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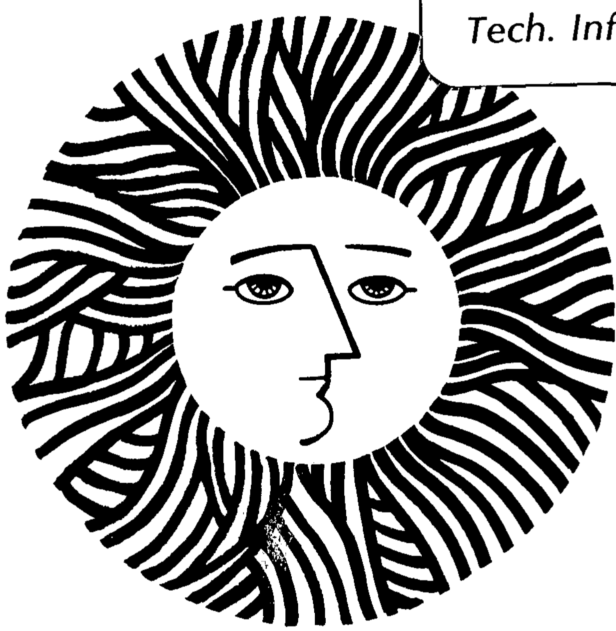

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Abstract

A sample of 58 occupied homes in Rochester, New York, most of which incorporated special builder-designed weatherization components, were studied to assess (1) the effectiveness of construction techniques designed to reduce air leakage; (2) the indoor air quality and air-exchange rates in selected tight houses, and (3) the impact on indoor air quality of mechanical ventilation systems employing air-to-air heat exchangers. The "specific leakage area" was measured in each house using the fan pressurization technique. Houses built with polyethylene vapor barriers and joint-sealing were as a group 50% tighter than a similar group of houses without such components. Mechanical ventilation systems with air-to-air heat exchangers were installed in nine relatively tight houses, some of which had gas stoves and/or tobacco smoking occupants. Air-exchange rates and indoor concentrations of radon (Rn), formaldehyde (HCHO), nitrogen dioxide (NO_2), and humidity were measured in each house for one-week periods with and without mechanical ventilation. More detailed measurements including concentrations of carbon monoxide, and inhalable particulates were made in two of these houses by a mobile laboratory. In all nine houses, air-exchange rates were relatively low without mechanical ventilation, 0.2-0.5 ach, and yet indoor concentrations of Rn, HCHO, and NO_2 were below existing guidelines. Mechanical ventilation systems were effective in further reducing indoor contaminant concentrations. We conclude that when contaminant source strengths are low acceptable indoor air quality can be compatible with low air exchange rates.

Introduction

With the cost of energy increasing, builders across the country are constructing houses specifically designed to reduce energy consumption. Some conservation measures being used, such as increased insulation, improve the thermal resistance of the structure while others, such as installation of continuous vapor barriers, caulking, and weatherstripping, reduce the quantity of air that leaks into and out of a building. A significant amount of energy is required to heat infiltrating air in residential buildings. Estimates range from 20 to 40 percent of the total heating load (Ford, et al., 1975) or, on a national scale, 2 to 4 quads of energy per year. Measures designed to reduce air leakage and thus energy use can be especially cost-effective because they are relatively inexpensive to implement.

A problem associated with houses which have low infiltration rates is that the concentrations of indoor-generated air contaminants tend to be higher than those in well-ventilated houses. Indoor-generated contaminants include combustion by-products (gaseous and particulate chemicals from cooking, heating, and tobacco smoking), odors and viable micro-organisms from occupants, radon from surrounding soil and rock, a broad spectrum of chemicals outgassed by building materials and home furnishings, and toxic chemicals from cleaning products and other materials used by occupants. The concentration of any indoor-generated contaminant is determined by its rate of emission (source strength) into and rate of removal from the indoor air space.

One of the primary removal mechanisms for indoor-generated contaminants is dilution with the outside air which naturally leaks into a house. Reducing air leakage can result in a reduction of the removal rate of indoor-generated contaminants and lead to correspondingly higher indoor concentrations.

Three frequently observed contaminants of indoor air are radon 222 (Rn), formaldehyde (HCHO), and nitrogen dioxide (NO_2), each of which can be monitored reliably with minimum inconvenience to house occupants.

Radon, a product of the natural decay of radium, is a chemically inert radioactive gas with a half-life of 3.8 days. It produces a chain of four short-lived daughters which constitute the primary health hazard to humans. These daughters, unlike radon itself, can attach themselves to airborne particulates which, if inhaled, can be retained in the tracheobronchial or pulmonary regions of the lung. Subsequent radioactive decay can irradiate the surrounding tissues with alpha radiation leading to an increased risk of lung cancer (Budnitz et al., 1979).

Any substance containing radium is a potential source of radon gas. Since radium is a trace element in most rock and soil, sources of indoor radon can include the soil under building foundations, building materials such as concrete or brick, and tap water from underground wells. Radon emanation rates from soil and rock can vary significantly.

Formaldehyde is present in the indoor environment as a component of building and furniture materials, primarily as urea-formaldehyde resin in particleboard. Formaldehyde from these resins is slowly released into the indoor environment, particularly when materials are new. Formaldehyde is currently being scrutinized as an allergenic and possibly carcinogenic substance (National Research Council, 1981). Exposure to low concentrations of formaldehyde (0.02 to 0.20 ppm) can cause dryness or soreness of the throat, irritation of the eye, and swelling of mucous membranes. At very high levels (50 to 100 ppm) it can cause pulmonary edema. Individual responses to formaldehyde vary widely and some individuals become increasingly sensitive to this toxic substance as a result of continued exposure.

Nitrogen dioxide is a combustion by-product generated by natural gas appliances, such as stoves, furnaces, clothes dryers, and water heaters and, to a lesser extent, by tobacco smoking. Exposure to nitrogen dioxide primarily affects the respiratory system. At low concentrations, exposure increases the susceptibility to respiratory disease; at high concentration, it can cause pulmonary edema and even death (U.S. Environmental Protection Agency, 1971).

The nature of these and other indoor air contaminants is extensively discussed in a recent publication from the National Academy of Science (Committee on Indoor Pollutants, 1981).

One potential solution to indoor air quality problems is to install a mechanical ventilation system with an air-to-air heat exchanger (MVHX). Such systems provide a controlled supply of ventilation air and recover much of the energy that would be lost without heat recovery. A residential heat exchanger generally consists of a core, two fans, and two filters all mounted in an insulated case. One fan brings outdoor air (supply air) through the core and into the house while the second fan causes an equal amount of house air (exhaust air) to pass through the core and out of the house. As the two airstreams pass through the core, heat is transferred from the warmer to the cooler airstream (without mixing), thus during cold weather the incoming air is warmed before entering the house. Laboratory tests (Fisk et al., 1980) indicate that MVHX systems can preheat or precool ventilation air by 45 to 85 percent of the difference between indoor and outdoor temperatures.

To address the issues of energy conservation and indoor air quality in residential structures, a study was conducted in a number of occupied homes in Rochester, New York under the joint sponsorship of the Lawrence Berkeley Laboratory (LBL), the New York State Energy Research and Development Authority (NYSERDA), and the Rochester Gas and Electric Corporation (RG&E). The objectives of the study were to assess (1) the effectiveness of construction techniques designed to reduce infiltration; (2) the indoor air quality and air-exchange rates in houses incorporating special weatherization measures; and (3) the impact on indoor air quality of mechanical ventilation systems employing air-to-air heat exchangers.

Two home builders in the Rochester area who have been constructing houses with a special emphasis on reducing air leakage agreed to assist the study. They were Ryan Homes Inc. and Schantz Homes Inc. Ryan is the second largest builder of single-family houses in the U.S. and employs a partial pre-manufacturing process. In 1976 Ryan introduced a number of design changes into its houses with the objective of reducing air leakage. The major changes were incorporation of a continuous polyethylene vapor barrier in the exterior walls, and sealing of all joints and plumbing penetrations.

The primary weatherization component used in Schantz houses is the inclusion of a polyethylene vapor barrier in the exterior walls. Our sample included 47 Ryan houses (35 built after 1976 with the added weatherization components and 12 built before 1976 without such components) and 11 Schantz houses, all of which were built since 1978 (nine with polyethylene vapor barriers in the exterior walls and two with a hi h R-value exterior sheathing).

Experimental Protocol

During the summer of 1980, the "effective leakage area" of each house was measured using the fan pressurization technique (Grimsrud _et al._, 1981). Ten of these houses were singled out for a detailed study of indoor air quality and air-exchange rates during the 1980-81 heating season. Summarized in Table 1 are specific characteristics of each house (construction, appliances, furnishings, and occupancy) that affect indoor air quality. Nine of the ten houses were selected because of their relative tightness; three contained gas cooking appliances (one with tobacco-smoking occupants) and six contained electric cooking appliances (three with tobacco-smoking occupants). The tenth home, which was built without special weatherization components, was a relatively loose structure that was monitored for the purpose of comparison with the tight houses.

Mechanical ventilation systems with air-to-air heat exchangers were installed in each of the nine tight homes. Information on the type of heat exchangers as well as their installation configurations is summarized in Table 1. Indoor air quality and air-exchange rates were monitored in each house for a one-week period without mechanical ventilation followed by a one-week period with mechanical ventilation. No mechanical ventilation was installed in the one loose house which was monitored for a single one-week period.

In eight of these ten occupied houses, an automated monitoring system, called the Aardvark (Nazaroff et al., 1981), was used to measure the air-exchange rate, radon concentration, the indoor and outdoor air temperatures, and the four air-stream temperatures of the air-to-air heat exchangers. The air-exchange rate was calculated every 90 minutes from tracer gas decays using sulfur hexafluoride (SF_6) as the tracer. Average indoor radon concentrations were calculated every three hours using a flow-through scintillation cell. The remaining two houses (#6 and #49) were monitored by LBL's Energy Efficient Buildings (EEB) Mobile Laboratory (Berk et al., 1981) which, in addition to measuring the above parameters, measured indoor and outdoor concentrations of inhalable particulates, carbon monoxide (CO), carbon dioxide (CO_2), nitric oxide (NO), ozone (O_3), and sulfur dioxide (SO_2). In all ten houses, average weekly nitrogen dioxide (NO_2) concentrations were measured with small diffusion-type passive samplers (Palmes et al., 1976) and average daily formaldehyde (HCHO) and total aldehyde (RCHO) concentrations were measured using temperature-and flow-controlled gas bubblers developed at LBL (Miksch et al., 1981).

In this paper we present and discuss the results of leakage area, air-exchange rate, and indoor air quality measurements. In addition, we compare the effects of mechanical ventilation on indoor contaminant concentrations with those predicted from a simple conservation-of-mass model. A comprehensive final project report will incorporate the energy data collected in these houses as well as the results of field performance measurements of the air-to-air heat exchangers installed in nine houses (Offermann et al., 1981).

Results and Discussion

Leakage Measurements

In the full sample of 58 houses, the specific leakage area (effective leakage area in cm^2/floor area in m^2) averaged 3.3 ± 1.8 cm^2/m^2 and ranged from a low of 1.3 cm^2/m^2 to a high of 11.8 cm^2/m^2. The 35 Ryan houses built after 1976 with added weatherization components (polyethylene vapor barriers in the outside walls and sealing of all joints and plumbing penetrations) were relatively tight; i.e., their average specific leakage area of 2.8 cm^2/m^2 is 50% lower than the 5.5 cm^2/m^2 average measured in 12 similar Ryan houses built before 1976 without such components. Based on a model of infiltration developed at LBL (Sherman and Grimsrud, 1980) and using typical weather data for

Rochester, New York, these average specific leakage areas correspond to average heating season infiltration rates of 0.47 air changes per hour (ach) for post-1976 houses and 0.97 ach for pre-1976 houses. The 11 Schantz houses (built between 1978 and 1980) tested also proved to be relatively tight; i.e., the average specific leakage area was 2.9 cm^2/m^2, which corresponds to an average heating season infiltration rate of 0.48 ach.

The nine relatively tight houses selected for indoor air quality measurements, had as a group an average specific leakage area of 2.4 ± 0.7 cm^2/m^2, while the one looser house selected for comparison had a specific leakage area of 5.4 cm^2/m^2.

Figure 1 compares the specific leakage areas for the three groups of Rochester houses with measurements made by LBL researchers and others on groups of houses located in other parts of North America (Grimsrud *et al.* 1981). As can be seen from this figure, the 35 post-1976 Ryan homes and the 11 Schantz homes are among the tightest houses tested.

Indoor Air Quality Measurements: Unventilated Period

Measurements of air-exchange rate and concentrations of Rn, NO_2, HCHO, RCHO, and RH in the ten houses selected for a detailed study of indoor air quality are summarized in Table 2. The measurements of Rn, NO_2, and humidity represent an average of the data from samplers located in the four major conditioned air spaces of the house (living-dining room area, kitchen, master bedroom, and basement). The measurements of HCHO and RCHO represent data from one sampling point in a central air space of the house (living-dining room area). The indoor concentrations of Rn, NO_2, and HCHO measured during both ventilated and unventilated periods were below the various guidelines presently used to assess indoor air quality (Dudney and Walsh, 1981). The indoor concentrations of CO, CO_2, NO, O_3, and SO_2 measured by LBL's mobile laboratory in houses #6 and #49 were also below existing guidelines; however, the concentrations of inhalable particulates in these two houses were relatively high. As expected, the indoor concentrations of Rn, HCHO, RCHO, and water vapor were lowest in house #37, which was a relatively loose house monitored for comparison.

To provide some framework for evaluating these results, we have compiled in Table 4 a listing of outdoor standards for NO_2 (U.S.), recommended indoor standards for HCHO (U.S. and Europe), and region-specific guidelines for Rn (Florida, U.S.). (These guidelines are the only "standards" available to us at the present time; There is an urgent need for comprehensive studies of the health risks associated with indoor air contaminants so that such guidelines will be more meaningful to indoor air quality issues.)

<u>Air-Exchange Rate</u>. The air-exchange rates in the nine tight houses were relatively low, averaging 0.35 ach and ranging from a low average of 0.22 ± 0.09 ach in house #1 to an average of 0.50 ± 0.13 ach in house #56. The one loose house monitored for comparison, house #37, averaged 1.17 ± 0.65 ach and had a high measurement of 4.46 ach during a 90 minute period when the average windspeed was 10 m/s. Throughout the week-long measurement periods, the air-exchange rates in the nine tight

houses were relatively stable, as indicated by the average standard deviation of 0.10 ach in contrast to the standard deviation of 0.65 ach in the one looser house. An example of the impact that occupant activity can have on air-exchange rate was seen in house #33 where the use of the fireplace was seen to increase the air-exchange rate from approximately 0.4 to 0.8 ach on several occasions.

Radon. The average indoor radon concentrations ranged from less than 0.2 pCi/l in house #37 to 2.2 pCi/l in house #60. The guidelines for radon, listed in Table 4, are expressed in working levels (WL), a measure of the "potential alpha energy concentration" of radon daughters specifically devised to indicate relative health hazards (Budnitz *et al.*, 1979). The concentration of radon equivalent to the 0.02 WL guideline depends on the radioactive equilibrium existing between radon and its daughters. Given typical indoor equilibrium factors of 0.3 to 0.7 (Haywood, 1980), the 0.02 WL guideline corresponds to radon concentrations in the range of 3 to 6 pCi/l. None of the concentrations of radon measured in this study exceeded the upper limit of this range, although several measurements approached the lower limit.

All of the houses in this study had basements constructed with floating concrete slabs. The gap between the slab and foundation in this type of construction can be a significant pathway for the infiltration of soil gas, which is often a major source of indoor radon. That indoor radon concentrations and air-exchange rates were low, however, suggests that the emanation rate of radon from soil in this area is fairly low (e.g., the concentration of emanating radium in soil is low and/or the permeability of the soil is low). It is interesting to note that the two highest average indoor radon concentration measurements in this area were made in house #45 (2.1 pCi/l) at the beginning of the study (November) and in house #60 (2.2 pCi/l) at the end of the study (April), which were the warmest measurement periods of the study and the only periods of the study when the surface of the ground was not frozen.

Formaldehyde. The indoor concentrations of HCHO measured in each house during the unventilated period were all lower than 100 ppb, which is the most stringent recommended guideline. The average indoor concentrations ranged from 7 ppb in house #10 to 64 ppb in house #52; the outdoor concentrations were consistently below the detection limit of 5 ppb. No HCHO data were collected during the unventilated period in house #56 as a result of a malfunction in the HCHO air-sampling system; however, RCHO data was collected during this period. Since the average ratio of HCHO to RCHO was found to be about 50% in these residences, we estimate that the unventilated HCHO concentration in house #56 was on the order of 30 to 45 ppb.

Because particleboard and chipboard, which are often used in the construction of cabinets and furniture, can be major sources of HCHO, especially during the first few years after its manufacture, it was decided to conduct an inventory in each house of the amount of these materials less than three years old. Plywood, which is a less significant source of HCHO, was used in similar amounts in constructing the floors, ceilings, and roofs of both the Ryan and Shantz houses. A comparison of the particleboard inventory in Table 1 and the HCHO and RCHO measurements in Table 2 reveals that the three houses with the highest RCHO concentrations, houses #52, #56, and #60, are also the only houses with any significant amounts of new particleboard. Houses #52 and #60 also exhibited the highest HCHO concentrations.

Nitrogen Dioxide. In the case of NO_2, indoor concentrations were consistently lower than outdoor concentrations (10-30 ppb, typical of urban environments) except in house #33 (which had an unvented gas clothes dryer as well as a gas cooking range) where the average indoor NO_2 concentration was 23 ppb, the highest measured in this study. As expected, in houses with gas cooking appliances the average indoor concentrations of NO_2 were higher (14.7 ± 7.2 ppb) than in houses with all electric cooking appliances (4.1 ± 3.9 ppb). The fact that indoor NO_2 concentrations were as low as they were in these relatively tight houses with gas cooking ranges may be partially attributed to the occupants' reported use of outside-vented range hoods.

Inhalable Particulates. LBL-developed automatic dichotomous air samplers (Loo *et al.*, 1979) were used at the two EEB Mobile Laboratory field sites (houses #6 and #49) to monitor indoor and outdoor concentrations of inhalable particulates (IP), i.e., those particulates with an aerodynamic diameter less than 15 μm. Each sampler is equipped with a high-efficiency single-stage virtual impactor which collects and separates suspended particulate matter into two size ranges, the inhalable fraction (less than 15 μm) and the respirable fraction (less than 2.5 μm). The mass of the particulate samples are later measured using beta-ray attenuation. The particulate data reported in Table 3 represent the average of indoor and outdoor measurements made in houses #6 and #49. In both houses the indoor particulate concentrations averaged nearly twice the outdoor concentrations. Tobacco smokers occupied both houses and tobacco smoke most likely constituted the major indoor source of suspended particulates.

Presently there are no standards, indoor or outdoor, for inhalable particulate concentrations. The Environmental Protection Agency (EPA) does have an annual outdoor standard for total suspended particulates (TSP) of 75 $\mu g/m^3$; however, because of recent recognition that it is the particulate size fraction less than 15 μm in diameter that actually penetrates to the tracheobronchial and alveolar regions of the lung where adverse health effects are most likely (larger particulates are removed in the upper respiratory tract), the EPA is considering adopting a new primary standard for inhalable particulates. The average indoor IP concentration measured in house #6 was 76 $\mu g/m^3$ which is just above the recommended outdoor TSP standard of 75 $\mu g/m^3$, while in house #49 the average indoor IP concentration was 52 $\mu g/m^3$. However, the appropriateness of applying outdoor particulate standards to indoor particulate concentrations is highly questionable since indoor and outdoor particulate matter may differ significantly in chemical composition and size distribution.

Humidity. In the selected ten houses, the average relative humidities ranged from 25% (4.0 g/kg) in house #9 to 52% (8.2 g/kg) in house #60, values which are within established health and comfort guidelines (ASHRAE, 1981). In several houses, however, indoor relative humidities were high enough that some homeowners experienced problems with excessive condensation and/or frosting on windows and other cold surfaces during cold weather periods. The occupants in house #60, which had the highest indoor humidity level (52%), also experienced problems with mold and mildew formation on the surfaces of some walls.

Indoor Air Quality Measurements: Ventilated Period

During the period when mechanical ventilation was used, the average air-exchange rate in these nine tight homes was increased 80% (from 0.35 to 0.63 ach). Under these conditions the average indoor radon concentration decreased 50% (from 1.0 pCi/l to 0.5 pCi/l), average HCHO concentration decreased 21% (from 35.5 ppb to 28.0 ppb), and average relative humidity decreased from 39% (6.2 g/kg) to 35% (5.5 g/kg). These decreases are consistent with our expectations, since outdoor concentrations of Rn, HCHO, and water vapor were much lower than indoor concentrations. On the other hand, in the case of NO_2 concentrations, which were generally higher outdoors than indoors, mechanical ventilation had the effect of increasing the average indoor concentrations slightly (from 7 to 9 ppb). In houses #6 and #49, mechanical ventilation reduced inhalable particulate concentrations 30% on the average.

For our studies of mechanical ventilation, we installed two different types of air-to-air heat exchangers, sensible and sensible/latent. The latter is designed to transfer water vapor as well as heat -- particularly desirable in hot, humid climates were air must be both cooled and dried for indoor comfort. The sensible-type heat exchangers were tested in seven houses and the sensible/latent-type heat exchangers, constructed of specially treated paper designed to provide moisture exchange between the exhaust and supply airstreams, were tested in two houses (#45 and #52). A concern with this type of heat exchanger core is that the effect of the ventilation on indoor contaminant concentrations may be significantly compromised if indoor contaminants are transferred along with the water vapor.

Figure 2 presents a comparison of the changes in the air-exchange rates, indoor contaminant concentrations, and humidity observed in the seven houses ventilated with sensible-type heat exchangers with those observed in the two houses (#45 and #52) ventilated with sensible/latent-type heat exchangers. From this comparison, it appears that ventilation with sensible/latent-type heat exchangers is less efficient in lowering the concentrations of some indoor contaminants. Most apparent are the reductions in HCHO -- an average reduction of 30% ± 20% for those houses ventilated with sensible-type units in contrast to virtually no change in houses ventilated with sensible/latent-type units. The absence of reductions in these houses may possibly be due to the transfer of HCHO along with the water vapor from the exhaust air stream into the supply air stream. However these results should not be taken as conclusive evidence of HCHO cross-stream transfer in this type of heat exchanger, since the sample of houses is small and HCHO emission rates may change with indoor humidity levels, temperature, and time. These findings, nevertheless, do illustrate the need for further research.

Predicted Effects of Ventilation on Indoor Contaminant Concentrations

The steady-state concentration of any indoor air contaminant is directly related to its rate of emission into and rate of removal from the indoor air space. The two processes that increase indoor contaminant concentrations are the flow of outdoor contaminants into the interior environment (less the fraction that is removed by the building shell), and the rate at which contaminants are generated indoors (i.e., the contaminant source strength); the two processes that decrease indoor contaminant levels are the flow of indoor air out of the interior environment, and the net removal rate of indoor contaminants via various chemical and physical removal processes that occur completely within the interior environment (e.g., wall adsorption). Both Alonzo *et al*. (1979) and Dockery and Spengler (1981) incorporated these processes into a single conservation-of-mass model. The model assumes that the contaminant concentration in the air that flows out of the chamber is the same as the average indoor concentration (i.e., the mixing of indoor air is perfect). Based on this work and using notation similar to that used by Traynor *et al*. (1981a), the equation that describes the steady state indoor-contaminant concentration in a well-mixed space is:

$$\frac{S}{V} + PaC_o = (a + k)C_i \tag{1}$$

where: C_i = the indoor air contaminant concentration ($\mu g/m^3$)

a = the air-exchange rate, ach (hr^{-1})

C_o = the outdoor air contaminant concentration ($\mu g/m^3$)

P = the percent transmission of outdoor contaminant indoors

k = the net removal rate by mechanisms other than air exchange (hr^{-1})

S = the indoor contaminant generation rate ($\mu g/hr$)

V = indoor volume (m^3)

For contaminants where $C_i >> C_o$, this equation becomes:

$$\frac{S}{V} = (a+k)\ C_i \tag{2}$$

If we make the further simplifying assumption that contaminants are emitted at a constant rate, S, then the ratio of contaminant concentrations for two periods with different air-exchange rates (periods 1 and 2) can be expressed as:

$$\frac{(C_i)_2}{(C_i)_1} = \frac{(a+k)_1}{(a+k)_2} \tag{3}$$

According to this equation, for nonreactive contaminants such as radon, which are removed from indoor spaces predominantly as a result of air exchange ($k \cong 0$), the change in concentrations is inversely proportional to the change in air-exchange rate. In this study the average reduction of indoor radon concentrations in houses ventilated with sensible-type heat exchangers was 45% ± 37% which compares to a predicted reduction of 41% ± 20%. The average reduction of radon in houses ventilated with sensible/latent-type heat exchangers was 59% ± 22%, which compares to a predicted reduction of 51% ± 31%.

In houses #1, #10, #45, #52, and #56, air was specifically exhausted from the basement areas, where the major sources of radon would be expected to be located. In these houses the average reduction of indoor radon concentration was 58% ± 40% which is significantly higher than the 46% ± 26% reduction we would predict, while in the remaining four houses where air was specifically exhausted from spaces other than basements (e.g., first or second floor locations) the average reduction was 40% ± 41% which compares well with the 42% ± 19% reduction we would predict. Thus it appears that sensible and sensible/latent heat exchangers in this study were equally effective in reducing radon concentrations, and that reductions obtained by exhausting air from basements were slightly greater than those predicted.

For reactive contaminants such as HCHO, NO_2, suspended particulates, and radon daughters, which are significantly removed from indoor spaces by physical and/or chemical reactions with indoor surfaces ($k > 0$) as well as by air exchange, we can expect the change in concentrations resulting from increased ventilation to be less than the inverse of the change in air-exchange rates. In other words, to reduce HCHO concentrations by one-half, it is necessary to more than double the ventilation rate. Similarly, a house-tightening retrofit that reduces the air-exchange rate by 30% can be expected to increase HCHO concentrations by less than 30%, assuming the average HCHO source strength remains the same; however, decreasing ventilation generally causes an increase in indoor humidity which, in turn, may increase the rate of HCHO emission. Laboratory tests have shown that the outgassing of formaldehyde from building materials is influenced by the indoor humidity level, higher humidities being associated with higher outgassing rates of HCHO (Berg et al., 1980). In short, the extent to which ventilation is effective in controlling indoor contaminant concentrations depends largely on the reactivity of the contaminant. If the contaminant reactivity is high relative to the air-exchange rate, ($k >> a$), we can expect that in a well-mixed space either increasing or decreasing ventilation will have little effect on the steady-state concentration of indoor contaminants. Thus, knowing the reactivity of contaminants is important in predicting the effects of ventilation on indoor contaminant concentrations.

In chamber studies performed at Lawrence Berkeley Laboratory (Traynor et al., 1981a), researchers have measured HCHO reactivities of 0.40 ± 0.24 h^{-1}, a value we used to predict the impact of increased ventilation on HCHO concentrations in this study. In actual indoor environments, contaminant reactivity may vary significantly depending on the physical and chemical nature of the indoor surfaces. The average reduction in HCHO concentrations for houses ventilated with sensible-type heat exchangers, omitting house #56, which lacks HCHO data for the unventilated period, was 30% ± 20% which compares to the predicted average reductions of 27% ± 8%. In fact, we might have expected to see somewhat larger than predicted reductions since the relative humidity in these houses was reduced during the ventilated period and, as mentioned above, a decrease in humidity may reduce the rate of outgassing of HCHO from building materials. The absence of observable HCHO reductions in the houses ventilated with sensible/latent-type heat exchangers contrasts with an average predicted reduction of 32% ± 5%. As discussed earlier, we suspect that this discrepancy may be a result of cross-stream transfer of HCHO in the core of this type of heat exchanger.

In the case of NO_2, only house #33 exhibited an average indoor concentration that measured significantly higher indoors than outdoors. Since NO_2 is a much more reactive gas than HCHO, we can expect that changes in ventilation to have a lesser effect upon reducing NO_2 concentrations. Researchers at Lawrence Berkeley Laboratory have observed NO_2 reactivities of 1.29 ± 0.67 h^{-1} in an actual residence (Traynor et al., 1981b). These values are consistent with the reactivity of 1.39 h^{-1} reported by Moschandreas and Stark (1978). Assuming the average source strength for NO_2 remained the same during the two measurement periods in house #33 (and a log of cooking activities supports this assumption), and using an NO_2 reactivity of 1.30 h^{-1} and a penetration factor, P, of 1.0 to account for infiltration of outdoor NO_2, we would predict a 7% reduction in average NO_2 concentrations. The actual reduction observed in this house was somewhat higher, 13%, perhaps because air was specifically exhausted from the kitchen area where NO_2 concentrations would presumably be higher than the average concentration in the house.

Conclusions

Special weatherization components such as continuous polyethylene vapor barriers and joint-sealing are effective in reducing the leakage area of houses and, hence, infiltration, as evidenced by the direct measurements of leakage area and air-exchange rates made in this study. In the nine tight houses studied, the air-exchange rates measured during the unventilated period were low, averaging 0.34 ± 0.10 ach, and indoor concentrations of Rn, HCHO, and NO_2 were below existing air quality guidelines, findings which suggest that the source strengths of these contaminants were relatively low in these houses. Clearly, one key to having an energy-efficient house with both low air-exchange rates and acceptable indoor air quality is to construct and furnish it such that indoor contaminant sources are low. Evidence that this is achievable in standard residential housing (at least with respect to the contaminants we monitored) is provided by our findings in these nine houses. However, it should be noted that concentrations of carbon monoxide and inhalable particulates were measured in only two houses and certain contaminants such as organic compounds other than formaldehyde were not measured at all.

When designing houses to have low air-exchange rates, builders should be selective in choosing building materials that are not potential sources of indoor air pollution. Research has been initiated at LBL and other organizations to study contaminant emissions from various building materials. However, many sources of indoor air pollution are occupant-related and beyond the control of builders, such as tobacco smoking, use of unvented combustion appliances and toxic cleaning products, and selection of house furnishings constructed with urea-formaldehyde based resins. Homeowners must accept responsibility for controlling these sources.

Sources of indoor radon could be effectively controlled in new housing. One could avoid the use of building materials with high concentrations of emanating radium; domestic water taken from underground springs or wells, another potentially significant source of indoor radon, could be aerated before use. The influx of radon from soil, possibly the dominant source of indoor radon in the United Stated, could be controlled, in principle, by adopting building designs and construction practices which minimize the transport pathways between the house and the soil. Further work is needed to test the effectiveness of various approaches and,perhaps, to identify those parts of the country were radon from soil is likely to be an endemic problem.

In tightly-constructed houses where it is uncertain whether the natural ventilation from air leakage together with ventilation occasioned by occupant activities (e.g., opening doors and windows, using exhaust fans, etc.) will adequately maintain acceptable indoor air quality, mechanical ventilation systems with air-to-air heat exchangers (MVHX) can be installed. These units provide a controlled supply of ventilation air while recovering much of the energy that would otherwise be lost and are effective in reducing concentrations of indoor-generated contaminants, as demonstrated in this study.

The extent to which mechanical ventilation is effective in controlling indoor contaminant concentrations depends largely on the reactivity of the contaminant, its outdoor concentration, and its concentration in the exhaust airstream. Except for the HCHO reductions in the houses ventilated with sensible/latent type heat exchangers, the contaminant reductions actually observed compared well with those predicted from a simplified conservation-of-mass model. The absence of observable HCHO reductions in the houses ventilated with sensible/latent-type heat exchangers indicate that there may be cross-stream transfer of HCHO in this type of heat exchangers. Further research is needed to evaluate the extent of cross-stream transfer of HCHO and other contaminants in heat exchangers designed to transfer water vapor as well as heat.

In addition, further research concerning MVHX systems is needed to study (1) condensate freezing within heat exchanger cores and various freeze-protection strategies, (2) the ventilation efficiencies of ducted and unducted (e.g., window mounted) systems, and (3) the cost-effectiveness of the use of air-to-air heat exchangers in various residential settings.

Although mechanical ventilation with heat recovery is a promising strategy for maintaining acceptable indoor air quality in tight houses, it is possible that other contaminant control strategies may be equally or more effective. Researchers at LBL have begun to examine the potential of such alternate control strategies as air washing (e.g., simple air-water contact systems) for removing HCHO and other water-soluble contaminants, and electronic air cleaning for removing suspended particulate matter and radon daughters.

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Table 1. Summary of house characteristics and air-to-air heat exchanger installations in ten occupied Rochester, New York residences.

House ID#[a]	Year Built	House Volume (m^3)	Specific Leakage Area (cm^2/m^2)	Occupancy Adults	Occupancy Children	Smoking Activity[b]	Combustion Appliances[c]	Particleboard[d] (m^2)	Air-to-Air Heat Exchanger: Type	Air-to-Air Heat Exchanger: Exhaust Location	Air-to-Air Heat Exchanger: Supply Location
#1	1977	467	2.4	2	1	0	none	0	ducted sensible	basement	furnace return
#6	1977	402	2.8	2	3	pipe	WS (not used)	0	ducted sensible	first floor	furnace return
#10	1976	357	1.4	2	0	5	none	0	ducted sensible	basement	furnace return
#33	1979	496	2.5	2	2	0	FP, GD, GF GS, GW	<1	ducted sensible	kitchen	furnace return
#37	1974	411	5.4	2	2	5	GF, GW	0	none	--	--
#45	1979	650	2.0	2	3	20	FP, GF, GW	<1	ducted sensible/latent	basement	furnace return
#49	1973	425	3.5	2	2	25	GF, GS, GW	0	ducted sensible	kitchen	furnace return
#52	1980	357	1.4	2	1	0	none	17.7	2 window units sensible/latent	living room downstairs den	living room downstairs den
#56	1981	360	3.2	2	3	0	GD, GF, GS, GW	10.2	ducted sensible	basement	furnace return
#60	1979	493	2.7	2	2	0	GF, GW	7.0	ducted sensible	2 upstairs bathrooms	furnace return

[a]All houses were occupied single-family dwellings with full basements.

[b]Estimated number of cigarettes smoked indoors per day.

[c]Key: (FP) fireplace, (GD) gas dryer, (GF) gas furnace, (GS) gas stove, (GW) gas water heater, (WS) woodstove.

[d]Estimated sq. meters of particleboard or chipboard less than three years old.

Table 2. Summary of air-exchange rate and indoor air quality measurements made in ten occupied houses in Rochester, New York. (November, 1980-April, 1981)

House ID#	Measurement Periods[a] Mech. Vent. Off / Mech. Vent. On	Air-exchange rate[b] (ach)	Rn^c Indoor (pCi/l)	HCHO[d] Indoor/Outdoor (ppb)		RCHO[d] Indoor/Outdoor (ppb)		NO_2[c] Indoor/Outdoor (ppb)		Relative Humidity[c] Indoor (%)
#1	12/7-15	0.22 ± .09	0.4	36	<5	40	6	1	7	47
	12/16-21	0.47 ± .19	0.1	19	<5	26	<5	3	10	38
#6	1/8-22	0.38 ± .09	1.6	29	<5	63	6	4	16	30
	1/23-30	0.66 ± .16	0.7	22	<5	37	<5	4	13	26
#10	1/6-13	0.30 ± .09	1.2	7	<5	29	6	1	9	35
	1/14-20	0.61 ± .70	0.7	<5	<5	23	9	5	25	30
#33	2/21-28	0.38 ± .15	0.3	33	<5	56	7	23	9	42
	3/4-10	0.78 ± .16	0.0	19	<5	33	5	20	12	33
#37	3/14-21	1.17 ± .65	0.0	17	<5	26	<5	6	11	29
#45	11/13-20	0.37 ± .10	2.1	28	<5	56	17	2	14	44
	11/21-26	0.61 ± .23	0.9	29	<5	58	14	6	29	39
#49	2/5-19	0.42 ± .11	0.1	30	<5	60	5	11	15	25
	2/20-3/2	0.64 ± .17	0.2	29	<5	61	<5	16	11	27
#52	3/24-30	0.28 ± .10	1.1	64	<5	123	<5	3	12	41
	3/31-4/7	0.73 ± .13	0.4	62	<5	98	22	1	11	42
#56	1/28-2/4	0.50 ± .13	0.2	e	<5	75	<5	10	15	36
	2/11-16	0.61 ± .21	0.0	18	<5	45	<5	9	18	33
#60	4/10-21	0.33 ± .10	2.2	57	<5	88	<5	12	18	52
	4/21-28	0.52 ± .06	1.6	42	<5	53	<5	13	18	45

[a]Dates of indoor air quality sampling periods (without and with mechanical ventilation)

[b]Average of consecutive 1½ hr SF_6 tracer gas decay measurements, ± one standard deviation.

[c]Indoor measurements of Rn, NO_2, and relative humidity represent averages of the data from samplers located in the four major conditioned air spaces of each house (living-dining room area, kitchen, master bedroom, and basement).

[d]Indoor measurements of HCHO and RCHO represent the data from one sampling point in each house (living-dining room area).

[e]No HCHO data for this period.

Table 3. Summary of inhalable and respirable particulate measurements made in two occupied houses in Rochester, New York (January-February, 1981).

House ID#	Measurement Period Mech. Vent. Off Mech. Vent. On	Air Exchange[a] rate (ach)	Inhalable Fraction (<15 μm)[b] ($\mu g/m^3$) Indoor	Outdoor	Respirable Fraction (<2.5 μm)[b] ($\mu g/m^3$) Indoor	Outdoor
#6	1/8-22	0.38 ± 0.09	76	28	54	19
	1/23-30	0.66 ± 0.16	49	13	31	9
#49	2/5-19	0.42 ± 0.11	52	20	38	14
	2/20-3/2	0.64 ± 0.17	43	6	30	6

[a] Average of consecutive 1½ hr SF_6 tracer gas decay measurements, ± one standard deviation.

[b] Particulate concentrations reflect the arithmetic mean values of consecutive 24 hour integrated measurements made at one indoor location (living-dining room area) and one outdoor location.

Table 4. Selected air quality guidelines

Pollutant	Concentration	Country	Status	Reference
Formaldehyde (Indoor)	200 ppb - maximum	U.S. (California)	Proposed	1
	200 ppb - maximum	U.S. (Wisconsin)	Proposed	2
	120 ppb - maximum	Denmark	Recommended	3
	100 ppb - maximum	The Netherlands	Recommended	4
Nitrogen Dioxide (Outdoor)	50 ppb - annual average	United States	EPA Standard	5
Radon (Indoor)	.015 WL - annual average	United States	Proposed standard for buildings contaminated by uranium processing	6
	.02 WL - annual average	U.S. (Florida)	Recommendation to Governor of Florida for buildings on reclaimed phosphate mining land	7
	.02 WL - annual average	Canada	Policy statement by AECB	8

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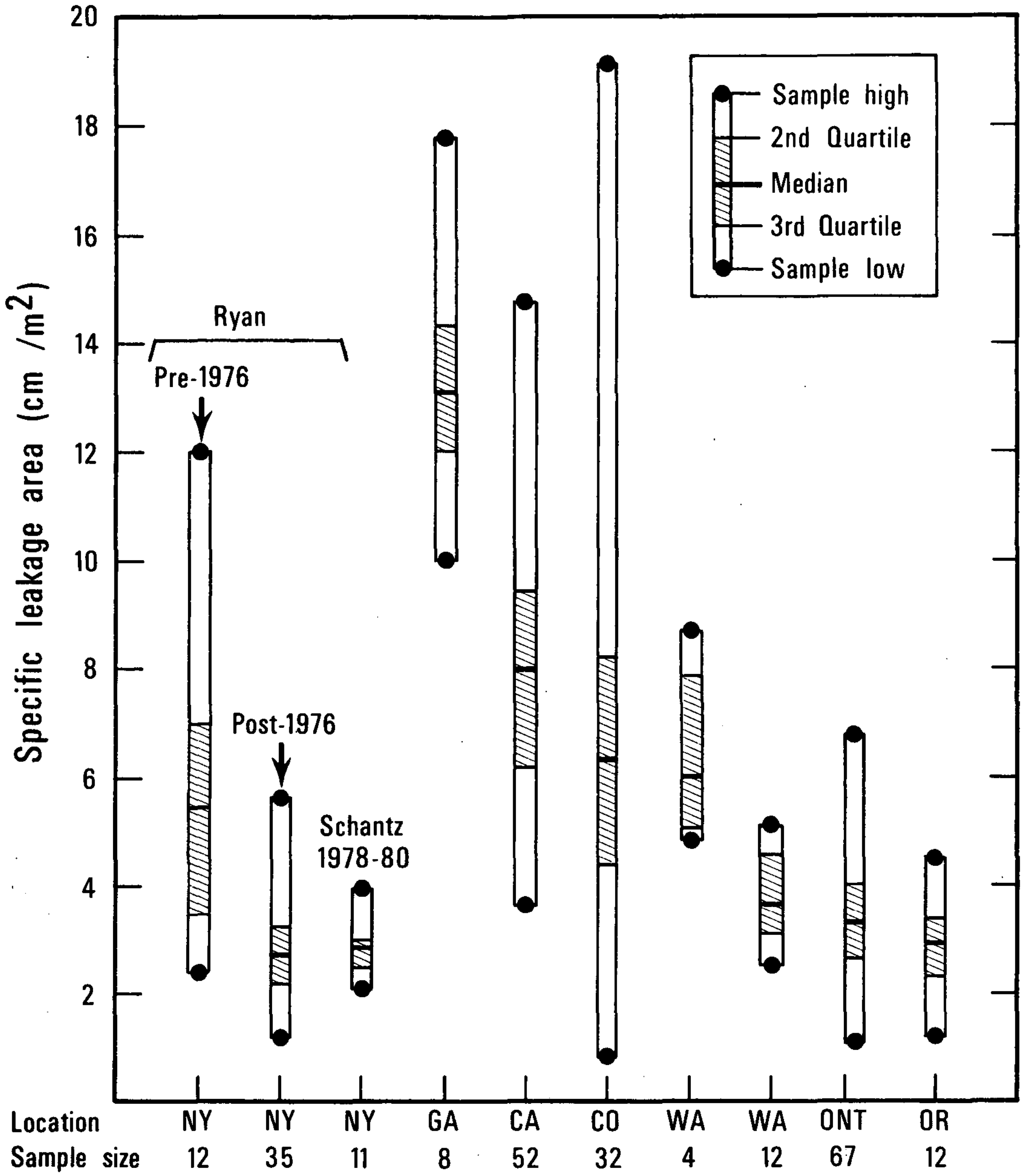

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Figure 1. Comparison of specific leakage areas for three groups of houses in Rochester, New York with those of other groups of houses studied in North America: Ryan pre-1976 (no special weatherization components), Ryan post-1976 (polyethylene vapor barriers in exterior walls and sealed joints and plumbing penetrations), and Schantz 1978-80 (polyethylene vapor barriers in exterior walls).

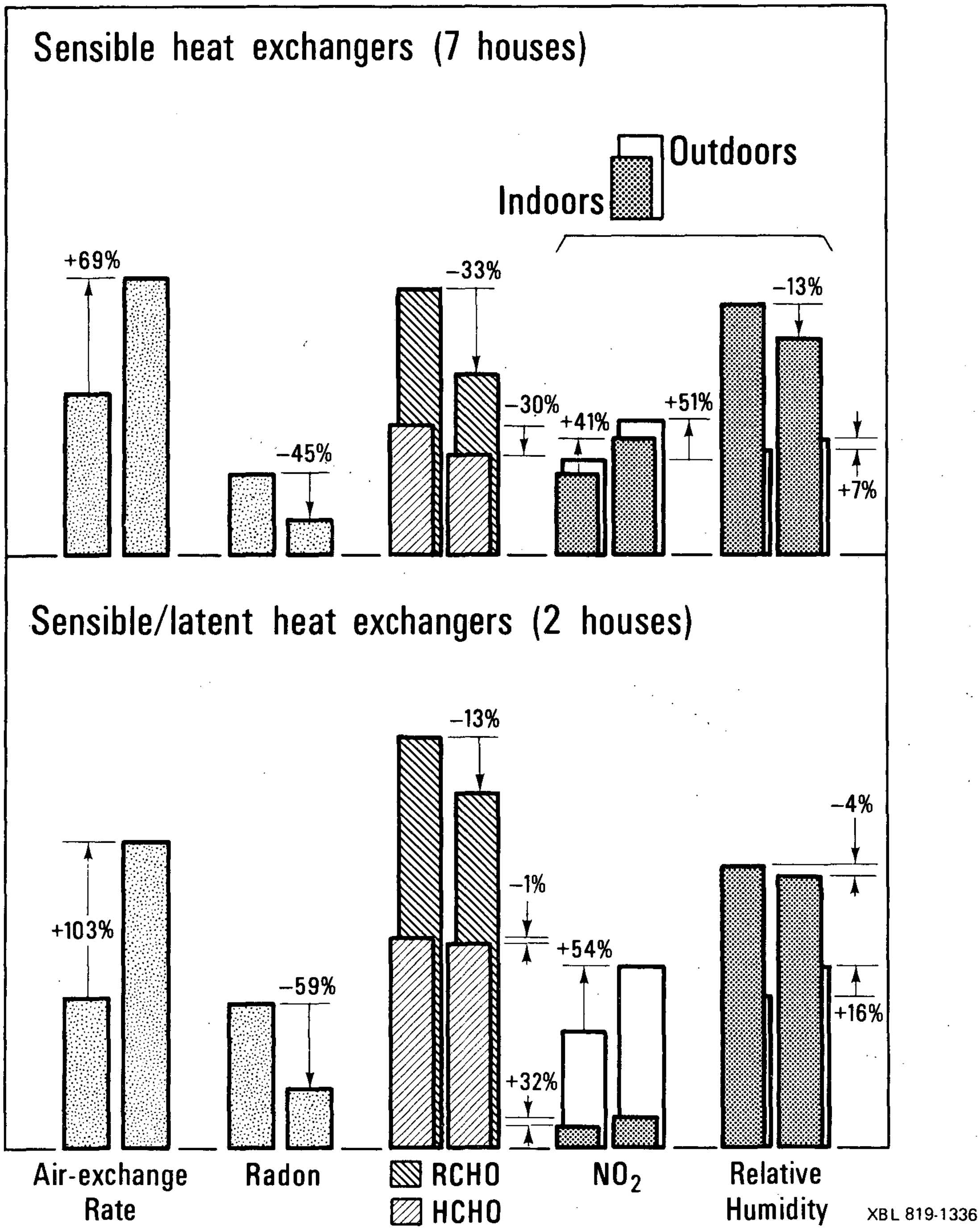

Figure 2 Comparison of changes in air-exchange rates, indoor contaminant concentrations, and humidity following ventilation with sensible-type heat exchangers (7 houses) and with sensible/latent-type heat exchangers (2 houses). (Left bar of each pair - unventilated measurements; right bar - ventilated measurements.)

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