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# Indoor Air Quality

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## Abstract

Indoor air pollution is an international health concern because people spend a majority of their time indoors. Children are at a higher risk of health problems from pollutant exposure, especially because air in the child breathing zone is more polluted than it is in the adult breathing zone. Pollutants of concern include biological contaminants, combustion pollutants, volatile organic compounds, and radon and other soil gases. Humans have a history with lead and asbestos that goes back thousands of years to the ancient Romans and Egyptians. These two pollutants are still problems in older homes and apartments. All of these toxicants can be minimized or abated. Awareness of these issues is a critical first step in improving air quality in places where people live.

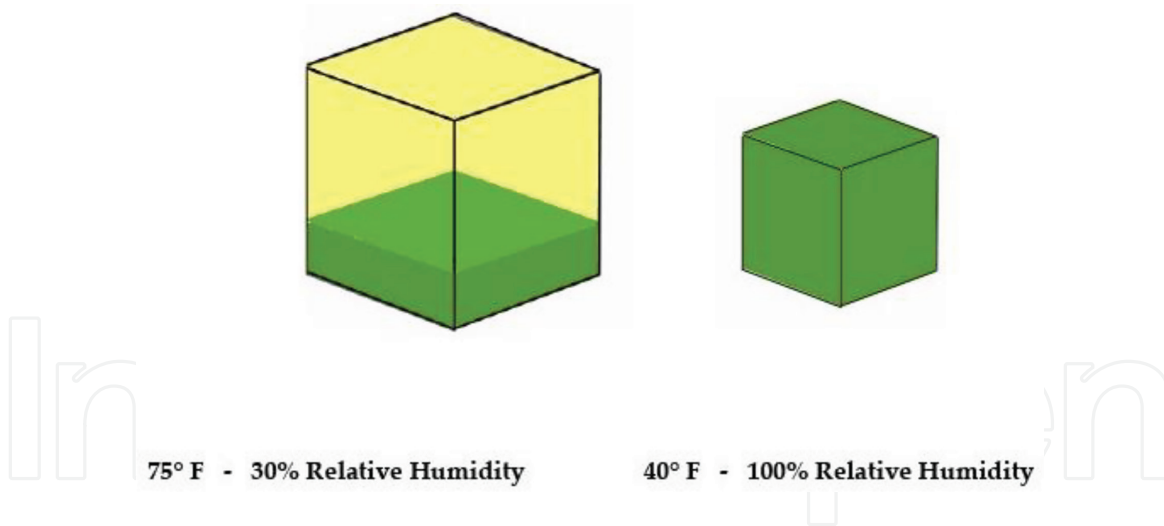
**Keywords:** biological contaminants, combustion pollutants, volatile organic compounds, radon, lead, asbestos, child breathing zone

## 1. Introduction

In recent years, indoor air pollution has become an international health concern. Research has shown that people spend about 90% of their time indoors [1] and 75% of their time indoors in their homes [2]. Some people such as children, the elderly, and infirm spend most or all of their time indoors [3, 4]. Research also indicates that pollutant levels can be higher indoors than outdoors [5]. Concerns about indoor air quality have led to indoor air management becoming a new consumer skill. Steps involved in indoor air management include identifying a pollutant of concern, controlling it at its source, and if that fails, mitigation. Residential indoor air pollutants include biological contaminants, volatile organic compounds, radon and other soil gases, combustion pollutants, lead, and asbestos.

## 2. Biological contaminants

Biological contaminants include mold, viruses, bacteria, pollen, animal dander, and dust mites. Moisture plays an essential role in the presence of biological contaminants. As shown in **Figure 1**, warm air holds more water vapor than cold air. The cube on the left represents a volume of air that is at 75°F, with 30% relative humidity. This means that it is holding 30% of the moisture that it is *capable* of holding. When that same amount of air cools to 40°F, it contains the *same amount* of water, but it is now at 100% relative humidity. In other words, it is holding all of the moisture that it *can* hold. Moisture will condense at 100% relative humidity. This is also called the saturation point or the dew point temperature.

**Figure 1.**

*Warm air holds more moisture than cold air.*

When warm, moist air comes in contact with a cold surface, the water vapor in that air condenses to liquid water. In the case of a cold window, when warmer, humid air moves closer to the window, its temperature drops, and therefore its moisture-holding capability also drops. When this air touches the window, it condenses. The same thing happens on a warm and humid summer day, when warm, humid air condenses on cold beverage bottles, cans, or glasses. Sometimes, condensation on a window can be a nuisance. Other times, it can be serious enough that moisture will accumulate on the sash and on the sill, causing mold growth, warping that will damage the airtight seal between panes of glass, and even rotting. Mold spores are ubiquitous, and when a spore lands on a surface at the right temperature, with a food source—in this case, cellulose—and moisture, mold will grow.

Mold is a fungus; and as fungi grow, they release large numbers of spores into the air. And as mold digests cellulosic products, such as wood, as food, it releases carbon dioxide, water, and microbiological volatile organic compounds (mVOCs) into the air. Airborne spores affect asthmatics and people with allergies by acting as asthma triggers and the cause of respiratory illness. Microbiological volatile organic compounds are responsible for the musty smell associated with mold growth. Inhalation of mVOCs by humans can cause mycotoxicosis, symptoms of which include difficulty breathing, sore throat, bloody nose, and skin rashes.

Preventing health problems caused by exposure to mold is done by controlling moisture in homes. This means maintaining relative humidity at levels that do not allow for moisture condensation on windows and other surfaces, regularly inspecting plumbing pipes and fixtures for leaks, and preventing the entry of water from outside the home by maintaining roofs and siding and having a water-managed foundation.

Another biological contaminant commonly found in homes is the house dust mite, which feeds on skin cells that are naturally shed from human bodies. Fecal pellets from this microscopic arachnid contain a protein that is an allergen and asthma trigger. Dust mites thrive in humid environments and live in upholstered furniture, bedding, carpeting, and stuffed animals. They cannot survive at relative humidity levels below 50% [6]. Other biological contaminants in indoor air include viruses, bacteria, pollen, and animal dander. All of these can be controlled through regular house cleaning.

## 2.1 Ventilation

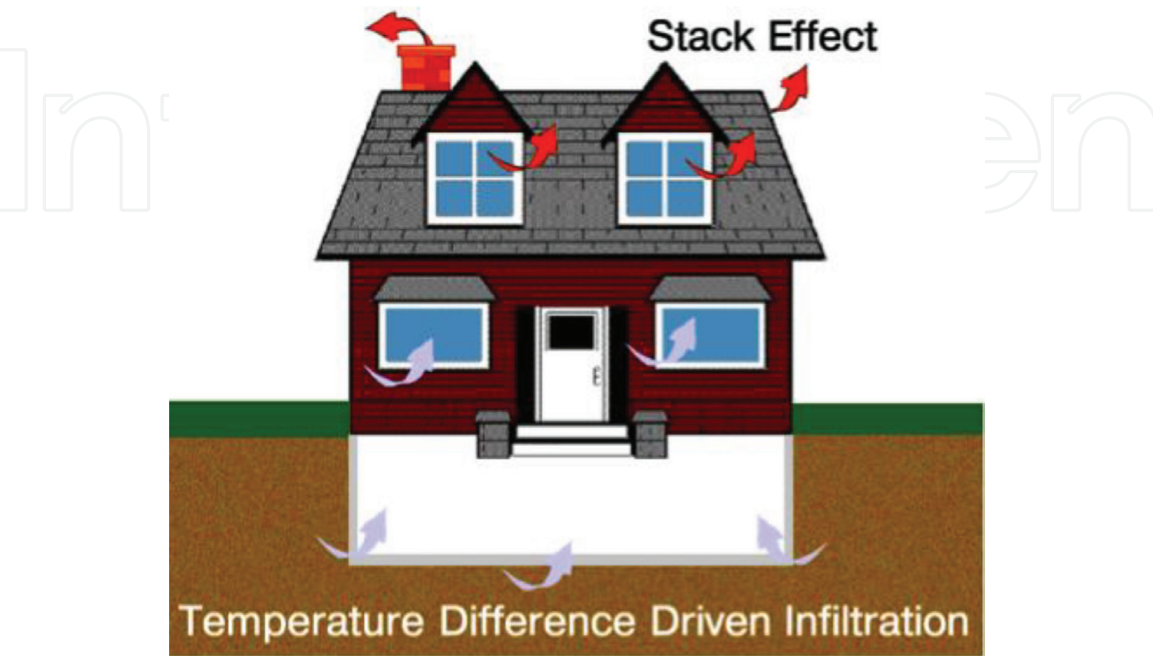
A number of factors contribute to the high levels of energy efficiency that are now possible in new and existing homes. Airtightening measures—those that

prevent air infiltration through the building shell—are among the most critical of these. In new construction and in the improvement of an existing home, low air infiltration rates are achieved through an attention to the details of both construction materials and practices. And as air leakage has decreased in homes, ventilation has become a residential design issue because of problems that arise from excess moisture and other indoor air pollutants.

Before airtightening measures were as widespread as they now are, ventilation of homes was achieved naturally, as air leaked in and out of cracks in the building shell—around windows and doors, where dissimilar building materials meet, and other places. Natural ventilation is undesirable because it can never be controlled. Its rate depends on wind speed, vegetation around a house, site topography, and other variables. And natural ventilation imposes large energy costs on a home because the incoming infiltration air must be heated in the winter in cold climates. But in the absence of natural ventilation, mechanical ventilation is necessary for removing moisture and other pollutants as well as bringing fresh air into a home.

A basic mechanical ventilation system consists of exhaust fans, which are ducted to the outdoors, in kitchens and bathrooms. Conventional clothes dryers should always be ducted to the outdoors, although some electric clothes dryers vent into the washer. And some clothes washers also act as dryers. An issue that arises in airtight homes is the provision of make-up air for exhaust systems. As exhaust fans pull air out of a house, that air must be replaced. In a leaky house, that air is supplied through infiltration. This happens because the fans place negative pressure on a house and, if no windows are open, pull in air from cracks that exist in the building enclosure or from a chimney, which can be dangerous if the chimney is connected to an operating combustion appliance. Other ventilation systems exist that not only pull air out of a house but also provide make-up air.

**Figure 2** shows temperature-difference-driven infiltration, also called the stack effect. In simpler terms: a house comes under negative pressure as warm air naturally rises to upper levels of a house. That warm air escapes through various faults in the building enclosure, including cracks that form at junctions of different types of construction materials, such as those where brick meets wood siding. Warm air



**Figure 2.**  
*The stack effect.*

also escapes from unsealed cracks around windows and doors. All air that leaves a house in this manner must be replenished. This happens when air leaving the house creates suction pressure on lower house levels, which causes soil gases, including radon, to be pulled into the house.

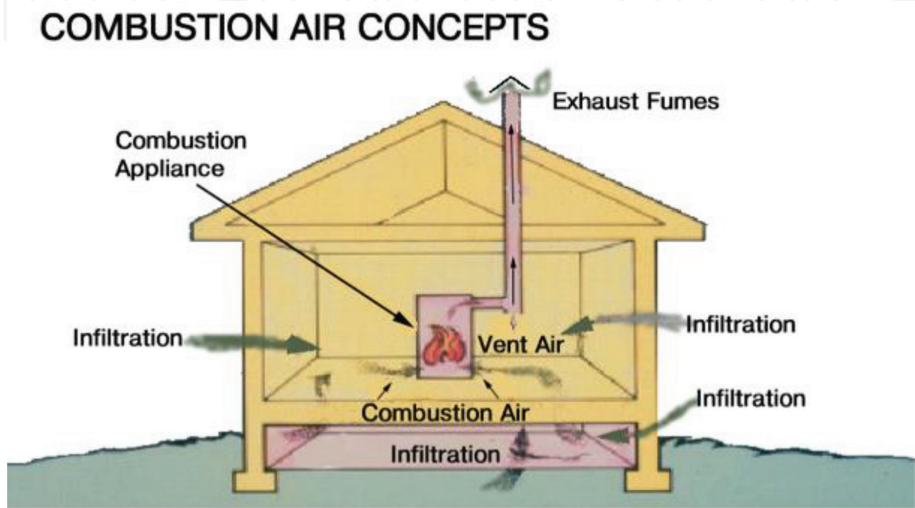
**Figure 3** shows how combustion appliances can also bring a house under negative pressure. All combustion appliances use some type of fuel, whether it is fuel oil, natural gas, propane, or wood. Oxygen is needed to fuel the fire, and if that oxygen comes from indoor air, it will put negative pressure on a house, just like the stack effect does. Air gets drawn into the appliance, fuels the fire, and that air needs to be replaced. The replaced air comes in through cracks in the building enclosure as well as cracks in the foundation of the basement, which can allow soil gases to enter the home.

A solution to negative pressure caused by a combustion appliance is to use a sealed combustion appliance. This type of furnace or boiler brings air to the combustion chamber through a pipe that originates outside the house. Sealed systems typically have a second heat exchanger that extracts heat from combustion gases that would normally be exhausted by the chimney in a conventional system. Instead, extracting additional heat from combustion gases results in exhaust gases that are cool enough to be exhausted from the house through a pipe through an exterior wall, much like a clothes dryer vent. Because the combustion air comes from outside the house, the building does not come under negative pressure.

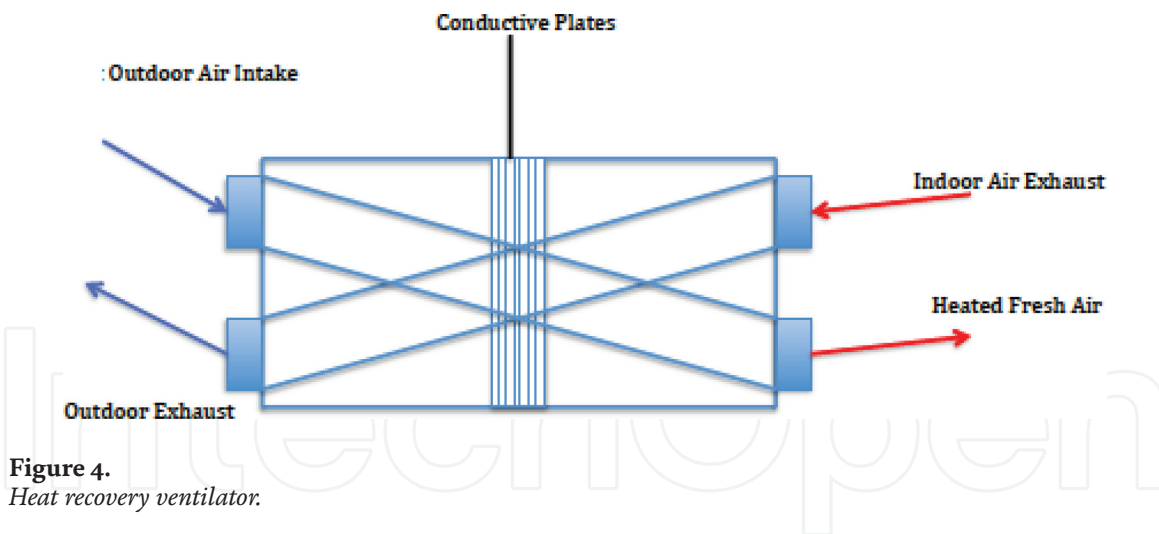
Approaches to residential ventilation can be categorized as exhaust, supply, and balanced systems. Fans that pull air out of a space such as a bathroom exhaust fan or a kitchen range ventilation hood comprise basic exhaust ventilation systems that most people are familiar with. As noted above, however, these fans can place an airtight house under negative pressure.

Variations of exhaust systems provide make-up air to the house in some manner. The simplest way to do this is to install passive vents, which are small, screened openings in exterior walls. These admit air by opening when the home comes under negative pressure, such as when an exhaust fan is turned on. Passive vents are only recommended for use in very small, airtight homes in which depressurization is safe. Home depressurization is safe if all combustion appliances receive combustion air from outside the home; there are no fireplaces in the home; the home has no attached garage; and the home is not located in a high radon area.

More commonly used than exhaust fans with passive vents is a central exhaust system that pulls air out of a house combined with a fan that pulls fresh air into the house and delivers it through ducts to individual rooms, usually each bedroom



**Figure 3.**  
*Combustion air concepts.*



**Figure 4.**  
*Heat recovery ventilator.*

and living area. Whole-house fans are effective in this type of supply system. A variation of this system, if the house has a forced air furnace, is to deliver outdoor air to the return duct, so that it can be mixed with indoor air and heated before it is delivered to the rooms.

A heat recovery ventilator (HRV)—also referred to as an air-to-air heat exchanger—is a balanced system that consists of a device which pulls fresh air into a home at the same time that it is exhausting air out of the home. As seen in **Figure 4**, the two airstreams are separated but pass over a core of conductive plates or heat exchanger that transfers heat from the warmer airstream to the colder one. A heat recovery ventilator also dehumidifies the home, because the warmer airstream contains moisture that condenses during the exchange process. The resulting water is delivered to a drain through a tube. HRVs can be stand-alone units with ducts or they can be integrated with the ducts of a forced air furnace. In addition to the basic systems described above, other variations exist, including central exhaust/supply systems with dehumidification and systems with air filtration options. Several studies have analyzed the cost effectiveness of various ventilation systems by examining purchase and installation costs, annual operating costs, and additional imposed heating costs (to heat incoming air). In addition to costs, benefits that are difficult to quantify include increased human comfort and the prevention of moisture problems.

Taylor et al. [7] examined the cost-effectiveness of heat recovery ventilators and concluded that these units provide positive life-cycle cost savings throughout much of the United States, although not in the colder, northern tier states.

The International Residential Code (IRC) specifies mechanical ventilation standards for new homes, which vary depending on the size of the house, number of bedrooms, and tested air infiltration rate [8]. The infiltration rate is measured with a blower door test, a specialized piece of equipment that measures a home's air change per hour (ACH). ACH measures the extent to which outdoor air leaks into homes through cracks around windows, doors, and where dissimilar building materials meet. An airtight home has a low ACH; a leaky, drafty home has a high ACH.

### 3. Volatile organic compounds

Volatile organic compounds (VOCs) are gases released from some solids or liquids at room temperature. Many VOCs found in household air have adverse health impacts, including eye, nose, and throat irritation; asthma exacerbation; lung, kidney, and central nervous system damage; and cancer [9]. VOC sources include building products, paints, strippers, solvents, wood preservatives, air fresheners, hobby supplies, pesticides, dry-cleaned clothing, and more.

The World Health Organization (WHO) categorizes VOCs by the ease with which they are emitted from materials and uses the terms very volatile organic compounds (VVOC), volatile organic compounds (VOCs), and semivolatile organic compounds (SVOCs) [10]. As mentioned earlier, VOCs produced by mold are referred to as microbiologic volatile organic compounds (mVOCs). But all of these fall into the broad category of VOCs.

Formaldehyde, a colorless, strong-smelling gas, is a common VOC used in the production of building materials, cabinets, furnishings, household cleaners, paints, landscape materials, and other products. It is used in the production of plywood, particle board, and medium density fiberboard. Formaldehyde is released into the air in a process referred to as off-gassing. Formaldehyde is also a component of cigarette smoke and a combustion product of wood, kerosene, natural gas, oil, and gasoline.

Adverse health effects from formaldehyde exposure include eye, nose, and throat irritation; wheezing and coughing; and allergic reactions. Long-term exposure to high levels of formaldehyde can cause cancer in humans.

Other VOCs of concern in indoor air include benzene, styrene, xylene, and methylene chloride. Benzene is a human carcinogen that is present in environmental tobacco smoke, solvents, plywood, particle board, fiberglass, wood paneling, adhesives, paint, caulking, and wood strippers. Styrene is used in the manufacturing of plastics, rubber, food containers, carpet backing, vinyl flooring, and resins. Acute health effects from styrene exposure include mucous membrane irritation; depression; muscle weakness; and eye, nose, and throat irritation. Chronic effects include hearing loss, peripheral neuropathy, and kidney damage. Xylene is a solvent and is a component of rubber and adhesives. Health effects from exposure include depression of the central nervous system, dizziness, irritability, and vomiting. Methylene chloride, which is also known as dichloromethane, is used in paint, paint strippers, and adhesives. Exposure can cause damage to the central nervous system, liver cancer, and lung cancer. This is not an exhaustive list of VOCs found in homes but is meant to illustrate potential hazards from common materials.

### **3.1 VOCs and safety**

When using any product that contains VOCs, provide adequate ventilation to the work area, meet or exceed any label precautions, buy in quantities that will be consumed quickly, and dispose of containers safely. Do not allow children or pets to become exposed to these products. Low-VOC- and No-VOC-containing products are becoming widely available. When possible, use these products instead of conventional alternatives.

## **4. Radon**

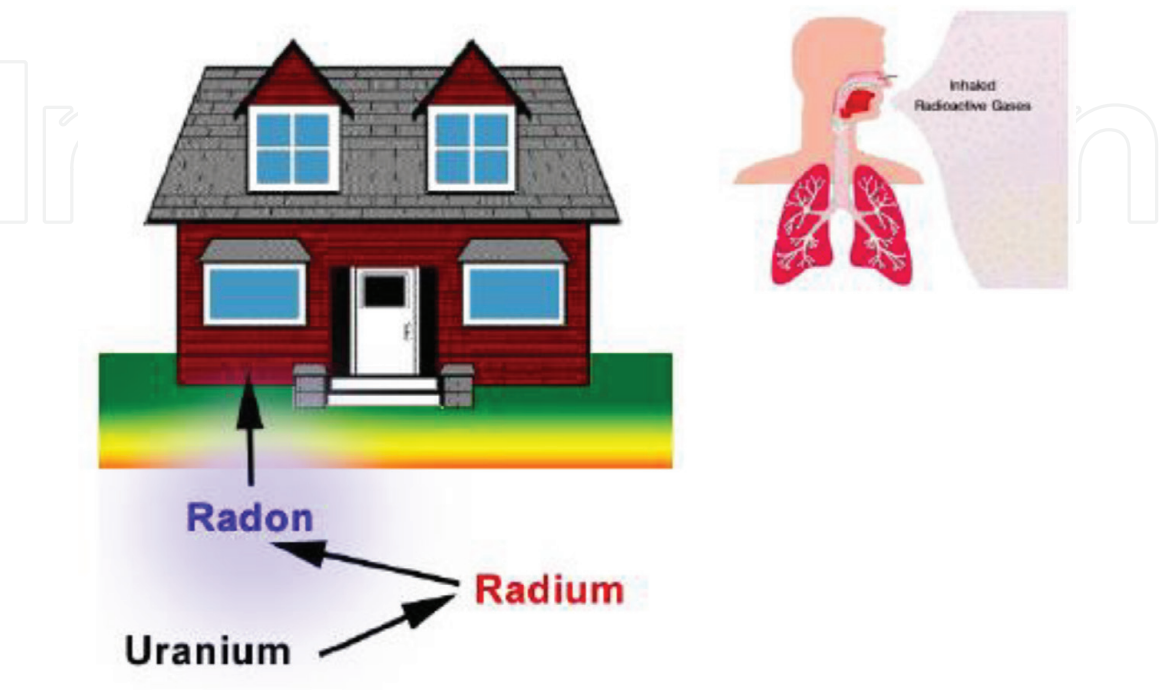
Radon is a radioactive gas that has no odor, taste, or color. It is produced during the decay of uranium, has a half-life of 3.8 days, and emits alpha and gamma radiation [11]. Uranium exists in soils all over the world. The radioactive decay process causes uranium to decay to uranium. Uranium and radium are solid elements. But radium decays to a gas: radon. Radon moves easily through permeable soils, such as gravelly and sandy soils, than it does through impermeable soils, such as clay [12]. Cracks in a house foundation and other openings, such as those around pipes that penetrate a house foundation, serve as radon pathways into the house. Radon continues in the decay process once it is inside a home. Radon's decay products are lead, polonium, and bismuth. These decay products become attached to microscopic particulates in house air, which are inhaled by people in the house and lead to lung cancer.

The process through which radon enters a home is displayed in **Figure 5**. Radon is the second-leading cause of lung cancer after cigarette smoking; radon exposure is responsible for 21,000 deaths per year in the USA [13]. Between one and seven percent of lung cancer fatalities in the USA have been attributed to radon exposure [13].

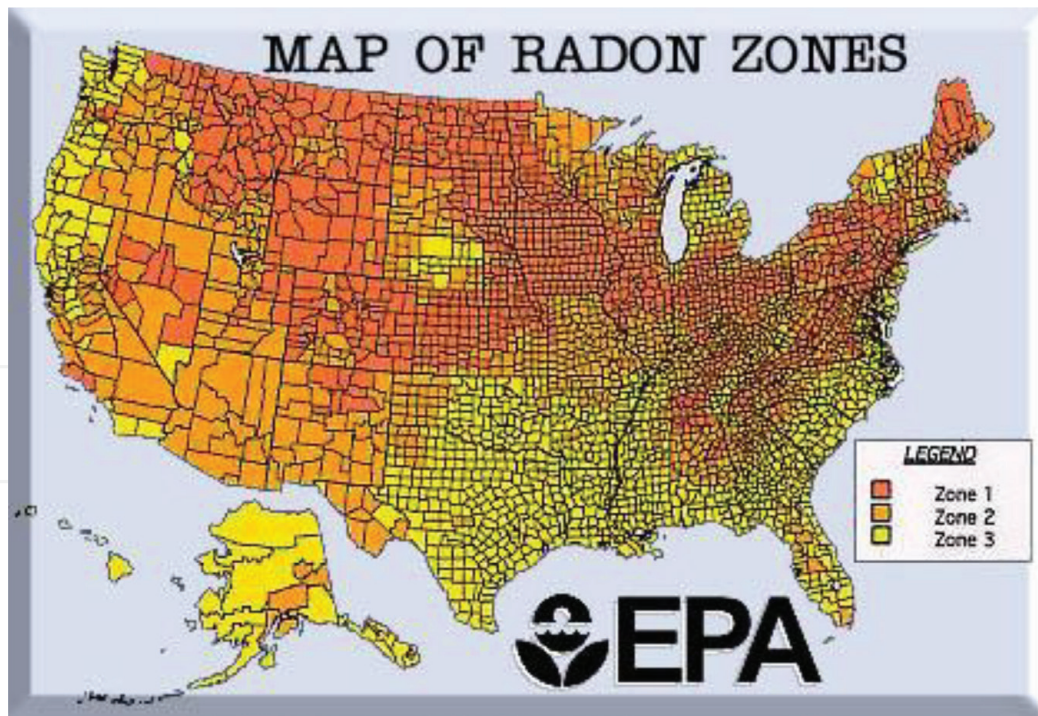
Radon's presence can be confirmed through the use of short- or long-term radon detectors. A short-term detector consists of activated carbon, which adsorbs (collects on the surface of carbon granules) radon, is inexpensive and simple to use. Once activated, it is placed in the lowest room of the house and kept in place for three days. The house should be tested under closed house conditions. This means all windows are closed for the duration of the test, and doors are used only for normal entrances and exits. After the test period, the detector is sent to a laboratory for analysis. The laboratory then reports the test results to the sender. Radon levels in a house vary over time because of changes in weather and atmospheric pressure. So, a short-term test is effectively a snapshot of radon levels at a particular time. A long-term radon test uses what is known as an alpha track detector. This is placed in a home's living room and stays there for 90 days to a year. This type of test provides a better result of a home's radon level.

The U. S. Environmental Protection Agency (EPA) recommends that mitigation systems be installed at or above the Action Level of 4 picocuries per liter (pCi/L) of air [14]. A mitigation system for an existing home consists of a PVC pipe that is installed through the floor of the lowest level of a home, often a basement, into a layer of gravel. That pipe is carried up through the house attic and through the roof. This pipe can also be installed on a house exterior wall. Often, an inline exhaust fan is connected to the PVC pipe and is used to pull soil gas from below the house. When that fan is used, the mitigation system is referred to as an active system. An inline fan is not always necessary and a passive mitigation system is used instead.

The EPA has developed a U.S. map that designates counties into zones. In EPA-designated Zone 1 counties, indoor radon levels are expected to be 4 pCi/L or higher; houses in Zone 2 counties are expected to have radon levels between 2 and 4 pCi/L; homes in Zone 3 counties are expected to have radon levels below 2 pCi/L.



**Figure 5.**  
*Radon entering a home.*



**Figure 6.**  
*EPA Radon Zone Map.*

**Figure 6** shows the EPA Radon Map. Zone 1 counties are red; Zone 2 counties are orange; and Zone 3 counties are yellow.

Radon-resistant construction techniques are recommended for new homes built in Zone 1 counties [15].

## 5. Combustion products

Combustion products comprise another category of indoor air pollutants. They consist of nitrogen oxides, sulfur dioxide, carbon monoxide, respirable particulates, and water. Nitrogen oxides, sulfur dioxides, and respirable particulates are lung irritants, and carbon monoxide (CO) can kill. To avoid indoor these pollutants, combustion-based, unvented space heaters should not be in the home. Central heating system systems should be regularly serviced: annual servicing for fuel oil-based systems and every 2 years for gas systems. Smoking should not be permitted in a home, and a gas kitchen range should have an exhaust fan over it that is vented to the outside.

Combustion products can pollute the air inside a home when components of a central heating system are damaged and leak combustion gases into indoor air. Indoor use of combustion-based electric generators will also do this. And when a house comes under negative pressure, combustion gases can be drawn from a chimney or fireplace into the home.

Normally, when a person breathes healthy air, oxygen binds with hemoglobin in blood to form oxyhemoglobin. When a person breathes air that is polluted with CO, CO binds with hemoglobin, and carboxyhemoglobin is formed, which prevents oxygen from getting to the brain. At low levels, this causes tiredness and dizziness. At higher levels, gradual suffocation and death occur. Carbon monoxide is responsible for hundreds of deaths and thousands of emergency room visits in the USA per year [16]. These are all preventable deaths and often occur when people are sleeping. Every home and apartment should have at least one carbon monoxide

detector installed in the hallway outside the sleeping area. Carbon monoxide detectors are important, but they are no substitute for regular servicing of combustion appliances and common sense safety procedures with combustion appliances in the home.

## 6. Lead

People have used lead for numerous purposes for at least 7000 years [17]. Before 1550 BCE, ancient Egyptians used lead as a medicine and for decorative purposes. When babies were born, a lead ball was placed on their belly buttons to stop bleeding. Women would decorate their nipples with lead and breast feed their babies. People have been aware of lead poisoning for over 2000 years [17]. In spite of this, lead was not banned as an ingredient in residential paint in the USA until 1978 and in gasoline until 1986. There are an estimated 24 million homes and apartments in the USA with lead-based paint [18].

Negative health impacts from lead exposure include reduced IQ levels, behavioral problems, organ damage, anemia, convulsions, and death. Children face higher risks of health problems from lead exposure, but adults are affected as well. Pregnant women can experience damage to a fetus from lead. Exposure occurs through inhalation, ingestion, and dermatological contact. The U.S. Centers for Disease Control and Prevention (CDC) set 5 micrograms of lead per deciliter ( $\mu\text{g/dL}$ ) of blood as a reference for public health actions, but there is no minimum level of exposure that is considered to be free of negative health effects. No level of exposure to lead is safe [19].

Lead-painted surfaces can produce a fine dust that is poisonous, especially to infants and children. This dust accumulates on floors under lead-painted windows and other building components. Toddlers crawl through this dust and ingest it through hand-to-mouth contact. This can also occur as children play outside in lead-contaminated soil. These hazards can be reduced or eliminated by following Lead Safe Work Practices to remove or encapsulate lead-based paint on a home's interior and exterior surfaces [20]. For soil contaminated with lead from paint chips or vehicle exhaust, that soil should be replaced, or barriers such as bushes should be planted to discourage children from playing in that soil.

Lead is also present in many household products, including slow cookers; lipstick and other cosmetics; house keys; hair dyes; faux leather purses, sandals, and wallets; and others [21].

Consumer education on this topic is necessary to inform the public about this issue.

## 7. Asbestos

The term asbestos refers to naturally occurring silicate minerals that are heat-resistant and fibrous. The fibers are soft and can be easily incorporated into building materials. Chrysotile, or white asbestos, was most commonly used in construction materials. Asbestos is found in older homes. It was used as insulation on heating systems and heating ducts. In some older homes, it actually covers entire boilers. Asbestos was also a component of joint compound, sheet goods that were used as fire barriers behind wood-burning stoves, roof sealants, floor and ceiling tile adhesives, gaskets, and automobile brake pads. Asbestos was also used in ironing board covers and potholders.

Like lead, humans have used asbestos for thousands of years. In ancient Egypt, pharaohs were embalmed in asbestos cloth. Ancient Roman aristocrats used asbestos tablecloths and napkins. After these items were used, they were placed in fires to clean them. The ancient Roman philosopher, Pliny the Elder, wrote about asbestos-caused lung disease and how asbestos mining slaves suffered from lung disease and made crude respirators to protect themselves [22].

Asbestos exposure occurs when asbestos fibers become friable, or airborne, and are inhaled. These fibers are microscopic and cannot be seen. This makes it possible for someone to inhale a large amount of fibers without knowing it. The fibers become embedded deep within the lungs, and the body cannot expel them. Exposure causes asbestosis, a type of lung cancer, and mesothelioma, which is a cancer of the mesothelial lining of the lungs. These diseases begin to show symptoms 10–40 years after initial exposure to asbestos.

Asbestos abatement is not a do-it-yourself activity. Its removal and encapsulation are regulated in the USA and must be performed by certified abatement contractors. These contractors seal off the work area where asbestos will be removed and wear disposable full-body protective suits and full head protection with respirators.

## **8. The child breathing zone**

Children face higher risks than adults do from being exposed to environmental toxicants and from health problems caused by such exposure [23]. This is because children breathe larger amounts of air per body size when compared to adults. Sucking on hands and toys that have accumulated pollutants adds to these risks [24]. Another source of VOC exposure to infants is those that are emitted from crib mattresses and crib mattress covers [25].

The fact that 80% of children's alveoli are formed postnatally, and changes in the lung continue through adolescence, make children more vulnerable to developing health problems from air pollutants [26]. During the early postneonatal period, developing lungs are very susceptible to pollutants; and the immature immune, pulmonary, and nervous systems of children can be damaged by environmental pollutants, including routinely applied residential pesticides.

Young and older infants and young children breathe through their mouths than adults do. This difference in breathing patterns is likely to increase a child's risk of exposure to respirable particulates [27]. This risk is lower for adults whose breathing through their noses causes air to become filtered as they breathe it through the upper respiratory airway [27].

Toddlers crawl on the floor and young children walk, run, and play on the floor. These factors cause the breathing zone of children to be much lower (up to 3 feet from the floor). This zone is known as the child breathing zone (CBZ) [28]. Walking-induced turbulence in a room causes resuspension of respirable particulates, and shorter people are exposed to more resuspended particulates than taller people. IAQ can be significantly worse in the CBZ than in the adult breathing zone (ABZ), and the assumption of uniform pollutant concentration in indoor environments can be an erroneous assumption of breathing concentration risk. Although there is an increasing awareness that children are vulnerable to poor IAQ in the scientific community, there is very limited research with a focus on IAQ in the CBZ. There is no current IAQ management system that specifically focuses on improving IAQ in the CBZ.

## 9. Conclusion

The most effective strategy for controlling indoor air pollution is to control the problem at its source. Ventilation is also important, especially in the case of moisture. Expel moisture to the outside through exhaust fans that are vented to the outdoors. In the case of combustion pollutants, regular servicing of heating systems and other appliances that are combustion based is necessary. Radon gas is a radioactive human carcinogen that is colorless, tasteless, and odorless. This pollutant can be controlled through mitigation in existing homes and with radon-resistant construction techniques in new homes. Exposure to some VOCs, which are present in building materials, paints, strippers, and other substances, can be hazardous to human health. Adequate ventilation should be provided when using these materials. Low- or no-VOC emitting products are now available and should be considered as safer alternatives. Lead and asbestos are present in older homes and apartments and pose considerable health risks to humans. Only trained professionals should perform abatement or encapsulation of both materials. Children are at a higher risk of health problems from pollutant exposure, especially because air in the child breathing zone is more polluted than it is in the adult breathing zone. Awareness of these issues is a critical first step in improving air quality in homes and apartments.

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