Reducing Indoor Residential Exposures
to Outdoor Pollutants

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July 17, 2003

The basic strategy for providing indoor air quality in residences is to dilute indoor sources with outdoor air. This strategy assumes that the outdoor air does not have pollutants at harmful levels or that the outdoor air is, at least, less polluted than the indoor air. When this is not the case, different strategies need to be employed to ensure adequate air quality in the indoor environment. These strategies include ventilation systems, filtration and other measures. These strategies can be used for several types of outdoor pollution, including smog, particulates and toxic air pollutants. This report reviews the impacts that typical outdoor air pollutants can have on the indoor environment and provides design and operational guidance for mitigating them. Poor quality air cannot be used for diluting indoor contaminants, but more generally it can become an indoor contaminant itself. This paper discusses strategies that use the building as protection against potentially hazardous outdoor pollutants, including widespread pollutants, accidental events, and potential attacks..

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INTRODUCTION

Air quality is a major societal concern leading to significant direct human health effects and monetary damage (e.g., Rabl and Spadaro, 2000; Woodruff et al., 2000; and Brunekreef and Holgate, 2002). As a result of severe pollution episodes such as the infamous "London fogs," most early scientific and regulatory attention focused on the quality of outdoor air. However, based on time-activity pattern studies (e.g., Klepeis et al., 2001), we know that citizens of developed countries spend, on average, nearly 90% of their time indoors where concentrations of many pollutants can be two to five times greater than in outdoor air (Wallace, 1987). Thus, there has been increased attention to the indoor environment as the source of most personal exposure to harmful pollutants. Yet the two environments are not distinct; they are inextricably linked through ventilation and infiltration of outdoor air that can both dilute indoor pollutant concentrations and introduce pollutants of outdoor origin to the indoor environment.

The primary strategy for reducing pollutants generated indoors has been dilution and flushing through ventilation with outdoor air. For this strategy to improve indoor air quality, the outdoor air must have lower concentrations of indoor-generated pollutants than the indoor air. This may not always be the case. In certain circumstances, outdoor air may contain higher concentrations of the same pollutants that are of concern indoors. Outdoor air may also contain other pollutants that are not primarily associated with the indoor environment. In addition, even if the outdoor air concentration is lower than indoors, it may nevertheless be unhealthful and thus indoor exposures worse. This paper provides a brief summary of common outdoor pollutants of concern, an overview of scenarios where outdoor air quality is of concern to people indoors and recommends strategies for reducing indoor exposures to potentially hazardous outdoor air pollutants.

DEFINITION OF ACCEPTABLE AIR QUALITY

Air pollution, broadly defined, is the presence of undesirable levels of physical or chemical impurities. For this document, our concern is the presence of contaminants that pose a potential health risk to humans. Many organizations such as the World Health Organization (WHO, 1999) and the United States Environmental Protection Agency (USEPA, 1999) recognize carbon monoxide, nitrogen dioxide, ozone, lead, particulate matter and sulfur dioxide as pollutants presenting a hazard to sensitive populations such as asthmatics or children. These six contaminants are commonly called criteria pollutants. The WHO describes "classical" pollutants; see Table 1a. In the United States these six pollutants are listed in the National Ambient Air Quality Standards (NAAQS); see table 1b.

It is logical to suggest that a definition of acceptable outdoor air used for ventilation indoors meets these criteria. Unfortunately, much of the population of the world lives in areas that are out of compliance with one or more of these, forcing us to consider strategies that can mitigate the harmful effects of these pollutants.

There are many more pollutants that are harmful to human health than just the six criteria pollutants. (See appendix I for a list of relevant contaminants considered by the World Health Organization (1999)). Therefore, a broader definition of acceptable outdoor air would require that outdoor air should not contain levels of any known pollutants that may be unhealthful to any population. Because such a standard is generally considered unnecessarily onerous and ambitious, regulators and other relevant authorities have used the concept of an acceptable, *de minimus* risk in setting standards for "safe" concentrations of pollutants[1]. ASHRAE, in its Standard 62, defines acceptable indoor air as "*air in*

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[1] Standards based on this concept are used, for instance, by the USEPA to establish cancer potency factors (or slope factors) for carcinogens and inhalation Reference Concentrations (RfC) for noncarcinogens.

which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction" (ASHRAE, 2001). This is also a necessary requirement for acceptable outdoor air that is going to be used for residential ventilation.

TABLE 1a: WHO guideline values for the "classical" air pollutants
(WHO 1999)

Compound	Annual Ambient air Conc. [µg/m^3]	Health endpoint	Observed effect level [µg/m^3]	Uncertainty factor	Guideline Value [µg/m^3]	Averaging time
Carbon Monoxide	500-700	Critical level of COHb <2.5%	n.a.	n.a.	100 000 60 000 30 000 10 000	15 minutes 30 minutes 1 hour 8 hours
Lead	0.01-2	Critical level of Pb in blood <100-150 µg Pb/1	n.a.	n.a.	0.5	1 year
Nitrogen dioxide	10-150	Slight changes in function in asthmatics	365-565	0.5	200	1 hour
Ozone	10-100	Respiratory function responses	n.a.	n.a.	120	8 hours
Sulphur dioxide	5-400	Changes in lung function in asthmatics Exacerbations of respiratory symptoms in sensitive individuals	1000 250 100	2 2 2	500 125 50	10 minutes 24 hours 1 year

TABLE 1b: U.S. National Ambient Air Quality Standards (USEPA 1999)

POLLUTANT	STANDARD VALUE*		STANDARD TYPE
Carbon Monoxide (CO)			
8-hour Average	9 ppm	(10 mg/m^3)	Primary
1-hour Average	35 ppm	(40 mg/m^3)	Primary
Nitrogen Dioxide (NO$_2$)			
Annual Arithmetic Mean	0.053 ppm	(100 µg/m^3)	Primary & Secondary
Ozone (O$_3$)			
1-hour Average	0.12 ppm	(235 µg/m^3)	Primary & Secondary
8-hour Average	0.08 ppm	(157 µg/m^3)	Primary & Secondary
Lead (Pb)			
Quarterly Average	1.5 µg/m^3		Primary & Secondary
Particulate (PM 10) *Particles with diameters of 10 micrometers or less*			
Annual Arithmetic Mean	50 µg/m^3		Primary & Secondary
24-hour Average	150 µg/m^3		Primary & Secondary
Particulate (PM 2.5) *Particles with diameters of 2.5 micrometers or less*			
Annual Arithmetic Mean	15 µg/m^3		Primary & Secondary
24-hour Average	65 µg/m^3		Primary & Secondary
Sulfur Dioxide (SO$_2$)			
Annual Arithmetic Mean	0.03 ppm	(80 µg/m^3)	Primary
24-hour Average	0.14 ppm	(365 µg/m^3)	Primary
3-hour Average	0.50 ppm	(1300 µg/m^3)	Secondary

* Parenthetical value is an approximately equivalent concentration.

SUMMARY OF OUTDOOR AIR CONTAMINANTS OF CONCERN INDOORS

Air contaminants can be gases or particulate matter (small particles containing solids and/or liquids). Contaminants can be emitted through natural processes or from human activities. Compounds emitted in a form that can be directly hazardous to humans are referred to as primary pollutants. Examples of primary pollutants include sulfur dioxide emitted from the combustion of sulfur-containing fuels and polycyclic aromatic hydrocarbons (PAHs) that are products of incomplete combustion. Alternatively, if hazardous compounds are formed in the air, e.g., from chemical reactions, they are referred to as secondary pollutants. One important example of a secondary pollutant is ozone.

Air pollution can result from activities spread over a large area, for instance motor vehicle use in an urban area, or from a release from single source, such as from a power plant or an industrial accident. In the case of distributed sources, concentrations are relatively uniform throughout large areas. For point sources, concentrations can be tracked in a plume that starts at the point of release and spreads as it is transported with the wind. In general, outdoor air pollution is mostly of concern in areas of dense population or industrial activity, although there are cases of significant emissions coming from natural sources (e.g., volcanoes).

The following discussion introduces some major groups of outdoor air pollutants and briefly discusses their sources, major health effects, scenarios of concern and important characteristics relevant to indoor dynamics and removal.

PHOTOCHEMICAL SMOG

Smog, or more correctly photochemical smog, is a mixture of gas- and particle-phase compounds associated mainly with urban areas. A notable feature of smog is that the components that cause the adverse effects are mainly secondary pollutants. The main reaction product of concern is ozone; other products of concern include aldehydes and other carbonyls, nitrogen dioxide (NO_2), nitric acid and peroxy acetyl nitrate (PAN). The primary pollutants that are precursors of photochemical smog are nitrogen oxides (mainly nitric oxide (NO)) and volatile organic compounds (mainly hydrocarbons). Sources of nitrogen oxides (NO_x) are mainly fossil-fuel combustion devices; in urban areas, motor vehicles are the primary source. Sources of volatile organic compounds (VOCs) are more diverse, including fuel evaporation and exhaust from motor vehicles, consumer and industrial use of solvents, e.g., for paint and aerosols, and even plants and trees. Given sufficient quantity of the precursors and enough time in the presence of sunlight, photochemical smog will result. Because of the necessity of sunlight, concentrations of ozone and other constituents of photochemical smog typically follow diurnal patterns with peak concentrations lasting for a few hours or less during the sunny, midday hours and declining to zero overnight.

The effects of photochemical smog are diverse. Significant health impacts have been associated with outdoor air pollution generally[2] and many constituents of photochemical smog specifically (e.g., Brunekreef and Holgate, 2002; Samet et al., 2000; Cohen, 2001). Health effects range from those associated with short-term exposures, including asthma attacks and hospitalizations, to those more long-term in nature, including lung cancer, as well as other morbidity outcomes and causes of mortality. In addition, photochemical smog deteriorates visibility due to absorption of blue light by NO_2 and the

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2 Most of the effects observed from these epidemiological studies of outdoor air pollution are found in urban areas where photochemical smog, and its suite of constituents, is the primary culprit.

formation of fine particles, which effectively scatter light. Ozone is the most important constituent of photochemical smog and is discussed with the other gaseous criteria pollutants.

PARTICULATE MATTER

Particulate matter (PM) is a mixture of liquid droplets and solid particles that vary in size, shape and composition. Each of these characteristics of PM can also vary with time for any given spatial location. Particles greater than 2.5 μm are known as coarse; particles less than 2.5 μm are known as fine. This latter category can be subdivided into the accumulation mode (0.1 - 2.5 μm) and the nucleation, or ultrafine, mode (less than 0.1 μm), however there is only one standard[3] associated with the entire class of fine particles.

Particulate matter is both a primary and a secondary pollutant. Coarse particles are formed mainly by mechanical processes (e.g., grinding, abrasion) and emitted as primary pollutants. Ambient sources include vehicles traveling on unpaved roads, construction, agricultural emissions and wind erosion of soils. Fine particles tend to be formed by gas-to-particle conversion processes (i.e., coagulation and condensation). Precursor species include NO_x, SO_2, ammonia and VOCs, forming, for instance, ammonium sulfate and nitrate. Fine particles can form from fuel combustion in motor vehicles, electricity generation and industrial processes, as well as residential fireplaces and wood stoves. With a solid core, these particles often have semi-volatile compounds absorbed onto their surface. Biogenic sources of PM include forest fires and pollen and can be either in the coarse or fine modes. Most pollens and allergens (e.g., animal dander) are coarse, although some pollens can be smaller.

Particle behavior is a sensitive function of size. Coarse particles tend to settle by gravity and do not persist in the atmosphere for long periods (atmospheric lifetime of hours to days). Given momentum, they will deposit by inertia impaction onto obstacles, such as surfaces and filter fibers. Ultrafine particles deposit onto surfaces by molecular diffusion (Brownian motion); molecular diffusion is also primarily responsible for coagulation, which is the term used to describe the collision of two particles that permanently adheres them. The atmospheric persistence of particles in the ultrafine range is a few days to a few weeks. Accumulation mode particles are often formed by secondary processes such as coagulation and condensation. They are not well controlled by any of the above mechanisms and thus their atmospheric persistence is significantly longer, on the order of weeks to months. In addition, filtration efficiency is also lowest for accumulation mode particles. Trends in size distribution will be impacted by trends in particle generation[4].

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3 Two NAAQS standards limit particulate matter of different sizes. The PM10 standard limits the mass concentration of particulate matter of aerodynamic diameter less than 10 micrometers (μm). The PM2.5 standard applies to particles of aerodynamic diameter less than 2.5 μm. The two separate NAAQS standards were promulgated in recognition of the different sources, composition and mechanisms of transport and deposition for each size range.

4 According to the latest report from the USEPA, the U.S. average of annual mean PM10 concentrations decreased 19% between 1991 and 2000. This coincided with a 10% decrease in mass emissions. However, in 2000, approximately 8 million people lived in 10 counties with PM10 levels above either the annual or 24-hour NAAQS standard (USEPA, 2002d). Areas of the U.S. that were designated as particulate matter non-attainment areas in 2002 included parts of the Pacific and Mountain regions. In addition, parts of California, Nevada, Arizona and Washington are classified as having serious non-attainment levels for PM10. Moderate classifications are found elsewhere (USEPA, 2002a).

"Dust", "soot" and "ash" are all vernacular terms. While their definitions are not precise, they can be useful descriptors. *Dust* usually refers to solid particles ranging in size from ultrafine particles to grains of sand or plant spores. Holmes (2001) reviews the wide impact that dust plays in the environment. *Soot* usually refers to carbonaceous (i.e. black) particles formed from incomplete combustion; *ash* typically refers to powdered minerals from combustion, industry or volcanism.

Health Impact of Particulate Matter

The general comments on particle deposition mechanisms have direct application to the mechanism and location of deposition in the respiratory system. Coarse particles tend to deposit in the upper airways (head and throat) by inertial impaction and secondarily deposit in the deep lung by gravitational settling. Ultrafine particles deposit by diffusion to surfaces, especially in the smaller airways deep in the lung. Accumulation mode particles deposit in neither region effectively. Depending on where particles deposit, the lungs have different defense mechanisms. In the upper airways, cilia and mucus collect the particles and sweep them upwards to be swallowed. In the deep lung, deposited particles can be attacked by macrophages or absorbed into the blood after dissolution.

Thus, both coarse and fine particles can accumulate in different regions of the respiratory system. There, they can cause numerous health impacts[5]: PM_{10} has been epidemiologically associated with many adverse effects, including asthma attacks in patients with preexisting asthma; admission to hospitals for cardiovascular and respiratory causes; and deaths from heart attacks, strokes, and respiratory causes (e.g., Donaldson et al., 2001; Morris, 2001; Samet et al., 2000). Other studies have shown that the association between PM exposure and premature death is stronger for $PM_{2.5}$ than for PM_{10}, which typically deposit deeper in the lungs (Schwartz et al., 1996; Pope et al., 2002). Still others have shown that PM from particular sources, such as diesel engines or residential natural gas home appliances, has even larger health impacts (OEHHA, 2000; Rogge et al., 1993).

Some particles can cause damage from very short-term exposure, notwithstanding accumulation in the lungs. Acidic particles may dissolve and distribute into the body or do contact damage where they land. Allergens do not need to penetrate the lung to cause a reaction as they typically contain proteins that cause a histaminic reaction in certain people.

Lead

Since the advent of unleaded gasoline, airborne lead (ash) is rarely of concern in developed countries beyond areas in close proximity to large point sources such as smelters and battery manufacturers. When it is locally of concern it should be treated as a hazardous air pollutant.

GASEOUS CRITERIA AIR POLLUTANTS

The remaining criteria pollutants – ozone (O_3), nitrogen dioxide (NO_2), carbon monoxide (CO) and sulfur dioxide (SO_2) are all gaseous and will be discussed briefly below.

Ozone

Ozone is a secondary pollutant formed from a mixture of VOCs and NOx exposed to sunlight. Ozone concentration depends directly on sunlight intensity and the ratio of NO_2 to NO. VOCs, in the presence of sunlight, react to form radicals that are necessary for the sustained production of ozone. Thus, ozone concentrations exhibit a strong peak during the daylight hours and do not persist at night. In

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5 The mechanism of these health effects is still unclear, whether merely from an overload of foreign matter in the respiratory system or from particular constituents of PM, such as metals or absorbed polycyclic aromatic hydrocarbons (PAHs).

addition, ozone is not transported over long distances. However, its precursors can be transported, forming ozone significant distances downwind from where the precursors were emitted. Unacceptable concentrations are found worldwide near large cities.[6] However, even in many of these areas, ozone concentrations exceed the appropriate standard typically only a few times a year.

While ozone may not be a direct concern to people indoors beyond days of concentration exceedances, once indoors, ozone is a strong oxidant, reacting rapidly with gases and readily decomposing by reaction at surfaces. In a recent review, Weschler (2000) describes a number of reactions of ozone (whether of indoor or outdoor origin) relevant to human exposures indoors. Reaction with NO is so fast that any ozone present will be titrated. However, remaining concentrations of ozone can react with a number of airborne, unsaturated VOCs to form chemicals (mainly aldehydes) of greater health impact than the ones initially present. In addition, reactions with terpenes can be a significant source of sub-micrometer particles indoors. Finally, reactions of ozone with surfaces, such as carpets and paints, can also produce aldehydes; for carpets, the emissions can continue for long periods after ozone exposure ceases. Thus, infiltration of outdoor ozone can be an important initiator of chemical reactions resulting in products with known health impacts.

NO_2

NO_2 is principally a secondary pollutant formed through the oxidation of nitric oxide (NO). NO is a combustion by-product. Because NO is readily converted to NO_2, emissions of NO are typically summed with NO_2 and (with other minor oxides of nitrogen) termed NO_x. Indoor sources include home heaters and gas stoves. NO_2 is an irritant with respiratory health effects as a result of both short-term and long-term exposures. Its concentration in ambient air is regulated as a result of these effects[7]. NO_2 is still an air quality concern for its role as an ozone and particulate matter precursor and in acid deposition.

SO_2

SO_2 is directly emitted from the combustion of sulfur-containing fuels (mainly coal and oil), as well as from industrial processes[8]. SO_2 can be oxidized in ambient air to form sulfuric acid which, along with nitric acid, are the principle causes of acid deposition. SO_2 is also a precursor for $PM_{2.5}$, which significantly effects human health and visibility. However, it is SO_2's direct health effects as a respiratory irritant that underpin its designation as a criteria pollutant.

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6 In the United States, for example, severe and extreme classifications are found in California (Sacramento and San Joaquin Valleys and Los Angeles Basin), Texas (Houston), the Chicago area and the north shore of Lake Michigan, and the Eastern Seaboard. Other areas have marginal to serious classifications (USEPA 2002a). In all, 40 and 110 million people still live in counties in the US that are out of compliance with the 1-hour and 8-hour NAAQS, respectively (USEPA, 2002d).

7 In 2000, the ambient sources of NO2 in the U.S. were 54% transportation and 39% other fuel combustion activities (USEPA, 2002d). Despite an increase of 7% in national emissions (primarily from transportation sector increases), all areas of the country that once violated the NAAQS are now in compliance (USEPA, 2002d).

8 82% of U.S. ambient emissions come from fuel combustion, most of that from electricity generation using coal (USEPA, 2002d). Thus, large, often remotely located, point sources are principally responsible for national emissions and can create local exceedances of the NAAQS. Despite presenting a local hazard in these areas, there has been a 50% reduction in composite annual average ambient concentration since 1981 as a result of a 27% decrease in emissions (USEPA, 2002d).

CO

CO is directly emitted as a product of incomplete combustion. Ambient concentrations typically peak in the winter months due to increased automotive emissions and the greater frequency of nighttime inversion layers[9]. CO is unreactive on the timescales of transport through cities and in the indoor environment, so its concentration is in direct proportion to emissions. The health effects of CO are related to its great affinity to hemoglobin in red blood cells. This reduces the blood's capacity to deliver oxygen to organs and tissues. For individual's with cardiovascular disease, CO can be a threat at low levels; healthy individuals are not usually affected until much higher levels when CO-related oxygen displacement becomes poisonous. Similar to NO_2, indoor sources of CO include any combustion activities such as home heaters, gas stoves and motor vehicles left running in attached garages. The last of these sources led to over 19,000 accidental deaths in the US between 1968 and 1998 (Mott et al., 2002).

TOXIC AIR POLLUTANTS

For the purposes of this discussion, it is useful to divide toxic air pollutants into two categories, distinguished by the release and resulting exposure scenario. The first category we title "hazardous air pollutants" for which emissions are relatively consistent across time and locations, leading to exposures that are widespread and common. The second category we title "highly toxic agents" for which releases are of limited duration, leading to exposures that are characteristically short-term and localized. The chemicals of concern for each scenario could overlap although usually do not. Typically, hazardous air pollutants have health effects at low concentrations for which we are most concerned about long-term exposures. Highly toxic agents are normally of concern in situations where high concentration, short duration exposures could lead to very serious health impacts (e.g., death).

Hazardous Air Pollutants

In this report Hazardous Air Pollutants (HAPs) are be defined as those having specific characteristics with which we are concerned: widespread and common exposures to low-level concentrations of (typically industrial) pollutants. In the United States hazardous air pollutants (HAPs) is a legal term rather than a comprehensive list of all chemicals exhibiting a particular set of characteristics, consisting of 188 hazardous air pollutants (HAPs) specifically listed in the Clean Air Act (CAA) and regulated by the US EPA[10]; many of the compounds listed by the WHO in appendix I are HAPs. Examples include heavy metals (e.g., mercury), VOCs (e.g., benzene), combustion by-products (e.g., dioxins) and solvents (e.g., carbon tetrachloride). While HAPs are quite diverse in chemical composition and physical properties related to their transport, potential for degradation and ultimate fate, all HAPs share the common characteristic of having serious health effects. Depending on the toxicity of a particular HAP, the quantity, frequency and duration of exposure as well as other factors, health effects of HAPs range from cancer to reproductive and developmental toxicity to respiratory damage.

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9 U.S. ambient emissions, which may be indicative of other developed countries, are mainly (70%) from motor vehicles; as much as 95% of emissions in urban areas can be from motor vehicles (USEPA, 2002d). During the last decade, ambient concentrations have decreased 38% due to better emission controls and increased oxygen content in automotive fuels (leading to more complete combustion) (USEPA, 2002d).

10 The Clean Air Act (CAA) requires the EPA to regulate emissions of HAPs from all "major sources," i.e., large, point sources. Under the Urban Air Toxics Strategy and other CAA mobile source programs, EPA has also instituted programs to reduce HAPs emissions from area and mobile sources. Emissions are roughly equal between major, area and two sub-categories of mobile sources, on-road and off-road (USEPA, 2002d). EPA reports that the sum of all HAPs emissions has decreased 24% between 1996 and the baseline years of 1990-1993 (USEPA, 2002d). However, not all exposure to HAPs is from these sources; indoor sources such as air fresheners, certain building materials and tobacco smoke can be significant.

HAPs exhibit many chemical and physical forms and will likely exhibit varying concentration patterns outdoors, so there is no one strategy for reducing exposure to all HAPs. That being said, many HAPs are organic compounds and thus may be removed using activated carbon filters.

Currently, there is no monitoring network from which to extract trends in individual HAP concentrations in ambient air. In the US, EPA's National Air Toxics Assessment (NATA) program combines emissions data with pollutant dispersion modeling to estimate ambient concentrations[11].

Highly Toxic Agents

Highly toxic agents can be any chemical that has severe health effects, including death, that result from short-term exposures. Chemicals in this category include hydrogen sulfide (H_2S), sarin and chlorine gas. Release of highly toxic agents can either be accidental or intentional. Examples of accidental releases could include chemical fires, pipeline ruptures, toxic spills, truck or train collisions, or power-plant accidents. Examples of intentional releases include terror attacks using chemical or biological agents. In both cases, plumes can carry agents to residential environments where the typical exposure will be transitory. For many highly toxic agents, short-term peak concentrations are of most concern. In such cases, any strategy to reduce the peaks, even if integrated exposures remain unchanged, could provide substantial reductions in adverse health effects.

Migration of Outdoor Pollutants to Indoors

As background for the subsequent discussion of strategies to reduce indoor residential exposures to outdoor pollutants, it is informative to explore what we know already about the degree of protection that buildings provide. The simplest measurement indicative of the protective capacity of buildings is the indoor-outdoor concentration ratio (I/O ratio)[12]. This measure can not account for the complexity of processes by which pollutants of outdoor origin migrate indoors or of the mechanisms that ultimately

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11 The NATA program also estimated health risks for all census tracts in the US using the modeled concentrations and unit risk factors. The upper bound cumulative cancer risk based on typical exposures to 32 HAPs was estimated to be greater than 10-5 for the entire US; 20 million people are estimated to live in areas where the cancer risk is greater than 10-4 (USEPA, 2002e). Three pollutants were found to be contribute the most to the cancer risk: chromium, benzene and formaldehyde. In addition, the NATA program concluded that acrolein poses the highest potential for noncancer effects. Diesel particulate matter was recently added to the EPA's mobile source air toxics list and, in studies focused on California, it was found to contribute even greater cancer and noncancer risks than chemicals in the NATA study (SCAQMD, 2000; CARB, 2000).

12 There are many chemicals for which indoor sources are more important to indoor concentrations in residences than outdoor sources, including many VOCs and PAHs. For these chemicals, our approach does not yield insights into the proportion of outdoor pollutant that migrate indoors and remain airborne, especially without information on indoor source strengths. The Total Exposure Assessment Methodology (TEAM) studies provide the most comprehensive data set on I/O ratio for up to 19 separate VOCs12 (total number depends on study location). For every pollutant measured in the New Jersey and California studies, the I/O ratio was greater than one, in most cases two to five (Wallace, 1987). A study in Germany investigated the I/O ratio for 12 aromatic hydrocarbons simultaneously measured inside and outdoors of two homes, one located on a heavily trafficked street and another in a rural location (Ilgen et al., 2001). For the rural home, the I/O ratio ranged between 6 and 9, with the exception of benzene which was 1.5. For the urban home, the I/O ratio was close to 1 except for toluene (3.5) for rooms facing the street, but rose to near 2 (except for toluene = 5.3) for a room facing the backyard. Thus, even with significant traffic emissions in close proximity to the homes, the indoor sources were generally predominant. Other chemicals for which indoor residential sources seem to be stronger include polychlorinated biphenyls (PCBs) (Currado and Harrad, 1998), 17 different PAHs (Van Winkle and Scheff, 2001) and many other VOCs12 (Kim et al., 2001), where I/O ratios typically ranged from nearly 2 to nearly 7. These findings have been confirmed in offices for formaldehyde specifically as well as the sum of 56 VOCs (Girman et al., 1995; Womble et al., 1995; Womble et al., 1996).

determine indoor concentrations, for which much is still unknown. Table 2 summarizes selected[13] I/O ratios for the following chemicals: NO_2, many metals, total fungi, ozone and PM. Similar measurements conducted in offices and other occupational settings have been reported for CO.

There are results from other studies worth mentioning as well as some clarification of the results presented in Table 2. Particles are probably the most studied in terms of indoor concentrations of outdoor pollutants. Yet, many key factors are yet to be fully elucidated (Thatcher et al., 2001). In reviewing the literature, Thatcher et al. found that penetration factors (fraction of outdoor particles that enter the building in infiltrating air) for particles were typically near 100% but that the variation was large, depending on particle size and geometry of infiltrating route among other issues. However, this is only one of many factors that control the concentration of particles of outdoor origin that remain airborne in the indoor environment. Other factors include the fraction of particles that are transported indoors via the air handling system, loss mechanisms such as deposition, and resuspension of particles of outdoor origin previously deposited to surfaces indoors[14]. In fact, these comments are relevant to all pollutants and serve as words of caution in interpreting the simple indoor/outdoor ratios reported here. Based on a simple model, Ozkaynak et al., (1996) estimated that the indoor-outdoor ratio[15] for outdoor $PM_{2.5}$ and PM_{10} were 0.7 and 0.6, respectively.

The review by Weschler (2000) reveals that indoor ozone concentration generally tracks the outdoor concentration and varies predictably with the air exchange rate. Thus, for a given air exchange and without any indoor sources, the I/O ratio should remain constant. Indoor concentrations of CO, on the other hand, were found to lag outdoor concentrations by an hour or more as well as dampen any peaks in outdoor levels (Flachsbart, 1999). However, this finding may be due to the difference in ventilation system and strategy between offices and retail establishments and residences. For NO_2, Levy et al. (1998) found through regression analysis that the most significant factors controlling the I/O ratio were the presence of indoor sources such as gas stoves, kerosene space heaters and smokers. The difference in I/O ratio between homes without smokers and those with smokers was 0.92 to 1.16.

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13 Data is lacking on many pollutants of concern. However, even for the pollutants for which data exist, it is beyond the scope of this report to summarize all of the extant literature. Therefore, the presentation here is not exhaustive, but relies on published reviews and selection of relevant articles, emphasizing where the pollutant in question is predominantly emitted outdoors (i.e., the I/O ratio is less than 1).

14 There is a debate in the literature regarding the fraction of ambient particles found indoors. One review has suggested that the I/O ratio is typically greater for fine particles than for coarse (Wilson and Suh, 1997) while the PTEAM study suggests that the fraction is roughly equal (Clayton et al., 1993). However, a more nuanced understanding informed by particle dynamics would suggest that, as with fibrous filters, collection efficiency of the building envelope should be lowest for accumulation mode particles and higher for nucleation and coarse particles. Partial support for this statement can be found from Wallace and Howard-Reed (2002) who found that indoor sources were responsible for 50-80% and 75-90% of nucleation and coarse mode particles, respectively, while only 40-50% of the accumulation mode.

15 The indoor-outdoor ratios for PM2.5 and PM10 within Table 2 are based on measurements of particle mass concentrations indoors that did not distinguish between particles from outdoor air and those from indoor sources. Therefore, the true indoor-outdoor ratios for particles from outdoors will be smaller than indicated in the table.

TABLE 2: Indoor/Outdoor (I/O) Concentration Ratios from Selected Studies

POLLUTANT	SCENARIO	I/O RATIO				INDOOR SOURCES?	SOURCE	COMMENTS
		Mean	Median	Range Low	Range High			
NO_2	total no gas stove gas stove	 0.7 1.2		0.3	2.8	y y y	Levy et al., 1998	1568 homes in 8 cities in 15 countries; some homes had smokers and/or gas heaters
Metals		0.4		0.1 (Copper)	0.73 (Potassium)	n	Van Winkle and Scheff, 2001	10 homes in Chicago monitored for 1 year; outdoor air measured at fixed sites in neighborhood; 14 metals
Total Fungi			0.16	0.0003	200	y	Shelton et al., 2002	1,717 buildings in total, 4% residences; also provides regional breakdowns in results
Ozone		0.6		<0.1	1	n	Weschler, 2000	total of 21 studies in homes were reported, all with negligible indoor sources
PM	0.3 - 0.5 μm 0.5 - 1 1 - 2.5 2.5 - 5 5 - 10 >10	0.26 0.19 0.19 0.17 0.21 0.39				n	Wallace and Howard-Reed, 2002	volume concentration of particles within size range; 1 home tested; these concentrations are when no indoor source was present
	sulfate	0.88				y	Wilson and Suh, 1997	this figure is the infiltration factor (concentration of ambient particles that have penetrated indoors and remain suspended) for non-air-conditioned homes
	black carbon	0.53 0.35				n	LaRosa et al., 2002	1 home; 2 years of measurement (1st number is first year average, 2nd is second year)
	$PM_{2.5}$-daytime	0.98	0.94			y	Clayton et al., 1993 (PTEAM)	178 homes in Riverside, CA; outdoor air measured directly outside home; personal air concentrations also reported
	$PM_{2.5}$-nighttime	0.72	0.74			y		
	PM_{10}-daytime	0.99	0.97			y		
	PM_{10}-nighttime	0.73	0.69			y		
CO		1		0.7	1	n	Flachsbart, 1999	the mean is from offices, the range is from retail shops

MITIGATION STRATEGIES

Before considering ways to mitigate the indoor impacts of outdoor pollutants, it is important to understand the way in which indoor air quality is typically managed in homes. There are a wide variety of indoor sources, including volatile organic compounds, combustion products, moisture, bio-effluents, environmental tobacco smoke and others. Using flues, vents or exhaust fans can help keep specific sources from contaminating the indoor air of the whole house, but for many low-level contaminants the only practical method of control is to ventilate the house with outdoor air. The outside air is introduced to the house through natural means (infiltration or window opening) or through exhaust or supply fans.

Given how indoor air pollutants are removed from a house, there are four basic strategies that can be used separately or in combination to reduce occupant exposure to contaminants in outdoor air: 1) shelter in place, 2) building air tightening and pressure management, 3) ventilation and air filtration, and 4) contaminant removal. The ability to respond with any of these options will depend on the design of the home, its mechanical systems, the types of pollutants and their release and exposure patterns (short-term, cyclical, seasonal, long term). An effective approach to reducing exposure to outdoor contaminants will typically require a combination of the four strategies, but there may still be some unacceptable periods.

SHELTER IN PLACE

The most fundamental function of a home is to provide shelter from outdoor conditions. The building is intended to be the first line of defense at separating the relatively uncontrolled outdoor environment from the desired indoor environment. It is not surprising that the first response of many people to poor outdoor air quality is to go inside and close the windows. Additionally, they could turn off their central heating and air conditioning systems and any other fans.

Closing windows (and other air intakes) will reduce the air exchange with the outdoors and therefore the immediate intrusion of outdoor air into the home. Since no home is perfectly airtight, closing doors and windows does not eliminate intrusion. Because all indoor air ultimately comes from outdoors, all else being equal, the indoor conditions will eventually come to a dynamic equilibrium[16] with the outdoor conditions. The tighter the building is, the longer it will take to come to equilibrium.

The delay time, or the amount of time it takes to completely change the air in a building, is determined by the ventilation rate. The effectiveness of sheltering within the home will thus depend on the envelope tightness. For a home that meets the ASHRAE ventilation standard of 0.35 air changes per hour, the delay time is roughly three hours (ASHRAE 2001). For a tight house without mechanical ventilation the delay time can easily be twice as long. Most houses in the U.S. are leaky (i.e., typically one air change per hour) and thus could have a delay time on the order of one hour (Sherman and Matson 1997).

Reactive gasses, such as ozone, can be filtered to some degree by the building envelope. For other outdoor contaminants, the building envelope serves to delay, not reduce, their introduction into the indoor environment. Such a delay is not very helpful at reducing exposures to outdoor contaminants that persist over days, but can be an effective strategy for short-duration sources (less than a few hours). In houses without indoor ozone sources, ozone levels tend to be higher in houses that do not have air conditioners than those with air conditioners. Ozone levels are larger when windows are open

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16 In general the concentrations of outdoor contaminants will be time varying and the indoor concentrations will never reach a stable steady state. It is more accurate to say that the building acts as a low-pass filter that smoothes out and delays changes in concentration. The tighter the building is, the more damping it provides.

than when they are closed (Weschler 2000). For outdoor exposure times shorter than the delay time, the house serves as a reservoir of clean air. After the outdoor contaminant is gone, windows can be opened to flush out the pollutants that entered during the exposure period.

SAFE HAVENS

Simply going inside may not be sufficient for highly unusual, but potentially lethal, events. Chemical spills or fires, explosions, bio-terrorism or similar toxic air pollutant releases can temporarily create clouds of outdoor air so noxious as to make all other air quality issues pale. With sufficient warning, occupants would be advised to leave the vicinity, but the unexpected nature of these events means that the only viable alternative may be to shelter in place.

This may work for short term releases. Homes, as a whole, are often too leaky to provide the level of protection needed for longer duration events[17], but individual rooms within homes can be temporarily sealed up to become safe havens. A safe haven should be chosen to have as little contact with any outside walls as possible and preferably be on the side of the house furthest downwind from the source. Duct tape can be used to seal leaks, cracks, seams and doors, with thick plastic sheeting used to span larger gaps (Sorensen and Vogt 2001). If such a shelter has an air change rate of 0.15 ACH with the house (one-half that of our previous house's air change rate with the outside), it will take four to six hours (up to two times longer) for the contaminated outdoor air to get to the safe haven.

Fortunately most people will never need to respond to an emergency of this type. There may, however, be a very small population of at-risk individuals or locations for which the event is not as remote. In such a case, it may be possible to design a safe haven in advance with a small, but highly efficient particle and gas phase filtration system capable of providing several hours of protection. Such a safe haven might be effectively combined with other emergency shelters (e.g., tornado or hurricane) to reduce cost.

BUILDING AIR TIGHTNESS AND PRESSURE BALANCING

Sheltering in place is an example of a barrier strategy intended to keep the "bad" air out and can be effective in critical situations. Careful design of the building envelope and its systems and attention to pressure management can control airflow in and out of a house and delay exposures.

BUILDING AIR TIGHTNESS

The construction of the building envelope (walls, roof, foundation) and its corresponding air tightness level dictates how long it takes for outdoor air pollutants to enter the house as well as how fast the air in the house is replaced with outdoor air to purge short term outdoor pollutant exposures and indoor air contaminants. The strategy of "Build it tight. Ventilate it right" offers a significant advantage when the outdoor air is unacceptable.

Sherman and Dickerhoff (1998) have summarized the air leakage of U.S. housing. Sherman and Matson (1997) based an analysis of residential ventilation rates and associated energy costs on that data. That dataset gave a good snapshot of the air tightness of U.S. building stock at the time it was taken, but the stock has changed in the intervening years. Beginning in the 1980s, energy resource concerns led to increased energy efficiency of new houses through a variety of regulatory and voluntary means. As dwellings became more air tight, the concern for new construction focused on whether new houses were so tight that whole-house mechanical ventilation should be considered. Sherman and

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17 For some kinds of contaminants peak exposures are much more important than the integrated dose. For these kinds of contaminants even moderate reductions in the peak can provide substantial protection, if the peak is near a critical value. If one considers a reasonably wide range of possible events, however, this statement still holds.

Matson (1997) investigated optimal tightness levels for the housing stock. Wray et al. (2000) looked at how tightness levels would interact with proposed residential ventilation standards in the U.S.

Sherman and Matson (1997) estimated that the existing U.S. stock is quite leaky as a whole with average normalized leakage values of 1.03 (as derived in ASHRAE Standard 119 [ASHRAE 1988]) or about 20 air changes per hour (ACH50). As such, these houses can meet minimum ventilation requirements through infiltration alone. More recently Sherman and Matson (2002) demonstrated that new construction is significantly tighter than the stock as a whole. Sherman (1999) evaluated how air leakage could contribute to meeting the residential ventilation standard currently being proposed by ASHRAE and found that air leakage alone is rarely sufficient to meet minimum ventilation standards in new homes (100 cfm/100 ft^2 plus 7.5 cfm/person; normalized leakage values of less than 0.5).

In terms of mitigation strategies in an existing house, air-tightening techniques (caulking and sealing cracks and holes in the building envelope and interstitial spaces) can reduce the amount of infiltration and, correspondingly, the ingress of outdoor pollutants. Studies have found that these techniques, applied properly, can reduce the normalized leakage values of existing houses by about 25% (See, for example, Sherman and Dickerhoff 1998). This increases the delay time by a similar fraction.

PRESSURE MANAGEMENT

Pressure management strategies can be used in situations with unacceptable outdoor air quality to maximize the exposure of the occupants to relatively clean indoor air and to minimize their exposure to the contaminated outdoor air. Houses are subject to natural pressures created by the wind and indoor-outdoor temperature differences. Short of rather extreme architectural changes, there is not much that can be done to change these pressures, but there are other pressures and flows induced by building systems that are more controllable. Pressure management includes controlling exhaust devices (flues, chimneys and exhaust fans) and air moving devices (air distribution systems, air cleaners and ventilation systems). While proper management of these systems can provide additional protection from outdoor contamination, improper management can negate the benefits of the other strategies.

The largest and most important piece of air-moving equipment in many homes is the central air handler or furnace fan. Air handlers can increase the amount of outdoor air that enters the home by differentially pressurizing certain rooms, by having leaky ducts outside the conditioned space, or by having intentional air inlets as part of the ventilation system. In all these cases, running the air handler is going to increase exposure to outdoor contaminants. When an air handler operates it also tends to equalize the concentration of contaminants in indoor air.

When attempting to shelter in place, running the air handler may be disadvantageous as some areas of the house will be less strongly connected to the outdoor source and provide better protection. If these cleaner rooms can be identified, the air handler should be turned off to prevent the distribution of contaminants throughout the house and the safe zone.

To maximize the value of sheltering, pressure management techniques (air sealing and balancing supply and return air flows between rooms) should be used to minimize the pressure difference across the envelope and lower the amount of air that comes into the home. For short-duration events it is best to shut off most air moving equipment including exhaust fans and other ventilation systems as well as the central air handler.

If the outdoor contamination is mild, or of sufficient duration, the occupants may wish to run the air moving systems either to dilute indoor sources or to provide thermal comfort. In such cases the

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pressure imbalances should still be minimized as much as possible by, for example, leaving internal doors open.

Pressure management can make any available filtration more effective. To the extent possible, outdoor air should be directed through available filtration before mixing with the house air. Thus large openings such as door or windows, or simple inlet ducts should be closed. When no active filtration is available, dedicated supply ventilation systems should be disabled to allow infiltrating air to take advantage of whatever gas phase filtration is available from the building envelope.

VENTILATION AND AIR FILTRATION

Ventilation systems that include filtration and air cleaning capabilities can be useful in removing pollutants and contaminants from the indoor environment. The type of system installed and used will depend on the types of pollutants most apt to be present. This section describes the various types of ventilation and filtration systems and their applicability to different pollutants.

VENTILATION SYSTEMS

All homes have some kind of ventilation system to dilute indoor contaminants. People often think of *mechanical ventilation* (i.e. fans) in this context but in fact there are several other kinds. *Natural ventilation* refers to the operation of openings like doors and windows. *Infiltration* refers to the uncontrolled leakage of air due to weather-induced pressure differences. *Passive ventilation* combines natural driving forces with designed controllable inlets and outlets. The tighter condition of new construction suggests that appropriately designed and operated natural ventilation, passive ventilation, and mechanical ventilation can all be used to meet minimum requirements, and achieve acceptable indoor air quality when outdoor air is clean. These very different operating strategies will have impacts on pressures, the flow of contaminants into and out of houses, and indoor air quality when the outdoor air is polluted.

Infiltration

Infiltration is the dominant source of ventilation for dwellings in most of the world. With the exception of kitchen or bath exhaust systems, most U.S. homes do not have mechanical ventilation and, therefore, rely on infiltration (i.e., leakage through the building envelope) and natural ventilation (i.e., window opening) to maintain acceptable indoor air quality. There are many ways to calculate infiltration (e.g., ASHRAE 2001), but all of them rely on coupling the air leakage of the building envelope to the natural driving forces of wind and temperature difference.

Mechanical Ventilation

Increasingly, homes are being built with tighter envelopes and mechanical whole-house ventilation systems. There are three types of mechanical ventilation systems normally considered.

1) Supply Ventilation is a mechanical ventilation strategy in which outdoor air is brought into the house, usually in a single place. Air is usually distributed throughout the house either by a dedicated duct system or through the central air handler. To balance the supply air, air leaks out of the house through the building envelope or through flues, chimneys or other similar vents. Supply ventilation tends to keep the house at a positive pressure relative to outside. Emmerich and Persily (1995) found that the operation of an outside air duct decreased coarse particulate concentrations by 9.9% on average because the outside air duct reduces the amount of unfiltered outside air entering the house through cracks and holes and increases the amount of outside air passing through the furnace filter.

2) Exhaust Ventilation is the opposite of supply ventilation. Air is exhausted through one or more dedicated ports, which could be part of the bathroom or kitchen exhaust system, and it keeps the house at a negative pressure relative to outside. Make-up air is drawn in through leaks in the building envelope. Sometimes dedicated inlets are installed in the envelope to moderate the pressure and to direct air to specific rooms. Outdoor air will enter through multiple pathways through the building envelope.

3) Balanced Ventilation is a combination of equal sized supply and return fans, which neither pressurizes nor depressurizes the house relative to outside. It is most often used as part of a heat - recovery system such as an air-to-air heat exchanger. If the pressures are not balanced throughout the house, outdoor air will enter the supply side of the balanced system and, if the pressures are not balanced throughout the house, will also enter through infiltration as though the ventilation system were not there. Similarly, an equal amount of air will be exhausted through the exhaust system or by exfiltration through the building envelope.

FILTRATION AND AIR CLEANING

Going indoors to escape from poor outdoor air quality may be a good solution when the period of high outdoor concentration is short, but when the outdoor contamination extends over a longer period of time, filtration (including air cleaning[18]) may be the only option to reduce indoor levels of outdoor contaminants. It would be ideal to remove the contaminants in outdoor air before they mix with the indoor air, but this is only possible if all the sources of incoming air are controlled. In such a case filtration could be applied to the incoming air stream, provided the single-pass efficiency of the filter is high enough. Filtration to control indoor sources is a separate function, but when efficient filtration of the entire outdoor air stream is not possible, filtration of the indoor air may be a workable alternative. This kind of re-circulating filtration can be done on a room-by-room basis, with a dedicated system, or as part of the whole-house air distribution system.

Filtration for Particulates

Particle filtration is a cost-effective strategy that can be used in the home to reduce the impact of allergens (molds, fungi, pollens and danders), soot and other particulates. Particle filters are rated by ASHRAE (52.2-1999) using the MERV (minimum efficiency reporting value) scale[19]. Although the ASHRAE approach is the most widespread, the European Union has adopted a somewhat similar system of filter ratings known as the "EU" rating[20].

MERV ratings below 6 are poor at filtering out respirable particulates, but can do an acceptable job at removing the large, visible particles such as fibers, insects or large dusts or pollens. These filters are best suited to be used as the first stage in multistage filtration. The common furnace filter is typically in this range.

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18 Some amount of air cleaning, especially for reactive compounds, may happen adventitiously as airborne contaminants come in contact with indoor surfaces or leakage pathways.

19 The effective filtration rate is based on the "clean air delivery rate" (CADR), a combination of the filter efficiency and the air flow rate through the filter. The CADR can then be compared to the effectiveness in removing particles by ventilation and deposition. To be effective in removing contaminants, CADR must be comparable in magnitude to the sum of other pollutant removal processes, such as by natural deposition on surfaces.

20 The Standard 'EU' rating categorizes filtration performance by means of the efficiency with which it can trap particles of varying size. For example, an EU3 filter would be used for pre-filtering, coupled to an EU6 or EU7 main filter. This gives approximately 97% efficiency down to 2.5 µm and between 44% (EU6) and 55% (EU7) at 0.1µm. (CEN 2002)

Filters with MERV ratings of 6-8 can substantially reduce the levels of the larger particulates (i.e., PM_{10}) and the particles that tend to settle on surfaces and provide matter for microbiological growth. Filters with MERV ratings of 9-12 have improved performance at removing fine respirable particulates (i.e., $PM_{2.5}$). These fine particles are the ones thought to be most important for health. High efficiency filtration, MERV 13-16, is necessary to substantially remove ultrafine particles.

Although higher efficiency filtration can provide improved removal of ultrafine particles, it is not particularly effective in most dwellings. A small amount of increased air bypass around the filter can negate the advantage of increasing the filter efficiency from relatively high to very high. The design and construction expense needed to remove that fraction of the particles is rarely cost-effective. Nevertheless, in special circumstances, such as for sensitive individuals or in hazardous environments, this technology can be usefully employed.

Allergen Filtration

As outdoor-related allergens tend to be seasonal, the best way to reduce exposure indoors is to keep windows closed and filter the outdoor air supplied to the house. Particle filtration of MERV 6-8 may work for many of the larger pollens and allergens. Higher efficiency filters are needed to remove the smaller allergens such as from grasses and birch trees. Often when installing and operating a filtration system, the cost differential of using improved filtration (i.e., MERV 9-12) is quite minimal[21].

If infiltration is insufficient, mechanical ventilation with filtration should be installed to provide acceptable indoor air quality throughout the season. A supply ventilation system that passes the air through particle filters is the preferred ventilation system for this application. If the supply air cannot be filtered and infiltration alone is insufficient, then an exhaust ventilation system may perform better because of the particle filtration provided by the building envelope. Thatcher and Layton (1995), however, found that this filtration level could be quite low.

If there is a central air handler, particle filtration should be integrated into it to remove allergens that are not filtered on the way in, or are re-suspended, as well as to reduce particle concentrations from other sources. To achieve full benefit from this filtration the air handler should be run full time (i.e., the fan switch set to "on") during the allergy season. To make most effective use of this continuous-fan strategy the duct system must be well sealed, as any leaks will reduce the effectiveness of the strategy. The pressure drop across the improved filters must be taken into account in the design to ensure sufficient airflow to the space. A MERV 11 filter used in conjunction with a central forced air system could reduce cat and dust mite allergens[22] by 30 to 40%.

If these approaches are impractical or insufficient, a stand-alone high-efficiency particle filtration system should be considered for use in a single room. This would create a relatively clean room and should be placed in the area(s) in which the affected individuals spend the most time, such as a bedroom, kitchen or family room

Soot Filtration

Like allergens, soot and other particles require particle filtration to remove them from the indoor environment. There are, however, some differences to consider based on the different chemical and physical nature of the particles.

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21 Fisk et al (2002) have found that operating costs for any of these central HVAC system-based filtration systems is less than $2 per person per month in the U.S.

22 Fisk et al (2002) have determined that at least a few air change rates per hour are required through the filters to get a 50% reduction in cat and dust mite allergen concentrations.

Soot normally contains a large amount of fine particles. Improved combustion technology has tended to reduce the average size of the soot particles. Since these fine particles are important contributors to lung disease, MERV 13 filtration or better is preferred over MERV 6-8 and 9-12. The higher rated filtration levels should be considered if a lot of ultrafine particles are expected. A MERV 13 filter in conjunction with a central forced air system could reduce environmental tobacco smoke particles (ETS) by 60% and outdoor fine mode particulates by 45 to 80%. Fisk et al. (2001) found that stand-alone fan-filters can reduce ETS and fine mode particulates by 40% (MERV 11, 2 air change rates) to 95% (HEPA, 10 air change rates).

Many soot particles contain semi-volatile organic compounds. Even when the particles themselves are filtered out, the semi-volatile compounds will continue to be emitted into the air stream. Normally, these emissions are not a significant problem, but if soot is allowed to build up over a long time on the filter or if control of similar organic compounds indoors is an issue, it could become a problem. Frequently changing filters or cleaning, when appropriate, can minimize this effect.

Soot containing larger particles such as that from uncontrolled solid fuel combustion can represent a challenge because larger particles quickly load filters that are capable of filtering out fine particles. Multistage particle filtration can mitigate this problem and may be as simple as using a relatively coarse filter directly on the outdoor air supply and a high efficiency filter for the central air handler. This process is sometimes called pre-filtering.

Gas-Phase Filtration

While the aerosol and fine particulate contaminants of urban air pollution can be handled by particle filtration, the gas phase constituents of smog cannot. The most important constituent of smog from the health perspective is ozone and there are usable approaches for reducing ozone concentrations in the home.

The building envelope itself can provide some filtration for gas-phase pollutants such as ozone. Air infiltrating through cracks in the building envelope can have a long and tortuous path that may not allow the outdoor contaminants to fully penetrate to the breathing zone. Reactive gases may decompose when interacting with the many surfaces associated with airflow through the envelope.

The removal of ozone from air depends on its reactivity rate with each material it comes in contact with. Materials with rougher surfaces (concrete, brick) have higher reactivity rates than smoother surfaces (plywood). Because of its high reactivity, ozone has a relatively low penetration factor when it infiltrates through cracks or long paths. This effect combined with its surface reactivity cause ozone to be one of the few contaminants that typically has a higher concentration outdoors than indoors. (Cano-Ruiz et al. 1992).

Ozone and a wide variety of gaseous contaminants can be effectively removed by gas phase filtration using activated carbon or charcoal[23]. Weschler et al. (1992) measured how effective activated carbon filters are in controlling indoor ozone, SO_2 and selected VOCs. They found that they were able to decrease indoor/outdoor ozone ratios from 0.7 to 0.1. Such an approach would be quite similar to that described for allergens, except the particle filter would be replaced by a charcoal bed or charcoal impregnated media. However, unless a very specific need has been identified, the corresponding initial and operational expenses usually make it unattractive for homes. Areas with persistently high levels of reactive gases such as ozone could benefit from charcoal filtration. New technologies (e.g., ultraviolet photocatalysis for VOC removal) are being actively pursued and have the potential to bring down costs in the future.

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23 There is a difference in performance between charcoal and activated carbon, but we will not discuss that issue here.

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Because of ozone's tendency to decompose when it contacts surfaces, even if no filter medium is available simply circulating the air within the house can lower ozone concentrations. Continuous air handler operation should be considered as part of the approach, but only if the gains from increased decomposition are not offset by additional ozone incursion caused by duct leakage or differential pressurization.

As ozone forms when volatile organic gases from evaporated petroleum products, cleaners, paints and other chemicals react with oxides of nitrogen in the presence of sunshine, ozone in the urban environment tends to follow a daily pattern of building up during the morning and then falling off rather quickly after sunset. Indoor ozone concentrations are directly related to outdoor concentrations and house air change rates (Weschler 2000). This suggests that sheltering may provide a cheap alternative to charcoal filtration. From their modeling, Cano-Ruiz et al (1992) found that indoor ozone levels were five times higher if windows are open than if the house is closed up and the air conditioner is used for cooling. During the peak outdoor concentration periods, ventilation should be minimized (although the air handler could still run). When the outdoor ozone concentration has become acceptable then ventilation can be substantially increased to keep the daily ventilation rate within a proper range.

CONTAMINANT REMOVAL AND COMBINED STRATEGIES

Sometimes simple hygiene measures can provide protection. Because coarser particles can settle on surfaces and be re-suspended later, cleaning and vacuuming may be needed to remove the particles. Care must be taken to assure that the vacuum system used actually removes the particles and does not just re-suspend and re-circulate them. Central vacuum systems with outside exhaust are best for this purpose, but many vacuum cleaners now have secondary filtration that can trap smaller particles.

Table 3 summarizes the combination of strategies to consider when trying to reduce indoor exposures to specific outdoor pollutants. Putting all these mitigation strategies together in a well-engineered system can help to protect occupants from contaminants in outdoor air. In addition to good system design, the occupants need to manage the system correctly.

Preferably, a well-designed house would have a supply ventilation system that brings the required amount of outdoor air into the home through a series of filters to remove any contaminants. The building envelope (and associated ducts and penetrations) should be sufficiently airtight so that the indoor environment would be maintained at a high enough pressure to keep any unfiltered air out. Sensors would be used to detect any threat or contaminant to allow the system to react accordingly.

This approach works well and is used by critical facilities, but is probably not a practical approach for most homes. The most important aspect of this approach, the tight envelope, can almost always be applied at some level, however. A tight envelope increases delay times for sheltering purposes and assists in pressure management.

Table 3: Strategies for Reducing Indoor Exposures to Outdoor Pollutants

	Shelter in Place	Building Air Tightening & Pressure Balancing	Ventilation (if insufficient infiltration)	Filtration	Contaminant Removal
Allergens	Yes	Yes	Supply ventilation with filtration (better) Or Exhaust ventilation	MERV 6-8 (minimum) MERV 9-12 (better) Or Stand-alone high efficiency particle filtration system	Cleaning and vacuuming (high efficiency particle filtered)
Soot and Other Particulate Matter	Yes	Yes	Supply ventilation with filtration (better) Or Exhaust ventilation	MERV 9-12 or higher efficiency filter if soot includes ultrafine particles	Cleaning and vacuuming (high efficiency particle filtered)
Gaseous Contaminants	Yes	Yes	Supply ventilation with filtration	Gas phase filtration (charcoal absorption)*	Reduce outdoor emissions
Toxic Air Pollutants	Yes	Yes	Shelter in Place and turn off central distribution system to minimize toxin circulation into safe haven – at-risk individuals may need to create a safe haven with high-efficiency particle filtration and gas phase filtration	Gas phase filtration (charcoal absorption) if the contaminant to be removed is known	Reduce outdoor emissions

*If no gas phase filtration in place, circulate air within the house to lower ozone concentration by decomposition and shelter in place during high ozone periods.

To reduce the impact of outdoor contamination, it is important that the pressure boundary that separates the indoor air and outdoor air be as tight as possible. The tighter it is, the easier it is to control the pressure, and the longer the building can be used to shelter in place. There are many techniques that can be used to tighten building envelopes and ducts, in both new construction and as a retrofit. If outdoor contamination of any kind is a concern, the first step is to reduce the air leaks.

Generally speaking, using operable windows to supply residential ventilation will maximize exposures to outdoor contaminants, so natural ventilation should be avoided when reducing exposures to outdoor pollutants is a priority. The optimal strategy to use will be a mixture of the four strategies discussed

above and will depend on the source of the outdoor contamination and the acceptance criteria of the occupants.

DISCUSSION AND SUMMARY

Although this report has focused on solving indoor problems due to poor outdoor air quality, this is not a significant issue most of the time, where there is adequate outdoor air quality. The populations of concern include people who live in areas where the criteria pollutants (Table 1) are not met, who suffer from seasonal allergies, who live near local contaminant sources, and those who may be exposed to other natural or man-made outdoor contaminants.

The amount of unacceptable indoor air that the occupants are exposed to will depend on the nature and duration of the outdoor contamination. For some contaminants, integrated exposure is the key predictor of risk and human response. For such compounds, a short period of exposure beyond acceptable limits is not likely to be considered serious, but long-term exposures near the limits of acceptability may be a serious health risk.

For contaminants with acute health impacts, short-term peaks are often of more concern than long-term dose. A small degree of mitigation at the peak (from for example filtering, sheltering or avoidance) can have a disproportionately larger impact on health. Such behavior is most typical for irritating compounds and compounds with thresholds.

Particle filtration is an accessible technology that is broadly applicable to a wide range of contaminants including allergens, soot and other particulate matter. In the context of designing a new system, or renovating an old one, putting in MERV 9-12 filtration should be considered, but almost any forced air system has the capacity to use improved filtration. Low efficiency furnace filters can often be replaced inexpensively with MERV 9-12 filtration, but may require system design changes.

Sheltering in place, either by simply closing up the house, or in more extreme situations, by retreating to an internal safe haven, can be used by any occupant to reduce exposure to short-term outdoor events such as ozone alerts and chemical spills. Residents need to be aware of these actions and have a plan (e.g., air the house in the morning and at night and close it up tight in the afternoon to minimize ozone and smog penetration). Safe havens also require advance planning in order to have materials on hand and a plan for what to do.

All of these strategies depend on the ability to control flows of air either through the building envelope, through filters or through duct systems. Air leakage in any of these components weakens the effect of the mitigation techniques, so it is advisable to fix leaks and bypasses wherever practical.

Preventive air tightening, correction of pressure imbalances, the implementation of appropriate filtration and ventilation measures, and evaluating the feasibility of a safe shelter in place zone (if needed) will help reduce the impact of outdoor pollutants on the indoor environment.

A good residential ventilation system provides adequate outdoor air to dilute indoor contaminants inexpensively and to a level acceptable to the occupants. The rates specified in residential ventilation codes and standards typically assume good outdoor air quality. When the outdoor air quality is poor, the best strategy for protecting indoor air quality is either to clean the contaminated air or to slow its entry during periods of high outdoor pollutant concentrations.

ACKNOWLEDGMENTS

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APPENDIX I: Contaminants of Concern from WHO
Table A1: Guidelines for air quality:
compounds with non-carcinogenic health endpoints (WHO 1999)

Compound	Average ambient air concentration [µg/m^3]	Health endpoint	Observed effect level [mg/m^3]	Uncertainty Factor	Guideline Value (GV) or Tolerable Concentration (TC) [µg/m^3]	Averaging Time
Acetaldehyde	5	Irritancy in humans	45 (NOEL)	20	2,000 (TC)	24 hours
		Carcinogenicity related irritation in rats	275 (NOEL)	1000	50 (TC)	1 year
Acetone	0.5-125	Odour annoyance	240 (OT)	n.a.	n.p.	-
Acrolein	15	Eye irritation in humans	0.13	n.p.	50 (GV)	30 min
		Odour annoyance	0.07	n.a.		30 min
Acrylic acid	No data	Nasal lesions in mice	15 (LOAEL)	50	54 (GV)	1 year
2-Butoxyethanol	0.1-15	Haematoxicity in rats	242 (NOAEL)	10	13,100 (TC)	1 week
Cadmium	(0.1-20) x 10^{-3}	Renal effects in the population	n.a.	n.a.	5x10^{-3} (GV)	1 year
Carbon disulphide	10-1500	Functional CNS changes in workers	10 (LOAEL)	100	100 (GV)	24 hours
		Odour annoyance	0.2 (OT)	n.a.	20 (GV)	30 min
Carbon Tetrachloride	0.5-1	Hepatotoxicity in rats	6.1 (NOAEL)	1,000	6.1 (TC)	1 year
1,4 Dicholorobenzene	0.2-3.5	Increase in organ weight and urinary proteins	450 (NOEL)	500	1,000 (TC)	1 year
Dicholoromethane	<5	COHb formation in normal subjects	-	n.a.	3,000 (GV)	24 hours
Diesel exhaust	1.0 – 10.0	Chronic alveolar inflammation in humans	0.139 (NOAEL)*	25	5.6 (GV)	1 year
		Chronic alveolar inflammation in rats	0.23 (NOAEL)*	100	2.3 (GV)	1 year

*For diesel exhaust two approaches were applied, which based on a NOAEL of 0.41 mg in rats. The corresponding levels were converted to a continuous exposure scenario. n.a. not applicable; n.p. not provided; OT Odour Threshold.

Table A1: Guidelines for air quality: compounds with non-carcinogenic health endpoints (cont.)

Compound	Average Concentration [µg/m³]	Health endpoint	Observed effect level [mg/m³]	Uncertainty factor	Guideline Value (GV) or Tolerance Concentration (TC) [µg/m³]	Averaging time
2-Ethoxyethanol	No data	Developmental effects in rats	37 (NOEL)	n.p.	n.p.	1 year
2-Ethoxyethylacetate	No data	Developmental effects in rats	170 (NOEL)	n.p.	n.p.	-
Ethylbenzene	1-100	Increase of organ weight	2150 (NOEL)	100	22 000 (GV)	1 year
Flourides	0.5-3	Effects on livestocks	n.a.	n.a.	1 (GV)	1 year
Formaldehyde	$(1-20) \times 10^{-3}$	Nose, throat irritation in humans	0.1 (NOAEL)	n.a.	100 (GV)	30 min
Hexachlorocyclopentadiene	No data	Inhalation effects in rats	0.45 (NOEL)	n.p.	n.p.	1 year
Hydrogen sulphide	0.15	Eye irritation in humans	15 (LOAEL)	100	150 (GV)	24 hrs
		Odour Annoyance	$(0.2 – 2.0) \times 10^{-3}$ (OT)	n.a.	7 (GV)	30 min
Isophorone	No data	Odour Annoyance	1.14 (OT)	n.a.	-	30 min
Manganese	0.01 – 0.07	Neurotoxic effects in workers	0.03 (NOAEL)	200	0.15 (GV)	1 year
Mercury, inorganic	$(2-10).10^{-3}$	Renal tubular effects in humans	0.020 (LOAEL)	20	1 (GV)	1 year
2-Methoxyethanol	No data	Developmental toxicity in rats	31 (NOEL)	n.p.	n.p.	
Methyl bromide	0.05-0.8	Reduction in fertility index in rats	12 (NOEL)	n.p.	n.p.	
Methyl Methacrylate	2.4×10^{-4}	Degenerate changes in olfactory ephithelium in rodents	102.5 (NOEL)	100	200 (TC)	1 year
Monochlorobenzene	0.2-3.5	Decreased food intake, increased organ weight, lesions and changes in blood parameters	341 (LOAEL)	1000	500 (TC)	1 year

* n.a. not applicable; n.p. not provided

Table A1: Guidelines for air quality: compounds with non-carcinogenic health endpoints (cont.)

Compound	Average ambient air concentration [µg/m³]	Health endpoint	Observed effect level [mg/m³]	Uncertainty factor	Guideline Value (GV) or Tolerance concentration (TC) [µg/m³]	Averaging Time
1-Propanol	0.05	Reproduction in pregnant rats	9001 (NOEL)	n.p.	n.p.	-
2-Propanol	1500-35000	Developmental toxicity in rats	9001 (LOEL)	n.p.	n.p.	
Styrene	1.0-20.0	Neurological effects in workers	107 (LOAEL)	40	260 (GV)	1 week
		Odour annoyance	0.07 (OT)	n.a.	7 (GV)	30 minutes
Tetrachloroethylene	1 – 5	Kidney effects in workers	102 (LOAEL)	400	250 (GV)	24 hours
		Odour Annoyance	8	n.a.	8,000 (GV)	30 minutes
,1,1,12-Tetrafluoroethane	No data	Development toxicity in animals	41700 (NOAEL)	n.p.	n.p.	
Toluene	5 – 150	Effects on CNS in workers	332 (LOAEL)	1260	260 (GV)	1 week
		Odour annoyance	1 (OT)	n.a.	1000 (GV)	30 minutes
1,3,5 Tricholorobenzene	0.5-0.8	Metaplasia and hyzperplasia of respiratory epithelium in rats	100 (NOEL)	500	200 (TC)	1 year
1,2,4 Trichlorobenzene	0.02-0.05	Increase in urinary porphyrins in rats	22.3 (NOAEL)	500	50 (TC)	1 year
Vanadium	0.05-0.2	Respiratory effects in workes	0.02 (LOAEL)	20	1 (GV)	24 hours
Xylenes	1 –100	CNS effects in human volunteers	304 (NOAEL)	60	4,800 (GV)	24 hours
		Neurotoxicity in rats	870 (LOAEL)	1,000	870 (GV)	1 year
		Odour annoyance	4.35 (OT)	n.a.	-	30 minutes

Table A.1: Guidelines for air quality: compounds with non-carcinogenic health endpoints (cont.)

Compound	Average ambient air concentration [µg/m^3]	Health endpoint	Observed effect level [mg/kg bw d]	Uncertainty factor	Tolerable Daily intake (TDI or ADI) [µg/kg bw d]	Averaging Time (over lifetime)
Chloroform	0.3-10	Hepatoxity in beagles	15 (LOEL)	1000	15 (TDI)	24 hours
Cresol	1-'10	Reduced body weight and tremors in mice	50 (LOAEL)	300	170 (ADI)	24 hours
Di-n-butyl Phthalate	(3-80).10^{-3}	Developental/Reproductive toxicity	66 (LOAEL)	1000	66 (ADI)	24 hours

			Estimated human daily intake [pg/kw bw d]		[TEQ/kg bw d]	
Dioxin-like compounds	n.p.	Neurobehavioural effects/Endometriosis in monkey offspring Decreased sperm count/immune suppression/increase genital malformations in rat offspring	14-37 (LOAEL)*	10	1-4 (TDI)	24 hours

* Estimated from the maternal body burden of exposed rats and monkeys by applying a factor of 2.

* kg bw d = killogramme bodyweight per day

Table A.1.2: Guidelines for Air Quality: compounds with carcinogenic health endpoints (WHO 1999)

Compound	Average ambient air concentration [$\mu g/m^3$]	Health endpoint	Unit risk [$\mu g/m^3$]	IARC classification
Acetaldehyde	5	Nasal tumours in rats	$(1.5\text{-}9) \times 10^{-7}$	2B
Acrylonitrile	0.01 – 10	Lung cancer in workers	2×10^{-5}	2A
Arsenic	$(1\text{-}30) \times 10^{-3}$	Lung cancer in exposed humans	1.5×10^{-3}	1
Benzene	5.0 – 20.0	Leukemia in exposed workers	$(4.4\text{-}7.5) \times 10^{-6}$	1
Benzo[a]pyrene	-	Lung cancer in humans	8.7×10^{-2}	1
Bis(chloromethyl)ether	No data	Epitheliomas in rats	8.3×10^{-3}	1
Chloroform	0.3 – 10	Kidney tumours in rats	4.2×10^{-7}	2B
Chromium ^{VI}	$(5\text{-}200) \times 10^{-3}$	Lung cancer in exposed workers	$(1.1\text{-}13) \times 10^{-2}$	1
1.2-Dicholoroethane	0.07 – 4	Tumour formation in rodents	$(0.5\text{-}2.8) \times 10^{-6}$	2B
Diesel exhaust	1.0 – 10.0	Lung cancer in rats	$(1.6\text{-}7.1) \times 10^{-5}$	2A
ETS	1-10	Lung cancer in exposed humans	10^{-3}	
Nickel	1-180	Lung cancer in exposed humans	3.8×10^{-4}	1
PAH (BaP)	$(1\text{-}10) \times 10^{-3}$	Lung cancer in exposed humans	8.7×10^{-2}	1
1,1,2,2,-Tetrachloroethane	0.1 – 0.7	Hepatocellular carcinomas in mice	$(0.6\text{-}3.0) \times 10^{-6}$	3
Trichloroethylene	1 – 10	Cell tumours in testes of rats	4.3×10^{-7}	2A
Vinychloride	0.1 – 10	Hemangiosarkoma in exposed workers Liver cancer in exposed workers	1×10^{-6}	1