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Energy and Environment Division

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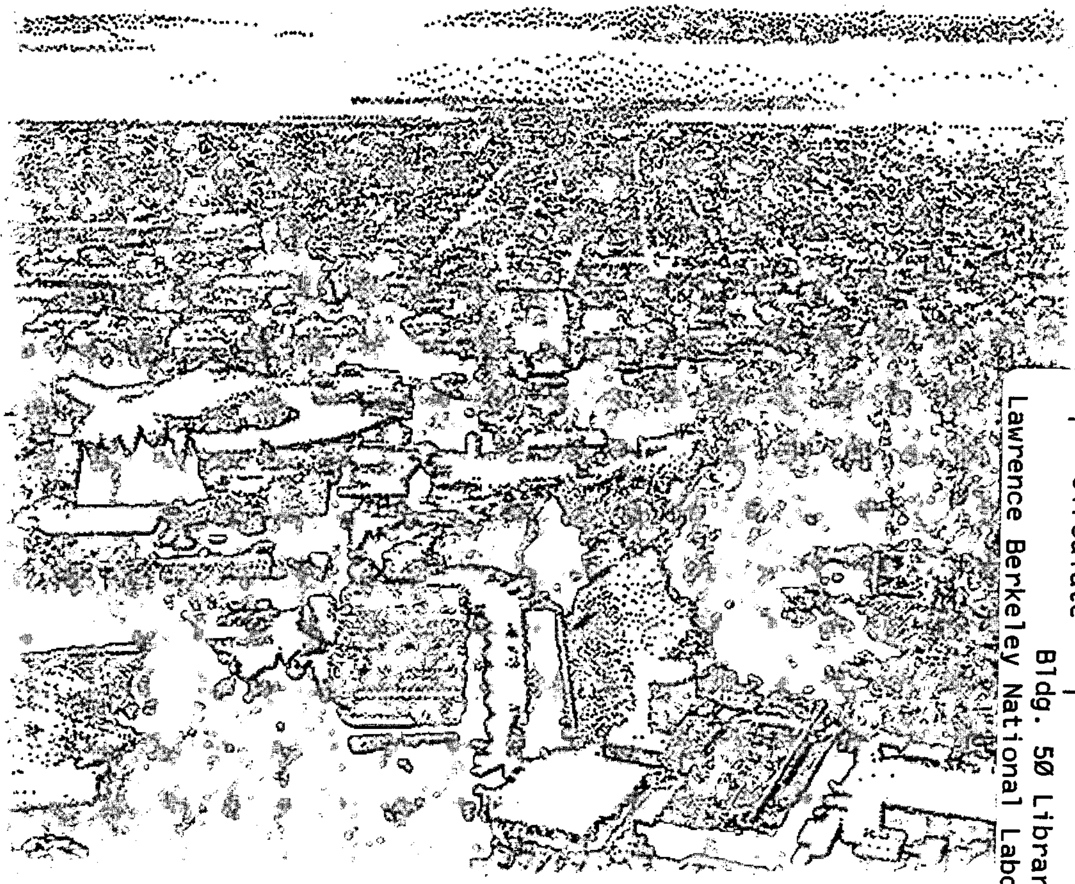

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Renewables in Ventilation and Indoor Air Quality

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RENEWABLES IN VENTILATION AND INDOOR AIR QUALITY

Max Sherman & Hal Levin

Abstract

Ventilation for acceptable indoor air quality is one of the key services a building provides to its occupants. Indoor air quality depends on a complicated interaction between pollutant sources in the building and key removal mechanisms such as ventilation. Renewable energy issues enter this picture through two important mechanisms: affecting pollutant sources, and providing ventilation. This overview paper is organized to address these two parts separately. Many of the renewable technologies being considered to reduce the energy demand of buildings have the potential to affect the introduction of additional pollutant sources into the building, but also have the potential to reduce them when compared to many conventional designs. This additional introduction of pollutants could either endanger the indoor environment or create a sufficient parasitic energy demand to counteract any benefit of the technology. Ventilation can often be provided directly using renewable technologies, either passively or actively, but additional ventilation, even when provided passively, can increase the thermal load of the building. This report reviews the subject of indoor air quality with particular emphasis on the role and impact of renewables.

KEYWORDS: Ventilation, Indoor Air Quality, Renewable Energy LBL Report No: LBL-38258

INTRODUCTION

The building sector is an important part of the energy picture. In the United States about 40% of all the energy expenses are attributable to the building sector. While buildings may consume about 20% of the fuel resources of the country, they consume over 75% of the electricity. The purpose behind all this energy consumption is to provide a variety of building services, which include weather protection, storage, communications, thermal comfort, facilities of daily living, aesthetics, work environment, etc. Some of these functions can be supplied in whole or in part by renewable energy.

The major function of buildings is to provide an acceptable indoor environment which allows occupants to carry on various activities. The three main energy-related building services are space conditioning (for thermal comfort), lighting (for visual comfort), and ventilation (for indoor air quality). The purpose of this report is to address issues that relate renewable energy to the last of these three. The two main sections of this report indicate how renewable technologies can contribute both to energy efficiency and to indoor pollution and help frame the discussion of the trade-offs.

Pollution-free environments are practical an impossibility. It is often useful to differentiate between unavoidable pollutants (such as human bioeffluents) over which little source control is possible, and avoidable pollutants (such as emissions of Volatile Organic Compounds) for which control is possible. Whole-building ventilation usually provides an effective measure to deal with the unavoidable emissions, but source control is the preferred and sometimes only practical method to address avoidable pollutant sources.

Achieving optimum indoor air quality relies on an integrated approach to the removal and control of pollutants using engineering judgment based on source control, filtration, and ventilation. Regardless of the kind of building involved, good indoor air quality requires attention to both source control and ventilation. While there are pollutant sources common to many kinds of buildings, buildings focusing on renewable energy may have some unique sources and, therefore, may require special attention.

In smaller (i.e. house size) buildings, renewable mechanisms are already the primary means for providing ventilation. That is, *infiltration* and *natural ventilation* are the predominant mechanisms for providing residential ventilation in the U.S. The trend in many countries, however, has been towards mechanical ventilation. This trend has been put in place to conserve non-renewable resources required to condition the excess ventilation air induced by infiltration; and natural ventilation.

VENTILATION

Ventilation is the building service most associated with controlling the indoor air quality to provide a healthy and comfortable environment. In large buildings ventilation is normally supplied through mechanical systems, but in smaller buildings such as single-family homes it is principally supplied by leakage through the building envelope, i.e. by (wind and stack driven) infiltration, which is a renewable resource, albeit unintendedly so.

Ventilation is the process by which clean air is provided to a space. It is needed to meet the metabolic requirements of occupants and to dilute and remove pollutants emitted within a space. Usually ventilation air must be conditioned by heating or cooling to maintain thermal comfort, using energy in the process. Ventilation energy requirements can exceed 50% of the space conditioning load; thus excessive or uncontrolled ventilation can be a major contributor to energy costs and global pollution. Thus, in terms of cost, energy, and pollution, efficient ventilation is essential, but inadequate ventilation can cause comfort or health problems for the occupants. Excess ventilation, even when provided by a renewable resource, can have an adverse energy impact when the ventilation air must be conditioned.

MECHANICALLY-DOMINATED VENTILATION

Most medium- and large-size buildings are ventilated by mechanical systems designed to bring in outside air, filter it, supply it to the occupants and then exhaust an approximately equal amount of stale air. In North America it is also quite common to have the ventilation system be the thermal distribution system as well. (Unless great care is taken in the design, this dual function can lead to poor operation of the ventilation system or the thermal distribution system.)

Ideally these systems should be based on criteria that can be established at the design stage. To return afterwards in an attempt to mitigate problems may lead to considerable expense and energy waste, and may not be entirely successful. The key factors that must be included in the design of ventilation systems are: code requirement and other regulations or standards (e.g. fire); ventilation strategy and system sizing; climate and weather variations; air distribution, diffuser location and local ventilation; Ease of operations and maintenance; and Impact of system on occupants (e.g. acoustically).

These factors differ for various building types and occupancy patterns. For example in **Office Buildings** pollutants tend to come from indoor sources such as occupancy, office equipment, building materials and furnishings, and motor vehicle emissions transmitted indoors. Occupant pollutants typically include metabolic carbon dioxide emission, odors and sometimes smoking. When occupants (and not smoking) are the prime source, Carbon Dioxide acts as a surrogate for occupancy and can be used to cost-effectively modulate the ventilation, forming what is known as a *Demand Controlled Ventilation* system, a technology under active scrutiny.

Schools are dominated by high occupant loads, transient occupancy, and high levels of metabolic activity. Design ventilation in **Hospitals** must aim at providing fresh air to patient areas, combined with clean room design for operating theaters. Ventilation in **Industrial Buildings** poses many special problems which frequently have to be assessed on an individual basis. Contaminant sources are varied but often well defined and limiting values are often determined by occupational standards.

INFILTRATION

Infiltration is the process of air flowing in (or out) of leaks in the building envelope, thereby providing (renewable) ventilation in an uncontrolled manner. All buildings are subject to infiltration, but it is more important in smaller buildings as many such buildings rely exclusively on infiltration when doors and windows are closed.

In larger buildings there is less surface area to leak for a given amount of building volume, so the same leakage matters less. More importantly, the pressures in larger buildings are usually dominated by the mechanical system and the leaks in the building envelope have only a secondary impact on the ventilation rate. Infiltration in larger buildings may, however, affect thermal comfort and control and system balance.

Typical minimum values of air exchange rates range from 0.5 to 1.0 h^{-1} in **office buildings** (Persily, 1989). Buildings with higher occupant density will have higher minimum outside air exchange rates when ventilation is based on outdoor air supply per occupant, typically 7 to 10 $l\ s^{-1}$ (15 to 20 $ft^3\ m^{-1}$). Thus, **schools** may have minimum outdoor air ventilation rates of 3 h^{-1} while fully occupied theaters, **auditoriums** and meeting rooms may have minimum air exchange rates of 4 to 7 h^{-1}.

It is in low-rise residential buildings (most typically, single-family **houses**) in which infiltration is the dominant force. In these buildings mechanical systems contribute little (intentionally) to the ventilation rate. Pandian et al (1993) reviewed data on air exchange rates in US residences. Observations in 1836 residences revealed ventilation rates as low as 0.1 h^{-1}, with about half of all observations ranging from 0.35 h^{-1} to 2.35 h^{-1} with an arithmetic mean of 2.0 h^{-1} and a standard deviation of 3.3 h^{-1}. The mean ventilation rates observed in summer (5.4 h^{-1}) are typically higher than those observed in spring (1.9 h^{-1}), fall (0.4 h^{-1}) or winter (0.5 h^{-1}). The mean ventilation rate in two-level homes (2.8 h^{-1}) was higher than the in single-level homes.

Infiltration is made up of two parts: weather-induced pressures and envelope leakage. Models like the LBL Infiltration model contained in the ASHRAE Handbook of Fundamentals (1993) can combine these two parts to make adequate predictions of infiltration rates for design purposes.

Complicating any analysis is the fact that infiltration, being weather dependent, is not constant. Because of the non-linearities involved, the equivalent constant infiltration rate is not simply related to the average of the instantaneous values. Sherman and Wilson (1986) have determined that the equivalent constant infiltration rate is generally higher than the average for energy-related purposes and lower for indoor air quality purposes, indicating that infiltration is not a particularly efficient ventilation strategy. Special purpose quantities such as effective ventilation rates are often required to take these effects into account.

Individual variations notwithstanding, Sherman and Matson (1993) have shown that the stock of housing in the U.S. is likely significantly over-ventilated from infiltration and that there are 2 EJ of potential annual savings that could be captured. While much of this savings could be captured by simple tightening of the envelope, a significant portion of the stock would need ventilation systems or strategies to assure adequate ventilation levels.

BLOWER DOORS

Since little of practical import can be done about the weather, it is the envelope leakage, or *air tightness*, that is the variable factor in understanding infiltration. Virtually all knowledge about the air tightness of small buildings comes through making *fan pressurization* measurements, done most typically with a **Blower Door.**

Blower Doors are used to find and fix the leaks, but more often the values generated by the measurements are used to estimate infiltration for both indoor air quality and energy consumption estimates. These estimates in turn are used for comparison to standards or to provide program or policy decisions. Each specific purpose has a different set of associated blower-door issues.

Compliance with standards, for example, requires that the measurement protocols be clear and easily reproducible, even if this reduces accuracy. Public policy analyses are more concerned with getting accurate aggregate answers than reproducible individual results. Measurements that might result in costly actions are usually analyzed conservatively, but "conservatively" for IAQ is diametrically opposed to "conservatively" for energy conservation.

"Blower Door" is the popular name for a device that is capable of pressurizing or depressurizing a building and measuring the resultant air flow and pressure. The name comes from the fact that in the common utilization of the technology there is a fan (i.e. blower) mounted in a door; the generic term is "Fan Pressurization". Blower-Door technology was first used in Sweden around 1977 as a window-mounted fan (as reported by Kronvall, 1980) and to test the tightness of building envelopes (Blomsterberg, 1977). That same technology was being pursued by Caffey (1979) in Texas (again as a window unit) and by Harrje, Blomsterberg and Persily (1979) at Princeton University (in the form of a Blower *Door*) to help find and fix the leaks.

During this period the diagnostic potentials of Blower Doors began to become apparent. Blower Doors helped Harrje, Dutt and Beyea (1979) to uncover hidden *bypasses* that accounted for a much greater percentage of building leakage than did the presumed culprits of window, door, and electrical outlet leakage. The use of Blower Doors as part of retrofitting and weatherization became known as *House Doctoring* both by Harrje and Dutt (1981) and the east coast and Diamond et al. (1982) on the west coast. This in turn led Harrje (1981) to the creation of instrumented audits and Sonderegger et al. (1981) to computerized optimizations.

While it was well understood that blower doors could be used to measure air tightness, the use of blower-door data could not be generally used to estimate real-time air flows under natural conditions or to estimate the behavior of complex ventilation systems. When compared with tracer-gas measurements, early modeling work by Caffey (1979) was found wanting. There was a rule of thumb, which Sherman (1987) attributes to Kronvall and Persily that seemed to relate Blower-Door data to seasonal air change data in spite of its simplicity: Namely that the seasonal air exchange can be estimated from the flow required to pressurize the building to 50 Pa divided by 20.

To overcome the physical limitations of such rules of thumb, it is necessary to model the situation physically which, in this case, means separating the leakage characteristics of the building from the (weather) driving forces. As the early versions of the ASTM Standard show, leakage is described conventionally as a power law which was found to be valid empirically but without theoretical substantiation (recent work by Sherman (1992a) has provided the theoretical basis for the expression). Using orifice flow as a physical model, the blower-door data can be used to estimate the Effective Leakage Area (*ELA*).

Using this orifice-flow paradigm, Sherman and Grimsrud (1980) developed the LBL Infiltration model (Equation 14) which was then validated by Sherman and Modera (1984) and incorporated into the ASHRAE Handbook of Fundamentals (1989). Much of the subsequent work on quantifying infiltration is based on that model, including ASHRAE (1988) Standard 119 and ASHRAE (1993) Standard 136.

Quantitative measurements can be made by converting the air flow and pressure data into values such as *ACH50* (the air changes of flow at 50 Pa pressure) or effective leakage area, which is the equivalent area of holes that provide the same leakage. These estimates in turn are used for comparisons to standards or to provide program or policy decisions, or to estimate the energy load caused by the infiltration.

Because infiltration depends on the weather, buildings with much infiltration can have quite variable ventilation rates. Determining when there is insufficient infiltration to provide adequate indoor air quality or energy-wasteful excess infiltration is not a simple matter. The trade-off in determining optimal levels depends on various economic and climatic factors.

NATURAL VENTILATION

Natural ventilation is a strategy suitable for use in mild climates or during mild parts of the year. As commonly interpreted natural ventilation is the use of operable parts of the building envelope (i.e. windows etc.) to allow natural airflow at the discretion of the occupants.

Natural ventilation shares many of the same properties as infiltration: it depends on weather for driving forces; it is a function of the leakage area of the buildings. The distinguishing feature of natural ventilation, however, is that it is under the control of the building occupants. It generally provides significantly more ventilation than leakage alone.

From the point of view of the HVAC designer, natural ventilation is quite bothersome, because a conservative ventilation designer cannot count on it, but one must consider its potential effects on the building load. From the perspective of the occupants, however, natural ventilation gives them more control of their environment and, usually, makes it more acceptable, therefore. Studies have shown that naturally ventilated building tend to suffer less Sick Building Syndrome and less respiratory disease (e.g. colds) then buildings that are fully mechanically ventilated (i.e. recirculate air).

New commercial buildings have been curtailing the availability of natural ventilation as a option by removing operable windows. Natural ventilation still dominates in the residential sector. Few residential buildings have mechanical systems and it is assumed that adequate ventilation can be achieved by the occupants as desired by the use of operable windows.

PASSIVE VENTILATION SYSTEMS

Passive ventilation systems share with infiltration the use of renewable energy to provide ventilation. But unlike air leakage and open windows, passive ventilation systems are designed to provide specific amounts of ventilation to minimize both energy liabilities due to excessive ventilation and periods of poor air quality due to under-ventilation.

The most common passive ventilation system is the "passive stack" which is normally used to extract air from kitchen and bath rooms. Prevailing wind and temperature differences are used to drive air flow through a vertical shaft; various stack designs can be used to control or enhance the performance based on local climate. Careful design is required to avoid backdraughting and to assure proper mean rates. Although there is significant experience with this approach in Europe, it has been rarely used in North America, but is similar to some approaches being considered for Radon mitigation.

Well-designed passive ventilation systems can be used to provide whole-building ventilation as well as local exhaust. Some efforts are currently underway to develop passive ventilation systems that incorporate heat recovery to minimize the need for conditioning the ventilation air. This approaches the fully-renewable ventilation system in that it requires no non-renewable resources for either providing the ventilation air or conditioning it.

INDOOR AIR QUALITY AND POLLUTANT SOURCES

Good indoor air quality may be defined as air which is free of pollutants that cause irritation, discomfort or ill health to occupants, or premature degradation of the building materials, furnishings, equipment and other contents. (See Table 1.) Thermal conditions and relative humidity also impact the perception of air quality in addition to their effects on thermal comfort. Focus on indoor air quality issues increased as reduced ventilation energy-saving strategies, and consequently increased pollution levels, were introduced A poor indoor environment can manifest itself as a sick building in which some occupants experience mild illness symptoms during periods of occupancy. More serious pollutant problems may result in acute, long-term or permanent ill-health effects.

Poor air quality in buildings sometimes manifests itself in the form of "Sick Building Syndrome" (**SBS**). Definitions of SBS vary but generally refer to a range of symptoms that an occupant experiences while present in the building, including lethargy, headaches, distraction, runny nose, and throat, nose, or eye irritation. There is no consensus about the underlying causes of SBS, the kind of sources that are prerequisites of SBS or the best mitigation strategies (Girman, 1989; Levin, 1989b).

While some authors claim a strong role for ventilation in SBS, others do not. Henssen (1993), reports on improved air quality in a school when ventilation is increased from 8 l/s-p, while Menzies (1991) reports on no change in the incidence of symptoms in an office building when the ventilation rate is increased from approximately 15 to 32 l/s-p. Burge (1990) also found no association with ventilation rates in offices in the range 4 to 23 l/s-p. Generally, however, increased ventilation up to 10 l/s-p has been found associated with reduced SBS symptom rates in both a large-scale Swedish office study (Sundell, 1994) and in a meta-analysis of several major epidemiological studies (Mendell, 1993).

Air quality standards for the protection of public health are generally specified in terms of not exceeding some average concentration for some specified time, ranging from one hour (e.g. for carbon monoxide) to one year (e.g. particulate matter), and are based on available data that has been generated by research over many years on the adverse health risks from exposures. The air pollutant standards for criteria pollutants in outdoor air have sometimes been adopted for indoor air. There are, however, significant differences between the pollutants found in indoor and outdoor air; most serious indoor pollutants (e.g. VOCs) appear at elevated indoor concentrations due to indoor sources. The concentrations of the individual compounds are often very low compared to standards set for industrial exposures, but the indoor air often has over an order of magnitude more compounds in it. The health effects of such mixtures are not yet sufficiently well enough understood to set standards to protect human health, although there is some evidence of SBS when concentrations exceed a few milligrams per cubic meter.

An almost limitless number of pollutants may be present in a space. Many pollutants are at immeasurably low concentrations and have largely unknown toxicological effects (Levin, 1989), but some specific building-related agents (e.g. Legionella) have been identified.. The task of identifying and assessing the risk of individual pollutants has become a major research activity in the past twenty years. Thus for a large number of compounds neither health nor comfort acceptability limits are available. Some pollutants can be tolerated at low concentrations, while irritation and odor often provide an early warning of deteriorating conditions. Health-related air quality standards are typically based on risk assessment and are specified in terms of a maximum permitted exposure, which is determined by exposure time and pollutant concentration. Higher concentrations of pollutants are normally permitted for shorter-term exposures.

Source strengths can vary by one or even two orders of magnitude for products that can perform the same function. It is, therefore, important to know the range and select well, to be cost-effective from a life cycle perspective. Similarly, materials that are stable and do not require frequent or toxic chemical maintenance are also cost effective. because they will result in far lower occupant exposures over the life of the product or building. Good thermal storage choices are also frequently stable materials that off-gas very little and can be cleaned, maintained and renewed with little or no harmful chemicals.

User operated or controlled ventilation and thermal control technologies can achieve reduced occupant symptom report prevalence while reducing reliance on mechanical equipment. These include operable windows, user-controlled radiant heat sources, radiant cooling systems, etc. radiant cooling using ground-source cool water pumped by solar photovoltaic generated electrical pumps represents a renewable technology that has not been much considered. The coincidence of the solar energy for electrical production and the cooling load makes this an appropriate technology for sustainablility.

SOURCES FROM RENEWABLE SYSTEMS

Materials and components used in renewable systems often introduce (either directly or indirectly) additional pollutant sources into the indoor environment.

Passive Solar Collection

Passive solar collection of heat generally involves collection on surfaces within the structure of IR wavelength solar radiation passing through glazing materials (glass or plastics) in the building envelope. The heat (thermal energy, warmth) is often then "stored" in building materials or in special materials incorporated into the building in order to serve the storage function. When the solar energy strikes certain materials, it can result in an increased release of pollutants (e.g., volatile organic chemicals - **VOCs**) from these materials due to the increased temperature and resulting concomitant increase in vapor pressure. Volatilization of VOCs is directly related to vapor pressure with each VOC having its own characteristic vapor pressure and to the material from which it is being volatilized. Sometimes distributed mass is used for thermal storage and materials receiving direct insulation are more rapidly broken down by the heat and UV radiation striking them.

Building interior surfaces most frequently used to "collect" passive solar energy are floors and walls. Typical flooring (such as carpets, resilient floor coverings, and finished wood) are sources of VOC emissions. Wall coverings (such as painted gypsum board, wallpaper, and hardwood plywood paneling) are also sources of VOCs. Heating of these materials results in increasing their vapor pressures and, therefore, increasing emissions of VOCs from them. While the total VOC emissions over the life of a material are limited by the VOC content of the material, accelerating the emissions can result in larger occupant exposures than might otherwise occur due to higher peak concentrations. Also, due to adsorption of VOCs on exposed surfaces and subsequent re-release, longer term exposure can also be elevated unless ventilation is sufficient to remove excess emissions.

Passive solar strategies have included the construction of massive (Trombe) walls or placement of liquid containers just inside south facing window walls. These massive storage systems have also been replaced by eutectic salt systems or other phase change materials for thermal energy storage, which can allow releases of the construction materials and component pollutants.

Atria

Atria can be used to buffer transient or rapid air quality changes and thermal load changes. This normally involves using "transfer air" from the atria as make-up air for adjacent spaces. If too little outside air is provided to the atria, air quality can deteriorate significantly. Thus, stale, contaminated air can be a dominant component of transfer air from atria.

While outdoor air should be introduced directly into the breathing zone for best ventilation, it is usually tempered in atria for thermal comfort reasons. This can result in odors and toxins produced by flora and mold often incorporated into atrium spaces. Atria might be more safely used when air is introduced into other spaces and then exhausted through the atria, which con be powered by renewable technologies such as stack ventilation.

Minimum outside air exchange rates must be maintained in atria even though their performance as a thermal sink may be somewhat impaired by this means. Other problems observed in atria is their multi-function use often involving pollutant sources not normally associated with indoor spaces. Or, pollutants from such sources may not be adequately controlled by direct exhaust as they might be in other indoor spaces. This might be due to very large volumes and the desire to maintain an uncluttered appearance. Thus, designers might hesitate to install direct exhaust systems. Also, post-construction ad hoc modification may result in the introduction of strong pollutant sources without verification that the design contemplated the presence of such sources.

Earth Tubes, Rock Storage

Rock storage generally refers to a large volume of rocks with sufficient air space to allow passage of fan driven supply air. Gravity systems are also possible when there is a driving force such as from stack effect. Warmth or coolth is stored in the rock bed and used when needed to temper supply air. Night-time cooling of the rock bed is often accomplished in order to take advantage of off-peak utility rates. Solar or wind energy sources or stack effect could be used as the driving force when these are available and fit the need for tempering the rocks.

Earth tubes are usually buried conduits for supply air to a building. Their contact with the earth allows for heat exchange to occur on the surface. Microbial contamination of earth tubes or rock storage systems can occur when moisture from circulating air condenses on cold surfaces of earth tubes or rock storage systems. If water activity level - a measure of moisture available at the surface of a material - exceeds 70%, spores, microbes etc. will be likely to reproduce. This 70% water activity level is reasonably consistent with a 70% relative humidity level immediately adjacent to the surface.

Other Potential Sources

Methane produced from bio-matter decomposition can be used to power electrical generators or gas-fired appliances. However, if the production system is not properly isolated from the occupied space, building occupants can be exposed to the methane gas and other by-products of the decomposition process. These gases can be odorous and potentially noxious.

Ultraviolet light can lead to deterioration and decomposition of certain plastics. If these materials are on surfaces directly exposed to incident solar energy, they can decompose and release plasticizers and other components into indoor air.

Solar and wind energy generators typically involve storage of the electrical energy in batteries. These batteries may contain chemicals that are toxic or noxious. Battery storage systems should be isolated from the occupied space to avoid indoor air contamination from the electrolytes and gaseous emissions.

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Table 1 . Principal Indoor Pollutants, their Sources and Typical Concentrations (Samet et al. 1988)

Respirable Particles	Tobacco smoke, unvented kerosene heaters, wood and coal stoves, fireplaces, outside air, occupant activities, attached facilities	> 500 mg/m^3 bars, meetings, waiting rooms with smoking 100 - 500 mg/m^3 smoking sections of planes 10 to 100 mg/m^3 homes 1,000 mg/m^3 burning food or fireplaces
NO, NO_2	Gas ranges and pilot lights, unvented kerosene and gas space heaters, some floor heaters, outside air	25 to 75 ppb homes with gas stoves 100 to 500 ppb peak values for kitchens with gas stoves or kerosene gas heaters
CO	Gas ranges, pilot lights, unvented kerosene and gas space heaters, tobacco smoke, back drafting water heater, furnace or woodstove, attached garages, street level intake vents, gasoline engines	> 50 ppm when oven used for heating > 50 ppm attached garages, air intakes 2 to 15 ppm cooking with gas stove
CO_2	People, unvented kerosene and gas space heaters, tobacco smoke, outside air	320 to 400 ppm outdoor air 2,000 to 5,000 ppm crowded indoor environment, inadequate ventilation
Infectious, allergenic, irritating biological materials	Dust mites and cockroaches, animal dander, bacteria, fungi, viruses, pollens	> 1,000 cfu/m^3 homes with mold problems, offices with water damage (colony forming units) 500 (200 cfu/m^3 homes and offices without obvious problems
Formaldehyde	Urea Formaldehyde Foam Insulation[1] (UFFI), glues fiberboard, pressed board, plywood, particle board, carpet backing, fabrics	0.1 to 0.8 ppm homes with UFFI 0.05 ppm average in mobile homes
Radon and radon daughters	Ground beneath a home, domestic water, some utility natural gas	1.5 pCi/l estimated average in homes > 6 pCi/l in 3 to 5% homes
Volatile organic compounds: benzene, styrene, tetrachloroethylene, dichlorobenzene, methylene chloride, chloroform	Outgassing from water, plasticizers, solvents, paints, cleaning compounds, mothballs, resins, glues, gasoline, oils, combustion, art materials, photocopiers, personal care products	Typical concentrations of selected compounds: benzene - 15 µg/m^3; 1,1,1 trichloroethylene - 20 µg/m^3; chloroform- 2 µg/m^3; tetrachloroethylene - 5 µg/m^3; styrene - 2 µg/m^3; m,p-dichlorobenzene - 4 µg/m^3;m,p-xylene - 15 µg/m^3;
Semivolatile organics: chlorinated hydrocarbons, DDT heptachlor, chlordane, polycyclic compounds	Pesticides, transformer fluids, termicides, combustion of wood, tobacco, kerosene and charcoal, wood preservatives, fungicides, herbicides, insecticides	limited data
Asbestos	Insulation on building structural components, asbestos plaster around piupes and furnaces	> 1,000 ng/m^3 when friable asbestos, otherwise no systematic measurements

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[1] No longer used in the U.S.

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