable strategy. Ventilation strategies that control the distribution of pollutants once they are inside a building are less effective. Air cleaning strategies can be helpful, especially in smaller spaces, and can complement ventilation strategies. Consider these strategies as a "basket of solutions" that can be used either individually or in combination for the particular circumstances of the building and its occupants. Many of these strategies can also improve the energy efficiency and durability of the building.

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[101] (Deziel et al. 2012)
[102] (Chowdhury 2013)
[103] (Giardino and Andelman 1996)
[104] (EPA 2013d)(EPA 2013e)(Chowdhury and Hall 2010)
[105] (Pennell et al. 2013)
[106] (Cummings et al. 1995)

Obviously, reducing vehicle emissions and other major sources of nearby pollution is essential, but achieving this goal in will take time, especially in some areas with especially severe outdoor air pollution. In the meantime, other strategies can also be used to protect people in indoor environments:

1. **Setback:** Increasing the distance (setback) of a building from nearby pollutant sources reduces the outdoor pollutant concentrations that reach the building. Buses, shuttle vehicles, delivery trucks, construction activities, parking lots, and vehicle traffic are common outdoor sources that are often adjacent to or near commercial buildings. Examples of setbacks include limits on school bus idling near schools, locating schools a minimum distance from roadways, nonsmoking areas near building entrances, and creating buffer zones for agricultural pesticide use near residential areas.

   Roadway setbacks can be implemented in new building design and land use planning, but can be problematic for existing buildings. However, in some cases, heavy truck traffic has been diverted from sensitive neighborhoods.

   Setback strategies have already been used in many regions. Thirteen states have regulations to limit bus idling near schools.[107] For example, Allegheny County in southwest Pennsylvania limits idling of buses to within 100 feet of school air intakes and prohibits any idling over five minutes, with some exceptions.[108] Pennsylvania limits the idling of any diesel vehicle over 10,000 pounds to no more than five minutes per hour, with some exceptions.[109] California has limited bus idling at or near schools since 2003.[110]

   California law also requires new school site plans to be evaluated for on-site or nearby sources of hazardous or toxic emissions, including roadways, airports, pipelines, hazardous waste, and commercial activities.[111] The U.S. Green Building Council's LEED for Schools rating system awards credits for building schools beyond 1,000 feet of landfills or avoiding contaminated sites without proper remediation. This was done in part because those sites may be mined in the future, re-emitting the soil contaminants as airborne pollutants.

   The California Air Resource Board (CARB) has recommended different setback distances when siting new schools, daycare centers, medical facilities, playgrounds near freeways, distribution centers, rail yards, ports, refineries, chrome plating facilities, dry cleaners, and gasoline dispensing facilities.[112] To reduce exposure to environmental tobacco smoke (ETS) in nonresidential buildings, California and

[107] (Wiki-pedia 2014)
[108] (ACHD 2004)
[109] (Westlaw 2009)
[110] (CARB 2012a)
[111] (California Department of Education 2013)
[112] (CARB 2005a)

other jurisdictions specify that outdoor smoking areas must be at least a specified minimum distance from building entries, outdoor air intakes, and operable windows.[113]

Pesticide use near or on school grounds can also pose a serious health risk for students and staff, and setback requirements are used to help reduce these risks. For example, in California substantial quantities of highly hazardous pesticides were used as of 2010 for agriculture near 226 schools.[114] Over 500,000 students go to schools within ¼ mile of this pesticide use. Central Coast and San Joaquin Valley students are most likely to attend to such schools. Several counties in California limit the agricultural pesticide application near schools, with respect to the timing, notification, and method of application, and the restrictions vary among counties.[115] For pesticides applied on school grounds, a California right to know law requires notification, posting, and record keeping, but there is no specific enforcement authority.

2. **Air intake location:** The outdoor air supply for a mechanical ventilation system can be contaminated by nearby pollutant sources such as idling vehicles, traffic, cooking, cooling towers (legionella bacteria), parking lots, dumpsters, sewer vents, lab hood exhaust, and commercial and industrial activities. Traffic, windblown debris, and other contaminants can easily contaminate air intakes near ground level. Moisture intrusion from rain or snow can foster microbial contamination in air intakes, which are seldom inspected or cleaned. Debris, bird feces, and insects can also contaminate air intakes.

   Building ventilation standards and green building programs for commercial buildings usually include requirements for minimum distances from nearby pollutant sources.[116] The City of Seattle recommends placing air intakes as high above the ground as possible.[117]

   Placing air intakes well above ground also helps protect a building from chemical and biological release. Measures can also be taken to prevent unauthorized access to air intakes, e.g., locked access, video surveillance. New York City recommends locating air intakes 100 feet or higher above ground level on tall buildings, to protect against the threat from a ground release of a chemical, biological, or radiological (CBR) weapons.[118] CBR agents can be propelled upward by the "urban street canyon effect," common in urban environments with tall skyscrapers.

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[113] (CBSC 2013a)
[114] (Californians for Pesticide Reform 2014)
[115] (CEHTP 2014)
[116] (ANSI/ASHRAE 2014)(Collaborative for High Performance Schools 2009)
[117] (ANSI/ASHRAE 2014)(Collaborative for High Performance Schools 2009)
[118] (New York Police Department 2014)

Relocating air intakes in existing buildings will entail some expense, but it may be necessary to avoid major outdoor pollutant sources that were not anticipated during building design. It may also increase the air resistance in the HVAC system and adversely affect the performance of downstream components. Potential benefits of this strategy include reduced soiling of filters, ducts, and heat exchangers, reduced odor and irritant complaints by occupants and visitors, and improved security from vandalism, terrorism, and accidental spills of hazardous materials.

3. **Air sealing (above and below grade):** Commercial buildings are often not very airtight, especially older buildings. Increasing building tightness by air sealing can help reduce infiltration of outdoor air pollutants and vapor intrusion of soil gases such as radon and VOCs.

   Results from blower door tests in commercial buildings are expressed as the airflow rate created in a 50 or 75 Pascal (Pa) pressure test and normalized (divided by) the square meter or foot of building enclosure surface area. HVAC system leakage from ducts, dampers, grills, and vents can also be measured. Leakage from the HVAC system can be quite substantial – as much as half of the total building leakage.[119] If this ductwork is located outside of the building envelope, major energy and control issues can result. An extensive review of the methods, previous studies, standards, and costs of air sealing is available in a recent report on multifamily buildings.[120]

   The air leakage rates of commercial building envelopes and HVAC systems can range from relatively tight to very leaky. Compared to the large data set on residential buildings, there are few data on air leakage in commercial buildings (about 300 buildings). The available data are summarized below, in metric units:[121]

   - In a 2011 review of U.S. studies, the average airtightness of 228 commercial and institutional buildings was 7 L/s-m^2 @ 75 Pa, or 0.25 cfm/ft^2 at 75 Pa.[122] This average was a little over 10% tighter than the average reported for 139 U.S., Canadian, and Swedish buildings by Persily in 1998.[123] This average was tighter than the average of all U.S. houses but leakier than conventional new houses.

119 *Ibid.*
120 (RDH Building Engineering 2013)
121 A spreadsheet for converting measurement units typically found when conducting whole building air tightness testing is available at http://www.airbarrier.org/whole_building/F-115-052%20Rev%201%20ABAA%20Whole%20Building%20AirTightness%20Testing%20-%20Air%20Leakage%20Unit%20Conversions.xlsx
122 (S. J. Emmerich and Persily 2011)
123 (A. K. Persily 1998)

- Several newer buildings in this review met the 2009 U.S. Army Corps of Engineers air leakage standard of 1.3 L/s-m^2 @ 75 Pa; these buildings had much less average leakage and variability of leakage rates. Taller buildings tended to have lower leakage rates, but no clear trends were observed for other building characteristics.

- A recent study of 16 non-residential U.S. buildings, mostly higher performance buildings, found measured leakiness of from 0.30 to 3.80 L/s-m^2 @ 75 Pa.[124] The researchers reported that lower leakage rates were achieved in buildings where a building envelope consultant was involved.

- The 2011 review above has been updated recently to include some of the buildings below.[125] In addition, energy and cost savings are estimated for a range of U.S. climates (see below).

Schools and multifamily buildings have not received much attention in terms of building air leakage research. Available data are summarized below:

- Honeywell conducted envelope and/or HVAC sealing at four schools in Colorado and one in Kansas. Major reductions in air leakage, energy usage, and indoor air quality problems were reported, but the measurement results were not published.[126]

- A recent review of multifamily studies reported results for 43 buildings, mostly in Canada and only four in the U.S.[127] The air leakage averaged 3.66 L/s-m^2 and varied widely. Leakage rates were lower in newer buildings, buildings with newer air barriers, taller buildings, and buildings with certain wall types.

Air sealing of buildings and their HVAC systems is very cost effective in new construction, and air leakage testing is now required in several U.S. jurisdictions.[128] Air sealing can also yield substantial energy and equipment cost savings by allowing the downsizing of HVAC systems. In existing buildings, air sealing can be cost effective, depending on the climate and amount of potential leakage reduction. For example, for a two-story office building of 24,000 square feet in size, the estimated annual energy savings ranged from about $750 in Phoenix and Miami to almost $3,700 in Minneapolis.[129] Savings for a four-story apartment building ranged from $133 in Phoenix to over $2,200 in Minneapolis; however, savings would be higher if the building had continuous mechanical

[124] (Anis and Brennan 2014)
[125] (S. Emmerich and Persily 2014)
[126] (Honeywell BES 2014) (Honeywell BES 2013)
[127] (RDH Building Engineering 2013)
[128] (ABAA 2013)
[129] (S. Emmerich and Persily 2014)

ventilation or an economizer (periodic operation).[130] Emmerich et al. (2005) also reviewed the few existing studies of measured or modeled infiltration reduction and energy savings in commercial buildings.[131]

Air sealing can also be cost effective in existing multifamily units, especially on a per-unit basis. For example, the air sealing of a school, a library, and an office building in Canada produced substantial energy savings, with payback periods ranging from less than one year to two years.[132] In a review of the limited data on the cost-effectiveness of air sealing in multifamily buildings, Dentz et al. (2012) found that air sealing can often be cost-effective in older buildings.[133] They also estimated payback periods for apartment and townhouse buildings in North Carolina, Ohio, and Indiana of 1.4-12.2 years, with returns on investment of 8-73%.

One limitation of air sealing is that care must be taken to avoid undesirable consequences. An airtight building is easier to both pressurize and depressurize. If it is depressurized, it may increase the intrusion of subslab gases and moisture, if the building foundation is not well sealed. In addition, tighter buildings should have sealed combustion appliances that have direct venting to the outdoors. Otherwise, chimney or open flue vents of combustion appliances can backdraft and release CO, NO_x, PM and other combustion pollutants into occupied spaces. In buildings that rely on natural ventilation, which is common for older buildings, air sealing may trigger requirements to install mechanical ventilation with air filtration. Heat recovery ventilators may help recoup the cost of ventilation, depending on the climate and the building. Before any extensive air sealing, care must be taken to assess and minimize moisture and any other existing sources of indoor air pollution.

4. **Pressure boundaries:** The next step in reducing pollutant infiltration is to control the building pressure with fans. All major penetrations through the slab should also be sealed, e.g., sumps, utility connections, major cracks and gaps.

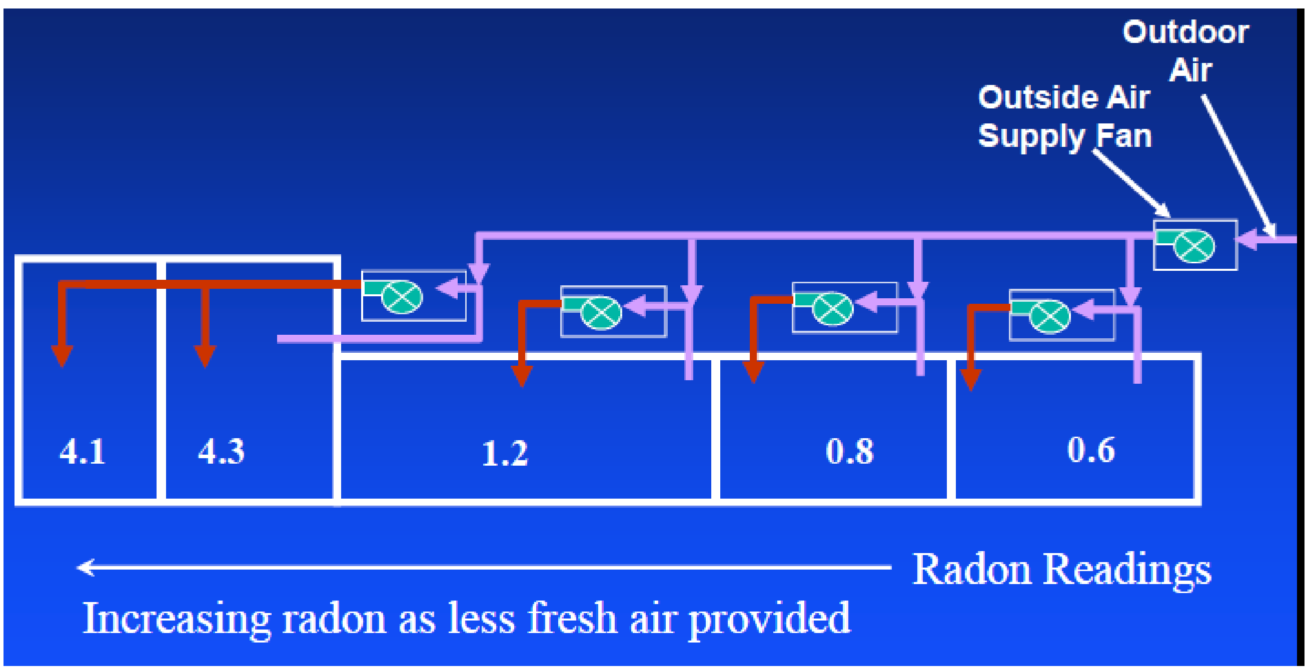
   The most common example is the radon subslab depressurization fan, which draws air out from underneath the slab. This creates a slight negative pressure under the slab (relative to the building). Any hole or crack will, therefore, leak from the building to the air space under the slab and be exhausted by the fan. No air (from below the slab) should enter the building through this pressure boundary. Subslab depressurization for radon control is discussed in more detail in the companion white paper on homes.

130 (S. Emmerich, McDowell, and Anis 2005)
131 *Ibid*.
132 (Dentz, Conlin, and Podorson 2012)
133 *Ibid.*

Other types of building pressure strategies for buildings with foundations in contact with the ground include drain-tile suction, sump-hole suction, or block-wall suction. For buildings with crawlspaces, depressurization options include an airtight membrane over the soil, along with a subsurface depressurization fan system, an exhaust fan in the crawlspace, and passive ventilation of the crawlspace. The different approaches to controlling infiltration from soil gases are compared in the EPA guide on mitigating vapor intrusion[134] and in the EPA's Consumer Guide on Radon Reduction.[135]

The extent of depressurization should be checked during the fan installation. Multiple entry points may be necessary for adequate protection across the whole slab. Radon systems should be monitored continuously by a pressure sensor or a real-time radon sensor to ensure that all the components are working as designed. The airflows from the HVAC should also be adequate and balanced in order to produce balance levels of indoor radon and provide good ventilation, as shown in Figure 6 from a school radon study.

Figure 6: Effect of unbalanced ventilation system on indoor radon levels



Source: (Case & Moors 2011)

It is possible to create a pressure boundary in the above-grade portion of the building, but that has to be accomplished by pressurizing the building with outdoor air. It should only be attempted if the building has been tightened to a

[134] (EPA 2008)
[135] (EPA 2013b)

level to make it feasible. In multifamily buildings and commercial buildings with multiple compartments, pressure boundaries between compartments can be used to keep air pollutants from entering occupied space. For example, putting an apartment unit under positive or balanced pressure will keep out the cooking and smoking pollutants from nearby apartments or restaurants. Operating exhaust fans in attached garages, and adjoining spaces with pollutant emissions, plus sealing major leakage paths between adjoining spaces, can prevent the pollution infiltration from adjoining spaces. Sealing pathways becomes critically important for pressure controls to work.

One disadvantage of using a pressure boundary strategy is that it requires money and labor for equipment, energy, maintenance, commissioning, and re-commissioning. Also, the outdoor air used to pressurize the building has to be filtered effectively to avoid introducing outdoor pollutants, if high pollutant loads in outdoor air are present. If an air filter is used, it is susceptible to filter loading and the effects of damp outside air that encourage mold and bacteria growth in the HVAC system. This will require more frequent inspection and replacement of the filter to avoid blockage of the filter, pollutant build up, and re-emission from the filter.

Another complication of using pressure is that moisture management can be difficult. Even a slight positive pressure in the building during cold weather forces warm, moist air outward through cracks, leaks, and electrical outlets in outside walls. This can cause moisture buildup and mold inside the exterior walls, particularly on the exterior sheathing, which can be roughly the same temperature as outside. Software for modeling moisture transport and condensation in building assemblies is now available to help predict such problems.

When using building pressurization in hot, humid climates, care should also be taken to avoid moisture condensation in wall cavities. For example, the building should be tightened up and the pressure should be positive or balanced to avoid pulling hot, moist air into a building, where it can condense on cooler inside surfaces.[136] Negative pressure would bring hot, humid air in, thereby increasing the cooling and dehumidification load and the risk of mold contamination. This problem is usually avoided by providing supply air for any exhaust ventilation, installing pressure relief vents and pressure sensors, compartmentalizing building spaces, and using dehumidification when necessary.[137]

For control of vapor intrusion of soil gases from contaminated soil and ground water, another strategy is to divert the ground water away from the building by digging a drainage trench or installing pumps to remove the contaminated water. These approaches reduce or remove the soil gas pressure into the building. The

[136](MacPhaul and Etter 2010)(Stanke and Bradley 2002)
[137] *Ibid*.

limitations of trenching are that it may not fully divert the plume of contaminants and it may lead to pollutant exposures in other locations. The limitations of pumping are that it can be costly and require routine maintenance, alarm systems, monitoring, and treatment of the volatile gases.

5. **Timing of building ventilation:** Flushing out a building with outdoor air that has little or no pollution can improve IEQ. Even brief, periodic flushing can be helpful if the building air volume is exchanged several times. This flushing can also be a major energy saver during mild and dry weather when cooler and drier outdoor air can be used to cool the building, especially at night or early morning. However, if the outdoor pollutant levels are high, e.g., during rush hour, peak ozone periods, or a wildfire episode, then increasing outdoor air ventilation can worsen a building's IEQ. Flushing should not be done during periods of high outdoor humidity.

   The ventilation timing strategy can be used in both routine and emergency situations. For example, the California building energy efficiency standard requires that nonresidential buildings be flushed for one hour every day before occupancy, in order to reduce overnight buildup of indoor air pollution.[138] For wildfire episodes, California and other jurisdictions have recommended that workplaces temporarily reduce outdoor air ventilation rates as long as sufficient air pressure is maintained for exhaust vents in bathrooms and special use areas.[139] In the case of a toxic spill or terrorist attack, building ventilation can be reduced.[140] The approaches to minimizing the infiltration of CBR in commercial buildings through ventilation and air filtration strategies are discussed in detail in a 2002 NIOSH guidance document.[141] Any strategies that reduce ventilation rates temporarily must also ensure that major indoor sources of pollution that produce fumes, smoke, water vapor, or odors are avoided during that time.

   The limitations to this strategy, in addition to increased costs, are mainly with system controls and maintenance in emergency situations. Large HVAC systems cannot always be shut down rapidly, so the challenge would be to get advance warning and be prepared for such incidents. High security facilities can employ special sensors, warning systems, and video surveillance to detect CBR hazards. Although real-time pollutant sensing technology can be used, sensors for many pollutants are still under development (sensor technology is discussed below). In order to be reliable and ready when needed, any technology also requires routine maintenance, effective training of building operators, and redundant systems for critical infrastructure or life support applications. Air cleaning equipment and

[138] (California Energy Commission 2013)
[139] (Lipsett et al. 2008). See Appendix D, Cal OSHA Interim Guidance regarding temporary reductions in ventilation.
[140] (Andrew Persily et al. 2009) (FEMA 2006)
[141] (NIOSH 2002)

rigorous control of indoor pollutant sources are recommended if the ventilation rate is reduced for an extended period; these preventive measures can also increase costs.

6. **Air cleaning devices:** Particle filtration of air can be achieved using fabric filters or rigid pleated filters in HVAC systems, and/or portable standalone air cleaners that usually have their own fan system. Electronic air cleaners that use electrostatic precipitation to remove particles are available, for stand-alone or in-duct applications.[142] Gas-phase air cleaners are available for removing many organic and inorganic gases such as VOCs and ozone, but are not generally effective in removing non-reactive gases such as carbon monoxide. Air cleaning in the residential setting is discussed at more length in the white paper on homes, and in a guidance document by CARB.[143] NIOSH and FEMA have provided guidance on designing, installing, and operating particulate filter and gas phase air cleaning systems for shelter-in-place applications in commercial buildings.[144]

   Large commercial buildings usually already have an air filter in the HVAC system that filters particles from the outdoor air and the recirculating indoor air. However, depending on the climate and the age of the building, some small and medium commercial buildings rely on natural ventilation and thus may lack an HVAC filter.[145] Air filters that remove gaseous pollutants are expensive to install and operate, and hence are rarely used except for special applications such as "clean rooms" for manufacturing or medical procedures or for situations where indoor emissions from building materials, occupants, or activities cannot be controlled sufficiently.

   Table 3 shows the different performance ratings for air filter efficiency in removing particles of different size. The ratings use the Minimum Efficiency Reporting Values (MERV scale) from the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) Standard 52 test method. [146] This method is used to evaluate filter performance at different particle sizes. It includes dust loading of the filter and a break-in period to simulate in-use performance and loss of any initial electrostatic charge. However, ultrafine PM (less than 0.1 micron in diameter), which is present near combustion sources such as traffic and cooking, is not included in the standard test method.

   The table also shows the sizes and types of particles controlled by the different MERV rated filters. Clearly, some filters are not designed to remove particles from certain pollutant sources and are not appropriate for certain building applications.

[142] (EPA 2013c)
[143] (CARB 2012b)
[144] (EPA 2012a)
[145] (Piazza and Apte 2011)
[146] (ASHRAE 2007)

Commercial building designers and operators tend to specify air filtration levels for HVAC systems that meet the minimum requirements in building standards, i.e., low efficiency filters to keep debris from the duct work and heat exchangers, also known as “boulder catchers”. These filters have MERV ratings of 4 or less.

In recent years, building standards and green and healthy building programs have required more efficient air filters, e.g., MERV 8 filters and MERV 11 filters or greater as optional.[147] [148] In urban or dusty areas where the filters load up quickly, some building operators add a lower-MERV pre-filter to extend the life and effectiveness of the higher MERV filter. The CHPS best practice design standards for new sustainable schools require MERV 10 filters, which also help avoid pressure drop problems in the HVAC system; LEED allows a credit for MERV 13 in new construction of commercial buildings.[149] [150] Existing HVAC systems may need lower MERV filters to avoid pressure drop problems.

For very small buildings and smaller, enclosed spaces, the portable, standalone air cleaners that remove particles, gases, or both can also help remove air pollutants. The performance of portable air cleaners is typically tested, listed, and labeled for a Clean Air Delivery Rate (volume of clean air provided) and the appropriate room volume for the device. [151] Electronic air cleaners, either portable or in-duct devices, can generate indoor ozone, which can be hazardous. California has established ozone emission limits, certification requirements, and labeling requirements for portable electronic air cleaners.[152]

Improved air cleaning can be considered when a building frequently experiences extreme levels of outdoor air pollution, such as heavy traffic congestion, or when building occupants require very clean supply air, e.g., hospitals, manufacturing clean rooms, computer server rooms, and green and healthy schools. This approach has also been used for “sanctuary rooms” or “clean air spaces” for persons with respiratory problems or for surgery rooms.[153] However, depending upon the size of the building, the use of a stand-alone filter in one room will have a limited effect on the air in other parts of the building. Even with a central fan operating intermittently, a stand-alone filter will have far more effect in the room in which it operates than in adjoining spaces.

[147] (CBSC 2013a)
[148] (CBSC 2013b)
[149] (CHPS 2014)
[150] (LEED User 2014)
[151] (AHAM 2012)
[152] (CARB 2014b)
[153] (CDC 2014)

Table 3: ASHRAE Minimum Efficiency Reporting Values (MERV) ratings and approximate effectiveness for various particle sizes [154]

MERV Rating	Average Particle Size Efficiency (PSE) (Microns and % Removal)			Typical Controlled Contaminant or Material Sources	Typical Building Applications
	0.3-1.0	1.0-3.0	3.0-10.0		
1-4			<20%	**>10 Microns** Textile Fibers, Dust Mites, Dust, Pollen	Window AC Units Common Residential Minimal Filtration
5			20-35	**3.0 to 10.0 Microns** Cement Dust, Mold Spores, Dusting Aids	Industrial Workplace Better Residential Commercial
8			>70		
9		<50	>85	**1.0 to 3.0 Microns** Legionella, Some Auto Emissions, Humidifier Dust	Hospital Laboratories Better Commercial Superior Residential
12		>80	>90		
13	<75	>90	>90	**0.3 to 1.0 Microns** Bacteria, Droplet Nuclei (sneeze), Most Tobacco Smoke, Insecticide Dust	Superior Commercial Smoking Lounge Hospital Care General Surgery
16	>95	>95	>90		
17**	≥99.97			**<0.3 Microns (HEPA/ULPA filters)** Viruses, Carbon Dust, Fine Combustion Smoke	Clean Rooms Carcinogenic & Radioactive Matls. Orthopedic Surgery
18**	≥99.99				
19, 20**	≥99.999				

*Adapted from EPA 2009; originally from ANSI/ASHRAE Standard 52.2-2007. Not all levels are shown.
**Not part of the official ASHRAE Standard 52.2 test, but added by ASHRAE for comparison purposes.

There are several limitations to air cleaning devices, especially regarding proper installation, operation, and maintenance. Air filters in the HVAC systems of commercial buildings often have substantial air bypass through gaps in the filter holder, thereby reducing the effectiveness in pollutant removal.[155] [156] Some stand-alone air cleaners can be obtrusive and noisy, particularly if the airflow is high, so that they tend to be used less often. Costs for filter replacement and the electricity costs for running stand-alone filter fans can be substantial. Because most air cleaners do not remove many types of air pollutants, especially gases (which tend to be invisible and odorless), using an air cleaner may give building occupants a false sense of security.

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[154] (CARB 2014a)
[155] (CARB 2004b)
[156] (M. J. Mendell et al. 2008)

Air filters that are not changed frequently can become loaded with dust and debris and rapidly drop in removal efficiency. In addition, filters and air cleaners that become damp or wet can become breeding grounds for bacteria and fungi, which can then be blown into the occupied spaces. Some filters have been found to emit VOCs, SVOCs, formaldehyde, metals, and/or possibly microbial contaminants.[157] Finally, operator training and quality control are essential for proper operation and maintenance of any air cleaning system, but are not always provided, especially in schools and multifamily buildings where operation and maintenance budgets may be limited.

Other limitations to air cleaning devices affect their real-world effectiveness in removing pollutants. As discussed above, air filters may remove a high percentage of some particle sizes, but very little of other particle sizes that also pose a potential health risk, such as ultrafine particles (UFP). For controlling cat and dust mite allergens, air filters are not very effective because these allergens are larger than 1 micron in diameter and settle quickly onto surfaces before an air filter can remove the allergens.[158] Much of indoor exposure to PM is due to re-suspension of surface dust by human activities. Consequently, an air cleaner in one part of the building may not significantly reduce PM exposures of persons in other parts of the building, especially if the interior volume is large.

In addition, filters in an air circulation system are only effective when the fan is in operation, which is not always the case in schools, multifamily buildings, and some office buildings. No airflow means no air cleaning by the filter. If a high-efficiency (e.g., MERV 16) filter is put into a circulation system, it is necessary to verify that the HVAC fan and ducting system are suited to the filter resistance, and also to install a monitor to warn of excessive filter resistance as the filter loads up.[159] It is also necessary to ensure constant fan operation during occupied periods, especially in smaller buildings and multifamily buildings where control systems, operation, and maintenance may not be optimal. To keep energy costs down in multifamily buildings, the filter should be part of a whole building ventilation system that uses an energy efficient fan. In many commercial buildings, a pre-filter with a medium MERV level (about 7-8) is often used upstream of a high MERV filter to reduce the costs of replacing the high efficiency filter.

Filters or adsorbing materials can also be used to reduce gases such as VOCs, although such filters are expensive and not commonly used unless there is a special process requirement by the building occupant. Usually a gas filter will have a pre-filter to catch the majority of particles, as well as a bed of charcoal, potassium permanganate, or some other chemical media bed to absorb the gas-phase pollutants as they pass through. The effective life of a gas filter depends on

[157] (Sidheswaran et al. 2013)
[158] (Fisk et al. 2002)
[159] (IS Walker et al. 2013)

the mass of the filtration material, the amount of pollutant it has to treat, and other factors. The chemical media bed can be tailored for the pollutant of interest, if its chemical makeup has been identified.

Reports of "filter emissions" indicate instances in which the collected chemical or biological debris on the filter becomes a pollutant source in itself.[160] A filter loaded with debris for months or years can be a long-term pollution source or reservoir. It can also be an episodic source, much like a carpet or furniture taking in VOCs in high periods and then re-emitting them. Whether the amount of VOC or mold spores re-emitted from a filter is significant is another question, and one that has not been well answered in the literature. A washable or changeable pre-filter may be a very good option for minimizing stored material on either a supply air filter or a recirculation air filter, if it is serviced regularly. Another issue with supply air filters is the intrusion of airborne rain, mist, or snow and the consequent wetting of the filter material, which can then foster microbial growth. A rigorous filter replacement schedule is critical for the success of any filtration system. Despite these potential drawbacks, the installation and usage of proper filters is almost always part of a good IEQ solution.

Houseplants and living walls. Although many claims have been made regarding the effective removal of air pollutants by houseplants and "living walls", this effectiveness has not been demonstrated clearly. A critical review of the issue in 2009 found that the laboratory test results indicated a very low removal rate of VOCs by houseplants, even with a heavy loading of houseplants – equivalent to 680 plants in a 1,500 square foot home.[161] Even so, the VOC removal rate was effectively less than the very low air exchange rate from natural ventilation in a very tight home. The laboratory studies were plagued by significant methodological problems, e.g., non-constant emissions of formaldehyde, unrealistic air mixing by fans, unrealistic high concentrations of pollutant exposures, potential artifacts from potting soil, and lack of pollutant removal rates that could be compared to other studies.

Furthermore, the field studies of houseplants did not use accurate methods to measure pollutants and did not measure building ventilation rates, so the results could not be interpreted adequately. Houseplants and living walls may actually pose health risks due to watering, which can promote the growth of mold and bacteria, and the use of fertilizers and insecticides.[162]

In a recent review of VOC removal pathways in houseplants, the authors discussed the studies of VOC removal by plants, potting soil, and soil bacteria, as well as the

[160] (Schleibinger and Rüden 1999)
[161] (Girman, Phillips, and Levin 2009)
[162] (Levin 2014)

effects of plant species, light intensity, and VOC concentration.[163] The authors concluded that studies conducted in real-life settings such as offices and homes were few and showed mixed results for VOC removal; various research needs were also discussed.

7. **Cleaning and reducing track-in:** Dust and debris on the floors and other surfaces of buildings create two main types of health risk. For infants, toddlers, and others who play on the floor, the pollutants in the dust and debris can be ingested directly or via wet fingers or toys that go into the mouth. Such ingestion is a common pathway for lead and one of the main reasons that children under two are at a high risk in a building with significant quantities of lead in house dust. The other main risk is contact through re-suspension of surface dust that occurs whenever there is activity. Walk-off mats at building and room entrances are used to control the track-in of soil and dust into buildings, especially where soil contamination is known or suspected.

   Routine cleaning can also greatly reduce dust buildup on surfaces. However, cleaning activities, especially the use of a vacuum cleaner with a beater brush, will raise clouds of dust and microbes.[164] The re-suspended dust is at that point available to be inhaled. HEPA vacuum cleaners that reduce the amount of dust released from the vacuum bag are available; some come with sensors that indicate when the carpet dust level is removed sufficiently. Vacuum cleaners that minimize the dust released from the vacuum head and filter bag are also available. They are rated and listed by the Carpet and Rug Institute (CRI) for soil removal, dust containment, and carpet surface protection, and are recommended as best practice for sustainable schools.[165] Deep cleaning using green cleaning products and methods can also help reduce indoor emissions of pollutants from the cleaning process itself.

   Note that pollutants such as lead, SVOCs, and VOCs can also build up within building furnishings such as carpets and upholstery. Normal activities can bring people in skin contact with these furnishings. Normal activities can also suspend or release these pollutants into the air repeatedly. A recent exposure modeling study has suggested that, for some VOCs, such as phthalates, the dermal (skin) exposure can be as important or more so than the inhalation exposure.[166]

   Controlling the episodic resuspension of surface dust is also important. Animal and insect debris can accumulate in walls, insulation, and ductwork. Airborne industrial pollutants, feces from birds, bats, and rodents, and microbial contamination can gather in attics, basements, crawlspaces, or other spaces that

[163] (Dela Cruz et al. 2014)
[164] (Veillette et al. 2013)
[165](Carpet and Rug Institute 2014)(CHPS 2014)
[166] (Gong, Zhang, and Weschler 2014)

are rarely used or visited. When these places are disturbed through periodic renovation or maintenance, for instance, pollutant exposure can be significant and unexpected. Proper work practices such as isolation and depressurization of the workspaces and safe removal of contaminated materials, similar to lead paint and asbestos removal procedures, can prevent occupant exposures to the hazardous pollutants in the surface dust. Also, return air ductwork routed through attics, crawl spaces, and basements, when it has significant leaks, can pull dust and other pollutants from these spaces and transport them to conditioned spaces.

Limitations to cleaning and track-in control strategy are more social than technical. Budgets for deep and routine cleaning, walk-off mats for track-in reduction, and HEPA or CRI-listed low emission vacuum cleaners are often inadequate, especially in schools and multifamily buildings. Awareness of the importance of routine maintenance and track-in reduction, along with staff training, are other hurdles to keeping indoor spaces free of dust buildup.

8. **Water treatment:** Municipal water systems in the U.S. that use ground water are required under the Safe Water Drinking Act to periodically test for contaminants and report the results.[167] States where well water is frequently contaminated with radon have provided consumer fact sheets about how to pretreat water to remove contaminants.[168] States also approve the water testing laboratories and the water treatment technologies for removing hazardous pollutants. Commercial buildings that have their own wells may also be required to test and treat the water. The EPA has also proposed a regulation to limit radon levels in drinking water.[169]

   In the case of radon, either aeration of the incoming water or treatment with granulated activated carbon (GAC) will effectively reduce radon levels in the water and consequently in the home. The New Hampshire fact sheet on radon in homes does not recommend the use of GAC generally because the GAC filter becomes saturated with radioactive material, making safe disposal difficult and expensive.[170]

   Water filters can also be used to reduce THM and other chemical or biological pollutants from well water sources. If the filter is not being contaminated by radioactive sources, filter disposal is not a problem. For arsenic, uranium, and radium, the EPA recommends various types of water treatment, including ion exchange and reverse osmosis, among others.[171] THMs can also be found in municipal water, but decontamination of municipal water supplies is beyond the scope of this paper.

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167 (EPA 2012b)
168 (NHDEH 2014)
169 EPA 2012 op cit.
170 NHDES 2014, op cit.
171 (EPA 2013d) (EPA 2013e)

9. **Benefits of multiple approaches:** None of the solutions above stand-alone. The effects of one solution can sometimes amplify or render useless the utility of another. Airtightness is a good example: a building with a tight envelope will not let in much outdoor air. The lower air change rate means that an indoor filter has less pollution to remove. A tight building can be pressurized by a smaller fan, resulting in less noise, less operating expense, and fewer filter changes on the incoming air. A combination of improved airtightness with pressurization may be just as effective, but less expensive, than a substantial effort at rendering the building airtight. Subslab depressurization benefits from a sealed foundation: the pressure is easier to establish and a smaller, quieter fan can be used. If the main source of radon is due to showering with radon-rich water, a closed bathroom door and an operating exhaust fan can create a pressure barrier, which will keep airborne radon from migrating to other parts of the building.

   A tighter building (and HVAC system) with good air filtration and less uncontrolled infiltration can require less cleaning and be less susceptible to microbial growth. However, buildings that are not properly cleaned will have higher concentrations of indoor particles, and any indoor air filter will have to be changed more frequently. Similarly, buildings that are tightened but do not provide or maintain adequate ventilation are increased risk for buildup of pollution from indoor sources. Hence the warning in wildfire guidance documents to avoid creating any significant emissions from indoor activities or products when building ventilation is reduced temporarily.

How effective are these mitigation strategies?

All of the above mitigation strategies can help to reduce the effects of outdoor air pollutants on IEQ, but there are limitations or caveats for each one. In addition, people with extreme sensitivities or vulnerabilities may need better air or water quality than these generic defenses can provide. For these people, indoor air can be brought to a standard set by hospital or laboratory “clean room” technologies, but usually at great expense for equipment installation, operation, and maintenance.

To be effective, these strategies require careful implementation. For building owners and employers who will benefit from the strategies described in this section, the onus is on them to ensure that the systems work as designed. To achieve good building performance, buildings and their systems must be commissioned initially, and afterwards periodically. Building operations and maintenance staff must be properly trained and certification would be desirable. For example, systems may be installed improperly, operated counter to the design intent, or not maintained routinely.

The potential benefits of these strategies can include lower operating costs, higher employer productivity and student performance, increased market value, and reduced liability. For building occupants, training and motivation are also necessary. Occupants need to understand why and how to use windows and fans, and how to avoid activities and products that create indoor pollution.

The demonstrated effectiveness of the various mitigation approaches is summarized below. Technology reviews and case studies of pre- and post-intervention assessments are relied on, where available.

1. **Setback:** A study of school bus idling at school dismissal in New York City concluded that school bus idling and redirecting school bus traffic could have small but measurable effects on diesel soot concentrations near schools.[172] An exposure study of students on school buses in southern California with different kinds of fuels and emission controls measured pollutant levels on the bus and in the passenger loading area, but not in the school buildings. The researchers concluded that the largest source of student exposure was during the bus commute, due the re-entrainment of the school bus emissions from leaky exhaust systems. Measurement and modeling of roadway impacts has focused on homes much more than on larger buildings so far.

2. **Air intake location:** Numerous anecdotal examples of moving air intake location or height to avoid nearby contamination, but documented cases that show the effectiveness of this measure are not readily available. For example, isocyanates (strong irritants and sensitizers) from roofing materials were thought to have entered roof top air intakes and possibly open windows in a Texas school, causing various respiratory symptoms.[173] Remedial measures to prevent this infiltration problem were recommended, but results of any remediation were not reported. There are also several cases where the motor vehicles idling or boiler exhausts were too close to air intakes and caused CO poisonings in schools; however, the remediation actions were not reported.[174]

   Outdoor air intake location relative to outdoor traffic emissions is very important, as suggested by an EPA field study of 96 large U.S. office buildings. The study results showed that outdoor air intake heights less than 60 meters above the ground were generally associated with substantially increased odds for multiple health symptoms.[175] These symptoms included including lower and upper respiratory symptoms, fatigue or difficulty concentrating, headache, and skin symptoms. The results also suggested that indoor concentrations of vehicle-related pollutants such as VOCs, PM, and CO were greater with lower air intakes.

   Another example related to air intake location is the avoidance of Legionnaires disease (legionellosis). Legionellosis has a high mortality rate and is under-diagnosed. It can be contracted by inhaling particles from cooling tower drift that enters nearby air intakes. It is still a problem in the U.S. An estimated 8,000 to 18,000 cases of legionellosis from various sources are reported annually in the

172 (Richmond-Bryant et al. 2009)
173 (Kullman et al. 1998)
174 (Safe Kids Worldwide 2013)
175 (M. J. Mendell et al. 2008)

U.S.[176] For example, reported cases spiked in 2013 in Toronto; the cases were mainly associated with office building cooling towers.[177]

Best practices for preventing legionellosis include locating the cooling tower away from building air intakes in such a manner that cooling tower drift or splash out is not fed into the building air supply system.[178] Source control of legionella microbes is also necessary, e.g., water treatment with biocides, and a well-designed and well-fitted drift eliminator can greatly reduce water loss and potential for *Legionella* or water treatment chemical exposure. The best practices have been successful in reducing legionella from cooling tower emissions. However, major outbreaks with several fatalities are still occurring. To stem this tide, better diagnostics of patients, better maintenance of cooling towers, and further research on drift eliminators are needed.

3. **Air sealing:** Studies on the reduction of outdoor pollutant infiltration in commercial buildings by reducing air leakage are very limited. Such studies have focused on reducing energy use, and many are also done to repair or prevent moisture intrusion problems. One study of two high-rise apartment buildings in Ontario, Canada found a 30-40% reduction in air leakage and no negative impacts on the air quality and comfort levels in the building.[179]

   Several studies have confirmed the large reduction in air infiltration achieved by air sealing of commercial buildings. A review of multifamily studies reported that air sealing of six existing buildings resulted in an average leakage reduction of 31%.[180] Air sealing of 51 units in an existing two-story building in North Carolina reduced air leakage by nearly half.[181]

   A study of four multifamily buildings and another study of one apartment building in Minnesota achieved substantial reductions in whole building leakage and leakage between apartments.[182] [183] Also, in the single apartment, balancing the pressure between apartments after the air sealing resulted in large reductions in the infiltration of environmental tobacco smoke (ETS) from neighboring units.[184]

   The data on air leakage studies suggest that a many existing commercial buildings could be tightened very cost effectively, depending on the potential air leakage reductions and the climate. In situations where the building exterior or façade is

[176] (ASHRAE 2011).
[177] (Alamenciak 2013)
[178] (Cooling Technology Institute 2008)
[179] (Public Works and Government Services Canada, R&D Division 1993),
[180] (RDH Building Engineering 2013)
[181] (Dentz, F Conlin, and Podorson 2012)
[182] (Weber. et al. 2009)
[183] (Bohac et al. 2007)
[184] (Bohac et al. 2011)

undergoing major repairs or replacement, air sealing can be very cost-effective. New buildings could also be much more airtight. Several U.S. jurisdictions require air sealing of new commercial buildings.[185] The co-benefits of air sealing with respect to health, comfort, worker and student productivity, durability, and market valuation could also be very attractive to building owners and tenants.

4. **Air cleaning devices**: HVAC filters and portable air cleaners have been demonstrated to achieve large reductions in indoor air concentrations of particles below $PM_{2.5}$ in size. Reductions of gaseous pollutants have been much more modest. The effectiveness of air filtration by filters and by portable or standalone air cleaners in homes is also discussed in the companion white paper on homes.

   Studies of air filtration effects in schools or other commercial buildings on IEQ and human health are very limited. In a 2013 review of peer-reviewed literature, Fisk identified a total of sixteen high-quality studies, mostly in residential buildings, since the last major review in 2001. The author concluded that "particle filtration can be modestly effective in reducing adverse allergy and asthma outcomes, particularly in homes with pets." In most cases, when symptoms or signs of allergy and asthma improved, the improvement was less than 25%.

   Only three of the reviewed studies reviewed by Fisk were conducted in office or school buildings.[186] The designs of the studies were strong (control groups, placebos, blinding of subject, crossovers), although the studies were not double-blinded and only lasted 1-4 weeks. The studies found large PM reductions in some cases (range of 14-94%, depending on PM size).

   - A study of 396 adults in a U.S. office building using high efficiency fibrous filters in the HVAC did not find any statistically significant reductions in acute health symptoms.[187]

   - A study of 72 adults in a European office building using electronic air cleaners (electrostatic precipitators) to remove PM and activated carbon filters to remove VOCs. Some statistically significant improvements in objective health measures were reported, but not any significant improvements in health symptoms.[188]

185 (ABAA 2013)
186 (Fisk 2013)
187 (Mark J. Mendell et al. 2002)
188 (Skulberg et al. 2005)

- A study of 190 children was conducted in ten Danish classrooms.[189] The authors found no consistent and statistically significant improvements in health symptoms with operation of electrostatic precipitators, but did find two cases of a statistically significant worsening of a health outcome (headache).

Two notable studies have been completed since the review above: a study schools and a study in homes. In a pilot study of three elementary schools in Los Angeles County, California tested the effectiveness of an HVAC panel filter, an air register air purifier, and a standalone air cleaner, alone and in combination (all rated at MERV 16).[190] All three schools were near major outdoor sources of pollution: refineries, highways, railroad, and shipping port. Baseline efficiencies of pollutant removal (no air cleaners) were 8-33% among the schools and pollutants. The panel filters reduced $PM_{2.5}$, black carbon, and UFP by an average of 90%, and the combination of a panel filter and a register purifier achieved reductions of 87-96%. Early morning peaks in indoor and outdoor black carbon were observed during early morning drop off of students. Results for the removal of gaseous pollutants were inconclusive.

In the study of 83 adults in Vancouver, homes impacted by traffic and wood smoke emissions, the effect of high efficiency air cleaners (HEPA) was examined for one week.[191] Indoor $PM_{2.5}$ was reduced by about 50% in homes using HEPAs, from 6.6 to 3.2 ug/m^3. After adjustment for indoor temperatures and time spent in traffic, the associations of HEPA use and $PM_{2.5}$ with a marker of heart inflammation (endothelial function) were not significant. In homes impacted by traffic, increased indoor $PM_{2.5}$ was significantly associated with a marker of systemic inflammation, infection, and liver damage (C-reactive protein).

Local health and air quality agencies are looking at air cleaning as a possible mitigation measure of outdoor pollution problems. High efficiency filtration has been used or planned for use in over 70 schools in the Los Angeles and San Francisco Bay areas of California, but plans to evaluate air cleaner performance are very limited. [192] A 5-year study of air cleaners and other mitigation strategies in public schools is underway in Detroit.[193]

San Francisco's Department of Environmental health has modeled the IEQ and health benefits of adding an air cleaner to HVAC system of homes in high PM areas of the city with high $PM_{2.5}$ estimates.[194] The report concluded that this would be cost-effective measure if done in concert with home weatherization measures. San Francisco currently requires new multifamily construction in neighborhoods with

[189] (Wargocki et al. 2008)
[190] (Polidori et al. 2013)
[191] (Kajbafzadeh et al. 2013)
[192] (CARB 2012b)
[193] (University of Michigan News 2014)
[194] (SFDPH 2013)

high $PM_{2.5}$ modeled values to install HVAC air cleaners and include a five-year maintenance service.[195]

Another data gap in air filtration or cleaning effectiveness is long-term performance in real world conditions. Compliance with recommended actions over a long period of time is a common problem in health interventions. In a recent study in Detroit of low-income households with asthmatic children, the median usage rate for the free air cleaners was initially 95%.[196] However, the median rate dropped to 25% within months and never rose above 65% for the rest of the year, even though electricity and maintenance for the air cleaners were free. Major studies on the effectiveness of HVAC air filters and the health effects of air cleaners for asthmatic households are ongoing at Lawrence Berkeley National Laboratory and the University of California Davis, respectively.[197]

5. **Timing of ventilation:** Very little data are available to assess the effectiveness of this approach in commercial buildings, other than two modeling studies. Infiltration of outdoor PM in a Beijing office building was calculated to be lower if outdoor air ventilation was reduced and high efficiency particle filtration was used during episodes of very high outdoor PM_{10} levels.[198] The estimated cost impact averaged $20,000 for equipment and installation, while incremental filtering costs and building energy operating costs increased by 2%. In a modeling study of chemical releases near a building, the effects of reducing outdoor air ventilation, along with air sealing and room pressurization, were modeled for one- and two-story office building.[199] Building sealing reduced the peak indoor pollutant concentration, but extended the duration of pollutant increase and increased indoor CO_2 buildup.

6. **Building pressurization plus interior filtration**: Data on the effectiveness of this strategy are not readily available for commercial buildings. Examples of successful residential applications for reducing outdoor PM infiltration are discussed in the white paper on homes.

7. **Soil gas exclusion:** EPA has summarized the information on the effectiveness and costs of controlling infiltration from soil gases.[200] Many schools and homes have had subslab radon control systems installed, indicating that this remediation strategy is effective, mature, and widespread. If the fan continues to operate, and the subslab pressure is reliably maintained, soil gas entry becomes minimal.

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[195] (Cohn 2014)
[196] (Batterman et al. 2012)
[197] (CARB 2013)
[198] (NIBS 2014)
[199] (Andrew Persily et al. 2009)
[200] (EPA 2008)

An informative study of a radon subslab radon control systems was conducted in five Colorado Springs, Colorado schools.[201] The systems were initially installed after high radon levels were measured in some classrooms, and the radon levels were reduced below target levels. Sixteen years later, the systems were inspected. The systems were operating as designed but were lacking in maintenance. Monthly maintenance checks were recommended, e.g., fan operation, fan indicator, and visible pipe connections. Repairing broken air handlers for the HVAC system and balancing airflows achieved a significant reduction in indoor radon levels achieved so that the target level was not exceeded.

8. **Cleaning and reducing track-in:** For residential settings, including multifamily buildings, this strategy has proved to be an important part of a cost-effective multi-prong strategy to reduce asthma symptoms, as demonstrated by multi-city studies in the U.S.[202] When used in combination with a home weatherization program and asthma education, this strategy effectively improves childhood asthma control.[203] Experiments involving regular cleaning in residences with asthmatic children have shown good results in the reduction of their respiratory symptoms.[204] In addition, using walk off mats and HEPA vacuums has been shown to reduce tracked-in lead dust by up to 90%.[205]

   However, studies on the effectiveness of cleaning and reduced track-in schools and office buildings in reducing indoor pollutant exposures to outdoor pollutants, health symptoms, or human performance are limited. Most of the research has focused on reducing indoor air and surface dust levels of pet allergens, mold, and bacteria, and on reducing asthma symptoms.

   In a review of school cleaning, indoor, air, and health, Tranter (2008) identified a clear association between cleaning and levels of allergens, including mold and pollen from outdoors.[206] Several studies have measured sizeable reductions in surface dust loadings after floor vacuuming and/or surface cleaning. There are many reports on the effectiveness of vacuum cleaning, the comparative cleaning efficiency of different vacuum cleaners, and the effects of more frequent cleaning. [207] Essentially, regular and effective vacuuming will reduce the amount of dust in carpets and on floors, and suspension of particles will be minimized. In a study of six schools and seven child care centers in Minnesota, interventions such as cleaning, entry mats, and non-fleecy furnishings, flooring, and classroom items were found to be effective in reducing indoor allergen concentrations.[208] Fleecy

[201] (Case and Moors 2011)
[202] (F. Wu and Takaro 2007)
[203] (Breysse et al. 2014)
[204] (Morgan et al. 2004)
[205] (Roberts et al. 2009).
[206] (D. Tranter 2008)
[207] (CMHC 2007)(CMHC 2003)
[208] (D. C. Tranter et al. 2009)

materials that were not adequately cleaned, such as upholstered furniture, appeared to be the most significant allergen reservoirs in the Minnesota study. The long-term effectiveness of the track-in reduction and cleaning strategy will depend heavily on the training of building maintenance staff, and the proper maintenance of vacuum cleaners, and a support from school administrations.

9. **Water treatment:** EPA has reviewed the various water treatment technologies for the removal efficiencies and their pros and cons.[209] For well water treatment, the aerations technology is somewhat more efficient (95-99%) and must be cleaned annually. The granular activated carbon system (GAC) is 85-99% efficient; special handling of the filter for disposal and a protective radiation shield may be needed. Capital costs for these systems are in the thousands of dollars, with annual maintenance costs in the hundreds.

Conclusions

Outdoor pollutant sources in the air, water, and soil have a major impact on IEQ, health, human performance, and productivity in commercial buildings. These sources are becoming even more important in the U.S. and Canada due to continuing and sometimes dramatic increases in population, industrial activity, and climate change.

Various mitigation strategies are available, often in combination, to block or remove outdoor pollutants from commercial buildings. Some of these strategies are well characterized and commonly used, while other strategies have little or no test data on their effectiveness in commercial buildings. Some of these strategies, such as air sealing and commissioning of buildings to reduce infiltration and duct leakage, are cost effective based on energy savings alone. Affordable monitoring methods are available for some outdoor pollutants, and low-cost portable sensor technology is emerging from research groups around the world.

Research and demonstration is needed in several areas to provide science-based guidance for mitigating impacts of outdoor pollution on building occupants. These areas include:

- Building commissioning and re-commissioning of buildings and their systems
- Pollutant and pressure monitors and sensors
- Effective drift eliminator for cooling towers
- Air cleaner and air filter performance and persistence
- Air leakage test method
- Cost of mitigation measures
- Long-term effectiveness of mitigation measures
- Health effects and occupant satisfaction surveillance
- Outreach and training
- Data management and sharing, especially for community-based groups

[209] (EPA 2013b)

Existing research and demonstration programs offer opportunities for communities to become involved mitigating outdoor pollutant impacts on indoor spaces. For example, EPA has produced a roadmap for developing low cost, portable air sensors, and will soon fund research on community monitoring of air pollution. The U.S. Centers for Disease Control and Prevention (CDC) funds community monitoring of environmental pollution in several U.S. cities. The California Energy Commission and the California Air Resources Board fund research on indoor pollutant exposures, monitoring methods, and mitigation measures. A listing of ongoing international research and demonstration projects on IEQ, along with recommended research priorities for California, is available online.[210]

Recommendations

All politics are local, and so are buildings and their occupants. For any given building, the appropriate mitigation strategies for reducing impacts of outdoor pollutants on indoor spaces will depend on the types and concentrations of pollutants present, the vulnerability of the exposed population to health impacts, the types of buildings, and other local factors specific to each case. Nonetheless, we can make some broad recommendations to help expedite progress in these mitigation efforts.

The recommended actions below are suggested in no particular order. They are all inter-related, so they should be considered as a whole, for both short- and long-term actions.

- *Build the evidence base.*
  Objective research and demonstration studies are necessary to evaluate the effectiveness of single and multiple mitigation strategies. Pre- and post mitigation data on key IEQ parameters, occupant symptoms and complaints, costs, and persistence of mitigation performance are needed. Common metrics, databases, and case studies to document the project results and recommendations will allow the evidence base to be built and shared. Sharing the results and lessons learned in applying best practices and new methods would accelerate progress on this issue.

- *Build a better toolbox.*
  Focused research, development, and demonstration of pollutant monitoring, exposure monitoring, and health effects measurements are necessary to fill the many data gaps. The development of sensor technologies and applications is very promising in the near- to mid-term. The field of biomonitoring (measuring pollutants or their metabolic products in the body) should also be applied to this issue. Opportunities to leverage funding for field studies and data sharing should be pursued.

- *Implement and improve best practices.*
  Sustainable building standards and guidelines address indoor pollutant sources and ventilation and air filtration issues, but do not address many of the mitigation

[210] (Levin and Phillips 2013)

strategies discussed above. These standards and guidelines need to incorporate more measures to address outdoor pollutants, at both the design stage and the operation and maintenance phase of a building's life. Several school districts and commercial building managers have taken proactive steps to prevent IEQ problems due to outdoor and indoor pollutant sources. These approaches should be added to existing best practices for sustainable, healthy buildings.

- *Stress awareness and training.*
  To take these mitigation actions will take a big leap in awareness and incentives for the many decision makers and stakeholders, and it will require a long-term effort as well. It will be tempting to select a quick fix to a real or perceived IEQ problem, especially in the heat of an emergency or public relations crisis. Training of building designers, owners, managers, and tenants periodically can raise the priority given to mitigating outdoor pollutant source impacts. It is also necessary to achieve good performance of mitigation measures. Community-based or citizen observation efforts can also help build awareness and personal engagement in finding solutions to IEQ problems. Stressing the linkages among IEQ, health, human performance, and economic productivity will also help motivate personal, professional, and community action.

- *Take a seat at the table.*
  Finally, awareness of indoor and outdoor pollution sources and pathways needs to become part of decision making at all levels and in all forums that affect building occupants, e.g., environmental health, education, resource use, land use, transportation planning, and community development. Working with various decision makers and stakeholder groups to share experiences in mitigation efforts and help integrate them into other health and building programs is essential to building a strong base of support.

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Appendix: IAQ Information Resources and Topics

Newsletters and/or listservs are also provided by most of these resources.

1) **Collaborative for High Performance Schools, Best Practices resources**
   http://www.chps.net/dev/Drupal/node
   a) Planning and design criteria
   b) Maintenance and operation
   c) Commissioning
   d) Relocatable classrooms
   e) Training

2) **U.S. Environmental Protection Agency (EPA), Indoor Air**
   http://www.epa.gov/iaq/
   a) Schools
      i) IAQ Tools for Schools
      ii) Energy Savings Plus Health Upgrades
      iii) Healthy Schools Environmental Assessment Tool (Healthy SEAT)
   b) Homes
   c) Large Buildings
      i) Indoor Building Education and Assessment Model (I-BEAM)
      ii) Other publications
   d) Federal Interagency Committee on Indoor Air Quality webinars
   e) My Environment: maps and data on pollutant sources in the U.S. (air, water, soil), http://www.epa.gov/myenvironment/
   f) Air pollutant sensors, http://www.epa.gov/research/airscience/next-generation-air-measuring.htm

3) **Lawrence Berkeley National Laboratory, Indoor Air**
   http://indoorair.lbl.gov/
   a) Indoor Air Quality Scientific Findings Resource Bank, http://www.iaqscience.lbl.gov/
   b) Research groups, http://energy.lbl.gov/ied/
   c) Webinars

4) **U.S. Department of Energy (DOE)**
   a) Multifamily Buildings, https://www4.eere.energy.gov/challenge/partners/multifamily
   b) Commercial Buildings, http://www.energy.gov/public-services/commercial-buildings
      Weatherization Assistance Program, http://www.wxplushealth.org/about/department-energy-weatherization-assistance-program

5) **National Center for Healthy Homes**
   http://www.nchh.org/
   a) Elder Apartments Green Rehab, http://www.nchh.org/Research/GreenRehabilitationofElderApartmentTreatments.aspx
   b) Research
   c) Training
   d) Resources
   e) Policy

6) **National Institute for Standards and Technology, IAQ & Ventilation Group**
   http://www.nist.gov/el/building_environment/airquality
   a) IAQ
   b) Ventilation
   c) Air Cleaning
   d) Sustainability
   e) Modeling
   f) R&D

7) **National Institute for Building Science, Whole Building Design Guide**
   http://www.wbdg.org/
   a) Air sealing and building commissioning
   b) Ventilation and air filtration
   c) Moisture control
   d) Operation and Maintenance
   e) Guidance on various other topics

8) **California Air Resources Board (CARB), IAQ and Personal Exposure Program**
   http://www.arb.ca.gov/research/indoor/indoor.htm
   a) Schools, http://www.arb.ca.gov/research/health/school/school.htm
   b) Community Health and Environmental Justice, http://www.arb.ca.gov/ch/ch.htm
   c) Air Cleaning Devices
   d) IAQ Guidelines
      Wood burning Handbook, http://www.arb.ca.gov/research/indoor/wood_burning_handbook.pdf
      Land Use Handbook, http://www.arb.ca.gov/ch/landuse.htm
   e) IAQ Research and webinars
   f) Review and recommendations: Report to the Legislature

9) **California Department of Public Health (CDPH), IAQ Program**
   http://www.cdph.ca.gov/programs/IAQ/Pages/default.aspx
   a) Regulations
   b) Resources

10) **Centers for Diseases Control and Prevention (CDC) and National Institute of Occupational Safety and Health (NIOSH), IEQ Programs**
http://www.cdc.gov/niosh/topics/indoorenv/
   a) Resources, guidance
   b) Legionellosis
   c) Filtration guidance

11) **Federal Emergency Management Administration (FEMA)**
   a) Shelter and Safe Room design guide, http://www.fema.gov/pdf/plan/prevent/rms/453/fema453.pdf

12) **Canada Mortgage and Housing Corporation, High-rise and Multifamily Buildings**
https://www.cmhc-schl.gc.ca/en/inpr/bude/himu/
   a) R&D
   b) Healthy high rises
   c) Education

13) **National Research Council Canada, IAQ Program**
http://www.nrc-cnrc.gc.ca/eng/reports/2013_2014/clean_air_regulatory_agenda.html

14) **Health Canada**
   a) Residential Indoor Air Quality Guidelines, http://www.hc-sc.gc.ca/ewh-semt/air/in/res-in/index-eng.php

15) **Environment Canada**
   a) Environmental indicators, monitoring, emissions, http://www.ec.gc.ca/indicateurs-indicators/default.asp?lang=En

16) **European Union**
   a) Indoor air review, http://ec.europa.eu/health/scientific_committees/opinions_layman/en/indoor-air-pollution/index.htm
   b) Research, http://www.env-health.org/news/latest-news/article/indoor-air-quality-results-from-euWorld Health Organization
   c) Indoor Air Guidelines, http://www.euro.who.int/en/health-topics/environment-and-health/air-quality/publications/2010/who-guidelines-for-indoor-air-quality-selected-pollutants
   d) Air sensor R&D, EuNetAir, http://www.eunetair.it/

17) **American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE)**
    a) IAQ Guide (best practices), https://www.ashrae.org/resources--publications/bookstore/indoor-air-quality-guide
    b) Ventilation Standards, https://www.ashrae.org/resources--publications/bookstore/standards-62-1--62-2
    c) Commissioning Guideline, http://www.techstreet.com/ashrae/products/1573306
    d) Air Filter Standards

18) **Air Infiltration and Ventilation Centre, International Energy Agency**
    http://www.aivc.org/
    a) Publication database, annotated bibliographies, literature lists
    b) Technical reports, guides
    c) Annual conference

19) **Air Barrier Association of America**
    http://www.airbarrier.org/

20) **Building Ecology**
    http://www.buildingecology.com/articles

21) **Building Green**
    http://www2.buildinggreen.com/
    a) Environmental Building News
    b) Green Spec
    c) Training webcasts