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Indoor Air Controls

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Indoor Air Controls

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INDOOR AIR CONTROLS

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INTRODUCTION

The spatial average concentration of a pollutant in indoor air depends, at the steady state, on the outdoor concentration, the indoor pollutant source strength and the total rate of pollutant removal. Since the outdoor pollutant concentration cannot be changed, indoor pollutant control strategies are based on reducing pollutant source strengths and increasing the rate of pollutant removal.

Measured data indicate that for many pollutants the variation in source strengths from building-to-building is larger than the variation in the rate of pollutant removal processes (see, for example, Nero & Nazaroff, 1984; Nitschke et al., 1985). Thus, excessive concentrations of indoor pollutants should generally be attacked by reducing or eliminating the sources, rather than by increasing pollutant removal rates. The basic methods of source control include source elimination, source modification and local exhaust ventilation to prevent the spread of pollutants from their sources throughout the building. Pollutant removal occurs by several processes, including ventilation, air cleaning, deposition on surfaces, chemical reactions (on surfaces or within the air) and radioactive decay. Of these removal processes, only ventilation and air cleaning are practical pollutant control measures at the present time.

Source control, ventilation and air cleaning are discussed in the remainder of this chapter. Each is considered for the pollutant classes of radon, vapour phase organic compounds, combustion products (including particles) and microbial contaminants. For a more comprehensive review of this topic the reader is referred to earlier reviews (Fisk, 1986; Fisk et al., 1984).

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CONTROL OF POLLUTANT SOURCE STRENGTH

Radon source control

(1) *Introduction.* In the majority of US buildings with high indoor radon concentrations, the primary source of radon is the pressure-driven flow of radon-laden soil gas into the building through cracks or other penetrations in the building's substructure (Nero & Nazaroff, 1984). The pressure difference that drives this soil gas entry may result from a combination of the wind, indoor-outdoor temperature differences, and operation of mechanical ventilation systems or combustion devices that tend to depressurize the building. Methods for reducing the rate of radon entry due to pressure-driven flow include elimination of sealing of specific radon entry pathways, ventilation of crawl spaces, sub-slab ventilation, basement pressurization and ventilation of the cavities within walls constructed from hollow concrete blocks. Each of these methods is described below.

(2) *Sealing.* Attempts to inhibit radon entry by sealing cracks and other penetrations through basement floors and walls and blocking other radon entry pathways have met with mixed success. In Elliot Lake, Ontario (DSMA, 1979, 1980), and Sweden (Ericson et al., 1984) such measures have frequently reduced indoor radon concentrations by a factor of 3 to 10. On the other hand, sealing was found to be relatively ineffective for radon control in remedial studies performed in New York (Nitschke et al., 1985), Pennsylvania (Sachs & Hernandez, 1984), and the state of Washington (Turk et al., 1987). The difference in results might be due to differences in the permeability of a layer of soil or aggregate in contact with the basement floor and walls. If this soil or aggregate has a high permeability, soil gas will readily flow beneath the slab along the exterior surface of basement walls. In this case, when only a fraction of the soil gas entry points are sealed, the soil gas could easily be drawn into the house through the remaining entry points. However, if the soil has a generally low permeability, but regions of high permeability or high soil gas radon concentration, sealing penetrations near the high permeability or high-radon soil might be more effective.

(3) *Crawl space ventilation and sealing of floors.* Elevated indoor radon concentrations seem to be less frequent in houses with ventilated crawl spaces than in houses with basements or slab on grade. In general, soil gas and radon transport into a crawl space is not inhibited by a barrier over the surface of the soil. The same factors that lead to pressure-driven flow of soil gas through penetrations in a basement or slab on grade can cause crawl-space air to be drawn into a house through the floor above the crawl space. Sealing leakage paths through this floor is, therefore, an obvious radon control measure. This procedure is sometimes combined with increased crawl-space ventilation. Quantitative information on the effectiveness of crawl-space ventilation and/or sealing of floors above crawl spaces as a radon control measure is limited (Ericsson et al., 1984; Nazaroff & Doyle, 1985; Vivyurka, 1979). Available data from a few residences suggest that natural crawl-space ventilation and/or sealing of floors is moderately to highly effective (i.e., indoor radon concentrations may be reduced by roughly 50% or more when openings are provided in crawl-space walls) and that mechanical ventilation of crawl paces is highly effective in reducing radon entry from the crawl space.

(4) *Sub-slab ventilation.* Sub-slab ventilation (SSV) is generally accomplished by using one or more fans to draw soil gas from beneath a slab floor and exhaust this soil gas to the outside. This procedure is also referred to as sub-slab depressurization (SSD). The fan(s) may draw from a drain tile system located beneath the slab or around the perimeter of the foundation or from one or more pipes that penetrate through the slab floor and terminate in a dry sump.

SSD systems decrease the pressure within the soil beneath the slab and, therefore, decrease or reverse the normal pressure gradient that drives soil gas into buildings. In addition, an SSD system may decrease the radon concentration in the soil gas beneath the slab because it draws low-radon outdoor air from the soil surface to the region beneath the slab. SSD systems have been utilized in hundreds of buildings and in numerous geographical locations - for example in Canada (Vivyurka, 1979), Pennsylvania (Henschel & Scott, 1986; Sachs & Hernandez, 1984), New York (Nitschke et al., 1985), Washington state (Turk et al., 1987) and Sweden (Ericson et al., 1984). Through SSD and the sealing of large and accessible penetrations to the soil, investigators have generally been able to reduce indoor radon concentrations by 50% to more than 90% and to below typical radon concentration guidelines. However, SSD has failed to reduce indoor radon concentrations to acceptable values in a few houses, particularly those with concrete block basement walls (Henschel & Scott, 1986). Theoretical considerations and available experimental data indicate that the effectiveness of SSV should be increased by the following factors: (a) drawing air from an extensive drain tile or duct system beneath the foundation; (b) drawing air from several penetrations through the slab when a drain tile or duct system is not present and placement of these penetrations near major points of radon entry; (c) the presence of a highly permeable layer of aggregate beneath the slab; (d) a decrease in the size and number of cracks or other penetrations through the slab or basement walls; (e) increased fan flow rate and depressurization; (f) decreased soil permeability.

A variation of the usual technique of sub-slab ventilation is to reverse the direction of flow and force low-radon outdoor air beneath the slab. While this procedure of sub-slab pressurization (SSP) will increase the driving force (i.e., pressure differential) for soil gas entry into the house, it should also reduce the concentration of radon in the soil gas that enters the building to a greater degree than SSD. In studies of SSP within three residences located in a region with highly permeable soil and only moderate soil-gas radon concentrations (Turk et al., 1987), a lower flow rate and lower pressure fan were required for SSP than for SSD to achieve the same perfomance. However, SSP was much less effective than SSD in a study of radon mitigation in New Jersey (Turk et al., 1988), where the soil is less permeable and non-homogeneous and where soil gas radon concentrations are unusually high.

(5) *Basement pressurization.* Because soil gas transport into buildings is driven by a small (e.g., few pascal) pressure difference across the barrier between a building and the soil, increasing the pressure within a building or its basement by a corresponding amount should inhibit or eliminate radon entry. Turk et al. (1987) have pressurized the basements of five houses to examine this possibility. The process is relatively simple and inexpensive in structures without ductwork for a forced-air heating or cooling system. Obvious leakage paths between the basement and the first floor were sealed and each door to the basement was modified to close automatically after use. A low-pressure fan was then utilized to draw 120 to 190 L/s of air from the first-floor level, force this air into the basement and increase pressures in each basement to one to five pascals greater than the pressure measured at a point within the soil at the same elevation. Indoor radon concentrations decreased by approximately 65% to 95% to below typical radon concentration guidelines. This simple procedure can only be utilized in buildings that have a relatively air-tight basement. Opening a basement window or leaving the door to the basement in the open position would make these basement pressurization systems ineffective.

(6) *Venting the cavities within concrete block walls.* It is particularly difficult to prevent soil gas, and thus radon, entry into buildings with basement walls constructed from hollow-core

concrete blocks. Soil gas may enter the cavities within the concrete blocks through cracks and imperfect mortar joints and directly through the porous concrete from which the block is constructed, move horizontally and vertically within the wall through the interconnected network of cavities and enter the house again through cracks, joints and the porous block. In addition, the openings to the wall cavities at the top of the concrete block wall provide another route for soil gas entry into the building. A method of inhibiting or preventing soil gas entry through such walls is to seal all major accessible openings to the network of wall cavities and to use one or more fans to draw air from this network and exhaust it outside. Results from field studies of wall-cavity ventilation are provided by Henschel and Scott (1986). Indoor radon concentrations were reduced by more than 90% in two houses where it was possible to seal all major openings to the network of wall cavities. In four other houses, wall-cavity ventilation was highly effective only during the summer, and in one house it was ineffective even during the summer. To make wall-cavity ventilation more widely applicable, practical methods for closing the hard-to-reach openings to the wall cavities are needed. More recently, wall-cavity ventilation has been combined with sub-slab depressurization in a few New Jersey houses, with greater than 95% reductions in indoor radon concentrations (Osborne, 1987).

Source control of organic compounds

(1) *Introduction.* Current knowledge about control of organic compounds (other than formaldehyde) in indoor air is rudimentary. However, some information is available, especially on the control of formaldehyde source strengths.

Source control or modification depends on source identification, often a difficult task for this pollutant class. This task is made more complicated by product variation. As an example, simply identifying the presence of a carpet adhesive is insufficient to associate it with a problem that may exist in a building. Girman et al. (1986) examined adhesives, both solvent-based and water-based, that are used in the construction and finishing of buildings. Of the 15 adhesives tested, five were strong emitters of organic compounds. In particular, two of the water-based adhesives were strong alkane emitters. Source control is most practical if it can be exerted at the design stage. Thus a need exists to develop an extensive data base of the VOC emission rates associated with various products.

(2) *Source exclusion or removal.* Complete exclusion or removal of sources is obviously effective in reducing indoor source strengths. When one is dealing with a ubiquitous organic compound such as formaldehyde, such a measure is difficult and expensive, since urea-formaldehyde resins are utilized in many products. Partial exclusion or removal of sources will reduce indoor formaldehyde concentrations. However, the formaldehyde emission rates from the remaining sources may increase and, to a degree, offset expected benefits of the source removal. Matthews et al. (1983) and Godish and Rouch (1984) provide some examples of the effectiveness of source exclusion and removal. Matthews and colleagues used a mathematical model to predict the indoor formaldehyde concentration in a hypothetical room as various indoor sources, and combinations of sources, were removed or covered with a barrier. A reduction in indoor formaldehyde concentration by 65% to 80% was predicted to result from extensive source removal and application of vinyl floor covering over the particle board flooring. However, only 16% to 43% reductions in indoor formaldehyde concentrations were predicted for less extensive measures, such as removal of the urea-formaldehyde foam insulation or the furniture that contained medium density fibreboard. Godish and Rouch (1984) studied source removal experimentally in a house with two major formaldehyde sources

- particle board flooring and hardwood plywood panelling. Removal of 75% of the panelling resulted in a 49% reduction in the indoor formaldehyde concentration and removal of 50% of the particle board flooring caused a 29% reduction.

(3) *Product composition and manufacturing processes.* As manufacturers of products containing strong organic emitters learn of problems with their products, one can expect changes in product composition. For example, many manufacturers of pressed-wood products have modified the composition of their products and manufacturing processes in order to reduce formaldehyde emission rates (Meyer & Hermans, 1985). In addition, standard methods for measuring formaldehyde emission rates have been developed and some quality control procedures have been implemented. These measures can be highly effective in reducing formaldehyde emission rates. For example, addition of 10% more urea and 5% melamine to a particle board resin can cause a ten-fold reduction in formaldehyde emission rate (Myers & Nagaoka, 1981). Due to reductions in the molar ratio of formaldehyde to urea in resins, the amount of unreacted formaldehyde in commercial products has fallen dramatically and lower emission rates have resulted. The large dependence of formaldehyde emission rate on the characteristics of the urea-formaldehyde resins has been discussed by Meyer and Hermans (1985). They show that the formaldehyde emission rate from samples of seven six-week-old medium density fiberboards, each made with a different resin that was commercially available during 1983, varies by more than a factor of 23 (see Meyer et al., 1985, for further information).

(4) *Coatings and barriers.* Another source control procedure consists of the application of coatings (applied as a liquid) and solid barriers on the surfaces of pressed-wood products. Some of the coatings contain formaldehyde scavengers (materials that react chemically with formaldehyde). Godish and Rouch (1987) have examined the effectiveness of surface coatings and barriers (varnishes and specialized sealants) when applied to particle-board underlayments. Formaldehyde reductions in whole-house conditions ranged from 8 to 95% with a median reduction of 63% for fifteen different treatments of the particleboard. The effectiveness of selected solid barriers applied over particleboard flooring has been studied by Matthews et al. (1985, 1986). Vinyl floor covering reduced formaldehyde emission by a factor of 30 in laboratory studies; however, application of vinyl floor covering in a house with several formaldehyde sources reduced indoor concentrations by only 50% to 60%.

Combustion product source control

(1) *Introduction.* The major indoor sources of combustion products are unvented space heaters, gas ranges, tobacco smoking and vented combustion devices from which pollutants leak into the indoor air. In addition, combustion products can be transported indoors from parking garages, loading docks and other areas with a high concentration of vehicular exhaust products. A variety of combustion products including carbon monoxide (CO), carbon dioxide (CO2), particles, sulfur dioxide (SO2), organic compounds and oxides of nitrogen (NOx) can enter indoor air from these sources. Oxides of nitrogen (NOx) include both nitrogen dioxide (NO2) and nitric oxide (NO). NO2 is considered to be much more signifiant than NO from a health standpoint; therefore, its control is generally emphasized. Source control measures are discussed on a source-by-source basis in the following paragraphs.

(2) *Unvented space heaters.* Unvented space heaters that burn kerosene, natural gas or propane can be a major indoor source of combustion produts (Leaderer et al., 1984; Nitshke et al., 1985; Traynor et al., 1983, 1984, 1987). The obvious and most effective source control measure

is to exclude or remove these unvented heaters and use electric or vented combustion space heaters as a substitute. Other less effective control measures are possible. Burner design and state of tune (i.e., air shutter or wick adjustment) have a large impact on the rates of CO and NO_2 emission. The emission rate of CO_2, however, depends only on the rate of combustion. Unvented kerosene space heaters with a two-stage burner (i.e., both a convective and a radiant stage) emit roughly 15% to 90% as much CO and 25% to 90% as much NO_2 as single-stage heaters (Apte & Traynor, 1986). One final control measure consists of reducing the operating time of the heater; for example, by adding thermal insulation to the building and decreasing the demand for heat.

(3) *Gas ranges*. Gas ranges emit combustion products at a lower rate than unvented space heaters, but are present in a large number of buildings. One source control option is to use an electric range. Three additional measures are the use of a range hood, substitution of an electronic ignition system for the gas pilot(s) and modification of burners.

Four investigations of the performance of residential range hoods have been reviewed, and, in each case, the results were characterized in a slightly different way. Macriss and Elkins (1977) found that the increase in kitchen NO_x concentration due to operation of a gas range was only 30% smaller when a range hood with an exhaust flow rate of 90 L/s was operated. Traynor et al. (1982) measured a 60% to 87% decrease in the amount of CO, CO_2 and NO_x that entered the occupied space of a research house when a range hood was operated with a flow rate of 40 to 120 L/s. Revzan (1986) injected a tracer gas 10 cm above an operating range-top burner to simulate the emission of pollutants. A range hood with a flow rate of 60 L/s caused a 77% decrease in the amount of tracer within the test space after a one-hour test, compared to the amount of tracer that would have been present in the test space if the indoor air were perfectly mixed during the test. Nagda et al. (1987) reported that the use of a range hood during cooking reduced peak CO and NO_2 concentrations by approximately 50%. Thus, one study indicates that range hoods are relatively ineffective, one study indicates a moderate effectiveness and two studies indicate that range hoods are highly effective. Since numerous factors, such as hood geometry and location, may affect range hood performance, these contradictory results are not unexpected. The study by Nagda et al. (1987) included a survey of range hood usage. Only 18%, 13% and 40% of those surveyed used their range hood -always or often" during breakfast, lunch and dinner, respectively. Thirty-nine percent of the respondents indicated that fan noise was the major reason for not using the range hood.

The effectiveness of the second source control measure mentioned above -- substitution of electronic spark ignition systems for gas pilots - has not been demonstrated by experiment, but available information suggests a reasonable degree of effectiveness. Macriss and Elkins (1977) provide data indicating that gas pilots emit roughly 150% as much NO_2 per unit of gas consumed as gas-range burners. Since the pilot(s) may consume 30% to 60% of the total gas used by the range (DeWerth, 1974; Macriss & Elkins, 1976; Meier et al., 1983), elimination of the pilot(s) should reduce the total NO_2 emitted from a range by 45% to 90%. However, peak NO_2 emission rates and peak NO_2 concentrations will not be as dramatically affected by this measure.

The third method of reducing pollutant emissions from gas ranges is to modify the burners. Reducing flame temperatures, e.g., by quenching the flame, will decrease the NO_2 emission rate; however, this process can also increase the CO emission rate. DeWerth and Sterbik (1985) have evaluated a number of burner modifications. They indicate that the most acceptable modifications considering CO emission rate, costs and marketability, were the addition of inserts constructed from stainless steel wire to range-top burners and the addition of dual rod inserts to the oven burner. These inserts caused a 25% reduction in NO_2 emission rates and increased the emission rate of CO to a variable degree, but by no more than a factor of four.

Source control of biological agents

Airborne biological agents are ubiquitous in the indoor environment. The majority of bioaerosols are nonpathogenic and cause disease only in sensitized people (Burge, 1985). Nonetheless, some (most notably the bacteria Legionella) can have severe effects on building occupants. Hence, their control remains important.

Indoor biological pollution problems result from growth on surfaces, followed by subsequent processes that cause the biological particles to become airborne. Growth requires an organic substrate (not uncommon in the indoor environment) and a consistent source of moisture. Burge (1985) points out that indoor relative humidities greater than 70% are optimal for growth of microorganisms.

Control of the sources of biological agents include source removal, especially where a thriving colony of an offending organism is present within the building, and moisture control to prevent growth of the biological agents. Source removal may inlcude: (a) removal of affected substrates where colonies of organisms are found to be growing; (b) cleaning non-removable structural elements or portions of a mechanical ventilation system; (c) proper maintenance of any portion of a mechanical ventilation system, including the filters, which may provide a growth medium; (d) filtration of air where outside sources such as pollen are the cause and (e) application of biocidal agents after cleaning portions of the affected mechanical system (Morey et al., 1984). Effective filtration should also reduce the amount of organic matter that deposits in ventilation systems and subsequently serves as a substrate for the growth of microorganisms. Moisture removal, as it applies to the control of sources of biological agents, can involve: (a) eliminating water leaks; (b) improving the drainage of water from coils, ducts, etc., to eliminate standing water; (c) changing to a steam humidifier from a humidifier with water sprays, standing water, or wet surfaces and (d) increased dehumidification of air when required.

VENTILATION AND AIR CLEANING

Although indoor pollutant concentrations depend most heavily on highly variable pollutant source strengths, indoor concentrations also depend significantly on the rate of pollutant removal (by ventilation, air cleaning, deposition, chemical reaction and radioactive decay), which also varies between buildings and over time. In cases where it is impractical to reduce pollutant source strengths, for example the emission of CO_2, and odours by people, control can only be accomplished via a pollutant removal process.

The dominant removal process, when the indoor concentration is substantially greater than the outdoor concentration, is usually ventilation. For a few relatively non-reactive pollutants, such as CO, CO_2 and radon, ventilation is generally the only significant removal process. In the case of NO_2, the rate of removal by reaction with indoor surfaces cannot be neglected and can even exceed the rate of removal by ventilation. Particle removal by deposition on indoor surfaces must also generally be considered. In addition, active air cleaning can be a significant, or even dominant, pollutant removal process for particles and, in theory, for reactive gaseous pollutants such as NO_2, formaldehyde and possibly many VOCs.

Another type of interaction that must be accounted for is the coupling between pollutant source strengths and removal rates. One significant example is the increase in formaldehyde emission rates from various building materials that occurs when the indoor formaldehyde concentration is reduced - this makes formaldehyde control by ventilation and air cleaning (and even by partial source removal) more difficult. Another important example is the positive coupling between the entry rate of radon from the ground and the rate of natural ventilation (infiltration) or mechanical exhaust ventilation, since each of these processes is driven by indoor-outdoor pressure differences.

To estimate the effect of a change in pollutant removal rate by ventilation, it is generally necessary to utilize mathematical models, based on a pollutant mass balance, that account for all significant removal processes and couplings between removal rates and source strengths. Figure 1 was generated primarily using the following simple, steady-state mass balance equation for a well-mixed space, where C_i is the indoor pollutant concentration.

$$C_i = (S + aPC_0)/(a + K + l + R)$$

where: S = pollutant source strength per unit volume indoor air,

a = air exchange rate (i.e., air flow rate/indoor volume),

P = fraction of outdoor pollutant that penetrates the building envelope or ventilation system,

C_0= outdoor pollutant concentration,

K= pollutant removal rate by deposition on surfaces and chemical reaction per unit volume indoor air,

l= pollutant removal rate by radioactive decay per unit volume indoor air, and

R= pollutant removal rate by air cleaning per unit volume indoor air.

The curves in Figure 1 are examples of relationships between ventilation rate and indoor pollutant concentration. The figure serves to illustrate three points. First, pollutant removal by processes other than ventilation, significant outdoor pollutant concentrations, and couplings between pollutant source strengths and removal rates cause indoor concentrations to be less sensitive to ventilation rate than is often assumed (concentrations are often assumed to vary inversely with the ventilation rate). Second, it is often impractical to reduce indoor pollutant concentrations by more than 60% in a well-mixed space using ventilation, because large increases in ventilation rate are required. Third, the largest benefit per unit increase of outside air delivered to the space occurs when the initial ventilation rate is low.

There have been surprisingly few field studies where the impact of an increase in the whole-building ventilation rate on indoor pollutant concentrations has been measured. In a study by Offermann et al. (1982) it was practical to increase ventilation rates by roughly 75% and indoor radon, formaldehyde, NO_2 and particle concentrations generally decreased by 50% or less.

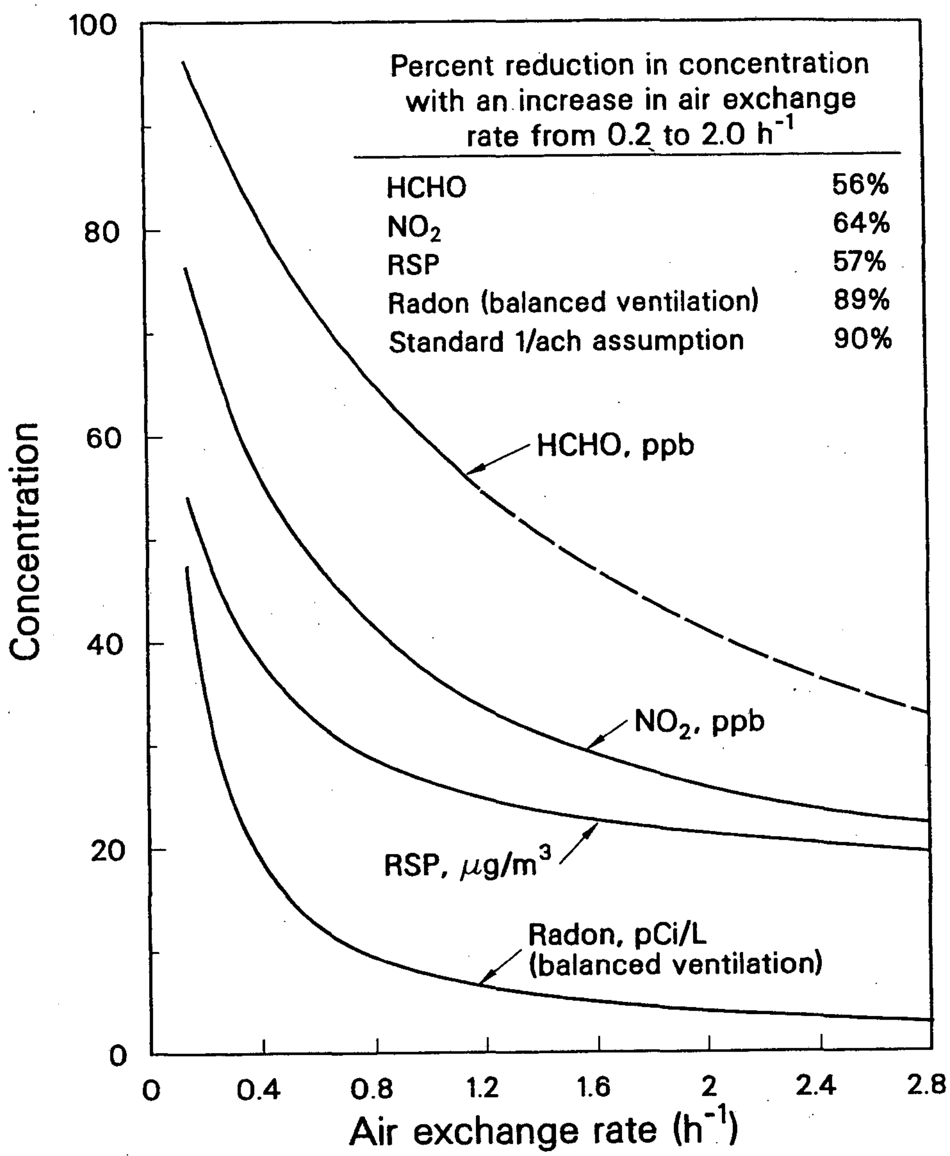

Figure 1. Examples of predicted relationships between pollutant concentrations and air exchange rates in residences with perfectly mixed air.

The formaldehyde (HCHO) curve is based on an equation presented by Matthews et al. (1986) which fits the data obtained from measurements in a research house with one primary HCHO emitter. The dashed portions of the HCHO curve extend beyond the range of conditions encountered during the measurements. The remaining curves were generated using Equation 1 (see text). The NO_2 curve is based on a time-weighted average source strength of 15 mL/h[a], typical of a kerosene heater, a house volume of 350 m^3, P = 1, C_0 = 10 ppb[a], K = 0.43/h[a] and I = R = 0. The RSP curve is based on a source strength of 2000 mg/h[a] from unknown sources and 3920 mg/h[a] from cigarette smoking, a house volume of 350 m^3, C_0 = 15 mg/m^3, P = 1, K = 0.2/h[a], and I = R = 0. The radon curve is based on a relatively high source strength of 280 pCi/L h (Nero & Nazaroff, 1984), P = 1, C_0 = 0.25 pCi/L, I = 0.00758/h and K = R = 0. The radon curve is also based on the assumption that the radon source strength and ventilation rate are independent - available data indicate that this assumption is valid only when the ventilation is provided by a balanced (supply and exhaust) mechanical system.

[a] See Nitschke et al., 1985

Ventilation can be a much more effective control measure if it is targeted at a concentrated source of pollutants. An example is the use of range hoods described in a previous section. Another example is balanced (supply and exhaust) mechanical ventilation of basements which has frequently reduced first-floor radon concentrations by more than 60%, based on data provided by Wellford (1986) and Turk et al. (1987).

The influence of active air cleaning, by such processes as filtration, electromagnetic precipitation and physical and chemical sorption, can be estimated in the same manner as the influence of ventilation if the performance of the air cleaning equipment is known. However, some important differences between air cleaning and ventilation should be mentioned. First, air cleaning is more pollutant-specific than ventilation. For example particle filtration will have little or no impact on the indoor concentration of many gaseous pollutants. Second, air cleaning is very difficult and thus highly impractical for many non-reactive gaseous pollutants (e.g., CO and CO_2.). Third, air cleaning often requires less energy than ventilation, since it often does not increase heating, cooling or dehumidification loads.

It is much more common to utilize air cleaning for particle removal than for removal of gaseous pollutants, although the performance of particle removal equipment varies widely (Offermann et al., 1985). High-efficiency filters and electronic air cleaners that remove respirable-size particles with high efficiency from a large volume of air are available; however, these high-efficiency systems are rarely used. There are few reports of the performance of particle removal equipment in occupied buildings. In a field study of electrostatic air cleaning in eleven Finnish restaurants (Kimmel, 1987), particle mass concentrations reportedly decreased by 20% to 50% with electrostatic precipitator operation. The investigator emphasized that regular cleaning of the precipitators is required.

To cleanse gaseous pollutants from indoor air, granular sorbent materials, such as activated carbon or alumina, are most commonly used. These sorbents may be impregnated with some chemical that reacts with selected indoor pollutants. Sorbents have a limited pollutant removal capacity and must periodically be replaced or regenerated. Based on available data (Fisk, 1986; Fisk et al., 1984; Kettrup et al., 1987; Relwani et al., 1987), some sorbent systems can remove a variety of gaseous pollutants (e.g., formaldehyde, NO_2 and VOC) with a moderate to high efficiency. However, the capacity (lifetime) and field performance of sorbent systems in actual use has not been fully documented. Thus, for many pollutants, gaseous air cleaning must be considered to be a largely unproven technology at the present time.

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REFERENCES

Apte, M.G. & Traynor, G.W. (1986) Comparison of pollutant emission rates from unvented kerosene and gas space heaters. *Proceedings of IAQ'86: Managing Indoor Air for Health and Energy Conservation*, Atlanta, ASHRAE, pp. 405-416

Berglund, B., Johansson, I. & Lindvall, T. (1982) The influence of ventilation on indoor/outdoor air contaminants in an office building. *Environ. Int.*, 8, 395-399

Burge, H.A. (1985) Indoor sources for airborne microbes. In: Gammage, R.B. & Kaye, S.V., eds, *Indoor Air Quality and Human Health*, Chelsea, MI, Lewis Publishers, pp. 139-148

DeWerth, D.W. (1974) *Energy Consumption of Contemporary 1983 Gas Range Burners and Pilots Under Typical Cooking Loads*, Cleveland, OH, American Gas Association, Cat. No. M50155

DeWerth, D.W. & Sterbik, W.G. (1985) *Development of Advanced Residential Range Burners with Low NOx Characteristics: Final Report - Phase II.* Chicago, IL, Gas Research Institute Report No. GRI-85/0204

DSMA (1979) (Dilworth, Secord, Meagher and Associates Limited and ACRES Consulting Services Limited) *Report on Investigation and Implementation of Remedial Measures for the Radiation Reduction and Radioactive Decontamination of Elliot Lake, Ontario*, prepared for the Atomic Energy Control Board, Canada.

DSMA (1980) (Dilworth, Secord, Meagher and Associates Limited and ACRES Consulting Services Limited) *Report on Investigation and Implementation of Remedial Measures for the Radiation Reduction and Radioactive Decontamination of Elliot Lake, Ontario*, prepared for the Atomic Energy Control Board, Canada

Ericson, S.O., Schmied, H. & Clavensjo, B. (1984) Modified technology in new constructions, and cost effective remedial action in existing structures, to prevent infiltration of soil gas carrying radon. *Proc. 3rd Int. Conf. Indoor Air Quality and Climate*, August 20-24, Stockholm, Swedish Council for Building Research, Vol. 5, pp. 153-158

Fisk, W.J. (1986) Research review: indoor air quality control techniques. *Proceedings of IAQ'86: Managing Indoor Air for Health and Energy Conservation*, Atlanta, ASHRAE, pp. 568-583

Fisk, W.J., Spencer, R.K., Grimsrud, D.T., Offermann, F.J., Pedersen, B. & Sextro, R. (1984) *Indoor Air Quality Control Techniques: A Critical Review*, Berkeley, CA, Lawrence Berkeley Laboratory Report No. LBL-16493

Girman, J.R., Hodgson, A.T., Newton, A.S. & Winkes, A.W. (1986) Emissions of volatile organic compounds from adhesives with indoor applications. *Environ. Int.*, 12, 317-322

Godish, T. & Rouch, J. (1984) Efficacy of residential formaldehyde control measures: source removal. *Proc. 3rd Int. Conf. Indoor Air Quality and Climate*, August 20-24, Stockholm, Swedish Council for Building Research, Vol. 3, pp. 127-132

Godish, T. & Rouch, J. (1987) Control of residential formaldehyde levels by source treatment. *Proc. 4th Int. Conf. Indoor Air Quality and Climate*, Vol. 3, Berlin, Institute for Water, Soil, and Air Hygiene, pp. 221-225

Henschel, D.B. & Scott, A.G. (1986) The EPA program to demonstrate mitigation measures for indoor radon: initial results. *Air Pollution Control Associations Specialty Conference on Indoor Radon*, February 24-26, Philadelphia, PA, pp. 110-121

Kettrup, A., Klusmeier, W. & Ohrbach, K.H. (1987) A new filter system for organic pollutant separation (particles, organic and inorganic gases). *Proc. 4th Int. Conf. Indoor Air Quality and Climate*, Vol. 3, Berlin, Institute for Water, Soil, and Air Hygiene, pp. 324-328

Kimmel, J. (1987) Performance of electrostatic precipitators in restaurants. *Proc. 4th Int. Conf. Indoor Air Quality and Climate*, Vol. 3, Berlin, Institute for Water, Soil, and Air Hygiene, pp. 226-230

Leaderer, B.P., Zagraniski, R.T., Berwick, M., Stolwijk, J.A.J. & Qing-Shan, M. (1984) Residential exposures to NO_2, SO_2, and HCHO associated with unvented kerosene space heaters, gas appliances, and sidestream tobacco smoke. *Proc. 3rd Int. Conf. Indoor Air Quality and Climate*, August 20-24, Stockholm, Swedish Council for Building Research, Vol. 4, pp. 151-156

Macriss, R.A. & Elkins, R.H. (1976) Standing pilot gas consumption. *ASHRAE Journal*, June 1976, pp. 54-57

Macriss, R.A. & Elkins, R.H. (1977) Control of the level of nitrogen oxides (NOx) in the indoor environment. *Proc. Fourth Int. Clean Air Congr.*, May 16-20, Tokyo, pp. 510-514, CONF-770557-2

Matthews, T.G., Reed, T.J., Tromberg, B.R., Daffron, C.R. & Hawthorne, A.R. (1983) Formaldehyde emissions from combustion sources and solid formaldehyde resin containing products: potential impact on indoor formaldehyde concentrations and possible corrective measures. *Proceedings of an Engineering Foundation Conference on Management of Atmospheres in Tightly Enclosed Spaces*, October 17-21, 1983, Atlanta, ASHRAE, pp. 23-43

Matthews, T.G., Reed, T.J., Tromberg, B.R., Fung, K.W., Thompson, C.V., Simpson, J.O. & Hawthorne, A.R. (1985) *Modeling and Testing of Formaldehyde Emission Characteristics of Pressed Wood Products*, Report XVIII, Oak Ridge, TN, Oak Ridge National Laboratory

Matthews, T.G., Dreibelbis, W.G., Thompson, C.V. & Hawthorne, A.R. (1986) Preliminary evaluation of formaldehyde mitigation studies in unoccupied research homes. *Air Pollution Control Associations Specialty Conference on Indoor Air Quality in Cold Climates*, April 29-May 1, Ottawa, Ontario, pp. 389-401

Meier, A., Wright, J. & Rosenfeld, A.H. (1983) *Supplying Energy through Greater Efficiency: the Potential for Conservation in California's Residential Sector*, Berkeley, CA, Univ. of California Press

Meyer, B. & Hermanns, K. (1985) Formaldehyde release from pressed wood products. In: Turoski, V., ed., *Formaldehyde Analytical Chemistry and Toxicology*, Washington, DC, American Chemical Society, pp. 101-116

Meyer, B., Hermanns, K. & Smith, D.C. (1985) Formaldehyde release from urea-formaldehyde bonded wood products. *Adhesion*, 17, 297-308

Morey, P.R., Hodgson, M.J., Sorenson, W.G., Kullmann, G.J., Rhodes, W.W. & Visvesvara, G.S. (1984) Environmental studies in moldy office buildings: biological agents, sources, and preventive measures. *Ann. Am. Conf. Gov. Ind. Hyg.*, 10, 21-36

Myers, G.E. & Nagaoka, M. (1981) Formaldehyde emission: methods of measurement and effects of several particleboard variables. *Wood Sci.*, 3, 140-150

Nagda, N.L., Koontz, M.D., Fortmann, R.C. & Billick, I.H. (1987) Detailed evaluation of range exhaust fans. *Proc. 4th Int. Conf. Indoor Air Quality and Climate*, Vol. 3, Berlin, Institute for Water, Soil, and Air Hygiene, pp. 324-328

Nazaroff, W.W. & Doyle, S.M. (1985) Radon entry into houses having a crawl space. *Health Phys.*, 48, 265-281

Nero, A.V. & Nazaroff, W.W. (1984) Characterizing the source of radon indoors. *Radiat. Prot. Dosim.*, 7, 23-39

Nitschke, I.A., Traynor, I.A., Wadach, J.B., Clarkin, M.E. & Clarke, W.A. (1985) Indoor air quality, infiltration and ventilation in residential buildings. New York State Energy Research and Development Authority, NYSERDA Report 85-10

Offermann, F.J., Sextro, R.G., Fisk, W.J., Grimsrud, D.T., Nazaroff, W.W., Nero, A.V., Revzan, K.L. & Yater, J. (1985) Control of respirable particles in indoor air with portable air cleaners. *Atmos. Environ.*, 6, 1761-1771

Offermann, F.J., Hollowell, C.D., Nazaroff, W.W. & Roseme, G.D. (1982) Low infiltration housing in Rochester, New York: a study of air exchange rates and indoor air quality. *Environ. Int.*, 8, 435-445

Osborne, M.C. (1987) Resolving the radon problem in Clinton, New Jersey, houses. *Proc. 4th Int. Conf. Indoor Air Quality and Climate*, Vol. 2, Berlin, Institute for Water, Soil, and Air Hygiene, pp. 305-309

Relwani, S.M., Moschandreas, D.J. & Billick, I.H. (1987) Indoor air quality control capabilities of desiccant materials. *Proc. 4th Int. Conf. Indoor Air Quality and Climate*, Vol. 3, Berlin, Institute for Water, Soil, and Air Hygiene, pp. 236-240

Revzan, K.L. (1986) Effectiveness of local ventilation in removing simulated pollution from point sources. *Environ. Int.*, 12, 449 -460

Sachs, H.M. & Hernandez, T.L. (1984) Residential radon control by subslab ventilation. *77th Annu. Meet. Air Pollution Control Assoc.*, June 24-29, San Francisco, CA, Paper No. 84-35.4

Traynor, G.W., Apte, M.G., Dillworth, J.F., Hollowell, C.D. & Sterling, E.M. (1982) The effects of ventilation on residential air pollution due to emissions from a gas-fired range. *Environ. Int.*, 8, 447-452

Traynor, G.W., Allen, J.R., Apte, M.G., Carruthers, A.R., Dillworth, J.F., Girman, J.R. & Martin, V.M. (1983) *Indoor Air Pollution Due to Emissions from Unvented Gas-fired Space Heaters: A Controlled Field Study*, Berkeley, CA, Lawrence Berkeley Laboratory Report No. LBL-15130

Traynor, G.W., Apte, M.G., Carruthers, A.R., Dillworth, J.F. & Grimsrud, D.T. (1984) *Pollutant Emission Rates from Unvented Infrared and Convective Gas-fired Space Heaters*, Berkeley, CA, Lawrence Berkeley Laboratory Report No. LBL-18258

Traynor, G.W., Apte, M.G., Carruthers, A.R., Dillworth, J.F., Grimsrud, D.T. & Thompson, W.T. (1987) Indoor air pollution and inter-room pollutant transport due to unvented kerosene-fired space heaters. *Environ. Int.*, 13, 159-166

Turk, B.H., Prill, R.J., Fisk, W.J., Grimsrud, D.T., Moed, B.A. & Sextro, R.G. (1987) *Radon and Remedial Action in Spokane River Valley Homes*, Berkeley, CA, Lawrence Berkeley Laboratory Report No. LBL-23430

Turk, B.H., Harrison, J., Sextro, R.G., Hubbard, L.M., Gadsby, K.J., Matthews, T.G., Dudney, C.S. & Sanchez, D.C. (1988) Evaluation of radon reduction techniques in fourteen basement houses: preliminary results. Paper No. 88-107.2, *Proceedings of the 81st Annual Meeting of the Air Pollution Control Association*, Dallas, TX. Pittsburgh, PA, Air Pollution control Association

Vivyurka, A. (1979) Assessment of subfloor ventilation systems. *Second Workshop on Radon and Radon Daughters*, March 12-14, Ontario, Canada

Wellford, B.V. (1986) Mitigation of indoor radon using balanced heat recovery ventilation systems (Air Exchange, Inc. Hingham, MA) *Air Pollut. Control Assoc. Int. Specialty Conf. Indoor Radon*, Feb. 24-26, Philadelphia, PA, pp. 122-129

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