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IMPROVING INDOOR AIR QUALITY AND SAVING ENERGY

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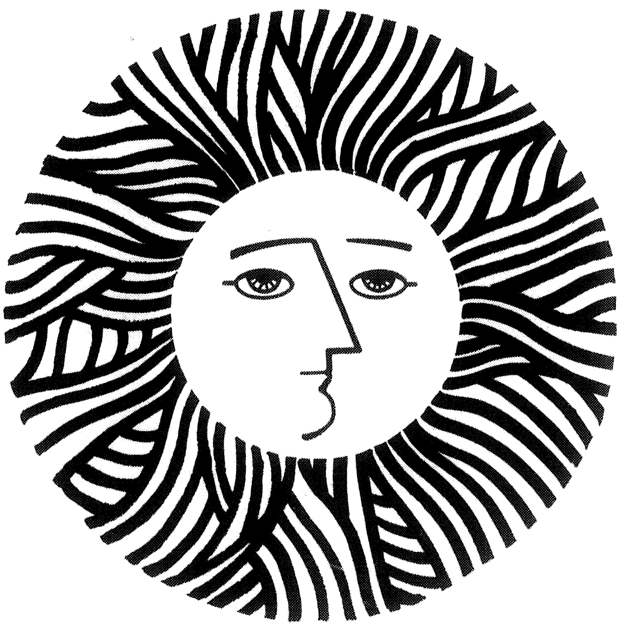

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ABSTRACT

Interest in conserving energy is motivating homeowners and builders to reduce natural infiltration to very low levels. This large reduction in ventilation can lead to indoor moisture problems and, more importantly in terms of human health, increased levels of indoor pollutants such as nitrogen dioxide, formaldehyde, and radon. This paper reports residential air-quality measurements conducted by Lawrence Berkeley Laboratory and, specifically, discusses the use of mechanical ventilation systems with air-to-air heat exchangers as a promising means of pollutant control. A particular advantage of this control strategy is that the heat exchanger permits recovery of a large portion of the heat that would normally be lost in a simple exhaust ventilation system, and therefore maintains the energy efficiency of the house. An economic analysis is presented showing that installation of these systems in newly constructed homes is cost-effective in most regions of the country.

INTRODUCTION

One of the most promising ways the United States can reduce its dependence on imported oil is to use energy more efficiently. Approximately 12% of the total energy used in the United States, the equivalent of almost 4.5 million barrels of oil per day, is for heating and cooling residential structures.[1]

Much attention is being focused on conserving energy in residences. Building codes are being modified to require that new houses be more energy-efficient. Builders in the United States, Canada, and Europe are constructing highly insulated houses that are also well sealed against the infiltration of outside air into the structure. In some cases, infiltration has been reduced from a typical rate of 0.75 air changes per hour (ach) in conventional houses to less than 0.2 ach in houses designed for energy efficiency.[2,3] When the natural infiltration of outside air into a structure is significantly reduced, the structure is clearly more energy-efficient. Not only is there an energy saving on both heating and cooling but, with uncomfortable drafts eliminated, occupants are less likely to raise thermostat settings.

One of the problems associated with relatively air-tight houses, however, is that the levels of indoor-generated air contaminants are increased.[4,5,6] Excessive humidity levels, odors from human activities, and increased levels of contaminants such as nitrogen dioxide, formaldehyde, and radon have been found in houses in which air exchange rates are low. One method of alleviating these air-quality problems in nearly air-tight houses is to introduce a mechanical system to provide ventilation. When coupled with an air-to-air heat exchanger, such a ventilation system can save energy by preheating or precooling the incoming fresh air to temperature and humidity levels closer to the desired indoor conditions.

This paper describes some of the research being conducted at the Lawrence Berkeley Laboratory (LBL) on the effect of reduced ventilation on indoor air quality, and presents an economic analysis of the residential use of mechanical ventilation systems with air-to-air heat exchangers in newly constructed houses. The ventilation unit serves to control indoor air pollution, and the heat exchangers minimize the energy consumed by its operation.

INDOOR AIR QUALITY IN RESIDENTIAL BUILDINGS

Until recently, air pollution research has focused almost exclusively on pollution in the outdoor environment while virtually ignoring the indoor environment, even though the major portion of the population spends far more time indoors than outdoors. Recent evidence suggests that concentrations of some pollutants in residential buildings can frequently exceed those levels commonly occurring in the outdoor environment.[7]

Chemical and biological contaminants released into indoor environments are undesirable but often unavoidable by-products of occupant activities. Typical indoor contaminants include gaseous and particulate pollutants from indoor combustion processes (e.g., cooking, heating, cigarette smoking), toxic chemicals and odors from cooking and cleaning activities, odors and viable microorganisms from occupants, odor-masking chemicals used in cosmetics and air fresheners, and a wide assortment of compounds and chemicals released from construction materials, furnishings and soil--e.g., asbestos, formaldehyde, vinyl chloride, and radon. Table 1 lists some of the major indoor air pollutants and their sources.

The level of indoor air contamination is directly related to the amount of ventilation in the building. Ventilation occurs as a result of 1) infiltration (the uncontrolled leakage of air to or from a space); 2) natural ventilation (e.g., opening doors and windows); and 3) mechanical ventilation. In the United States, mechanical ventilation is usually limited to nonresidential buildings. Ventilation is required to establish a satisfactory balance between the metabolic gases (oxygen and carbon dioxide) in the occupied environment; to remove excess heat and moisture arising from internal sources; to dilute human and nonhuman odors to an acceptable olfactory level; and to remove contaminants produced by activities, furnishings, construction materials, etc., in the occupied spaces.

Ventilation requirements are currently set by state and local governments and vary from one jurisdiction to another. Most of the ventilation requirements in existing building codes are based on rather limited health and safety considerations and were devised before energy conservation became a national imperative.

Because of recent concern and interest in the problem of indoor air quality, LBL has undertaken an extensive field-monitoring program to measure indoor air contaminants in a variety of building types. This field-monitoring program focuses on such indoor air-quality parameters as temperature and relative humidity, odor levels, toxic chemicals (gases and particulates), and microbial burden. For purposes of field monitoring, LBL designed a mobile facility, the Energy Efficient Buildings (EEB) Mobile Laboratory,[8] to facilitate on-site study of indoor air quality and energy utilization in residential, institutional, and commercial buildings.

A number of energy-efficient residences have been studied to date.[7] In this report, we will refer to four specific houses where infiltration rates typically ranged from 0.1 ach to 0.4 ach. Infiltration measurements made at the Minimum Energy Dwelling in Mission Viejo, California (MED-I) using a tracer gas with a simple decay technique yielded an infiltration rate of approximately 0.2 ach. Infiltration measurements at the Iowa State University Energy Research House in Ames, Iowa (ISUERH), an energy research house in Carroll County, Maryland (ERHM), and a second Minimum Energy Dwelling in Mission Viejo, California (MED-II) used an LBL-designed continuous tracer-gas system, and results varied. At the ISUERH, infiltration rates ranged from 0.1 to 0.4 ach with an average of approximately 0.2 ach. At the ERHM, infiltration rates varied from 0.05 to 0.4 ach with an average of approximately 0.15

ach. At the MED-II house, infiltration rates varied from 0.2 to 0.8 ach with an average of about 0.35 ach.

The pollutants identified at these sites comprised two major classes: those for which the primary sources were indoors and those for which the primary sources were outdoors. Substances in the former class showed higher concentrations indoors than outdoors; the indoor environment tended to be shielded from substances in the latter class.

The MED-I and MED-II houses both had gas kitchen appliances and were occupied. In these houses, NO_2 concentrations were found to be higher indoors; presumably, their source was natural gas combustion from cooking activities. At the MED-II house, indoor levels of NO_2 exceeded 250 ppb during periods when the gas oven was operating. A recirculating range hood with a charcoal filter was used when the oven was operated. The National Ambient Primary Standard for NO_2 is an annual average of 50 ppb and represents the limit necessary, with an adequate margin of safety, to protect the public health.[9] The United States Environmental Protection Agency (EPA) is considering establishing a short-term (one-hour) air-quality standard for NO_2 in the range of 250 to 500 ppb.[10]

Figures 1 and 2 show the distribution of total aliphatic aldehydes and formaldehyde during the monitoring periods at the ISUERH and ERHM. As can be seen, total aliphatic aldehyde and formaldehyde concentrations indoors, obtained from 24-hour samples, were considerably higher than those outdoors. Indoor formaldehyde levels at the ISUERH averaged 42 ppb, and occasionally exceeded 100 ppb, which has been promulgated in the Netherlands as an indoor standard for formaldehyde.[11] While the activities of building occupants, e.g., cooking and smoking, generate significant amounts of aldehydes, these houses were unoccupied; thus these levels are probably attributable to urea-formaldehyde resins used in furnishings and common building materials, such as plywood and particleboard.

Another potential contaminant of indoor air is radon-222, a radioactive noble gas which is the daughter product of radium-226 and appears as part of the uranium-238 decay chain. Because small amounts of radium are present in almost all soil and rock, potential sources of radon in buildings include the soil surrounding foundations, the building materials themselves, natural gas, and tap water if the water has come directly from an underground well. Prolonged exposure to the radioactive decay products of radon (known as radon daughters) may pose some health risk. It is even possible that radon-daughter concentrations in existing houses in the United States may cause thousands of lung cancer deaths each year.[6]

Although there is currently no national standard specifically limiting the permissible concentration of radon daughters in the general housing stock, the EPA has recommended a guideline to the state of Florida for houses built on phosphate-reclaimed land.[12] The unit used in health guidelines is the Working Level (WL), which is a measure of the total potential alpha energy concentration of the radon daughters in the air. The EPA guideline states that remedial action should be undertaken when radon-daughter concentrations exceed 0.02 WL, which is roughly equivalent to a radon concentration of 4 nanocuries per cubic meter (nCi/m^3). It further states that, in all cases, radon-daughter concentrations should be reduced to levels as low as reasonably achievable. A similar standard has been promulgated in Canada to limit radon-daughter concentrations in houses located in four communities engaged in uranium mining and processing. The Canadian standard calls for "prompt interim action" when the concentrations exceed 0.15 WL, mandatory "remedial action" when concentrations exceed 0.02 WL, and "more detailed investigation" when levels exceed 0.01 WL.[13]

In an effort to expand our data base on indoor radon, we initiated a field-monitoring project in May 1979 to study radon concentrations in both conventional and energy-efficient houses. A survey of conventional houses was conducted mainly in the San Francisco Bay Area. Measurements were taken under "worst case" conditions, i.e., doors and windows were shut for several hours prior to sampling to allow radon to build up to steady-state levels. Grab samples of air taken from thirty houses yielded radon concentrations ranging from 0.1 to 1.2 nCi/m^3, with an average of approximately 0.4 nCi/m^3. These levels are well below any established health guidelines. Air-exchange rates were also measured and found to range from 0.1 to 1.2 ach. (These low infiltration rates were probably due to the lack of indoor-outdoor temperature differences or winds that generally drive infiltration in fall and winter months.) The variety of housing types included in this survey made it difficult to correlate air-exchange rate and radon concentration.

A second phase of our field studies was concerned with measuring radon concentrations and air-exchange rates in energy-efficient houses around the country. A summary of the data gathered so far is presented in Figure 3. Measurements, again, were "worst-case" grab samples taken after the houses had been shut for several hours. As evident from the figure, radon concentration tends to increase with decreasing infiltration rates. Concentrations in excess of the EPA guideline recommended for Florida houses were found in several of the houses studied, particularly in those characterized by low infiltration rates.

The concentration of indoor air pollutants is determined by the pollutant source strength and the infiltration/ventilation rate. The types of building materials used in the structure and the appliances installed affect the former, and occupant activities (smoking, opening doors and windows, etc.) affect both. Accordingly, a variety of control strategies may be initiated, as appropriate:

1. Install a mechanical ventilation system coupled with an air-to-air heat exchanger to increase ventilation and dilute contaminants while simultaneously transferring heat (and not contaminated air) from the exhaust air to the fresh air stream in winter, and vice versa in summer.

2. Employ contaminant control devices such as filters, electrostatic precipitators, etc., to remove specific pollutants.

3. Incorporate measures during the building process that will seal in or eliminate certain contaminants at the source.

4. In new construction, select building materials with low pollutant emanation rates.

The effectiveness and advisability of incorporating these special design features in buildings also depend on the type of building and its geographical location. Our primary interest in this paper is the first control strategy, which is discussed in detail below.

MECHANICAL VENTILATION WITH HEAT RECOVERY

For a single-family dwelling, a mechanical ventilation system can use two small "balanced" fans, one to bring in outside air and the other to exhaust an equal amount of indoor air. These two air streams come into close proximity with one another inside the air-to-air heat exchanger. The exhaust and fresh air streams are separated by thin sheets of aluminum, plastic, or treated paper to transfer heat but prevent the mixing of the two air streams. Heat is transferred from the hot to the cold air stream by conduction through the material separating the air streams.

Mechanical ventilation units with heat exchangers in a size appropriate for residential use are currently being manufactured in Europe, Japan, Canada and, to a lesser extent, in the United States. Prices vary widely, from about $200 for a small window unit up to approximately $2,500 for a fully installed central mechanical ventilation system that takes exhaust air from the bathrooms and kitchen and supplies fresh air to the living room and bedrooms. It should be noted that the $2,500 price is for a fully installed system in Europe where, because existing central forced-air heating and cooling systems are rare, the cost of extensive new duct work is included. In the United States, where central forced-air heating and cooling systems are the norm in new housing, new duct work will not usually be necessary for the ventilation unit.

Besant[14] of the University of Saskatchewan has reported that ventilation systems using air-to-air heat exchangers made in their laboratory were installed in houses where natural infiltration had been purposely reduced. These units were installed in the basements of the houses and did not require extensive duct work. Outside fresh air was blown into the basement area and distributed throughout the house either by the existing forced-air heating system or, in the case of houses heated by means of electric resistance baseboard systems, by the natural flow of air about the house. These systems, installed, cost approximately 300 Canadian dollars. In all of these houses, the high humidity levels caused by the low infiltration rates were significantly reduced. Other parameters of indoor air quality were not measured. These findings suggest that adequate ventilation can be achieved in low-infiltration houses without the need for elaborate duct work. We are currently investigating the control of pollutants with mechanical ventilation in an unoccupied research house that is heated with an electric baseboard system.

In October 1978, LBL began a program to study the use of mechanical ventilation units with air-to-air heat exchangers in residential buildings in the United States. The program consists of four parts:

- analysis and experimental evaluation of air-to-air heat exchangers;
- testing of mechanical ventilation systems using air-to-air heat exchangers in research houses;
- installation and testing of a number of such systems in occupied houses;
- benefit-cost analysis of these systems in different climate zones of the United States.

All four aspects of this program are in progress; the results of a preliminary benefit-cost analysis are discussed below.

BENEFIT-COST ANALYSIS

The purpose of the benefit-cost analysis is to compare the benefits of mechanical ventilation over some specified period of time (20 years in this case) with the costs. In making this comparison, we have to determine 1) the elements of the costs and benefits as precisely as possible, 2) the benefit/cost ratio, and 3) the magnitude of the net savings (or cost). The determination of benefit/cost ratio is important for individual homeowners as well as for government planning purposes. Obviously, projects with large benefit/cost ratios should be undertaken (unless there are binding capital constraints), whereas projects with benefit/cost ratios in the neighborhood of 1.0 or lower should usually be deferred in favor of others with higher ratios. The magnitude of the net savings (or costs) is also important. Projects likely to result in large net savings merit more private and public attention than do those where savings will be negligible, regardless of the ratio of benefit to cost.

Although they are useful tools, benefit/cost studies are subject to several generic difficulties. In the present study, we face two such problems. First, it is impossible to quantify precisely all of the benefits and costs of mechanical ventilation. For example, mechanical ventilation can alter air quality, with either positive or negative effects on health. Yet health as a value is difficult to quantify. In this study, we circumvent this difficulty by maintaining air quality at a level comparable to that in the existing housing stock. The second problem is that the costs and benefits are likely to differ depending on whether private or social concerns are to be met. An example of this phenomenon is the public policy concern for reducing our national dependence on foreign sources of energy. Since the value of such a reduction cannot accrue to any individual, it will not enter into the individual's benefit/cost calculation; it will, however, be a factor in calculating the social benefit/cost. In this analysis we sidestep the problem of social benefits and costs altogether, and consider only the individual homeowner's outlook.

Because the decision to invest in mechanical ventilation for residences must be considered in the present, i.e., in competition with alternative investments, and because both the benefits and costs of mechanical ventilation extend into the future, the net present value (NPV) (defined below) of the project is the appropriate criterion to apply in reaching a decision. If the NPV of mechanical ventilation is negative, then the present value of its benefits will be less than the present value of its costs, and the project should be deferred. At some future date, price changes may dictate that the decision be reviewed. On the other hand, if the NPV is large, then the project is an important one. If the benefit/cost ratio is high, then it is likely that mechanical ventilation will be chosen over other investments.

The NPV of mechanical ventilation is given by the relationship

$$NPV = \sum_{t=0}^{N} \frac{\sum_j B_{tj} - \sum_k C_{tk}}{(1 + r)^t (1 + i_o)(1 + i_1) \ldots (1 + i_t)} \quad (1)$$

where

$\sum_j B_{tj}$ = the sum of all the benefits in year t,

$\sum_k C_{tk}$ = the sum of all the costs in year t,

r = the real interest rate (interest rate minus inflation rate), and

i_t = the general inflation rate in year t.

For some benefits or costs, and for energy in particular, future values are most easily expressed in yearly fractional increases. For example, we can express future values by the relationship

$$E_t = E_o(1 + f_1)(1 + f_2) \ldots (1 + f_t) \quad (2)$$

where

E_o = the cost in the base year, and

f_t = the expected fractional increase in the year t.

BENEFITS

The installation of a mechanical ventilation system with a heat exchanger in a structure that had no air-quality problems would be unnecessary. The following analysis, based on the research discussed above, assumes that indoor air quality is likely to be a problem in very tight houses.

The energy savings expected to be gained from installing mechanical ventilation systems with air-to-air heat exchangers in air-tight (low infiltration) houses were calculated and compared to energy consumption in conventional houses without mechanical ventilation. For these calculations, typical base-case house parameters used were: single-story, single-family detached house with a floor area of 140 m^2 (1,500 ft^2), 2.5-m-high ceilings (8 ft) and a total volume of 350 m^3 (12,000 ft^3). Using this base-case in four cities selected for variation in weather conditions, calculations were made for three different ventilation modes. In mode #1, which represents the current "loose" housing stock, 0.75 ach was assumed to be the average infiltration rate over the winter heating season.[3] In modes #2 and #3, representing "tight" houses, 0.2 ach was assumed to be the natural infiltration rate.[2] In these houses, an additional 0.3 ach (in mode #2) and 0.55 ach (in mode #3) is vented through the heat exchanger. Based on an assumed sensible heat transfer efficiency of 75%, ventilation rates in these two tight houses total 0.5 ach and 0.75 ach, respectively, but they lose heat to the outside air as if they had infiltration rates of 0.275 and 0.338 ach, respectively. That is,

$$0.2 \text{ ach} + (1 - 0.75)\, 0.3 \text{ ach} = 0.275 \text{ ach}. \qquad (3)$$

A sample calculation of the ventilation portion of the winter heating load for a house located in Minneapolis, Minnesota follows.

The indoor dry-bulb temperature in the house was assumed to be 20° C (68° F). The average winter dry-bulb temperature is -2.1° C (28.3° F).[15] The number of hours in the winter heating season in Minneapolis is 5,806.[16] An approximation of the ventilation portion of the winter heating load, in gigajoules (GJ), for the assumed average infiltration rate of 0.75 ach (mode #1) can be expressed by the equation

$$V_L \text{ (0.75 ach)} = q \; a \; B \; \Delta T \; t = 39.2 \text{ GJ (373 therms)} \qquad (4)$$

where

V_L = ventilation heating load,

q = 0.75 ach,

a = 340 m^3/hr/ach,

$B = 1.206 \times 10^{-6} \dfrac{\text{GJ}}{^{\circ}\text{C hr m}^3/\text{hr}}$,

$$\Delta T = (20^{o}C - (-2.1^{o}C)) = 22.1\ C^{o}\ (39F^{o}), \text{ and}$$

$$t = 5{,}806 \text{ hrs.}$$

For mode #2 -- where the ventilation rate is 0.5 ach, with a heat loss as if the ventilation rate were 0.275 ach -- the ventilation load is

$$V_{L(0.275\ ach)} = (0.275)\ a\ B\ \Delta T\ t = 14.4\ GJ\ (137\ therms). \qquad (5)$$

For mode #3 -- where the total ventilation rate is 0.75 ach, with a heat loss as if the ventilation rate were 0.338 ach -- the ventilation heating load is approximately

$$V_{L(0.338)} = (0.338)\ a\ B\ \Delta T\ t = 17.6\ GJ\ (168\ therms). \qquad (6)$$

Table 2 illustrates the yearly loads (in gigajoules and therms) for heating incoming outside air in the three different ventilation modes described above in four selected cities in the United States. Also shown in this table are the energy savings when the two low-infiltration houses are compared to the base-case house. These low-infiltration houses (with ventilation rates increased to 0.5 ach and 0.75 ach) have been included since, at this time, the ventilation rate sufficient to maintain adequate indoor air quality, while not known, is believed to be at least 0.5 ach.[17] The heating degree days (base temperature, 18.3° C and 65° F) for the four cities are shown for informational purposes.

Tightening a house and installing a mechanical ventilation system with an air-to-air heat exchanger will also save energy during the air conditioning season. Natural infiltration rates are relatively low during the summer, and the resulting savings will be much smaller. On the other hand, since air conditioning is the major source of peak utility loads in the summer, heat exchangers could reduce the need for new peak-power plants, which cost approximately one dollar per new Watt at the customer's meter. In addition, there are several models of air-to-air heat exchangers that transfer latent heat (water vapor) as well as sensible heat. Since a large portion of air-conditioning energy is spent for removing water vapor from the air, this type of exchanger would be beneficial during the cooling season. With these units, however, there is a possible transfer of pollutants along with the water vapor, and this problem needs further study. We have not included the benefits of reducing cooling loads in our analysis.

COSTS

This analysis assumes that the house has been tightened during initial construction so that the natural air-exchange rate has been lowered to approximately 0.2 ach. Tightening generally involves installing a polyethylene air-vapor barrier to the exterior walls and ceiling, caulking the sill plates and electrical and plumbing penetrations to the outside, and installing tight-fitting, weatherstripped doors and windows.

Incorporating these measures is currently estimated by some builders to add about $350 to the cost of a new home. (All initial costs are in 1980 dollars.)

Several models of air-to-air heat exchangers capable of supplying the ventilation rates used in this analysis are currently available and range in price from $400 to $700. We have selected $550 as the cost figure to be used in this analysis. As noted, mechanical ventilation units with heat exchangers are not now commonly used in houses in the United States; if their use increases, however, we expect that heat exchangers would cost about as much as a large window air conditioner, currently priced from $250 to $300. We will use the former number in a sensitivity analysis on initial costs. The cost of installing the exchanger is assumed to be $100. Thus, the total initial cost of tightening the house and installing the heat exchanger during initial construction ranges from a current estimate of $1,000, to an estimate of $700 -- assuming a reduction in initial price of the heat exchanger from $550 to $250.

The intake and exhaust fans are assumed to be running continuously during the heating season and are assumed to consume 25 Watts and 45 Watts each for modes #2 and #3, respectively.

Maintenance of a mechanical ventilation system with a heat exchanger includes cleaning the filters and possibly replacing a fan motor during the lifetime of the device, which is assumed to be 20 years. For maintenance, we have allowed $200 over the 20-year period and evenly distributed the cost divided over the 20-year lifespan of the heat exchanger. The rationale was that maintenance of the filters is a continuing yearly expense while the replacement of the fan motor is a random event whose probability is evenly distributed over time.

The January 1980 prices for oil, gas, and electric power given in Table 3 were obtained from the Department of Labor, Bureau of Labor Statistics, for each of the four sites.[18] Price escalation rates from the year 1980 to the year 2000 were derived from a consideration of several sources, including Department of Energy (DOE) and other economic projections. Our assumptions are presented in Table 4. The overall inflation rate is the change in the consumer price index (CPI). The real interest rate was chosen to be a constant 4%. (Real interest is nominal interest minus inflation.)

The inflation rate was assumed to decline monotonically from a high of 13% in 1980 to 6% in 1988, and to remain constant thereafter. Oil prices were assumed to increase 30% in 1980 and then to increase at decreasing rates approaching a constant real rate (rate of oil price increase minus rate of increase of CPI) of 0.5% by 1989. The scenario involving an increase in natural gas price was chosen to take into account deregulation. In this "gas high" scenario, gas prices increase by 50% in 1981 and 66% in 1982, resulting in a tripling of gas prices in nominal dollars by the end of 1982. An alternative schedule for gas price increase was constructed on the assumption that natural gas price deregulation does not occur. In this "gas low" schedule, gas prices are assumed to increase 16% in 1980 and thereafter to approach a constant real rate of increase of 0.6%. This 0.6% increase is maintained between 1988 and 2000. Electric power prices were assumed to increase at a rate of 24% in 1980 followed by a decline in real terms to a constant 2% increase after 1988. Maintenance was assumed to be provided by the service sector of the economy (even though a component is the cost of a replacement electric motor). Service-sector wage rates are assumed to increase by 9% in 1980. Wage increases are assumed to lag behind inflation rates until 1989, after which wage increases match inflation. Capital costs are assumed to be financed by a home mortgage loan either of the variable-rate type or one that is periodically refinanced as inflation rates, and consequently mortgage interest rates, fall. Mortgage rates are 13% in 1980 and 2% above the inflation rate thereafter.

The NPV and benefit/cost ratios for comparison between ventilation modes #2 and #3 and our base-case house, mode #1, are shown in Tables 5 through 8. In these tables, Minneapolis and Atlanta are the extreme cases, Minneapolis having the greatest savings because of its cold climate, and Atlanta the least. In Atlanta, the NPVs are often negative. Table 5 depicts the situation we feel to be most likely -- 75% efficiency and $1,000 initial cost. In Table 5, the present values are all positive except for gas heat in Atlanta in mode #3. The maximum present value is found in Minneapolis for electric heat (mode #2) of $4,961 with a benefit/cost ratio of 5.7. This is to be expected because the high cost of electric heat combined with Minnesota's cold climate produces the opportunity for large energy savings.

The assumed efficiency of 75% is one of the higher efficiencies catalogued for a standard unit. We expect that seasonal efficiencies will be a function of climate; for instance, in a winter situation condensation of water vapor in the outgoing air stream should increase efficiency while moisture freezing on the heat transfer surface would decrease efficiency. Our test program will address these problems but for this paper we can test only the cost-effectiveness sensitivity to other assumed efficiencies. Decreasing the heat-exchanger efficiency from 75% to 65% results in the values shown in Table 6. Present values become negative in Atlanta, and decrease slightly in the other cities. Further decreasing the assumed heat-exchanger efficiency to 55% results in the values shown in Table 7. In the 55% case, the NPV declines further and the NPV for Washington, D.C. (mode #3) is almost zero for both oil and gas heat.

Decreasing the initial capital cost to $700 gives the values shown in Table 8. The NPV in Atlanta (mode #3) for gas goes positive, but only slightly.

Because the cost of energy consumed in residential heating is high relative to maintenance, fan power, and interest costs, the projected economic results are highly sensitive to the cost of fuel. In Table 9 we present an example of the nominal changes, uncorrected to constant 1980 dollars, for the 75% efficiency, $1,000 capital-cost case, mode #3. Here, the dominance of the energy savings is clearly seen, hence this economic analysis, for its own accuracy, depends on the accuracy of our assumptions on future energy costs relative to inflation.

CONCLUSIONS

Making houses air-tight for energy conservation purposes may necessitate the use of some means of indoor pollutant control in order to maintain adequate indoor air quality. Installing a mechanical ventilation system with an air-to-air heat exchanger is one possible control measure that has the advantage of being energy-efficient. Both initial and operating costs are associated with the use of mechanical ventilation systems employing air-to-air heat exchangers, and additional costs are involved in adopting air-tightening measures. When the benefits outweigh the costs, it is logical to include both in new construction.

An important benefit of mechanical ventilation in residences is that it gives the occupants control of the ventilation rate. Because increased ventilation reduces indoor pollutant levels, it may also have effects on the health of the occupants. In this regard, it is difficult to determine the precise effects of pollutant levels on health; in our study, we chose a mechanical ventilation rate equal to the prevailing natural air-change rate, ignoring benefits other than the cost of the fuel saved. For this reason our results for the mode #3 case may understate the actual benefits; accordingly we offer the results of a 0.5 ach rate for comparison.

The use of mechanical ventilation systems with air-to-air heat exchangers installed during initial construction to maintain indoor air quality in "tight" houses or houses with significant indoor pollutant sources appears to be cost-effective in areas with climates like those of Minneapolis, Minn., Chicago, Ill., and Washington, D.C., whether oil, gas, or electric heat is used.

Should installation of mechanical ventilation systems with heat recovery become a widespread practice in the U.S., we expect the cost of heat exchangers to decrease, perhaps to the price of a large window air conditioner -- currently about $250. Such a cost reduction would lower our calculation of total investment cost from $1,000 to about $700. When this adjustment is made, the present value of the investment becomes positive for all fuels in all four cities using a heat exchanger with 75% efficiency.

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Table 1. Indoor air pollutants in residential buildings.

SOURCES	POLLUTANT TYPES
OUTDOOR	
Ambient Air	SO_2 NO, NO_2, O_3, Hydrocarbons, CO, Particulates
Motor Vehicles	CO, Pb
INDOOR	
Building Construction Materials	
Concrete, stone	Radon
Particleboard	Formaldehyde
Insulation	Formaldehyde, Fiberglass
Fire Retardant	Asbestos
Adhesives	Organics
Paint	Mercury, Organics
Building Contents	
Heating and cooking combustion appliances	CO, SO_2, NO, NO_2, Particulates
Furnishings	Organics, Odors
Water service; natural gas	Radon
Human Occupants	
Metabolic activity	CO_2, NH_3, Organics, Odors
Human Activities	
Tobacco smoke	CO, NO_2, HCN, Organics, Odors
Aerosol spray devices	Fluorocarbons, Vinyl Chloride
Cleaning and cooking products	Hydrocarbons, Odors, NH_3
Hobbies and crafts	Organics

Table 2. Annual Ventilation Heating Load

Gigajoules**
(Therms)

City	Degree Days Base 18.3°C (Base 65°F)	Mode #1 0.75 ach (Base Case)	Mode #2 0.5 ach*	Mode #3 0.75 ach*	Energy Saved Compared to Base Case 0.5 ach	Energy Saved Compared to Base Case 0.75 ach
Atlanta, Georgia	1645 (2961)	10.4 (99)	3.8 (36)	4.7 (45)	6.6 (63)	5.7 (54)
Washington, D.C.	2347 (4224)	18.3 (174)	6.7 (64)	8.3 (79)	11.6 (110)	10.0 (95)
Chicago, Illinois	3268 (5882)	27.6 (263)	10.1 (96)	12.4 (118)	17.5 (167)	15.2 (145)
Minneapolis, Minn.	4657 (8382)	39.2 (373)	14.4 (137)	17.6 (168)	24.8 (236)	21.6 (205)

*Total outside air of which 0.2 ach is infiltration.
**1 Gigajoule = 10^9 Joules = 9.48 Therms = 278 Kwh

Table 3. Fuel Prices - January 1980.

City	#2 Heating Oil ($/gal)/($/therm)	Natural Gas ($/therm)	Electricity (c/kWh)/($/therm)
Minneapolis, Minn.	.919/.681	.324	4.85/1.42
Chicago, Illinois	.929/.688	.349	5.34/1.57
Washington, D.C.	.946/.701	.425	5.68/1.66
Atlanta, Georgia	---	.393	4.69/1.37

Table 4. Price Escalation Rates.

Year	Oil	Gas (low)	Gas (high)	Electric Power	Maintenance	Capital Costs	Consumer Price Index
1980	.300	.159	.169	.236	.086	.130	.130
1981	.219	.129	.500	.142	.081	.120	.104
1982	.175	.141	.660	.114	.076	.098	.097
1983	.119	.142	.142	.103	.072	.098	.083
1984	.089	.119	.119	.092	.067	.092	.072
1985	.083	.103	.103	.087	.065	.087	.067
1986	.075	.087	.087	.083	.063	.082	.063
1987	.073	.075	.075	.082	.064	.080	.062
1988	.070	.066	.066	.080	.063	.080	.060
1989	.065	.066	.066	.080	.061	.080	.060
1990	.065	.066	.066	.080	.060	.080	.060
1991	.065	.066	.066	.080	.060	.080	.060
1992	.065	.066	.066	.080	.060	.080	.060
1993	.065	.066	.066	.080	.060	.080	.060
1994	.065	.066	.066	.080	.060	.080	.060
1995	.065	.066	.066	.080	.060	.080	.060
1996	.065	.066	.066	.080	.060	.080	.060
1997	.065	.066	.066	.080	.060	.080	.060
1998	.065	.066	.066	.080	.060	.080	.060
1999	.065	.066	.066	.080	.060	.080	.060
2000	.065	.066	.066	.080	.060	.080	.060

Table 5. **Net Present Values and Benefit/Cost Ratios of Investment in Residential Mechanical Ventilation**

75% = Heat Exchange Efficiency
Capital Cost = $1,000.

LOCATION		MODE #2 (0.5 ach) oil	MODE #2 (0.5 ach) gas	MODE #2 (0.5 ach) elec.	MODE #3 (0.75 ach) oil	MODE #3 (0.75 ach) gas	MODE #3 (0.75 ach) elec.
Minneapolis, Minnesota	NPV*=	3492	2377	4961	2675	1706	3947
	B/C =	4.3	3.3	5.7	3.2	2.4	4.1
Chicago, Illinois	NPV =	2166	1522	3590	1497	939	2740
	B/C =	3.1	2.5	4.4	2.2	1.8	3.2
Washington, D.C.	NPV =	1065	999	2176	563	506	1517
	B/C =	2.1	2.0	3.1	1.5	1.5	2.3
Atlanta, Georgia	NPV =	--	64	497	--	-234	139
	B/C =	--	1.2	1.6	--	.87	1.2

* NPV is expressed in 1980 dollars.

Table 6. Net Present Values and Benefit/Cost Ratios of Investment in Residential Mechanical Ventilation

65 % = Heat Exchange Efficiency
Capital Cost = $1000.

LOCATION		MODE #2 (0.5 ach) oil	gas	elec.	MODE #3 (0.75 ach) oil	gas	elec.
Minneapolis, Minnesota	NPV*=	3201	2156	4571	2092	1262	3192
	B/C =	4.1	3.1	5.3	2.7	2.1	3.6
Chicago, Illinois	NPV =	1941	1340	3275	1103	620	2167
	B/C =	2.9	2.3	4.1	1.9	1.6	2.7
Washington, D.C.	NPV =	922	860	1963	320	270	1151
	B/C =	2.0	1.9	2.9	1.3	1.3	2.0
Atlanta, Georgia	NPV =	--	-13	396	--	-362	-38
	B/C =	--	.99	1.5	--	.77	.99

* NPV is expressed in 1980 dollars

Table 7. Net Present Values and Benefit/Cost Ratios of Investment in Residential Mechanical Ventilation

55 % = Heat Exchange Efficiency
Capital Cost = $1000.

LOCATION		MODE #2 (0.5 ach) oil	gas	elec.	MODE #3 (0.75 ach) oil	gas	elec.
Minneapolis, Minnesota	NPV*=	2895	1923	4180	1579	871	2515
	B/C =	3.8	2.9	5.0	2.3	1.8	3.0
Chicago, Illinois	NPV =	1744	1180	2988	708	301	1622
	B/C =	2.7	2.2	3.8	1.6	1.3	2.3
Washington, D.C.	NPV =	779	722	1750	49	7	755
	B/C =	1.8	1.8	2.7	1.1	1.0	1.7
Atlanta, Georgia	NPV =	--	-77	295	--	-490	-214
	B/C =	--	.99	1.4	--	.66	.90

* NPV is expressed in 1980 dollars.

Table 8. **Net Present Values and Benefit/Cost Ratios of Investment in Residential Mechanical Ventilation**

75% = Heat Exchange Efficiency
Capital Cost = $700

LOCATION		MODE #2 (0.5 ach) oil	gas	elec.	MODE #3 (0.75 ach) oil	gas	elec.
Minneapolis, Minnesota	NPV*=	3731	2616	5200	2913	1944	4186
	B/C =	5.4	4.1	7.1	3.8	2.9	5.0
Chicago, Illinois	NPV =	2405	1761	3829	1735	1177	2979
	B/C =	3.8	3.1	5.4	2.6	2.1	3.8
Washington, D.C.	NPV =	1304	1238	2415	801	744	1756
	B/C =	2.6	2.5	3.9	1.8	1.8	2.7
Atlanta, Georgia	NPV =	--	303	736	--	5	377
	B/C =	--	1.5	2.0	--	1.0	1.5

* NPV is expressed in 1980 dollars.

Table 9. Fuel Savings and Costs (Dollars)

0.75 ACH
$1,000 Capital Cost
75% Efficiency

	FUEL SAVINGS				COSTS		
	Gas low	Gas high	Oil	Elec.	Fanpower electr.	Maint.	Interest
Minneapolis							
1980	111	111	259	360	31	11	130
1985	202	389	489	600	52	15	87
1990	285	551	685	885	77	21	80
1995	392	759	939	1301	113	28	80
2000	540	1045	1286	1911	166	37	80
Chicago							
1980	84	84	186	280	33	11	130
1985	153	296	351	467	55	15	87
1990	217	420	491	690	82	21	80
1995	298	578	673	1013	120	28	80
2000	411	795	922	1489	176	37	80
Washington, DC							
1980	68	68	124	195	31	11	130
1985	123	237	234	325	51	15	87
1990	174	336	327	480	75	21	80
1995	239	462	449	706	111	28	80
2000	329	636	615	1037	163	37	80
Atlanta							
1980	35	35		20	11	11	130
1985	64	124		153	33	15	87
1990	91	175		225	49	21	80
1995	125	241		331	72	28	80
2000	172	333		487	106	37	80

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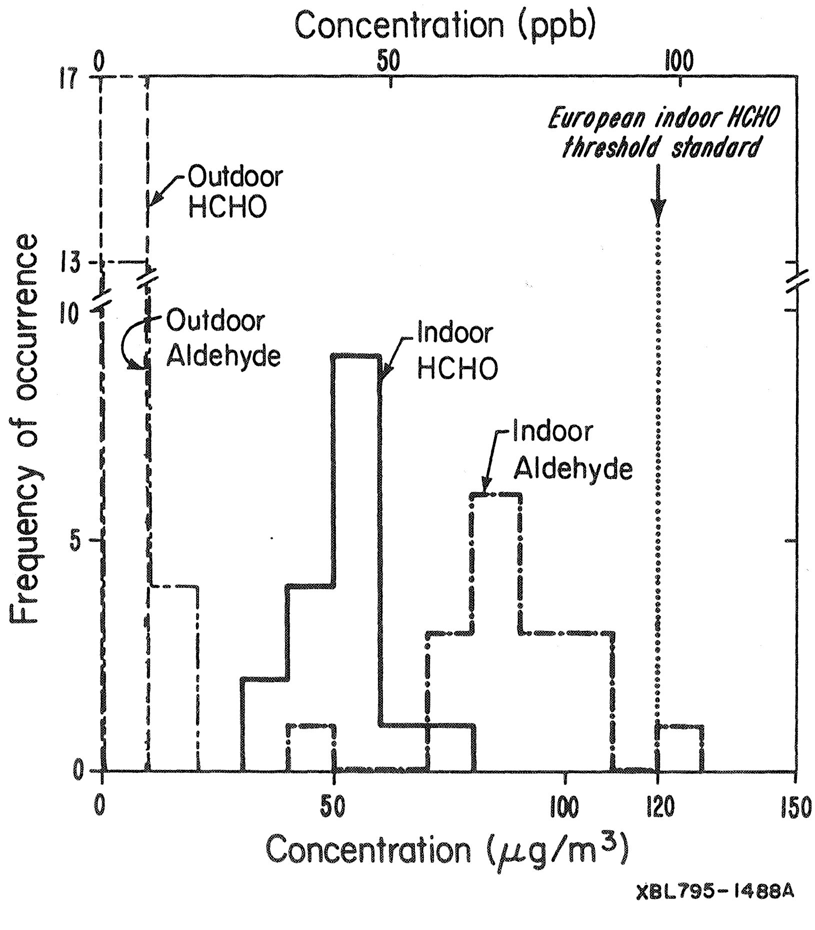

Figure 1. Summary of indoor/outdoor formaldehyde and aldehyde concentrations at the ISUERH house.

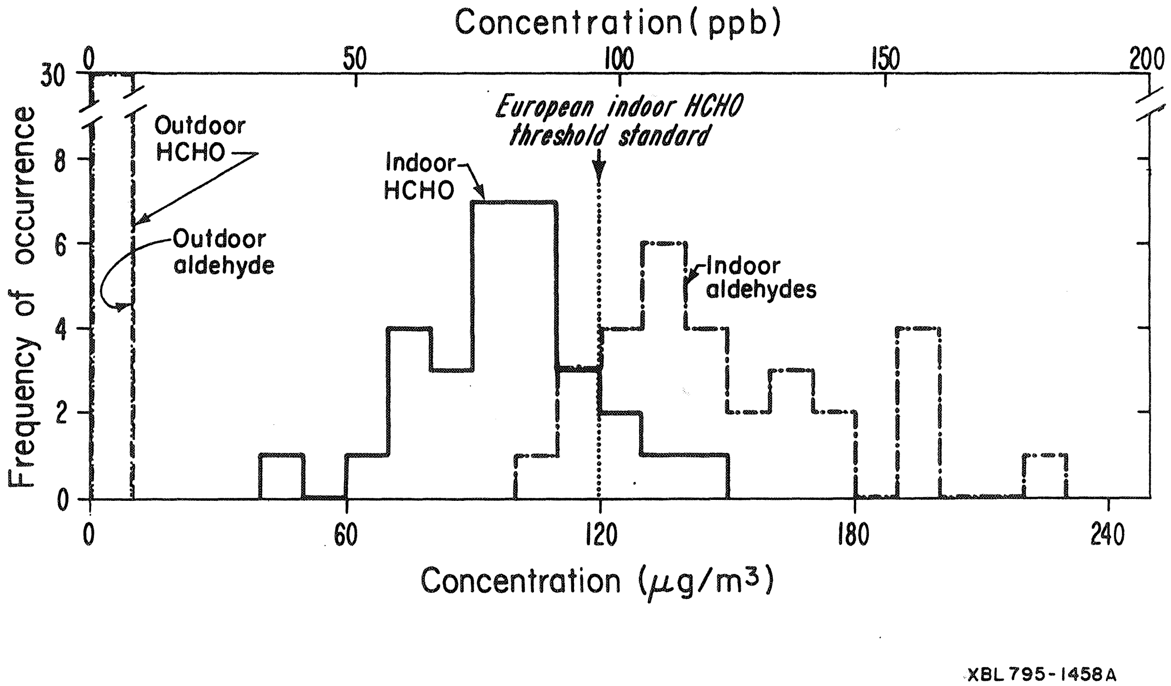

Figure 2. Summary of indoor/outdoor formaldehyde and aldehyde concentrations at the ERHM house.

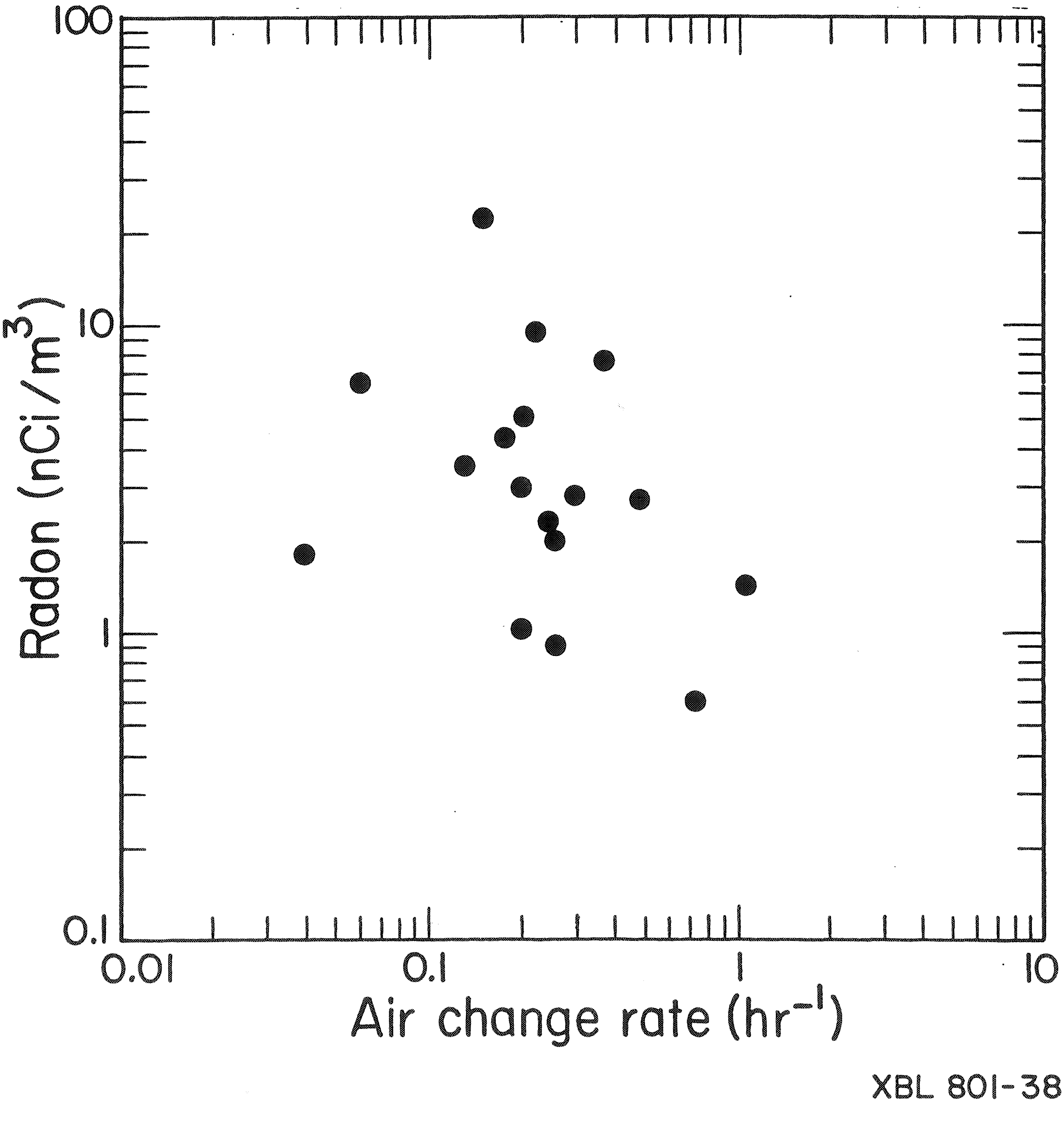

Figure 3. Radon concentration vs ventilation in energy efficient houses.

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