# Protecting Homes from Outdoor Pollutants

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**ROCIS Initiative**
Reducing Outdoor Contaminants in Indoor Spaces
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## About the Author: Don Fugler

Don spent 25 years conducting research projects for Canada Mortgage and Housing Corporation (CMHC), in the areas of residential energy use, ventilation, and indoor air quality. Between 1985 and 2010, he managed over 100 research projects. During that period, he published CMHC research reports; wrote and distributed summaries in Research Highlights and About Your House documents and lectured at conferences and meetings. Since 2011, Don's consulting work has addressed indoor air quality and energy issues for federal departments, NGOs, and individuals. He taught part of the IAQ course for Healthy Indoor Air Partnership training for HVAC and environmental professionals, and is continuing work on CSA standard committee F300 (depressurization issues), and CGSB (radon).

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## Executive Summary

Residential indoor air quality (IAQ) is affected both by pollutants generated inside houses and by pollutants that enter with outdoor air or water. For years, the emphasis on improving IAQ has been to reduce indoor pollutant sources and to facilitate the dilution of pollutants with ventilation by clean outdoor air. The ROCIS initiative deals with situations where outdoor sources – air, water, soil gases, etc. – are a significant source of indoor pollution and those pollutant loads have to be reduced. Establishing the health basis for reducing impacts in specific circumstances is beyond the scope of this paper. Rather, we intend this paper and the related white paper on commercial buildings to serve as guidance on how to identify and mitigate high concentrations of outdoor pollutants.

This paper examines these issues based on the data collected in American and Canadian housing stock. It presents the material as follows.

First, we review the range of outdoor pollutants that can cause problems and also list indoor sources of those same pollutants. We also touch on the established and emerging methods to detect the presence and concentrations of pollutants. These introductory sections establish a context in which to consider potential mitigation strategies. For more detail on air quality and health, readers are directed to another ROCIS document (The Public Health Basis for the ROCIS Initiative) or several excellent reviews on health effects.

We then describe the basic entry pathways for outdoor pollutants as well as approaches to protecting houses against outdoor pollutant entry. Entry pathways include infiltration of outdoor air; spaces attached to the house; soil gas; tracked-in dirt; and groundwater. Mitigation approaches include building envelope tightness (above and below grade); pressure boundaries; interior air circulation and filtration; cleanliness; and water treatment. We also include examples of actual houses where outdoor pollutants have been successfully minimized and emphasize the need to consider the house as a total system in which none of the solutions stands alone. The effects of one solution can amplify or render useless the utility of another.

We then consider potentially new solutions, including improved filter technology, cleaning equipment for tracked-in dirt, and envelope retrofits. We touch on the coming possibility of homeowner-operated detection devices in a widely-distributed, data-tracking network for locally generated pollutants such as wood smoke or industrial sources.

Finally, the recommendations section suggests that further research and monitoring in this relatively new field will help to optimize the mitigation solutions. Priority areas should focus on vulnerable populations and specific high-load pollutant areas.

## Introduction

Most health authorities emphasize the need for houses to be ventilated with adequate amounts of outdoor air. Mechanical or natural ventilation flushes out air pollutants generated inside the house. Ventilation can help to control excess humidity during cold climate winters. The recommended amounts of outdoor air to be introduced are quantified in heating, ventilating, and air conditioning (HVAC) standards as well as in many building codes (ANSI/ASHRAE 2013). The premise behind these regulations is that the outdoor air is significantly "cleaner" than the indoor air it replaces.

What if this premise is unfounded? What if the outdoor air carries a load of air pollutants that is more challenging to human health than the indoor air? Are there ways to determine if and when this occurs? Are there means to protect householders from the deleterious effects of poor outdoor air? Ventilation standards do reference that some outdoor air will require cleaning, although they do not provide much detail as to how this should be done (ANSI/ASHRAE 2013).

Let's look at some obvious examples. Houses downwind from a farm where pig manure is being spread will not be opening windows for "a breath of fresh air." In winter, communities in valleys with high levels of wood burning often have trouble with excessive outdoor particle levels (and odors). People with respiratory illnesses are advised to limit window opening during periods of high pollen counts in outdoor air or when hot, still summer days ramp up outdoor ozone concentrations.

There are certainly locations and times where restricting outdoor air entry makes more sense than facilitating it. Can such restriction be accomplished safely? While a householder could turn off any mechanical ventilation system that induces air exchange, many North American houses see far more air exchange through leakage than through intentional ventilation. How do you control leakage of outdoor air through the house envelope? Can house envelopes be made tight enough to restrict the entry of outdoor air? Even if the envelope effectively blocks entry of outdoor air, are there secondary paths such as through the garage or through the soil that can also introduce pollutants?

Outdoor air is not the only means of pollutant entry, although it is usually the largest. Soil gas can enter through cracks and leaks in the foundation. Pollutants can come in with municipal or well water, then become airborne once in the house. Other hazardous materials enter through dust that is tracked in on shoes or is piggybacked on clothing or the fur of pets.

This paper examines these issues based on the data collected in American and Canadian housing stock. It presents the material as follows:

- **Pollutants**: First, we review the range of outdoor pollutants that can cause problems and also list related indoor sources of those pollutants.
- **Detection methods**: We touch on detection methods to determine pollutant concentrations.

- **Entry pathways:** We describe the pathways of pollutant entry into houses.
- **Mitigation and examples:** What mitigation has been successful either at reducing outdoor entry or indoor concentrations of these pollutants? We list actual examples and data from several case studies.
- **Promising technologies:** We suggest promising technologies and strategies that, so far, have not been extensively tested.
- **Recommendations:** We propose the next steps in reducing risks due to the entry of outdoor pollutants.

The intent of this white paper is to provide a broad framework for understanding sources, pathways, and mitigation approaches. Additional information resources that include links to many papers are listed in Appendix A.

## Pollutants of Interest

The table below briefly describes the pollutants that the paper will cover. The fourth column lists the potential interior sources of these pollutants. If outdoor sources were completely excluded or mitigated, there would still be measurable quantities of many of these pollutants indoors due to the interior sources. 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, like heavy metals, can also be introduced to the house through dust movement on footwear. Most of the pollutants are known to create respiratory risks, but some can also be introduced to bodies through the mouth or skin.

This paper does not describe the health impacts of different pollutants, but the papers in Appendix A provide information on indoor air quality (IAQ) and health for those interested. Lawrence Berkeley National Laboratory (LBNL) has done a comprehensive job of summarizing IAQ issues and the effectiveness of intervention strategies in their “Resource Bank” (LBNL 2014).

**Table 1: 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 |
| Semi-volatile 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 1, *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 |

Note: Electro-magnetic fields (EMFs) are beyond the scope of this paper. Noise from outdoor and indoor sources can also be a significant stressor that can exacerbate health effects from other hazards. Although noise can be reduced by modifying building shells (walls, windows, doors) or by replacing heating or ventilation systems, it is beyond the scope of this paper.

Many of these outdoor pollutants have been around for millennia, but recent developments have led to new interest in them. Improved medical knowledge has revealed the effects of pollutants that were previously ignored. New measurement technologies allow researchers to better quantify contaminants. As well, climate change has had an effect on increased frequency of wildfires and forest fires. Longer spells of hot summer weather can lead to high spikes of ozone concentrations. European and Asian cities in 2014 were affected by high outdoor particle counts during weather conditions with stagnating air masses. Rail and road emissions have diminished on a per-unit vehicle basis, but increases in traffic can still create hot spots of outdoor pollution. Rail and road accidents with hazardous materials can cause crisis situations where protecting the house from outdoor pollutants is critical for the short term. For North America, the effect of industrial emissions has decreased with the decline of manufacturing and heavy industry on the continent, which has led to some improvements in outdoor air quality in many cities. The emissions of power plants have varied regionally, as some jurisdictions are switching to natural gas and renewable technologies, instead of coal burning, changing the type and quantity of power plant pollutants. Conversely, the rise of hydraulic fracturing (fracking) for oil and gas extraction has created air quality problems in many rural areas, including those that previously had good outdoor air without major pollutant sources.

## Methods of Pollutant Detection

It can be difficult for consumers or householders to detect many air pollutants, especially from outdoor sources. Commercial air testing companies are able to undertake an air pollutant scan in houses, but costs are high. Furthermore, unless the house occupant can narrow down the range of pollutants that they would like tested, the exploratory costs for sampling the pollutants in Table 1 would run into thousands of dollars in technician time and analysis. Even having a technician sample the indoor and outdoor air at a house for a single pollutant typically costs hundreds of dollars. Using these commercial services is therefore not an obvious or affordable choice for most consumers.

The last column in Table 1 identifies some pollutants that can be measured in the house with devices available to the consumer, generally at a cost of $200 or less. For those particular pollutants, it can be worthwhile to the householder to purchase the alarm or sensor that allows them to test or monitor house conditions. Having a record of pollutant variation can provide valuable information as to the pollutant source and the relative need for mitigation methods.

In certain instances, local public health officials can also be helpful. If there is an outdoor air pollution source, particularly with industrial emissions, public health or air quality agencies will often get involved in data gathering and mitigation. These bodies should have access to the instrumentation necessary for proper diagnosis, or they may hire independent measurement specialists.

## How External Pollutants Enter the House

There are several pathways for pollutants found in the outdoor environment to enter into houses and become indoor pollutants. These pathways are described below.

1. **Infiltration of outdoor air:** Outdoor air, or ambient air, is the prime carrier for most of the pollutants listed above. Usually outdoor air is the "clean" air with which the house is ventilated, but it can become a health threat when it contains a high load of pollution.

   There are three main mechanisms for outdoor air to enter or infiltrate the house: The first is natural ventilation produced by passive (non-mechanical) air leakage through windows, doors, and the building shell. For infiltration to take place into an enclosure, such as a house, there must be leakage holes, or paths, and a pressure difference across these holes. While you might imagine that a house wall construction is an airtight barrier, there are multiple leakage sites in every house envelope. These vary with the style of home, the type of construction and general condition of the structure. A two-story, frame home in Vermont will have a different profile than a slab-on-grade, masonry home in Florida. The way to measure house leakiness is with a device called a blower door (also known as a fan door).

   Results from blower door tests can be expressed in house air changes per hour at a 50 Pascal (Pa) test pressure ($ACPH_{50}$); the cubic feet per minute of airflow created at a 50 Pa test pressure ($CFM_{50}$); or an area known as the equivalent leakage area (ELA), which is the sum of all the measured leaks expressed as one big hole. The ELA is rated either at 10 Pa (Canada) or 4 Pa (US). Sometimes $CFM_{50}$ or the ELA are normalized, or divided, by the envelope area. See Appendix B for more information on airtightness metrics.

   Houses are therefore leaky to some degree, through holes, and there are usually pressures across these holes. One natural pressure is wind, which is variable in direction and velocity. For houses in winter climates, stack pressure is a more persistent and significant cause of air movement than wind (Reardon 2007). Stack pressures are due to the house air temperature (and density) being different from the outside air temperature. Wind pressures can certainly be the dominant infiltration driver in milder climates or during summer conditions.

   The second means of inducing infiltration is mechanical ventilation, which involves a fan or fans moving air across the house envelope. This is based on simple physics – air evacuated from the house must be made up with an equal amount of outside air. Mechanical ventilation includes bathroom and kitchen fans, heat recovery ventilators (HRVs), central vacuums vented to outside, heating systems with power vents, etc.

The HVAC system operation is the third mechanism by which outdoor air may enter the house envelope. A hot chimney, for example, pulls air from the house and creates a negative pressure within the house. A house with furnace ductwork that leaks to the outside will have higher air change rates when the circulation fan is operating. Duct leakage can also create strong negative pressures in depressurized zones. All types of mechanical ventilation and vents (such as chimneys) induce air exchange with the outside and facilitate the entry of outdoor air.

2. **Spaces attached to the house**: Air can enter from spaces attached to a house that are not typically recognized as being outdoors. For instance, in a row of town houses or in one apartment in a high-rise, air may enter from adjacent units. This air is not from "outside," but it does enter from outside the house envelope. Other attached spaces from which air enters include attached garages (containing vehicle emissions), attics vented to the outside, and open crawl spaces. (Note that some attics and crawl spaces are within the house envelope in that they are heated or air-conditioned.) A good example of poor air coming from an adjacent space occurred in a Toronto town house, where an idling car in the adjacent garage raised carbon monoxide (CO) levels in the house to the point that their CO alarms went off. The occupants escaped; the neighbor in the house with the idling car died.

3. **Soil gas:** Soil gas is actually a subset of outdoor air. It includes all gases that travel through the soil and enter the house in the below-grade sections, such as basements and under a slab-on-grade. Soil gas entry rates are influenced by the combination of foundation leakage areas and the pressures across the foundations. Radon is one notable soil gas; others include pesticides, water vapor, and volatile organic compounds (VOC) from leaking underground storage tanks. Some authors suggest that a house with a full basement may see up to 5% of its total infiltrating air entering as soil gas (CMHC 1997).

4. **Track-in:** Pollutants that are found in outside soil and dust are tracked into houses on shoes, feet, and pet traffic. This secondary entry route in terms of importance to health nevertheless showed up as a major source of lead in house dust for inner-city neighborhoods (Roberts 1992). As it is relatively easy to minimize this pathway, it should be included in any remediation strategy where surface soil and dust is a source.

5. **Water:** Some pollutants enter via household water, either from the municipal water source, well water, or spring water. Overland flooding can also bring in a host of contamination to affected houses. Municipal water is an often-noted source for organochlorine compounds such as trihalomethanes (Kim 2004), which are derived from chemicals introduced for the disinfection of water. Other possibilities of waterborne chemicals include various VOCs from contaminated sites and radon, both more common with well water sources. The pollutants are emitted from the water into air during normal household use such as baths, showers, and clothes

washing. Some waterborne pollutants are dangerous while drinking or through absorption by skin.

## Basic Approaches to Protecting Houses Against Pollutant Entry

There are several generic approaches to preventing or reducing pollutant entry, and these are listed below. While any one of those listed may be adequate, the most effective strategy for pollutant reduction will usually result from a combination of solutions.

1. **Building envelope tightness (above and below grade):** At least 30 years of practical research and demonstration have described how to tighten house envelopes (in the above-grade walls and ceiling). The leakier the house envelope, the greater the potential gains in airtightness following weatherization. Northern tier and Canadian houses are generally tighter than the housing stock in more clement climates, although tight and leaky homes can be found both north and south. New homes can achieve extremely low leakage rates, approaching 0.1-0.5 $ACPH_{50}$, through careful design, construction, and commissioning. This combined approach is commonly used to meet low-energy or low-carbon building energy standards.

   Whatever the starting point of envelope airtightness, it is usually possible to reduce infiltration to near zero under summer conditions and to very low under the more severe conditions in winter. Even in houses in Austin, Texas the penetration of outdoor particles goes near zero when the envelope is built tightly (Stephens 2012).

   It is more expensive to retrofit airtightness into an existing home than to build it into a new house. Costs can run in the thousands of dollars and will at least double if window replacement is necessary to achieve tightness goals. The expected degree of success is also dependent of the construction type (frame versus masonry, etc.). Tightening can concentrate indoor pollutant sources such as emissions from cook stoves, building materials, and furnishings, or exacerbate existing problems, such as substandard combustion venting, pollutant infiltration from attached garages, and gaseous pollutants from the soil. Therefore, it is important to have an integrated approach and trained contractors who recognize existing and potential problems in order to minimize unintended consequences and liability.

   Any house rendered tight enough to avoid significant pollutant entry will need a mechanical ventilation system to ensure an adequate air exchange rate. In an area with high concentrations of outdoor pollutants, the air intake of a mechanical ventilation system will have to treat the outside air to remove pollutants. Pollutant sensors may also be part of that system. High performance houses, which are built tight and have a mechanical ventilation system which can provide filtered outdoor air, are already protected to a large degree. A purpose-built air filter box at the air entry can provide effective yet inexpensive particle filtration of the incoming air.

The radon protection industry has thoroughly investigated the means of making foundations airtight. For poured concrete foundations, it is possible, if laborious, to fill cracks in the concrete and to seal the wall/floor joint. It is much more difficult to retrofit a seal to a concrete block basement, as the cores and voids in the mortar joints allow air to move throughout the wall, and the block face itself might be air porous. Regarding foundation leakage, the relative costs of foundation tightening vs. installation of a subslab depressurization fan favor the latter approach (see point 2 below).

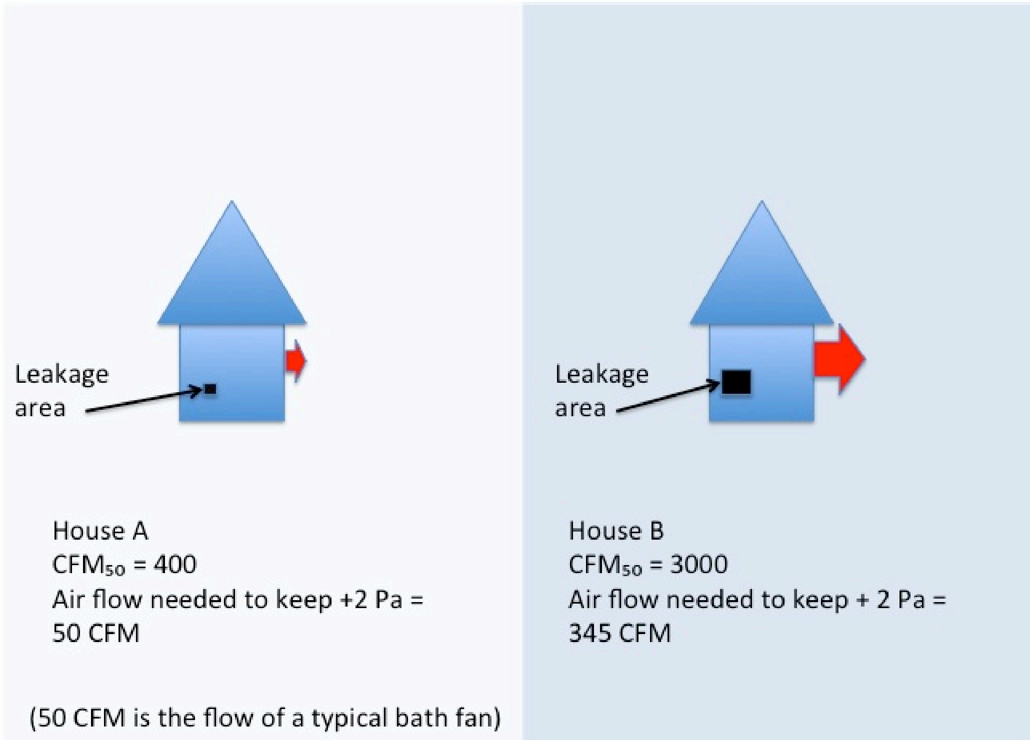
2. **Pressure boundaries:** As described earlier, infiltration of outdoor air requires an entry path and a pressure difference driving outside air into the house. Air sealing the building envelope is a preferred first solution, as it does not require much maintenance or a power supply. If the airtightness solution is not possible, or adequate for the situation, there are ways to change the house pressure with fans. The most common example is the radon subslab depressurization fan, which draws air out from underneath the slab. This creates a negative pressure under the slab (relative to the house). Any hole or crack will therefore leak from the house to the air space under the slab and be exhausted by the fan. No air (from below the slab) enters the house due to this pressure boundary.

   The effectiveness of subslab depressurization is dependent upon the material under the slab. If there is a good layer of gravel (with air spaces), then the depressurization caused by the fan will extend quite far from the fan access hole, possibly even to the footings. If the slab was poured on soil, or the aggregate has filled up with fines (such as clay), little air can move from one part of the subslab to another, and a single fan will be less effective. 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 remediation systems should be monitored by a pressure sensor or a real-time radon sensor to ensure that all the components are working as designed.

   A pressure boundary against soil gas entry can also be created by exhausting air from a crawl space or basement, depending upon how connected that foundation space is to the house above. A crawl space exhaust fan could also act as part of a whole house ventilation system, if properly designed.

   It is possible to create a pressure boundary in the above-grade portion of the house by pressurizing the house with outdoor air. There is an interplay of house tightness and pressurization air flow. A tight house requires very little air flow to create a significant positive pressure, meaning that filtration and conditioning of this air flow will be relatively easy. Conversely, a very leaky house will require large amounts of supply air to become pressurized, with the consequent problems of introducing high quantities of air into the house.

**Figure 1: Leakiness vs. air flow in pressurizing houses**




The outdoor air used to pressurize the house has to be effectively filtered to avoid introducing outdoor pollutants, if high pollutant loads in outdoor air are the problem. Pressurizing the house to reduce soil gas entry would not necessarily require outdoor air filtration, but subslab depressurization is the most recommended radon remedial strategy (EPA 2014). Depending upon the amount of outside air used for pressurization, and the condition of the outdoor air, house humidity levels may change. Another complication of this method is that current building science advises against pressurizing houses in cold climates in winter. Having a high pressure in the house forces warm, moist house air through cracks and leaks, which can cause moisture to buildup and mold to grow inside the exterior walls, particularly on the exterior sheathing, which can be roughly at outside temperatures. Research has not established yet what combination of house relative humidity and degree of pressurization might be acceptable. Until such guidelines exist, pressurizing houses in cold winters is discouraged.

Ventilation methods that only use exhaust fans can be effective at creating increased air exchange in houses. However, there is the risk of the induced negative pressure caused by these fans to increase the infiltration of soil gases or garage-based pollutants, compared to balanced ventilation options.

3. **Interior air circulation and filtration:** An air filtration solution is deceptive. While it seems reasonable to filter the indoor air to reduce the pollutant of interest, there are several issues that must be addressed. Filtration works at the filter, making it less effective for the air in other parts of the house. It also depends on routine maintenance to work effectively.

   Let's discuss stand-alone (not "in-duct") filters first. A high-volume fan with an effective filter (e.g. a high efficiency particulate air or HEPA) will markedly reduce particles in the air of a small room with a closed door. This arrangement has been used for "sanctuary rooms" for those with respiratory problems or for surgery rooms (CDC 2003). However, depending upon the size of the house, the use of a stand-alone filter in one room will have a limited effect on the air in other parts of the house. The larger the home, the less effect a stand-alone filter will have on the rest of the house. Even with a furnace fan operating intermittently, a stand-alone filter will have far more effect in the room in which it operates. Stand-alone filters need relatively high airflow rates to be effective, and such large flows can be obtrusive and noisy. Costs for filter replacement and the electrical costs for running stand-alone filter fans can be substantial.

   For houses with a duct system and a circulation fan for a forced-air furnace (or air conditioner), there is an alternate solution. The filter can be put in-line with the circulated air and treat all the conditioned air that is distributed through the house. There are many studies on the varying effectiveness of this filtered air in reducing house particle concentrations, some of which are cited later in this paper.

   The difference in the particle concentrations between the air entering and exiting the filter determines the effectiveness of the filter for particle reduction. Each filter will have a different performance level for different particle sizes. For instance, a filter that is effective for the larger airborne particles (e.g. hair, visible dust) can be completely ineffective for submicron particles (those with an aerodynamic diameter of less than one millionth of a meter, or one thousandth of a millimeter). The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) has a standard that is used to evaluate filter performance at different particle sizes and to agglomerate that effectiveness in Minimum Efficiency Reporting Values (MERV) ratings (ANSI/ASHRAE 2007).

**Table 2: ASHRAE Minimum Efficiency Reporting Values (MERV) ratings and approximate effectiveness for various particle sizes**

| MERV Rating | Performance |
|---|---|
| **Up to 4** | Coarse filter; stops particles of 10+ microns (µm) |
| **5-8** | Effective at stopping 10+ µm particles; increasing effects on 3-10 µm particles |
| **9-12** | Effective for 3+ µm particles; increasing effectiveness for 1-3 µm particles |
| **13-16** | Effective filtration for all particles > 1 µm; increasing effectiveness for 0.3-1.0 µm particles |

Note: For a more comprehensive table on MERV ratings, go to Appendix C.

A house can have a filter with near 100% efficiency at capturing particles of a particular size, but that does not mean that indoor air is free of those particles. Filtration efficiency is measured at the filter. The air exiting the 100% filter may well be particle free, but the air elsewhere in the house will have particles. Particles are created by household activities; they come in with infiltration air; they move from one part of the house to another. An effective filter in a circulation air system does not eliminate all particles in the house; it reduces them. If a filter is improperly installed and circulation air can go around rather than through it, that filter will be less effective than its rated performance. If a filter is old and heavily loaded, its performance will also be different than anticipated.

As well, filters in a furnace circulation system (for example) are only effective when the fan is in operation, which might be 50% of the time in peak season and less than 10% of the time in the shoulder seasons. No airflow means no air cleaning by the filter. Running a furnace circulation fan continuously to facilitate filtration can cost several hundred dollars a year in electrical costs, and will add to heating or cooling costs, or can introduce outdoor pollutants, when unsealed ducts are outside the house envelope (e.g. in an attic, vented crawl space, or garage). Most modern furnace and ducting systems can be retrofitted with a four-inch filter slot to accept a MERV 11 filter. Some furnace fans can be retrofitted as well to more efficient motors and blowers. If a high-efficiency filter is put into a circulation system, it is best to verify that the furnace or air conditioning fan and ducting system is suited to the filter resistance, and also to install a monitor to warn of excessive filter resistance as it loads up (Walker 2013). Be cautious of introducing a high efficiency filter if the house has ducts outside the envelope and potential leakage to and from the outside.

Filters can also be used to reduce gases or VOCs, although such filters are less commonly used in houses than particulate filters. 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-phase filter depends on the mass of the filtration material, the amount of pollutant it has to treat, and other factors such as the amount of moisture in the air. The chemical media bed can be tailored for the pollutant of interest, if its chemical makeup has been identified.

If a filter is used to reduce particles or VOCs in a pressurization strategy, it is susceptible to filter loading and the effects of wet outside air.

Reports of "filter emissions" indicate instances in which the collected chemical or biological debris on the filter becomes a pollutant source in itself (Schleibinger 1999). A filter loaded with debris for months or years has to be a pollution source, just like a carpet or furniture taking in VOCs in high periods and then re-emitting them. A loaded filter is a reservoir. 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 is a very good option for minimizing stored material in the high-efficiency filter. This situation applies either to recirculation filters or filters on supply air. The other issue with supply air filters is the ingestion of airborne rain, mist, or snow and the consequent wetting of the filter material. 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 air quality solution.

4. **Cleanliness:** This pollutant defense harkens back to parental advice: "Take your shoes off at the door!" and "Clean up your room!" Essentially, dust and debris on the floors of houses create two types of risk: For infants, toddlers, and others who play on the floor, the dust (and its pollutants) can be directly ingested or attached to wet fingers or toys that go into the mouth. This is a common pathway for lead and one of the main reasons that children under two are at a high risk in a house with significant quantities of lead in house dust. The other main risk is contact through dust re-suspension that occurs whenever there is activity. Even the head of a vacuum cleaner rubbing along a carpet or hard-surface flooring will raise clouds of dust (CMHC 1992). Some particles will also blow through non-HEPA vacuum bags. The re-suspended dust is at that point available to be inhaled.

   Note that pollutants such as lead or VOCs can build up within house contents such as carpets and upholstery. Animal and insect debris can accumulate in walls or insulation. Airborne industrial pollutants can gather in attics or other spaces that are rarely used or visited. When these places are eventually disturbed through renovation, for instance, pollutant exposure can be significant and unexpected.

5. **Water treatment:** States where well water is frequently contaminated with radon have provided consumer fact sheets about how to pretreat water to remove contaminants (NH 2014, PennState 2014). 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 pamphlet, Radon in Air and Water: An Overview for the Homeowner, does not recommend the use of GAC generally because the GAC filter becomes saturated with radioactive material, making safe disposal difficult and expensive.

   Water filters can also be used to reduce organochlorine compounds from municipal sources or other chemical or biological pollutants. If the filter is not being contaminated by radioactive sources, disposal is not a problem. Reverse osmosis treatment can also be effective for some pollutants, although it is not recommended for radon removal.

   Water decontamination at the level of municipal water supplies is beyond the scope of this paper.

6. **Interactions between these approaches to minimizing outdoor pollutants:** None of these solutions stands alone. The effects of one solution can amplify or render useless the utility of another. Airtightness is a good example: a house with a tight envelope will not let in much outdoor air. The lower air change rate means that an indoor filter has less pollutant to clean. A tight house envelope 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 house airtight. Subslab depressurization benefits from a tight basement floor: the pressure is easier to establish and the householder can use a smaller, quieter fan. A tighter house with less infiltration can require less cleaning.

   The presentation by Brent Stephens (Stephens 2014) does a good job of summarizing all the factors that control the entry of outdoor pollutants. The indoor concentrations of the pollutant will be higher in houses with leaky envelopes and smaller volumes. The concentration of outdoor pollutants in the house will be lower when the house has an effective filtration system which runs continuously at high flow rates. The reactivity of the outdoor pollutant is also a factor: the more it reacts or deposits coming through the house envelope, or after it enters the house, the lower the house concentrations.

   Houses that are not diligently cleaned will have higher concentrations of indoor particles and can be reservoirs for the outdoor pollutants that have entered. Houses with high amounts of airborne or settled dust will require more frequent filter changes.

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 that will keep airborne radon from migrating to other parts of the house.

Consider these suggestions a "basket of solutions" that can be used either individually or in conjunction for the particular circumstances of the house and its occupants.

**Limitations of Potential Solutions:** While the above measures can all work to reduce the effects of outdoor air pollutants on indoor air, there are limitations. People with extreme sensitivities or vulnerabilities may need better air or water 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.

For the large majority of householders who will benefit from the strategies described in this section, the onus is on them to ensure that the systems work as designed. Systems may be compromised, for example, by opening windows in an otherwise airtight house, or by not using or maintaining filters. Also, the additional costs of filter replacement and circulation fan use can be prohibitive for low-income households.

## Demonstrated Effectiveness of Remedial Measures

1. **Tightening up the house envelope:** The largest database of houses undergoing tightening comes from American weatherization programs. Often the houses involved are in poor condition, and large reductions of air leakage can be made by sealing their major pathways. Studies of thousands of houses from Ohio, Wisconsin, and Illinois (Francisco 2014) show that, typically, weatherization caused reductions of air leakiness of 20-40%. These reductions are beneficial for the energy usage of these households. However, the residual air leakiness of 2000-3000 $CFM_{50}$ (or roughly 5-10 $ACPH_{50}$) does not constitute an "airtight" envelope that excludes outdoor pollutants.

   In several studies, contractors made the effort to do deep energy retrofits (DER). The airtightness achieved by these initiatives resulted frequently in houses being tighter than 2 $ACPH_{50}$ (or $CFM_{50}$ in the low hundreds) (Gates 2014, Berges 2013), an airtightness that assures very minimal outdoor air entry except under severe conditions. Other house retrofits, notably those where houses are attempting to meet "net zero" goals or the Thousand House Challenge (THC), meet the airtightness standard of the Passive House program (www.passivehouse.us). Houses certified to Passive House standards have an airtightness criterion of 0.6 $ACPH_{50}$, or 1.0 $ACPH_{50}$ for retrofits, again making the building envelope near impervious to air. Most of these retrofits require significantly retrofitting the exterior wall (i.e. insulation, air sealing, siding) with very close attention to airtightness details. Reaching 0.5 $ACPH_{50}$, or even 2.0 $ACPH_{50}$, cannot be done without trained contractors and personnel working diligently towards that goal. Blower door testing during the progress of the retrofit is necessary to verify that the airtightness gains are being achieved.

There is also research on sealing garage or house leakiness to reduce the effects of garage air pollution inside houses (Mallach 2014). It is difficult to quickly judge the effectiveness of such sealing, as the garage-to-house leakiness is calculated indirectly from multiple blower door tests. As is true with regular house air sealing, large holes can be relatively easily located and closed up; smaller leakage areas are more diffuse and harder to seal.

2. **Filtration of indoor air:** Ten houses in Alaska with recirculated, HEPA-filtered air were reported to show an indoor $PM_{2.5}$ reduction of 76-87% with respect to the high outdoor $PM_{2.5}$ in a time of forest fires (Reynolds 2004). The report suggests that the HEPA units were stand-alone and not ducted, but this has not been confirmed. Barn et al. (2008) found a similar stand-alone (non-ducted) residential HEPA air cleaner effectiveness of about 65% in summer months in a sample of houses in British Columbia. Outdoor $PM_{2.5}$ concentrations in the BC study were high, but not as elevated as those found in the Alaska research project above. These results are useful in providing a level of performance for standalone filtration.

   Jeffrey Siegel and colleagues have looked at the effectiveness of portable air cleaners in reducing pollutants in house air (Kang 2008). The filtration efficiency, fan flow rate, and location of the portable device are all important, both for reducing pollutant loads in a single room and in the whole house. For a single room to be treated as effectively as possible with a portable air cleaner, the doors and windows need to be closed.

   MacIntosh et al. (2008) reported up to 80% particle reduction through the use of filters on a forced-air circulation system, but this was in response to a spike in (not sustained) loading. Canadian residential research (Bowser 1999) showed similar results on a single pass through high-efficiency residential filters, but the reduction in measured house particle concentrations was far lower than the pass-through filter efficiency, especially during periods when the occupants of the house were present and active. For instance, an electrostatic precipitator with a pass-through efficiency > 90% on $PM_1$ resulted in house $PM_1$ concentrations only 30% lower when the occupants were awake and active. Active people (or pets) create particle sources (e.g. cooking) or re-suspend settled dust in their use of the house. A filter 50 feet away in a duct is going to have much less effect on the particle concentrations in an occupied kitchen, for instance, than it has on the particles in the duct itself.

   Comparisons of filter effectiveness from one study to another are hampered by the use of different size particle cuts, magnitude of the particle challenge the filters face, and operating schedules of the fans driving the filters.

3. **House pressurization plus interior filtration:** In 2004, Alaska experienced numerous forest fires. Small particles ($PM_{2.5}$) in the outdoor air exceeded 1000 $\mu g/m^3$, well above any known health threshold (e.g. EPA 24-hour outdoor standard is 35 $\mu g/m^3$). The Cold Climate Housing Research Centre (CCHRC) in Fairbanks outfitted 19 houses with a combination VOC and HEPA filter with a maximum airflow capacity of 240 $ft^3$ per minute (cfm). Nine houses used the airflow through the filter to pressurize the house to about 1 Pa above outside atmospheric pressure.

   Despite the HEPA definition of 99.97% filtration of contaminants of 0.3 µm, the measured reduction of $PM_{2.5}$ in the post-filter airflow was between 92% and 97% compared to outdoor values. In these nine mildly-pressurized houses, indoor $PM_{2.5}$ was 87-92% less than outdoor (10-34 $\mu g/m^3$ vs. a range of 94-368 $\mu g/m^3$ of $PM_{2.5}$ in the outdoor air). A small study in Ontario in 2003 (CMHC 2003b) found a similar reduction of about 84% in $PM_1$ with HEPA-filtered supply air, but at much lower outdoor PM levels.

4. **Soil gas exclusion:** An 81-unit town house development was built in Kitchener, Ontario in the 1970s on an old dump site and adjacent to a small mountain of municipal landfill. Although simple vent stacks were put in place to reduce soil gas (methane) entry, the town houses suffered from high levels of explosive gases and were eventually abandoned. Canada Mortgage and Housing Corporation (CMHC), a quasi-governmental agency that also provided mortgage insurance, took the units over after mortgage default.

   This site was studied extensively from 1988 to 1992. The buildings were rehabilitated and a soil gas extraction system installed, based on radon gas remediation systems. Large, exterior fans drew from beneath the basement slabs of several units simultaneously and exhausted the subslab gases above the roof tops. Methane alarms in the houses and monitors linked to the operation of the exhaust fans. An engineering firm has performed annual audits of the system and its efficacy. The remedial measures reduced interior methane levels from near explosive to the low part per million (ppm) range (CH2M Hill 1990). The houses have been occupied by tenants since the early 1990s with no dangerous occurrences of soil gas entry.

   This example, and the millions of houses that have had subslab ventilation installed and monitored for radon problems, shows 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.

5. **Cleanliness:** To promote cleanliness, avoid tracking in dirt by removing shoes at the door or using a walk-off mat to remove shoe dirt. This strategy has been shown to reduce tracked-in lead dust by up to 90% (Roberts 1992). The other main means of reducing settled dust is by frequent cleaning, usually with an effective vacuum cleaner. For cleaning to be successful, the floors must have no significant amount of

miscellaneous debris to interfere with the cleaning process. First – tidy up; second – vacuum. There are many reports on the effectiveness of vacuum cleaning, the comparative cleaning efficiency of different vacuum cleaners (CMHC 1992), and the effects of more frequent cleaning (CMHC 2003a). Essentially, regular and effective vacuuming will reduce the amount of dust in carpets and on floors, and resuspension of particles will be minimized. Recent experiments involving regular cleaning in houses with asthmatic children have shown good results in the reduction of their respiratory symptoms (Morgan 2004).

6. **Water treatment:** One of the seminal research projects on this technique took place in the 1980s, where 22 residential water systems in seven states were treated with prototypical aeration systems (Lowry 1988). The results show 92-99% radon removal, with variations dependent upon the water flow rate. Distributors of current commercial aeration systems typically quote 97-99% in their literature. Capital costs are in the thousands of dollars, with annual maintenance costs in the hundreds.

**Table 3: Summary of remedial measures to keep protect houses from outdoor pollutants**

| Remedial measure | Potential effectiveness | Cost | Degree of necessary occupant interaction | Maturity of technology (readily available?) | Comments |
|---|---|---|---|---|---|
| | All ratings are qualitatively low, medium, or high | | | | |
| **Tighten house envelope** | High | High | Low | Medium | A tight house is 100% effective but will require mechanical ventilation (which will introduce outdoor pollutants) |
| **Filtration of indoor air (or incoming air)** | Medium (high at filter; medium in rest of house) | Medium | High (requires inspection, replacement, need to accept noise) | High (for particle reduction) | Almost always will be part of the solution |
| **House pressurization** | High | Medium | Medium | Low | This solution has not been extensively tested |
| **Subslab depressurization for soil gases** | High | Medium | Low | High | A specific pressure boundary solution |
| **House cleanliness** | Medium | Low | High | High | It takes diligence and the right tools |
| **Water treatment for gaseous pollutants** | Medium to high | High | Medium | High | |

**Potentially new solutions:** While there have been many claimed improvements in filter technology over time (stand-alone HEPA attached to forced air system, UV lights in ducting, various chemical filter additives, etc.), nothing has demonstrated improvement in filtration efficiency enough to be ready for a wider distribution.

An area requiring further research is the degree of permissible house pressurization in winter, as then more pressurization strategies could be attempted. Currently, there are few manufacturers of pressurization fans with filter cassettes and pressure control equipment. If the market were larger, more equipment would be available.

Cleanable filtration, at least for coarse particles, would lower the filter replacement costs for those solutions.

There has been no good scientific comparison of tracked-in dirt in houses with conventional cleaning equipment vs. those that have robotic, frequent-usage devices. Were the robotic vacuums shown to be far more effective, then they could be an affordable part of a settled dust reduction.

More research and reporting on envelope retrofits should provide guidance to efficient ways to achieve airtightness. Builders in Canada in the 1980s all had steep learning curves when they tried to meet R-2000 airtightness levels of 1.5 $ACPH_{50}$ in their new houses. Retrofit or weatherization crews trying to similarly tighten existing houses will find the means to do so for the different types and ages of housing stock in the US and Canada, but it will take some time to optimize procedures. A first analysis on the deep energy retrofit of American houses is available from Lawrence Berkeley National Laboratory (Less et al 2014).

At the other end of the spectrum from homeowner-operated detection devices is the coming possibility of widely-distributed, cloud-based data tracking. Once appropriate instrumentation is available at a reasonable price, there are good possibilities for using multiple sites of local data instead of a single pollutant measurement made at a central urban (or airport) government station. If the outdoor pollutants are very locally generated (e.g. woodstove emissions), then a distributed monitoring system will permit much better focused remediation.

There are still many unknowns. A preliminary list of research questions is attached as Appendix D.

**Recommendations:** One way to minimize the effects of outdoor pollutants is to start doing remediation. Selecting vulnerable populations or specifically high pollutant loads would be a good start. Doing the research to test and refine solutions to outdoor contaminants can be justified most easily by benefitting those who need it most. Community-based programs are also a good way to improve remediation methods and optimize limited resources. They can provide comprehensive programs, instrumentation, monitored results, expert interpretation, and publishing of the findings (EPA 2011). Community-based programs, by dealing with many factors, also have a better chance of seeing health improvements in the study population when compared to more narrow initiatives.

The Los Angeles Collaborative for Environmental Health and Justice (LACEHJ) is one example where a community group has made a difference. The LACEHJ developed a process called "ground truthing" which detailed air pollution sources and effects in parts of Los Angeles (LACEHJ 2010). The group surveyed four communities, identifying more detailed pollutant sources and susceptible populations than state regulatory agencies had been able to locate. Furthermore, they used monitoring equipment borrowed from the California Air Resources Board (CARB) and UCLA to show hot spots where pollutant concentrations far exceeded regional measurements. Their report, entitled "Hidden Hazards", is a good guide to how groups can effectively create a portrait of the air pollution risks specific to their communities.

Monitoring the performance of solutions is important; this verification process is often overlooked. Attempts at reducing indoor exposure to outdoor pollutants would benefit from good documentation. While all of the possible solutions will be useful, some will be more useful than others. Establishing their relative utility will require monitoring data.

Some mitigation strategies such as radon systems and reducing dust lead have a substantial documentation and procedures in place. Solutions for other pollutant sources will require a similar development before they become widely accepted.

**Conclusions:** Outdoor pollutants may affect indoor air. While the quality of outdoor air has generally been improving over the last several decades in many parts of North America, new stresses (such as fracking or climate change–induced pollution spikes) and established risks (adjacent highways and rail traffic) can result in elevated indoor pollutant levels. The solution sequence is straightforward:

1. Determine the pollutant of interest (and whether the source is internal or external);
2. Reduce or eliminate the source of pollution, if possible;
3. Identify the pathway into the house from the outside;
4. Use one or more of the available solutions to mitigate the remaining risk;
5. Monitor the effectiveness of the action; and
6. Disseminate this information.

Outdoor air pollutants can certainly be reduced in houses. The solutions identified in this paper have varying levels of effectiveness that should be evaluated against the critical nature of the contaminant and the available resources to conduct the remediation procedures. With continued research and monitoring, it will become clearer which solutions should be applied to each situation. Ease of use will improve; effectiveness should increase; installation and operating costs should fall.

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## Appendix A: Information Resources

1. Environmental Protection Agency (EPA) http://www.epa.gov/air/ (a government primer on all aspects of indoor and outdoor air pollution)
2. LBNL Indoor Air Quality Scientific Findings Resource Bank at: http://www.iaqscience.lbl.gov/ (a site that looks at IAQ, health, and remedial measures and evaluates current knowledge on these issues)
3. National Center for Healthy Homes http://www.NCHH.org (a healthy housing website with much information on lead, IAQ, and child health)

## Appendix B: Information on Units and Test Methods for Measuring Airtightness

As an example, let's use a 500 $m^3$, two-story house with a full basement. The six-sided envelope area (all walls, lowest floor, all ceilings under roofs) would be approximately 380 $m^2$. In US units, this would be a house of a volume of 17,657 $ft^3$ or a house with 700 $ft^2$ on each of two above-grade floors and a 700 $ft^2$ basement, with an envelope area of about 4150 $ft^2$. This could be a medium-size, suburban house with three bedrooms. If the house tested at 3.0 $ACPH_{50}$, this would mean that it has a measured $CFM_{50}$ of about 880 $CFM_{50}$. If the house had a typical value of the exponent "n" of 0.65, then the $ELA_{10}$ (Canadian) would be 587 $cm^2$ (91 $in^2$), and the US $ELA_4$ would be 313 $cm^2$ (49 $in^2$). Measurements of house leakiness in the US and Canada show that a leaky house can have an ELA at least 10 times bigger than a similar tight house.

Metrics using air leakage divided by the surface area of the envelope have also been used. In Canada, the normalized leakage area (NLA) was used for several years, although it was not clear if the above- and below-grade envelope area should be used, or the above-grade only. More recently, there has been uptake of the $CFM_{50}$ flow rate normalized by the six-sided envelope area in US weatherization and among those involved in new and existing high performance buildings.

Small houses appear to have relatively leakier envelopes than big houses. The number of envelope penetrations such as windows, doors, chimneys, cable access, gas lines, etc. are often not much different in small and big houses, but the big houses spread them over a much larger area of wall and ceiling. Using the measurement units above, a big house will usually have a larger $CFM_{50}$, or ELA, but can often have a smaller $ACPH_{50}$, as the leakage areas are normalized, or divided, by a larger volume in that calculation.

Each metric can be useful for some application. The goal is to use the most suitable metric for the situation at hand. Flow rate $CFM_{50}$ is generated by the blower door test results and is proportional to the envelope leakage area. Test results at the 50 Pa range are often more repeatable than those at lower pressures, as wind fluctuations have less relative effect.

Volume, though, makes a difference. If you put a quarter-inch diameter hole in a coffee cup or a cruise ship, you might find the same flow rate through that hole. A quarter-inch hole in coffee cup will cause consternation and a big mess. A quarter-inch hole in the hull of a big ship may not be noticed in the length of a voyage.

## Comparison of airflow vs. house characteristics

| House description | Bungalow, slab-on-grade | Suburban ranch with full basement | Large older house with three stories plus full basement |
|---|---|---|---|
| **Plan dimensions (ft)** | 30x40 | 35x50 | 30x40 |
| **Floor area ($ft^2$)** | | | |
| **In real estate terms** | 1200 | 1750 | 3600 |
| **Actual floor space** | 1200 | 3500 | 4800 |
| **Volume ($ft^3$)** | 9600 | 29750 | 42000 |
| **6-sided surface area ($ft^2$)** | 3500 | 6390 | 7300 |
| **Tight house with $CFM_{50}$ = 400 $ft^3$/min** | | | |
| **$ACPH_{50}$** | 2.5 | 0.81 | 0.57 |
| **$ELA_4$ ($in^2$)** | 28.9 | 28.9 | 28.9 |
| **CFM50/surface area** | 0.11 | 0.06 | 0.05 |
| **House with moderate leakiness $CFM_{50}$ = 2000 $ft^3$/min** | | | |
| **$ACPH_{50}$** | 12.5 | 4.03 | 2.86 |
| **$ELA_4$ ($in^2$)** | 110 | 110 | 110 |
| **CFM50/surface area** | 0.57 | 0.31 | 0.27 |

Note: Assumed 8 foot ceiling and 1 foot interior floor thickness included in volume (and surface area) calculation.
The airtightness test exponent is assumed to be n= 0.65 for these calculations

## Appendix C: MERV Explanation from Newell 2006

| MERV Value | Average minimum composite filtration efficiency (%) | | | Average % arrestance (ASHRAE 52.1) |
|---|---|---|---|---|
| | 0.3 to 1.0 µm | 1.0 to 3.0 µm | 3.0 to 10.0 µm | |
| **1** | | | <20 | <65 |
| **2** | | | <20 | 65-70 |
| **3** | | | <20 | 70-75 |
| **4** | | | <20 | 75-80 |
| **5** | | | 20-35 | 80-85 |
| **6** | | | 35-50 | 85-90 |
| **7** | | | 50-70 | >90 |
| **8** | | | >70 | >90 |
| **9** | | <50 | >85 | >90 |
| **10** | | 50-65 | >85 | >95 |
| **11** | | 65-80 | >85 | >95 |
| **12** | | >80 | >90 | >95 |
| **13** | <75 | >90 | >90 | >98 |
| **14** | 75-85 | >90 | >90 | |
| **15** | 85-95 | >90 | >90 | |
| **16** | >95 | >95 | >95 | |

## Appendix D: List of Questions Relating to Outdoor Air Pollutants in Houses

### Airtightness

1. How do indoor concentrations of airborne pollutants vary in response to differing building enclosure leakage rates and leakage characterization, as well as different types of air born pollutants? How does pollutant entry vary by pollutant size and type with the building leakage site characterizations, e.g. direct penetration such as gaps and cracks vs. indirect leakage through building cavities?

2. How do the building construction and/or building envelope materials influence infiltration rates and remediation options?

3. Many homes are so leaky that any effort to pressurize and filter air would be cost prohibitive. What options exist to pressurize a smaller zone within a home to enhance the air quality within that space?

4. Where natural night-time summer ventilation is used for cooling, are there strategies that can simultaneously reduce the entry of outdoor pollutants?

5. When driving forces are minimal as during a summertime inversion condition with little wind, what impact does house tightness have on pollutant entry?

### Monitoring & Measurement

1. Do proxies exist that can be used to estimate pollutant entries through building enclosures? If so, what proxies work for what types of pollutants; e.g. given constant occupancy can monitoring CO2 be a useful indicator of actual air exchange rates?

2. How can low-cost particle counters be used effectively to inform occupants and help to calibrate the operation of air filtration strategies (run time, fan speed, location, filter type and maintenance)?

3. Assuming that small amounts of radon gas are present, can radon effectively be used as a tracer for all soil gas sources?

4. Can filter contents be analyzed in order to get an accurate understanding of pollutant sources, or does the age of the filter contents and interactions over time overwhelm what can be usefully obtained from lab analysis?

5. With the emergence of online residential air quality monitoring, what can be learned about their effective use, and what level of accuracy is needed to support appropriate behavior or modification of a intervention strategy?

6. How can the mapping of both local air quality data as well as health data be used to target communities for the development of customized building interventions?

## Air Cleaning

1. Do guidance documents or field protocols exist to effectively address issues of to determine the appropriateness of high MERV filters in existing forced air duct systems in order to minimize unintended consequences of excessive air handler fan energy use and cost, exacerbating in/exfiltration due to either duct leakage or pressure imbalances, and creating static pressure conditions outside of the HVAC systems nameplate rating?

2. What conditions contribute to greater incidence of filter emissions? How can filter emissions be minimized, and how can they be identified or made visible to occupants?

## Interactions

1. Exhaust ventilation has been used to isolate garages from homes; under what conditions can the same strategy be deployed to isolate crawl spaces or basements from living spaces as an integrated approach to reduce entry of gases from these spaces into the living space while simultaneously providing controlled mechanical ventilation?

## Deployment

1. What practical field methods exist to fine tune the selection of a filter medium to a home's needs in order to optimize air quality and minimize cost?

2. Do guidance documents or field protocols exist to effectively address issues to determine the appropriateness of high MERV filters in existing forced air duct systems and to minimize unintended consequences of excessive air handler fan energy use and cost, exacerbating in/exfiltration due to pressure imbalances, and creating static pressure conditions outside of the HVAC systems nameplate rating?

3. How can radon remediation be integrated into energy use reduction initiatives without significantly affecting transaction costs?

4. What deployment strategies (equipment lease/loan) could work for pollutant sources that are episodic – such as forest fires or construction activity?

5. What deployment strategies can be deployed in order to properly size and calibrate the operation/run time of a filtration intervention?

6. How can feedback be successfully used to reinforce appropriate operation and maintenance?