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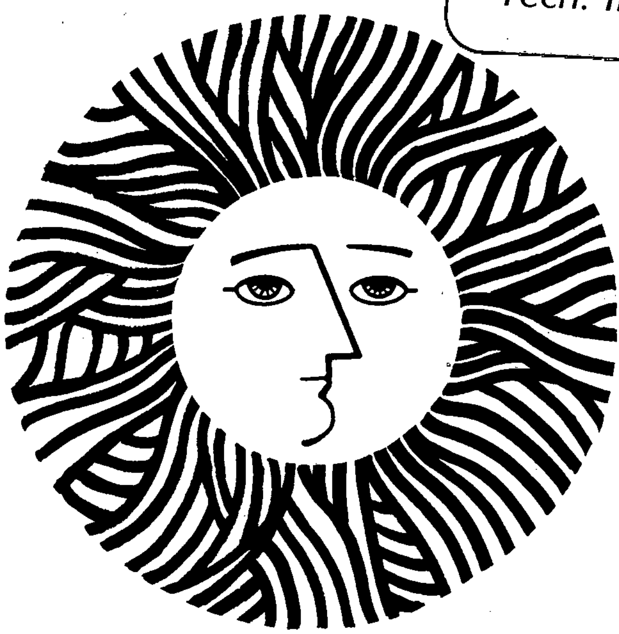

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ABSTRACT

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 and had a 30% lower overall average heat loss coefficient ($W/^{o}C\text{-}m^2$) 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 increasing air-exchange rates and in further reducing indoor contaminant concentrations. The average sensible effectiveness of the heat exchangers was 0.65 ± 0.16. We conclude that when contaminant source strengths are low, acceptable indoor air quality can be compatible with low air-exchange rates.

Keywords: air-to-air heat exchanger, energy conservation, formaldehyde, indoor air quality, infiltration, leakage area, nitrogen dioxide, radon, residential

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. Table 1 lists some indoor contaminants identified as potential health hazards, and their sources.

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, unvented space heaters, 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, 1981) indicate that MVHX systems can preheat or precool ventilation air by 45 to 85 percent of the difference between indoor and outdoor temperatures.

In July of 1979, researchers from the New York State Energy Research and Development Authority (NYSERDA) and the Lawrence Berkeley Laboratory (LBL) Energy Efficient Buildings (EEB) program met and discussed the issues of residential energy conservation and indoor air quality. Out of these discussions rose the idea of a jointly funded research project of residential air-leakage and indoor air quality. Later discussions between NYSERDA and the Rochester Gas and Electric Corporation (RG&E) led to the identification of a large sample of tight houses in Rochester, New York suitable for a field study. The builders of these houses were Ryan Homes Inc. and Schantz Homes Inc. Since 1976 both of these builders have modified their basic construction techniques to reduce air leakage.

To address the issues of residential air-exchange rates and indoor air quality, a protocol was developed for a field study in a number of occupied houses in Rochester, New York under the joint sponsorship of LBL, NYSERDA, and RG&E. The objectives of the study were (1) to assess the effectiveness of construction techniques designed to reduce infiltration; (2) to monitor indoor air quality and air-exchange rates in selected tight houses; and (3) to evaluate the thermal performance and impact on indoor air quality of mechanical ventilation systems employing air-to-air heat exchangers. The Rochester Institute of Technology (RIT) was contracted to conduct the air-leakage and indoor air quality field measurements.

EXPERIMENTAL PROTOCOL

The work for this study was divided into three separate phases:

Phase I - Recruitment of Acceptable Field Sites
Phase II - Leakage Area Measurements
Phase III - Air-Exchange Rate and Indoor Air Quality Measurements

Phase I - Recruitment of Acceptable Field Sites

During the spring of 1980 Rochester Gas and Electric in cooperation with Ryan Homes Inc. and Schantz Homes Inc. recruited a large group of volunteer homeowners. Selection of the houses for participation in Phase II was based on the following criteria:

a) ownership must not have changed within the past two years.

b) existing utility records must show a high ($r^2 > 0.9$) correlation between energy use and average outside temperature.

In addition the houses were chosen to include a sample:

c) with and without builder designed air tightening measures.

d) with forced-air heat (gas and electric) and electric-baseboard heat.

e) with gas and electric stoves.

f) with and without tobacco smoking occupants.

Survey forms and utility records were used to establish the above criteria. In May 1980, 60 homes were selected to begin Phase II.

Phase II - Leakage Measurements

To assess the relative tightness of the 60 houses selected, we measured the "effective leakage area" of each house, using the fan pressurization technique (Grimsrud et al., 1981). The concept of "effective leakage area" has been used at LBL to develop a predictive model of infiltration (Sherman and Grimsrud, 1980). (See Leakage Area Measurement Technique in Appendix A for a detailed description of this technique.)

In May 1980 LBL visited RIT to train technicians in the fan pressurization technique; leakage measurements were made by RIT throughout the summer of 1980, and by October, 60 houses had been tested.

Phase III - Air-Exchange Rate and Indoor Air Quality Measurements

Ten houses were selected and scheduled for detailed measurements of air-exchange rates and indoor air quality during the 1980-81 Rochester heating season (November-March). A summary of relevant characteristics of each of the selected houses (construction, appliances, and occupancy) are summarized in Table 2. Nine of these ten houses were relatively tight structures, three containing gas cooking appliances (one with tobacco-smoking occupants) and six containing electric cooking appliances (three with tobacco-smoking occupants). The tenth house, 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 houses, and air-exchange rates and air quality 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 the ten homes selected for the study of indoor air quality, a newly developed automated monitoring system, called the Aardvark (Nazaroff _et. al._, 1981) was used to measure the air-exchange rate, radon (Rn) concentration, indoor and outdoor temperatures, and the four airstream temperatures of the air-to-air heat exchangers. 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 monitoring the air-exchange rate and indoor radon concentrations, measured 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 other portable instruments were used to measure the average daily relative humidity and concentrations of formaldehyde (HCHO) and total aldehydes (RCHO). Passive monitors were used to measure the average weekly concentrations of nitrogen dioxide (NO_2).

A description of the various measurement techniques used in this study has been assembled into Appendix A along with photographs and figures of the instrumentation.

DESCRIPTION OF HOUSE CONSTRUCTION

All of the houses in this study were single family detached dwellings with basements. The 60 house sample included 48 houses built by Ryan Homes Inc., and 11 houses built by Schantz Homes Inc. One house (#59) constructed by a private contractor was included in the pressurization phase of the study when concern over the tightness of the house arose following an incident of carbon monoxide poisoning.

Ryan Homes Inc.

Ryan Homes Inc. is the second largest builder of single family homes in the U.S. In 1979-80 Ryan Homes, which employs a partial pre-manufacturing construction technique, built 10,000 houses (mostly in northeast U.S.). Basements are constructed with concrete block walls around a floating concrete slab floor. Walls are framed with 2" x 4" studs on 16" centers, and exterior walls are sheathed on the outside with fiberboard. Fiberglass batt insulation is used in the walls. Interior walls and ceilings are covered with plasterboard, windows are either sliding aluminum type or wooden double hung type, and floors are built of plywood and covered with carpeting. Attics are ventilated with ridge and soffit type vents and insulated with loose-fill cellulose. Most Ryan homes are sold with gas or electric forced-air type heating systems. In the sample of 48 houses, 45 were built with forced-air heating systems; 23 with gas heat, 12 with electric heat, 5 with electric heat pump/gas assist, and 5 with electric heat pump/electric assist. The remaining 3 houses were built with electric baseboard heating systems.

In 1976, Ryan introduced special design changes into all of their models. Special emphasis was placed on implementing construction techniques which would reduce infiltration. The design changes initiated in 1976 were:

1) insulation of basement walls with R11 fiberglass batts
2) increase insulation in ceilings from R-19 to R-30
3) installation of a continuous polyethylene vapor barrier onto the inside of the stud frame of exterior walls and special infiltration paper on the outside walls. No vapor barrier installed in the ceiling
4) use of one piece, plastic electrical boxes
5) sealing of all joints e.g. foundation and sole plate, ring joist and deck, wall panel, door, and window frames etc.

Figures 1 through 4 depict some of these weatherization components as photographed in a Ryan house under construction (house #56). Figure 1 is a photograph of the polyethylene vapor barrier which is stapled to the inside of the wall stud frame over the fiberglass batt insulation. Figure 2 is a photograph showing a foam gasket protruding from the joint between the soleplate and concrete block foundation. The special infiltration reduction sheathing can also be seen in place on the exterior wall in this photograph. Figure 3 is a photograph of some plumbing penetrations in the process of being sealed with polyurethane foam. Figure 4 is a photograph of a one piece plastic electrical conduit box installed on a joist in the ceiling of this house. Our sample of 48 houses included 36 built with these features (1976-1980) and 12 without these features (1973-1975).

Schantz Homes Inc.

Schantz Homes Inc. is a builder who constructs an average of 50 custom built houses each year. The sample of Schantz homes included 11 houses built between 1978-80. Basements are constructed with concrete block walls surrounding a floating concrete slab floor. Walls are framed with 2" x 4" studs on 16" centers, and exterior walls are sheathed with 3/8" plywood. A continuous polyethylene vapor barrier is installed onto the inside of the wall stud frame after which 3-1/2" of cellulose insulation is blown into the wall space behind the vapor barrier. Interior walls and ceilings are lathed and then covered with plaster. Windows are all wooden double hung type and floors are plywood covered with carpeting. Attics are ventilated with gable and/or roof type vents, and insulated with 10" of blown cellulose. All heating systems are forced air type (either gas, electric, or heat pump). Besides the continuous polyethylene vapor barrier, no additional special air tightening components have been included in the design of these houses. Two of the eleven houses, houses #27 and #60, were built without continuous polyethylene vapor barriers in the exterior walls and were constructed instead with a high R-value exterior sheath, and then insulated with 3-1/2" of Kraft-backed fiberglass batt insulation.

DESCRIPTION OF INSTALLATION OF MECHANICAL VENTILATION SYSTEMS WITH AIR-TO-AIR HEAT EXCHANGERS

In the nine tight houses selected for the study of indoor air quality, mechanical ventilation systems with air-to-air heat exchangers (MVHX) were installed. In tightly constructed houses where additional ventilation is desired, MVHX systems can be utilized to provide a controlled supply of additional ventilation air. The important feature in these systems is the air-to-air heat exchanger, which permits recovery of most of the energy which would normally be lost through conventional ventilation (e.g., exhaust fans, open windows, etc.). These systems include two fans, one which exhausts stale indoor air through the heat exchanger core to the outside and one which supplies fresh outside air through the heat exchanger core and into the house. Figure 5 depicts a typical residential MVHX system. The transfer of energy between the two air-streams takes place in the heat-exchanger core, without mixing between the two airstreams, usually across a series of thin membranes made of metal, plastic, or paper.

Some cores are designed to transfer moisture (latent exchange) as well as heat (sensible exchange) so that in climates where air conditioning is required, for example, hot, moist, outside air is cooled and dried. Cores which transfer only heat are called sensible cores, while those that transfer moisture as well as heat are called sensible/latent cores. At least two manufacturers are constructing residential air-to-air heat exchangers with sensible/latent cores.

Cores are also available with different air-flow configurations, two of which are counterflow and crossflow (see Figures 6a and 6b), the former being a theoretically more effective configuration for transferring heat. In a counterflow heat exchanger the two airstreams flow parallel to each other but in opposite directions, thus assuring the maximum average difference in temperature between the two airstreams (i.e., the maximum driving force for heat transfer). In a cross flow heat exchanger the two airstreams flow perpendicular to each other.

The two fans in an air-to-air heat exchanger may be configured to blow or draw air through the heat exchanger core. A system may include two blow-through, or two draw through, or one blow-through and one draw-through fan. The fan motors used with MVHX systems consume a significant amount of energy, most of which is immediately dissipated as heat, thus the fan configuration is an important design consideration. Assuming the fan motors are located within the airstreams, the most energy efficient fan configuration with respect to the delivery of fan heat to the residence (heating season scenario) is the pairing of a draw-through supply-air fan with a blow-through exhaust-air fan. In this configuration all of the energy consumed by the supply air fan is delivered directly to the residence as heat, and much of the energy consumed by the exhaust-air fan is transferred within the core to the supply airstream and then delivered to the residence. One disadvantage of this configuration is that it creates a larger differential pressure between airstreams then either blow-blow or draw-draw fan configurations, and this may increase the leakage between airstreams.

Some heat exchangers are designed to be installed as central units with a ducted air-distribution system (see Figure 7), while others are designed as completely self-contained units suitable for installation in a window or through a wall (see Figure 8) and require no external duct system.

For this study we installed several different types of heat exchangers built by different manufacturers. They included five sensible-counterflow units, two sensible-crossflow units, and three sensible/latent (paper core) crossflow units. Two of the three sensible/latent crossflow heat exchangers were small window units, all of the rest were central type units which required ducting. Compiled in Table 3 for each house are the physical characteristics of the nine residential heat exchangers installed in this study as well as the fan energy consumption, the 1981 retail price, and the installation cost.

The two window units were installed in house #52 which had an electric baseboard heating system and no existing duct system. One unit was installed in an upstairs living room window and the other was installed in a downstairs den window. The other seven houses which all had existing duct systems (forced air heating) were equipped with central type heat exchangers.

All central type heat exchangers were installed in the basement areas near the furnace except in house #60 where the heat exchanger was installed in the attic above the bathrooms. All of the ducted units were ducted so that incoming fresh air was supplied to the furnace return plenum, and indoor air was exhausted from area(s) where sources of specific indoor air contaminants were located (e.g. kitchens, bathrooms, basements). Exhausting air from areas where contaminant sources are located allows (if the mixing of indoor air is not perfect) higher contaminant concentrations to be exhausted, and results in more effective contaminant control. In houses #33 and #49, which had gas stoves, air was exhausted from the kitchen. In house #60 where problems with high humidity had been experienced, air was exhausted from the two upstairs bathrooms. In house #6 air was exhausted from a hallway adjoining a den area which had a wood stove. In houses #1, #10, #45, and #56 air was exhausted from the basement areas for maximum removal of radon.

After each unit was installed, it was necessary to balance the flow rates of the two airstreams passing through the heat exchanger using damper valves in the duct system. An imbalance in flow rates, such as exhausting more air from the house than is being supplied will cause an indoor-outdoor pressure difference which will increase the infiltration of outside air into the house or in the opposite case cause indoor air to leak out through the building envelope. In either case an imbalance in flow rates will degrade the heat exchangers thermal performance. For optimal performance the heat exchanger should have balanced mass flow rates. The outer surfaces of heat exchangers and/or ductwork located in conditioned spaces was insulated with a one-inch thick glasswool duct insulation which had an exterior vapor barrier to prevent both undesirable heat transfer and condensation on the outer surfaces.

RESULTS AND DISCUSSION

A. Leakage Area Measurements

Table 4 presents the results of the leakage area measurements in the three groups of Rochester houses. The pre-1976 group of Ryan homes has an average specific leakage area (i.e., effective leakage area in cm^2/floor area in m^2) of 5.5 cm^2/m^2 as compared to the post-1976 Ryan homes and Schantz homes which have an average specific leakage area of 2.8 cm^2/m^2 and 2.9 cm^2/m^2, respectively. The post-1976 Ryan homes show a rather significant reduction in specific leakage area of 50% when compared to the pre-1976 construction. The average heating season (November through March) infiltration rate predicted from the LBL infiltration model for the pre-1976 Ryan homes is 0.97 ach, substantially higher than the average heating season infiltration rates predicted for the post-1976 Ryan homes, 0.47 ach, and Schantz homes, 0.48. It should be noted that House #35 was not included in the results for the post-1976 Ryan homes because the leakage area measurement was performed before the house construction was completed. The leakage area and predicted infiltration results for each house can be found in Appendix B.

Figure 9 compares the specific leakage areas for the three groups of Rochester houses with measurements made by LBL researchers and others on groups of houses in other parts of North America (Grimsrud et al. 1981). The large difference between the specific leakage area distributions of the pre-1976 Ryan houses and the post-1976 Ryan houses and Schantz houses is easily observable in this figure. The pre-1976 Ryan houses range in specific leakage area from a high of 11.8 cm^2/m^2 to a low of 2.6 cm^2/m^2, a range of more than 4 to 1. A number more representative of the sample distribution is the spread between the first (25%) and third (75%) quartiles normalized by the value of the median (we call this the relative spread). We have calculated the relative spread of the specific leakage measurements to be 0.60 for the pre-1976 Ryan houses, 0.39 for the post-1976 Ryan houses, and 0.17 for the Schantz houses. The larger relative spread of 0.60 associated with the pre-1976 Ryan houses could be due either to differences in the construction (design or quality) and/or to actions the homeowners have taken to reduce air leakage area after the houses have been constructed. We would expect the post-1976 Ryan houses to have a smaller relative spread because of the introduction in 1976 of special air-leakage reducing design changes and improvements in the Ryan construction quality control program. The small relative spread in the custom-built Schantz houses suggests that these houses were constructed similarly (in design and in quality) with respect to air leakage reduction.

As can be seen from Figure 9, the 35 post-1976 Ryan homes and the 11 Schantz homes (built between 1978 and 1980) are among the tightest houses tested. They compare in specific leakage area to a group of energy-efficient houses that were built using similar air leakage reduction techniques in Eugene, Oregon.

One Ryan home that was not included in the original 58 house sample received a special house-tightening treatment also known as "house doctoring." Initially, the leakage area of the house was measured and found to be 857 cm^2, while the specific leakage area was 4.6 cm^2/m^2. After a number of leaks in the firewall were sealed the leakage area was reduced to 631 cm^2, a reduction of 226 cm^2 or 26%. Next, the gas furnace and water heater exhaust flues located in the basement were sealed in order to assess the tightness of the house without these openings. The resulting leakage area was 624 cm^2 which indicates a rather small reduction. We estimate that the actual reduction accomplished by sealing off the flues to have been about 80 cm^2 which is a reduction too small to be accurately observed with this measurement technique. The leakage area was further reduced to 446 cm^2 after openings around an I-beam and around the electric, gas and water services into the house were sealed. The overall reduction in leakage area was 411 cm^2 or 48% of the initial leakage of the house.

House #59 which was tested after concern over the tightness of the house arose following an incident of carbon monoxide poisoning. The house was built by a private contractor and is of standard construction without any special builder designed air-tightening components. The measured specific leakage area of this house was 4.7 cm/m^2 which corresponds to a predicted average heating season infiltration rate of 0.82 ach. This house had a gas water heater, gas furnace, and a fireplace, all of which are potential indoor sources of carbon monoxide. Since this house is not exceptionally tight it is believed the source of carbon monoxide was relatively large (i.e., capable of producing high indoor concentrations) and resulted from a malfunctioning of one of the exhaust flues.

a) Leakage Site Identification

With the house under pressurization, a search can be made with a smoke stick for areas where air is escaping from the house. Figure 10 is a photograph of a smoke stick being used to locate the leakage sites around a window. Specific leaks cannot be quantified in this manner, but such a visual inspection can yield much qualitative information concerning the relative size of individual leaks. This was done during the fan pressurization tests of the 58 houses tested in this study, and a summary of the leakage sites most commonly encountered has been compiled into Table 5.

B. Energy Performance Measurements

Tables 6 and 7 present the energy performance results for the pre- and post-1976 Ryan homes. An overall heat loss coefficient, or k-value ($W/^{o}C-m^2$), was computed for each house from energy consumption and outside temperature data. See the section on Energy Performance Measurement Technique in Appendix A for a more detailed discussion of this calculation. Analysis of the results shows that the average k-value of the post-1976 Ryan homes is 30% less than the average k-value of the pre-1976 Ryan homes. The difference between the average balance temperatures of the pre-1976 houses, 16.1 ^{o}C, and the post-1976 houses, 16.3 ^{o}C, is not significant. The average k-value computed for the pre-1976 houses is 1.34 $W/^{o}C-m^2$ (5.7 $BTU/ft^2-^{o}F$-day) while the average k-value computed for the post-1976 houses is 0.94 $W/^{o}C-m^2$ (4.0 $BTU/ft^2-^{o}F$-day). The latter value is equal to the once proposed Building Energy Performance Standard (BEPS) "strict" guideline of 4 $BTU/ft^2-^{o}F$-day which suggests that the houses with the additional weatherization package are indeed highly energy efficient.

Of the twelve pre-1976 houses in the study, House #49 is not included in the energy results because of substantial auxiliary space heating with a woodstove. This "hidden" energy use could have the effect of reducing the calculated k-value to an unrealistically low level. The results indicate that House #49 had the second lowest k-value, 0.92 $W/^{o}C-m^2$, in the group, well below the group average of 1.34 $W/^{o}C-m^2$. For this house, the k-value appears to have been affected by the use of the woodstove for space heating.

Among the 36 post-1976 Ryan homes, five houses were not included in the study due to missing energy consumption data. Two other houses, #31 and #36, were not included because the energy vs. outside temperature data did not show a good correlation (both houses had r^2 values of 0.78). One criteria for the houses to be included in the energy performance analysis was that they have an r^2 greater than or equal to 0.85. In addition, House #6 was not included in the results because a woodstove provided supplementary space heating during the winter.

Five of the houses included in the energy performance results had electric heat pump systems for primary space heating. Since heat pumps provide more usable energy in the form of heat than they consume in electricity, a Coefficient of Performance (COP) factor of 2.0 was used to adjust the energy consumption figures for the milder heating months

(October, November, April and May). To account for the decrease in COP during colder months a lower COP factor of 1.2 was applied to the energy consumption data during the winter months with average outside temperatures below 0 ^{o}C. When averaged over the heating season, these two COP factors give an average seasonal COP of 1.7 (Melville, 1981).

C. Air-Exchange Rate Measurements

During the unventilated measurement period (i.e., MVHX system off), the air-exchange rates in the nine tight houses were relatively low, as indicated in Table 8, 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, 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 high 10 m/s (22 mph) and the average outdoor temperature was -10^{o}C (14^{o}F). 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 which occupant activity can have on the house air-exchange rate was seen in house #33 where the air-exchange rate doubled from approximately 0.40 to 0.80 ach whenever the fireplace was used.

Figure 11 is a plot of the measurements made in house #37 of air-exchange rate, indoor-outdoor temperature difference, windspeed, and furnace fuel-consumption rate. The effects of windspeed on the air-exchange rate and furnace fuel-consumption rate in this relatively leaky house are obvious.

Figure 12 is a plot of measured air-exchange rates and predicted infiltration rates for 90 minute periods over the course of the six-day test in house #10. The LBL infiltration model used for these predictions is discussed in the Appendix A section on Leakage Area Measurement Technique. The windspeed and temperature data used for these predictions were obtained from data collected by the EEB Mobile Lab, which was located down the street at house #6 during this measurement period. Using the specific leakage area determined from fan pressurization tests and averaged weather data, the model predicted an average infiltration of 0.23 ach which compares with the average air-exchange rate measured during this time period with tracer-gas decays of 0.25 ach.

It should be noted that these model predictions yield only the natural infiltration portion of the air-exchange rate; ventilation from occupant activities such as opening doors and windows and use of fireplaces or exhaust fans must be estimated and added to the infiltration predictions. A current working estimate used at LBL to account for occupant-related ventilation during a heating season is 0.10 to 0.15 ach. Thus, we would expect our infiltration predictions to be slightly less than actual air-exchange rate measurements. A calculation of the occupant-related ventilation may be able to be made from a comparison of the night-time air-exchange rate data (with occupants asleep) with the daytime data.

Using monthly averaged weather data obtained from an off-site weather station located at the Rochester Monroe County airport, predictions of average heating season infiltration rates were made for each of the houses in the study. Compiled in Table 8 are the results of the actual air-exchange rate measurements made in the ten monitored houses and the predicted heating season infiltration rates. While the predictions were 10-15% high or low for some houses, the average air-exchange rate measured in the houses was 0.44 ± 0.27 ach which compares very well with the average predicted infiltration rate of 0.44 ± 0.20.

D. <u>Indoor Air Quality Measurements</u>: <u>Unventilated Period</u>

Measurements of air-exchange rate and concentrations of Rn, NO_2, HCHO, RCHO, and relative humidity in the ten houses selected for a detailed study of indoor air quality are summarized in Table 8. 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).

To provide some framework for evaluating these results, we have compiled in Table 9 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.)

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. The results of the measurements of the gaseous pollutants made in houses #6 and #49 by the EEB Mobile Lab are compiled into Tables 10 and 11 respectively. 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. The indoor contaminant concentrations are discussed in greater detail below.

a) <u>Radon</u> -- 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 9, 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 <u>et</u> <u>al</u>., 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. These results are graphically presented in Figure 13.

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 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.

b) 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 results of these measurements are presented graphically in Figure 14. 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 2 and the HCHO and RCHO measurements in Table 8 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.

c) 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. The results of these measurements are presented graphically in Figure 15.

d) 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 Tables 12 and 13 represent the average of indoor and outdoor measurements made in houses #6 and #49 respectively. Figures 16 and 17 are frequency distributions of the particulate concentrations observed in these houses. 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.

e) Humidity -- In the selected ten houses, the average relative humidities ranged from 25% (4.0 g/kg) in house #49 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.

E. Indoor Air Quality Measurements: Ventilated Period

During the period when mechanical ventilation was used, the average air-exchange rate in these nine tight houses was increased 80% (from 0.35 to 0.63 ach). Figure 18 is a graphic presentation of the average air-exchange rate measured in each house without mechanical ventilation (left bar of each pair) and the average air-exchange rate measured with mechanical ventilation (right bar). 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 where 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 in addition to the water vapor.

Figure 19 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 airstream into the supply airstream. 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.

F. 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 zone 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 (Birge 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, ($k \gg a$), 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 $1.29 \pm 0.67\ h^{-1}$ 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.

G. Heat Exchanger Thermal Performance Measurements

In order to assess the thermal performance of the nine MVHX systems installed in this study, we measured the temperatures and flow rates of the four airstreams associated with each heat exchanger. (For a description of the field measurement techniques employed see the Appendix A section on Heat Exchanger Measurement Technique.) From these measurements we were able to calculate several parameters of heat exchanger performance as described below.

a) Airstream Flow Rates -- compiled into Table 14 are the flow rates measured in each of the nine MVHX systems. Figure 20 shows a researcher measuring the flow rate with a pitot tube and micromanometer in one of the insulated ducts of an installed residential air-to-air heat exchangers. Flow rates ranged from 65 to 210 cfm which correspond to ventilation rates of 0.33 to 1.05 ach (i.e., in a 12,000 ft^3 house with perfect mixing of indoor air).

In house #52, where two unducted window type heat exchangers were installed, the flow rate data are from measurements made on an identical unit at the LBL Heat Exchanger Testing Facility (Fisk et al. 1981). The measurements required fitting the unit to the test facility duct system and measuring the air flow rates in each duct with orifice plates while simulating the unducted operating conditions by carefully adjusting and maintaining zero static pressure at the heat exchanger inlets and outlets. Such measurements could not be practically made in the field. In house #1, flow rate measurements were only made on the supply-out airstream (i.e., the supply airstream after passing through the heat exchanger) and the exhaust-out airstream (i.e., the exhaust airstream after passing through the heat exchanger).

To indicate the accuracy of the flow rate measurements the air mass balance ratio was computed (i.e., total mass flow rate into the heat exchanger/total mass flow rate out of the heat exchanger). The mass balance ratios ranged from 0.91 to 1.15, which reflect the accuracy we would expect from field measurements made with pitot tubes in short ducts.

At the time of these measurements, dampers valves in the duct system were adjusted to balance the flow rate of air entering the house (supply-out) with the flow rate of air leaving the house (exhaust-out), in order to minimize any forced infiltration or exfiltration of air. However the task of balancing the two airstream flow rates proved to be more difficult than anticipated--the main complication being the leakage between airstreams in the heat exchanger cores. Changing the flow rate of one airstream had the effect of changing the flow rate of the other airstream thus making the task of balancing the two airstreams a complicated iterative process. The results of the balancing efforts are illustrated in the flow rate measurements presented in Table 14. The flow rate balance ratios (supply air flow rate/exhaust air flow rate) ranged from 1.0 in houses #1 and #56 to 0.54 in house #6. The average balance ratio was 0.85 ± 0.15.

b) Ventilation Efficiency -- The three major ventilation efficiencies in an MVHX system are: (1) imperfect mixing of indoor air (e.g., short circuiting between the incoming supply airstream and the outgoing exhaust airstream), (2) internal cross-stream leakage, and (3) imperfect mixing of outdoor air. The extent to which there is imperfect mixing or short circuiting depends on design parameters for the MVHX system (e.g., proximity and design of the air entrance and outlet locations), on building geometry, on airstream conditions (e.g., velocity, direction, and temperature) and perhaps on a number of other parameters (e.g., outdoor wind speed and direction). The degree of internal leakage between airstreams depends on the integrity of the manufacturer's design and on the difference airstream pressures within the heat exchanger.

In this report we present calculations of the nominal ventilation efficiency which has been calculated as the ratio of the average increase in air-exchange rate observed during the ventilated period to the predicted increase if there were perfect mixing of indoor air and no cross-stream transfer between exhaust and supply airstreams.

The observed increase in air-exchange rate was calculated from the SF_6 tracer decay measurements. The predicted increase in air-exchange rate was calculated by dividing the larger flow rate of the two airstreams (supply out or exhaust out) by the house volume. Thus we assume that the air-exchange rate resulting from infiltration and occupant activities is the same for both ventilated and unventilated periods, and the difference in the air-exchange rates of these two periods is a result of mechanical ventilation. Since the weather conditions and occupant activities were similar for both measurement periods we feel this to be a reasonable assumption.

The ventilation efficiencies calculated ranged from a low of 0.22 in house #56 to a high of 0.73 in house #33 and are presented for each house in Table 14. The average ventilation efficiency omitting house #56, was 0.62 ± 0.05. As of yet we have not uncovered a reason for the very low ventilation efficiency of 0.22 in house #56. After two days of operation with air-exchange rates of 0.8 to 1.0 ach and ventilation efficiencies of 0.65 the air-exchange rate dropped precipitiously to 0.3 to 0.5 in this house. It appeared that the heat exchanger fans were turned off, although flow measurements taken during this period indicate no drop in flow rate.

The ventilation efficiency of the two unducted window model heat exchangers installed in house #56 was 0.63 which is comparable to the ventilation efficiencies measured for the ducted systems in this study.

c) <u>Effectiveness Calculations</u> -- The energy efficiency of heat exchangers is characterized by a parameter called effectiveness. Effectiveness of air-to-air heat exchangers is the measure of actual transfer of energy between airstreams (sensible and latent) divided by the theoretical maximum energy transfer possible. Measurement of effectiveness in an air-to-air heat exchanger requires accurate measurement and control of mass flow rates, temperatures, and specific humidities (Fisk et al., 1980). Measurements must be performed without operation of internal fans which generate heat and under conditions which preclude any condensation or freezing of moisture within the heat exchanger core. The effectiveness of ten different models of air-to-air heat exchangers has been measured at the LBL Heat Exchanger Test Facility.

In this field study, our air-stream temperature measurements were used to calculate sensible effectiveness (or temperature efficiency) which is the measured airstream temperature change divided by the maximum temperature change possible. Because the rate of heat transfer to the supply airstream is influenced by the flow rate balance, fan heat, freezing, and condensation, we call the calculated parameter "apparent sensible effectiveness" (ASE). Airstream temperature measurements were made in the houses visited by the Aardvark by installing thermistors in each of the four heat exchanger ducts. No heat exchanger temperature measurements were made in houses #6 or #49 which were visited by the EEB Mobile Lab. Temperature measurements were made for the window heat exchanger installed in the basement of house #56, however; no measurements were made for the second unit installed upstairs.

Assuming balanced air flow rates, the ASE for the supply airstream was calculated from the following equation:

$$\text{ASE (balanced system)} = \frac{T_{so} - T_{si}}{T_{ei} - T_{si}} \tag{1}$$

where

T_{si} - temperature of supply airstream into heat exchanger (outside air)

T_{so} - temperature of supply airstream out of heat exchanger to indoors

T_{ei} - temperature of exhaust airstream into heat exchanger (house air)

T_{eo} - temperature of exhaust airstream out of heat exchanger to outdoors

Out of balance systems, which exhaust more air than they supply (exhaust dominated systems) exhibit enhanced heat transfer to the supply air-stream through the heat exchanger core. However, the imbalance in flow rates causes air to leak into the building through the building envelope and this air is not preheated. Thus, the supply air-stream ASE calculated for exhaust dominated systems using equation (1) are misleading indicators of the energy impact on a home heating system.

To correct ASE calculations for this type of flow rate imbalance, one needs to consider the flow-rate averaged temperature change of all air supplied by the heat exchanger, which includes both the supply air out of the heat exchanger and the forced infiltration caused by the heat exchanger imbalance. Equation (2) was used to calculate a supply airstream ASE corrected for this type of flow-rate imbalance.

$$\text{ASE (unbalanced system)} = \frac{\dot{m}_{so}\,(T_{so} - T_{si}) + \dot{m}_i\,(0)}{(\dot{m}_{so} + \dot{m}_i)(T_{ei} - T_{si})} \quad (2)$$

where:

$\dot{m}_{so}$ = supply stream mass flow rate out of heat exchanger to inside.
$\dot{m}_{eo}$ = exhaust stream mass flow rate out of heat exchanger to outside.
$\dot{m}_i$ = air leakage caused by flow rate imbalance ($\dot{m}_i = \dot{m}_{eo} - \dot{m}_{so}$).

Thus, for exhaust-dominated systems (i.e., exhaust rate out of the house exceeds supply rate into the house) the ASE calculated from equation (1) is corrected for flow rate imbalance simply by multiplying it by the ratio of mass flow rates (supply-out to exhaust-out). For supply-dominated systems no such correction is necessary because the measured temperature change of the supply airstream will reflect the energy loss due to the flow rate imbalance. Maximum energy efficiency is achieved with balanced mass flow rates.

Because the heat exchangers used in this study were equipped with internal fans and fan motors, our external temperature measurements indicate the sum of the temperature rise across the core and the temperature rise across the fan. To compare the performance of the different heat exchanger cores, an effectiveness more representative of the actual heat transfer in the core of the heat exchangers was calculated by correcting for the temperature rise across each fan using equation (3).

$$\Delta T = \frac{Q}{\rho C_p \dot{v}} \quad (3)$$

ΔT = temperature rise (^oF).
Q = fan power release (Btu/hr).
C_p = specific heat of air (Btu/lbm - ^oF).
ρ = density of air (lbm/ft^3).
$\dot{v}$ = volumetric flow rate of air (ft^3/hr).

We assumed the fan power release, Q, into the airstream to be 90% of the power input to the fan, the remaining power being dissipated as the fluid power of the moving airstream and as heat losses to surroundings other than the airstream. The actual percentage depends on the efficiency of the fan and fan motors but small fan motors are typically very inefficient. Thus, we estimate that a 90 watt fan moving 100 cfm raises the temperature of that airstream approximately 2.6 ^{o}F. By subtracting a 2.6 ^{o}F temperature rise from the measured supply out temperature, one would calculate a corrected ASE of 75% for a heat exchanger with an uncorrected ASE of 82% if the indoor-outdoor temperature difference is 40 ^{o}F. If the indoor-outdoor temperature difference was only 20 ^{o}F, the corrected and uncorrected values for ASE would be 75% and 88%, respectively.

d) <u>Effectiveness Measurements</u> -- Compiled in Table 14 are the calculated values of supply airstream ASE without any correction, with correction for flow rate imbalance, and with both fan heat and flow rate imbalance corrections. The average ASE (uncorrected) for all seven monitored heat exchangers is 0.72 ± 0.13 and ranges from a low of 0.49 in house #1 to a high of 0.89 in house #56. Correcting for flow imbalance reduces the average ASE 10% to 0.65 ± 0.16; the fan heat corrections further reduces the average 12% to 0.57 ± 0.12. As indicated by the ASE, heat recovery performance varied significantly from unit to unit.

The low average heat exchanger ASE (corrected for flow rate imbalance) of 0.49 measured in house #1 is notable. This average reflects 35 sets of temperature measurements made over a five day period. The standard deviation of these measurements was ± 0.11, and the range was 0.27 to 0.68. The periods of low ASE appear to be associated with the daily shutting down and restarting of this heat exchanger. The homeowner turned the heat exchanger off each day between 9 PM and 7 AM because the noise level of the fans was found to be annoying to one of the occupants, especially during the evening hours. Also prompting the night shutdown was the fact that during the evening hours the outdoor air in this neighborhood frequently became permeated with the wood smoke generated by the nearby houses using fireplaces and woodstoves, and operation of the heat exchanger during these evening periods resulted in introduction of objectionable odors into the house. During this period of shutdown, the heat exchanger cooled off substantially as it was exposed to the cold outside air through short sections of ductwork for both the supply and exhaust airstreams. As a result of this cooling, significant heat transfer from the airstreams to the cooled heat exchanger mass may occur for a period of time after restart. Thus, the intermittent operation may have reduced the performance of the heat exchanger. Performance reductions of approximately 20% were noted during the first half-hour after restart.

Ice formation in the core of this heat exchanger was also observed during the study period. The onset of performance degradation generally occurred whenever temperatures fell below 17 ^{o}F. This model of heat exchanger (Flakt) was equipped with an electric pre-heat freeze protection system, however the power for the preheater was never connected. Freezing in the heat exchanger core and subsequent performance degradation was also observed in house #10 for a different model of heat exchanger (Des Champs) when outside temperatures fell below 17 ^{o}F. We are uncertain whether freezing adversely affected the performance of other units.

Because performance degradation due to freezing depends on indoor and outdoor conditions and the amount of time during which freezing has been occurring, the temperature of 17 ^{o}F can only be considered a rough estimate of the temperature at which freezing becomes a problem in these sensible heat exchangers. A lower onset-of-freezing temperature might be expected for heat exchangers with sensible/latent cores since the specific humidity and hence the dew point of the exhaust airstream is decreased somewhat as it passes through this type of core.

In house #52, two sensible/latent window type heat exchangers were installed (Mitsubishi VL-1500). These unducted heat exchangers are designed with an exhaust dominated flow imbalance. The unit installed upstairs was run at medium speed (65 cfm exhaust) and based on data from (Fisk et al., 1981) had a flow balance ratio (supply-out to exhaust-out) of 0.83. The downstairs unit was run at high speed (85 cfm exhaust) and had a flow balance ratio of 0.82. Temperature measurements were only made in the downstairs unit. The average uncorrected ASE was 0.65. After correction for flow rate imbalance this dropped 18% to 0.53, and after correction for fan heat the ASE dropped an additional 8% to 0.48. The larger ducted Mitsubishi heat exchanger (Mitsubishi LGH 50 R2) installed in house #45 had a similarly low ASE of 0.44 after correcting for fan heat and flow imbalance. In this heat exchanger a high rate of air leakage between airstreams was evident.

Excluding house #1, where the heat exchanger was run intermittently, the average ASE (corrected for flow imbalance and fan heat) for the four heat exchangers with sensible type cores was 0.66 ± .08, which is 40% higher than the 0.47 ± 0.04 average corrected ASE measured in the two heat exchangers with sensible/latent cores. For heating season operation, sensible cores will exhibit enhanced sensible heat transfer to the supply airstream as a result of condensation of water vapor in the exhaust airstream and this enhancement may partially explain the higher effectiveness observed in this study. However, other characteristics of the cores, including heat transfer area, are probably a more significant cause for the observed difference in effectiveness.

For heating season operation, the ASE of the supply air-stream corrected for flow rate imbalances indicates the energy impact of the increased ventilation with heat recovery on the home heating system. If the ASE of the supply airstream is unity then the outside air is being supplied out of the heat exchanger at the indoor temperature ($T_{so} = T_{ei}$) and there is no increased load on the home heating system. The electrical energy consumed by the heat exchanger fan system is another highly important performance parameter.

If the homeowner is using humidification equipment to maintain comfortable indoor winter-time humidities and the outside air is less humid than the indoor air, increased ventilation will cause an additional latent load on the humidification equipment. However, in tight houses winter-time humidities are often higher than desirable (causing condensation problems), and a reduction in indoor humidity due to increased ventilation is desirable. Alternatively, in humid air-conditioning climates, where much of the air-conditioning energy is used to remove moisture and indoor-outdoor temperature differences are relatively small, latent loads are significant. For such applications it may be desirable to use a heat exchanger with a sensible/latent core. However, as noted earlier, it appears that the heat exchangers with sensible/latent cores were less effective in lowering some indoor contaminant concentrations (e.g., formaldehyde) because there may be significant cross-stream transfer of contaminants in heat exchangers with this type of core.

H. Weatherization Package Economic Analysis

Table 15 presents the results of the economic analyses of the Standard Energy Package instituted by Ryan Homes Inc. Initially, the first year energy savings due to the weatherization package had to be calculated from the difference between the k-values of the pre-1976 and post-1976 Ryan homes. The heating season (October-April) degree days used in the analysis (5375 ^{o}F-day) were determined by using the average balance temperature of the two groups, 61^{o}F, as the base temperature for the degree day calculation. The weather data was obtained from the National Weather Service station at the Rochester airport. The energy savings calculation was based on a house with a 70% efficient gas furnace and a floor area of 2260 ft^2 (which is the average floor area of the two groups of houses).

The average yearly energy savings are found by the following equation:

$$\Delta E = \frac{\Delta k \cdot A \cdot DD_b}{\eta}$$

where

ΔE is the yearly energy savings (BTU)
Δk is the differential k-value (BTU/ft^2-^{o}F-day)
A is the floor area (ft^2)
DD_b are the heating season degree days (^{o}F-day)
b is the base or balance temperature (^{o}F)
η is the furnace efficiency

The average energy savings determined by this method is 300 therms (10^5 BTU) per year, or a savings of about \$150 per year at the current natural gas price of \$0.50 per therm in the Rochester area (Melville, 1981). The estimated differential cost of the weatherization package is \$500 (Tracey, 1981) which gives a simple payback of period 3.3 years. The weatherization package can be considered cost-effective at this low payback period.

Two other economic indicators, net benefit and cost of conserved energy, also show that the weatherization package is a good investment (see Appendix C for a detailed discussion of these two economic indicators). The cost of conserved energy ranges from \$0.085 to \$0.108 per therm when a thirty year amortization period is used. At a twenty year amortization period the cost of conserved energy ranges from \$0.112 to \$0.134 per therm. The cost of conserved energy from the weatherization package is much lower than the current natural gas price of about \$0.50

per therm. The net benefit ranges from a low of $1546, assuming a real discount rate of 5% and a real energy escalation rate of 1% over a twenty year period, to a high of $3382, assuming a real discount rate of 3% and a real energy escalation rate of 2% over a thirty year period. Clearly, the weatherization package is cost-effective at both the twenty year and thirty year amortization periods.

I. Energy and Economic Analysis of Heat Exchangers

Mechanical ventilation systems with air-to-air heat exchangers provide additional ventilation of the residence. While their operation increases the energy requirements for heating and cooling, a larger increase would occur if the additional ventilation was provided without heat recovery (e.g., by additional infiltration if the house was constructed less tightly). Using a computer program developed by Fisk and Turiel (1982), air exchange rates, heat exchanger performance data, and costs from this field study, an energy and economic analysis was performed for eight of the nine homes with heat exchangers. The analysis was not performed for home #56 because of uncertainty whether the data from this house was representative. The economic analysis was performed from the homeowner's point of view thus, average fuel prices were utilized. If instead we had performed the analysis from the perspective of the utility, the marginal cost for new energy could have been utilized and the economic results would be more favorable.

Three energy related parameters and four economic parameters were calculated for each house. One of the energy related parameters is the "ventilation heat load reduction" which compares the load on the home heating system with the heat exchanger operating to the load that would occur if the additional ventilation was provided without heat recovery. This reduction in heat load occurs because of the energy recovery in the heat exchanger core and because some fraction of the electrical energy consumed by the heat exchanger's fan motors is delivered to the residence in the form of heat. The second energy parameter is the electrical energy requirement for operation of the heat exchanger's fan system and the third energy parameter is discussed later.

The first three economic parameters calculated are based upon a comparison of two methods of providing the same amount of ventilation and we assume that identical levels of indoor contaminants result from each method of ventilation. The only economic benefit considered for this comparison is the reduced cost for energy to heat the home because of the reduction in ventilation heat load. Economic costs include the incremental cost to construct a more air tight residence, the purchase price of the heat exchanger system, installation and maintenance costs for the heat exchanger, and the costs for operating the heat exchanger's fan system. These three economic parameters are: (1) "net present benefit" which equals the present value of economic benefits minus the present value of costs, (2) "benefit-cost ratio" which equals the present value of benefits divided by the present value of costs, and (3) the "discounted payback period" which equals the number of years required for the net present benefit to become positive.

A third energy parameter and a fourth economic parameter were calculated to allow a comparison of each house without additional ventilation to the same house with additional ventilation provided by the heat exchanger.

These last two parameters are useful for a subjective comparison to the value of the improved indoor air quality resulting from the increased ventilation. The energy parameter "increase in ventilation heat load" is the increase in heat load that is expected if the heat exchanger is operated throughout the heating season. The economic parameter "net present value of costs" is a measure of all costs for the purchase, installation, and operation of the heat exchanger. When calculating the net present value of costs, the incremented cost for construction of a more air-tight house was not included because we are comparing the same house with and without a heat exchanger. However, we include in our calculations the increased cost for energy expended to meet the increase in ventilation heat load. A dollar value for the improvement in indoor air quality was not assigned, instead we only provide an indicator of costs for the home owner or reader to compare to the benefits.

A large number of assumptions were required for the analysis and they are described in Appendix D along with some of the potential sources for significant error. Two of the houses employed an electric heat pump with natural gas assist for heating. Because the existing computer program was not suitable for modeling this type of heating system, for these homes we present two sets of economic results to indicate a range of economic performance. For the first set of economic results, we assumed that the electric heat pump provided all heat and operated with an average coefficient of performance of 1.7. For the second set of results, we assumed that all heat was provided by a natural gas heating system with an efficiency of 70%.

Results for each of the eight houses are presented in Table 16. The "ventilation heat load reduction" ranges from 78 to 152 therms. The major factors affecting the value of this parameter are the increase in ventilation rate (i.e., the increase in air-exchange rate multiplied by the house volume) and the heat exchanger effectiveness. A second parameter, "fan energy consumption" ranges from 560 kilowatt-hours to 1283 kilowatt-hours. The ratio of fan energy consumption to ventilation heat load reduction ranges from 5.4 to 15.2 kwh/therm. Fisk and Turiel (1982) have demonstrated that this ratio has a large effect on the economic results. The net present benefit and benefit-cost ratio range from -$1313 to $345 and 0.45 to 1.20 respectively assuming a 20 year lifetime for the heat exchanger. Discounted payback periods range from 14 to over 30 years. One of the most important factors affecting the economic results is the type of heating system, i.e., the cost to supply heat to the residence. For three of the four houses with electric heat, the net present benefit is positive. The negative net present benefit for electrically heated house #1 is due primarily to the low heat exchanger effectiveness and small increase in air exchange rate for this house. As discussed in section G, this poor performance may be explainable by the periodic use of the heat exchanger and freezing in the core. For all cases where the house is heated with natural gas or an electric heat pump, the net present benefit is negative and, in all but one of these cases, the discounted payback period is greater than 30 years.

As discussed above, the last two parameters in Table 4 are useful for comparison of each house with and without additional ventilation provided by the heat exchanger. The increase in ventilation heat load ranges from 14 to 91 therms, depending on the heat exchanger performance and the magnitude of the ventilation increase. The net present value of costs ranges from \$2245 to \$4567. Capital costs for the purchase and installation of the heat exchanger are 25 to 46% (avg. 39%) of the net present value of costs.

In summary, based upon data from this study, utilization of a heat exchanger causes a significantly smaller increase in ventilation heat load than increasing the ventilation by some means without heat recovery. However, assuming that the increases in ventilation were required, utilization of the heat exchangers appears to be marginally cost effective (from the homeowners point of view) in three of the four electrically heated homes and not cost effective in the remaining homes. The estimated total cost for the increased ventilation over a 20 year period ranges from approximately \$2200 to \$3600. Because the economics of heat exchanger utilization depends highly on climate, type of heating system, heat exchanger performance, magnitude of the increase in ventilation, and other factors it is difficult to generalize from the economic results presented here.

SUMMARY AND CONCLUSIONS

Special weatherization components such as continuous polyethylene vapor barriers and joint-sealing materials are effective in reducing the leakage area of the houses, and hence infiltration, as evidenced by the direct measurements of leakage area made in this study. Our results indicate that the 35 post-1976 houses which received the weatherization package have an average specific leakage area that is 50% less than the average specific leakage area of the 11 pre-1976 houses which did not receive the weatherization package. In addition, the 35 post-1976 Ryan homes and the 12 post-1978 Schantz homes are among the tightest groups of houses tested in North America by LBL and others. The low average heating season infiltration rates that were predicted for the post-1976 Ryan homes (0.47 ach) and Schantz homes (0.48 ach) show that air-exchange rates of less than 0.5 ach are clearly obtainable in new residential buildings through the use of air leakage reduction techniques.

The improved energy performance of the post-1976 Ryan houses as compared to the pre-1976 Ryan houses can be attributed to the increased attic insulation, and the added R-11 basement insulation, and the air leakage reduction techniques. The post-1976 Ryan homes have a 30% lower k-value ($W/^{o}C{-}m^{2}$) than the pre-1976 Ryan homes. This lower energy consumption rate, on the average, is equivalent to an energy savings of 300 Therms (30 MBTU) per year for the typical Ryan home located in Rochester, New York.

An accurate determination of the energy savings directly attributable to the air leakage reduction would require further study in a sample of buildings which received only infiltration reduction measures; however, we have estimated that more than half of the energy savings resulted from the reduction in air-leakage. Considering that the increased cost to the builder associated with the air-leakage reduction was approximately $200 (or less than half of the total conservation package of $500), air-leakage reduction appears to have been a better investment than the increased levels of insulation.

Based on these measured energy savings and the estimated costs, the weatherization package is cost-effective at the current natural gas price of about $0.50 per therm. Over a thirty year period the cost of conserved energy resulting from the weatherization package is approximately $0.11 per therm of natural gas. Clearly, the cost of conserved energy is much lower than the current average natural gas price paid by residential customers in the Rochester area. In addition, the net benefits accrued over the same period were found to be in the range of $1543 to $3380. The $500 additional investment in weatherization for the post-1976 Ryan homes can be considered a very cost-effective investment.

In the nine tight houses studied, the air-exchange rates measured during the unventilated period were low, 0.2-0.5 ach, while 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 good 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. Thus, a "clean bill of health" cannot be awarded to these houses on the sole basis of these measurements, although it is encouraging that the concentrations of the contaminants measured were as low as they were considering the tightness of these houses. If these houses had been constructed even more tightly, so that air-exchange rates were much lower, the concentrations of indoor air contaminants could have been substantially higher than observed in this study. Until a sufficiently large indoor air quality data base is established for the United States, it is strongly recommended that all house-tightening programs include an indoor air quality measurement component to assure that the retrofits designed to reduce infiltration and thereby save energy do not have adverse effects on indoor air quality and human health.

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 to study contaminant emissions from various building materials. Many occupant-related sources of indoor air pollution, however, are 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 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 States, 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 where 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 results of this study indicate that MVHX systems are effective in providing supplementary ventilation while recovering much of the energy that would normally be lost without heat recovery. The apparent sensible effectiveness (ASE) corrected for flow imbalance of the units installed in this study ranged from 0.48 to 0.89 and averaged 0.65 ± 0.16. Freezing of moisture within the heat exchanger core, flow imbalances, and design differences are the primary reasons for the wide range in the measured thermal performance. The average ASE (corrected for flow imbalance and fan heat) of the heat exchangers with sensible cores was 0.66 ± 0.08, which is 40% higher than the 0.47 ± 0.04 average corrected ASE measured in the two heat exchangers with sensible/latent cores. Sensible-type heat exchangers will slightly dehumidify houses during cold weather and in most tight houses this reduction in humidity is welcome since winter-time humidities are often higher than desirable.

Based upon data from this study, we predict that utilization of the heat exchangers caused significantly smaller increases in ventilation heat load than increasing the ventilation by some means without heat recovery. However, assuming that the increases in ventilation were required, utilization of the heat exchangers appears to be only marginally cost effective (from the homeowners point of view) in three of the four electrically heated homes studied and not cost effective in the remaining homes. The estimated total cost for the increased ventilation provided by the heat exchangers for a 20 year period ranged from approximately $2200 to $3600.

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.

APPENDIX A - MEASUREMENT TECHNIQUES

A. Leakage Area Measurement Technique

From May through October 1980 personnel from RIT measured the "effective leakage area" of each house using the fan pressurization technique (Grimsrud et al., 1981). Fan pressurization involves the use of a large fan, or "blower door," to push air into (pressurize) or pull air out of (depressurize) a structure. The blower door is adjustable so it can be installed in doorways of different sizes. Figure 21 is a photograph of a blower door installed in the front door of a house. A direct-current controller regulates the fan speed while a digital tachometer displays the rotational speed of the fan. The pressure difference between the inside and outside of the house is measured with an inclined manometer, and the air flow rate through the fan is calculated using an experimentally determined fan calibration that correlates the air flow rate with the fan speed at known pressure differences. Analysis of the relationship between air flow through the fan and the pressure difference between the inside and outside of the house makes it possible to calculate the effective leakage area, or simply "leakage area," for the structure. The specific leakage area is the calculated leakage area normalized by the floor area of the house.

Natural infiltration is typically driven by pressure differences (ΔP) across the building shell in the range of 0 to 10 Pascals (Pa) and is characterized by large, short-term fluctuations. Fan pressurization uses a door-mounted, variable-speed fan capable of moving large volumes of air into or out of a structure. When ΔP is held constant, all air flowing through the fan must also be flowing through the building envelope. When ΔP is much greater than 10 Pascals, fan flow dominates natural infiltration and the latter may be disregarded. At a given pressure differential and fan speed (in RPM), the flow of air through the fan is determined by means of a previously established calibration curve. For each house, measurements are taken under conditions of both pressurization and depressurization at a series of fixed pressure differentials (for example, from 10 to 70 Pa at 10 Pa intervals), generating a pressure versus flow curve. This data is then used to find the effective leakage area of the house.

Air flow through a building envelope is a combination of viscous flow and turbulent flow. The former is proportional to ΔP while the latter is proportional to the square root of ΔP. Hence, air flow through the envelope can be characterized by the equation:

$$Q = K \, \Delta P^{n} \tag{1}$$

where:

- Q = air flow through the envelope (m^3/s);
- ΔP = applied pressure across the envelope;
- K = semi-empirical constant; and
- n = semi-empirical constant in the range $0.5 < n < 1.0$.

The curves generated by fan pressurization are extrapolated to a ΔP of 4 Pa (assumed to be representative of natural infiltration) using Equation 1. Next, it is assumed (based upon measurements performed by LBL) that in the pressure differential ranges characteristic of natural infiltration (-10 to +10 Pa), the flow versus pressure behavior of a building more closely resembles square-root (turbulent) than linear (viscous) flow and can be described by:

$$Q = A_{eff} \sqrt{(2/\rho)\Delta P} \qquad (2)$$

where:

Q = air flow through the envelope (m^3/s);
A_{eff} = effective leakage area;
ΔP = applied pressure of -10 to +10 Pa ($kg/m\text{-}sec^2$);
ρ = density of air (1.2 kg/m^3)

By combining the leakage area with local wind and temperature data and general topographic features, it is possible to estimate seasonal average infiltration rates using a theoretical infiltration model developed at LBL (Sherman and Grimsrud, 1980). Off-site average daily wind speed and temperature data was available from measurements made by the National Weather Service office in Rochester, N.Y. On-site windspeed estimates were made from this off-site data by incorporating terrain and shielding factors which were determined from an examination of the house surroundings. On-site wind speed data was recorded with anemometers at the two houses monitored by the EEB Mobile Lab. The LBL model predicts the infiltration portion of the house air-exchange rate; occupant effects on the air-exchange rate, opening of doors and windows and use of fireplaces, dryers, and exhaust fans, must be estimated and added to the infiltration rate. A current estimate used at LBL to account for the added ventilation caused by occupant behavior during the heating season is 0.10 to 0.15 air changes per hour (ach).

B. <u>Energy Performance Measurement Technique</u>

Information on energy consumption in each of the houses was obtained from monthly or bimonthly utility records. Electricity and natural gas consumption was examined for each of the houses for up to three years, except for fourteen houses built in 1980 and five houses built in 1979. Electricity was measured in kilowatt-hours (kwh) while natural gas was measured in hundreds of cubic feet (ccf).

The energy consumption data was converted to an average kilowatt-hour per day (kwh/day) consumption by dividing the total consumption by the number of days in the meter reading period. If natural gas was used for space heating, then the gas consumption (in ccf) was multiplied by a factor of 20.92 kwh per ccf of gas (based on a 70% furnace efficiency and a heat content of 1020 BTU per cubic foot of natural gas) to get kilowatt-hours. Daily outside temperatures were averaged over the same period as the energy consumption readings to allow for analysis of the correlation between energy consumption and outside temperature.

The rate of space heating energy consumption by a house (in Watts) is given by the equation:

$$E = [K(T_i - T_o) - S - G] \qquad (1)$$

where:

- E is the rate of energy consumption (Watts)
- K is the thermal coefficient of the house ($W/^oC$)
- T_i is the inside temperature (^oC)
- T_o is the outside temperature (^oC)
- S is the solar gain (W)
- G is the free heat generated by occupants and appliances (W)

The primary assumption in this model is that energy consumption is a linear function of the difference between the interior and exterior temperatures, where K is a constant of proportionality equal to the heat loss rate of the house per ^oC. The significance of K is seen if space heating energy is plotted as a function of outdoor temperature (see Figure 22). The slope of the resulting line is K.

Initially, linear regression analyses of the average daily energy consumption vs. average daily outside temperature were performed for each house that had at least five months of data (or five data points). The data was fit to an equation of the form:

$$E = K(T_o) + B \qquad (2)$$

where:

- E is the rate of energy consumption (Watts)
- K is the thermal coefficient of the house ($W/^oC$)
- T_o is the outside temperature (^oC)
- B is the y-intercept at $T_o = 0\ ^oC$ (W)

Once the overall thermal coefficient or K was calculated, it was then normalized by the total floor area of the house, including the basement area, to allow for a comparative measure of each building's energy performance. This value will be referred to as the k-value ($W/^oC\text{-}m^2$).

The k-value provides a basis for comparing the quality of the building design and construction as it relates to energy consumption. The more energy efficient the structure is, the lower the k-value will be. The k-value is actually composed of two terms: UA and I, where UA is the thermal conductance of the house and I is the infiltration load. The thermal conductance is a unique characteristic of a house and is the sum of the individual conductance terms of the windows, walls, ceiling and floors. It remains relatively constant so long as no changes are made to the shell. The infiltration load is composed of the individual infiltration terms due to the many cracks and openings in the building shell. In theory, the k-value should be a good measure of "envelope" performance that is relatively independent of occupant behavior.

However, another factor must be considered when comparing energy use among groups of buildings. This factor is known as the balance point or balance temperature of the building. The balance temperature is equivalent to the outside temperature when space heating becomes necessary. The general equation that defines the balance temperature is:

$$T_b = T_i - \frac{S + G}{K} \tag{3}$$

where:

- T_b is the balance temperature (^oC)
- T_i is the inside temperature (^oC)
- S is the solar gain (W)
- G is the free heat generated by occupants and appliances (W)
- K is the total heat transfer coefficient for the house ($W/^oC$)

This equation shows that the balance temperature is dependent on the thermostat setting, the internal heat gains, and the K-value of the building. As the K-value decreases, the balance temperature will also decrease, assuming that the thermostat setting and internal gains remain constant. All else being equal, one would expect the balance temperature to be lower for a group of houses with K-values less than the K-values of another group of houses.

The balance temperatures were calculated for each house to determine any differences between the two groups of houses. By setting the energy consumption in Eqn. 1 equal to the base energy use, averaged over a number of non-heating months, and solving the equation for T_o, the balance temperature can be characterized by the equation:

$$T_b = \frac{E_b - B}{K} \tag{4}$$

where:

- T_b is the balance temperature of the building (^oC)
- E_b is the base energy consumption (W)
- K is the thermal coefficient of the building ($W/^oC$)
- B is the y-intercept at $T_o = 0\ ^oC$ (W)

In addition to the K-value and balance temperature, the correlation coefficient or r^2 was calculated for each linear regression to determine the extent to which the variations in energy use could be explained by the change in outside temperature.

C. Aardvark Measurement Techniques

A common technique for measuring the air-exchange rate of a residential building is to inject a tracer gas into the building, mix it to a uniform concentration in the air, and then measure the rate at which the concentration of the gas decreases. Unfortunately, because the procedure requires many hours, involves expensive instruments, and is disruptive to occupants, little data has been collected on the variation of air-exchange rates over time in occupied houses. Similarly, little continuous data has been collected on indoor radon concentrations. To facilitate such work, LBL has developed an automated system for measuring air-exchange rates, radon concentrations, and seven temperatures continuously in an occupied residence. A microcomputer controls the measurement sequences and does preliminary data reduction. The results are recorded by a magnetic tape recorder and a printing terminal. The system, named Aardvark, is shown in Figure 23.

a) Air-Exchange Rate Measurement -- The air-exchange rate is measured over 90-minute intervals by tracer gas decay using sulfurhexafluoride (SF_6) as the tracer. The fact that SF_6 is both nonreactive and non-toxic gas was the primary reason for its selection as the tracer. The procedure for measuring air-exchange rate by tracer-gas decay involves two steps: injecting and mixing the tracer to a uniform concentration in the test space, then monitoring the concentration over time.

In order to ensure that the Aardvark measures the average concentration of tracer gas in the house and that the tracer is well-distributed and well-mixed during injection, up to four sampling and injection lines are used. In a typical house, we might place one sampling line in the basement, two on the first floor, and one upstairs for the bedrooms. For measuring SF_6 concentration we use a commercially-available portable, non-dispersive infra-red (NDIR) analyzer. During the system development we noticed that the calibration coefficients drifted substantially over time, so we incorporated into the Aardvark the capability of automatically calibrating the SF_6 analyzer.

The measurement sequence begins with a calibration procedure, which requires one minute to sample each of the three calibration gases (10, 25, and 50 ppm). After the calibration is completed, the Aardvark begins the tracer gas injection by opening the injection solenoid valve and turning on the furnace fan or remote mixing fans. The SF_6 concentration is measured roughly four times per minute until the concentration reaches 50 ppm, at which time the injection is terminated and the mixing fans are turned off. After five minutes have passed to allow for further mixing, the concentration of SF_6 in the house is measured at five-minute intervals until the decay is terminated (either when the SF_6 concentration drops below 10 ppm, the lowest value for which the analyzer is calibrated, or at the end of the 90-minute measurement period). After the decay measurement is completed, the microprocessor fits a straight line to the logarithm of the concentration versus time, using the method of least squares. The negative of the slope of this line is the air-exchange rate.

b) Radon Measurement -- In both the Aardvark system, and the EEB Mobile Lab, radon concentrations are measured with a Continuous Radon Monitor (CRM) developed at LBL. The detector consists of a cylindrical cell (an aluminum cup), 170 ml in volume, with a glass window at one end and two air-flow fittings at the opposite end through which filtered air is drawn (Th79). The inside of the cup is coated with a silver-activated zinc sulphide phosphor. When an alpha particle strikes the phosphor, a large number of photons are produced, some of which pass through the window and enter a photomultiplier tube producing a current pulse proportional to the number of incident photons. The alpha particles are produced by the decay of radon atoms and the radon progeny ^{218}Po and ^{214}Po in the cell. The output of the photomultiplier tube is converted to a voltage pulse, which is amplified; and -- if the peak exceeds a discriminator setting -- counted.

Before beginning to measure radon in the air, the background count rate of a previously flushed cell is measured over night. In addition the performance of the counting electronics and photomultiplier tube is checked by measuring the count rate of a cell containing a small amount of ^{226}Ra. An integration interval of 180 minutes is used for analyzing the CRM data. The average radon concentration is then calculated by inputing the measured net count rate and cell background count rate into a calibration equation.

c) Temperature Measurement -- The Aardvark is equipped to measure the air temperature at up to seven points once every thirty minutes. In this first field application of the Aardvark, we used two thermistors to measure indoor temperature, one to measure outdoor temperature and four to measure the airstream temperatures of the mechanical ventilation system incorporating an air-to-air heat exchanger. The calibration of the thermistors was checked every few weeks by immersing the probes in water at 0 ^{o}C and 20 ^{o}C and comparing their response with that of two precision thermometers.

D. Formaldehyde and Total Aldehyde Measurement Techniques

Portable refrigerated sampling systems developed at LBL, and depicted in Figures 24a and 24b, were used for formaldehyde measurements in all houses. The system consists of a pump box, sampling lines, and a sampler. The pump box contains a timer, two vacuum pumps, and a flow regulator. The sampler is a small, portable refrigerator with four sampling trains built inside, two for sampling outside air and two for sampling indoor air. Each train consists of two water-filled bubblers backed by a flow orifice for controlling the sampling rate. A line is run from the back of the sampler to a site suitable for sampling outside air, and another line is run from the back of the sampler to a site suitable for sampling inside air. The HCHO bubblers are each filled with 10 mL of distilled water, and the RCHO bubblers are filled with 10 mL of a .05% solution of 3-methyl-1-2-benzothiazolinone hydrazone (MBTH) in distilled water. Unexposed samples of distilled water and MBTH solution, analyzed later with the exposed samples, serve as blanks. The timer in the pump box is normally set to operate the vacuum pumps for a selected sampling period ranging from 12 to 24 hours. During this study, however, the bubblers were run continuously and changed daily. The vacuum regulator and flow orifice ensure a constant flow rate in each sample train of 2 cubic feet per hour ± 5%; the refrigerator maintains the proper temperature for optimum collection efficiency. Samples are collected daily and stored inside the refrigerator. At the end of each sampling period (approximately one week), the accumulated samples are packed with ice in an insulated container and shipped via air express to LBL for analysis. (Formaldehyde samples degrade significantly at room temperatures and must be kept chilled at all times.) The formaldehyde collected in the samples is analyzed with an improved pararosaniline technique developed at LBL (Miksch 1981). Total aldehydes collected are analyzed with a standard colorimetric procedure (Ketz 1977). Knowing the concentration of the samples, the volume of air sampled, and the collection efficiency, we can calculate the time-weighted average concentrations of formaldehyde and total aldehydes in the indoor air.

E. Nitrogen Dioxide Measurement Technique

Small passive samplers were used for nitrogen dioxide measurement in both Aardvark and EEB Mobile Lab monitored houses (Palmes et.al., 1976). As illustrated in Figure 25, the NO_2 passive sampler consists of a small plastic tube. A set of stainless-steel screens coated with triethanolamine (TEA), a substance which absorbs NO_2, is placed in the closed end of the sampling tube. The other end is fitted with a removable cap. In the field, samplers are assembled into packs of three and hung at several indoor locations and at an outside location. One pack of samplers is left capped as a zero reference for later analysis with the exposed packs, the others are uncapped for a period of one week. The NO_2 molecules from the surrounding air diffuse through the sampling tube and are absorbed onto the screens. When the sampling period is completed, the samplers are removed, capped, and mailed back to LBL for analysis. In the laboratory, the amount of NO_2 absorbed by each sampler is developed with a Salzman reagent and determined colorimetrically. Knowing the amount of nitrogen dioxide collected in the samplers, the diffusion rate through the sampling tube, and the elapsed exposure time, one can calculate the time-weighted average concentration of NO_2.

F. Humidity Measurement Technique

In the eight homes monitored with the Aardvark, humidity measurements were made using portable chart recorders (mechanical type). Three chart recorders were used to continuously monitor the indoor humidity in three major living spaces e.g., living-dining room area, kitchen and bedroom. No on-site outdoor humidity measurements were made. Instead, outdoor humidity data was collected from the Rochester weather station. As a check on the accuracy of the recording equipment, measurements were made each day using a fan powered psychrometer. In the two houses monitored with the EEB Mobile Laboratory, dewpoint temperatures were measured with lithium chloride hygrometers at three indoor locations and one outdoor location.

G. Energy Efficient Buildings Mobile Laboratory Instrumentation

The EEB Mobile Laboratory, is a facility designed to conduct detailed on-site measurements of indoor air quality. Figure 26 is a photograph of the Mobile Lab situated at one of the Rochester sites. Its instrumentation and the contaminants it is designed to measure are shown in Table 13. Figure 27 shows the instrumentation rack of the Mobile Lab. The laboratory contains sampling, calibration, and monitoring systems, which provide an index of the overall air quality in a building.

a) Gases: CO, CO_2, NO, NO_2, O_3, and SO_2-- The EEB Mobile Laboratory, shown in Figure 5, is positioned outside the building to be studied. Air from three indoor locations (e.g. kitchen, master bedroom, family room) and one outdoor location is drawn through teflon sampling lines into the trailer for analysis. Air from each location is sequenced at 10 minute intervals to the gas analyzers. Thus each location is sampled for 10 minutes every 40 minutes. The principle of operation for each of the gas analyzers (CO, CO_2, NO, NO_2, O_3, and SO_2) is listed in Table 13. Each gas analyzer was calibrated daily by supplying a zero and span gas. Analyzer linearity was verified at the beginning and end of each field experiment. In addition the EEB Mobile Laboratory is periodically audited by certified independent agencies.

b) Weather -- In addition to monitoring air contaminant levels the EEB Mobile Laboratory is equipped to monitor on-site weather data. Thermistors and lithium chloride hygrometers are installed at each of the four sampling sites to measure air temperature and humidity. A weather tower is erected for monitoring on-site wind speed and direction.

c) Data Acquisition -- A microcomputer system controls all of the measurement sequences in the mobile lab and performs preliminary data reduction. Data is collected from the gas analyzers, temperature, humidity, and wind sensors each minute and recorded onto a floppy disc. The recorded information is transmitted back to LBL by telephone or by sending the floppy disks back to LBL where they may be read into the main frame computer system.

d) Air-Exchange Rate -- In the two houses monitored by the EEB Mobile Laboratory, air-exchange rates were calculated from manually performed SF_6 tracer gas decays. Decays were made during daytime hours only. On the average, two decays, each lasting 2-3 hours, were performed each day. The SF_6 analyzer, was a portable NDIR instrument and was calibrated once at each field site.

e) Particulates -- Portable dichotomous air samplers (DAS), developed at LBL and depicted in Figure 28 were used to collect particulate matter. One DAS unit was used in the Mobile Lab to sample outside air and an identical unit was installed in the family room of each house. The unit separates the aerosols into two size ranges, the inhalable fraction (less than 15 μm) and the respirable fraction (less than 2.5 μm), using a flow controlled virtual impaction system, which deposits the particulate matter on teflon filters. The particulates collected on the filters are analyzed back at LBL using beta-ray attenuation to measure mass concentration, and X-ray fluorescence to determine chemical composition for 27 elements.

H. Heat Exchanger Measurement Techniques

In order to assess the sensible energy impact on the houses equipped with mechanical ventilation systems and air-to-air heat exchangers we measured air flow rates and temperatures.

a) Air Flow Rate -- In the eight ducted heat exchanger installations, flow rates were calculated from velocity measurements made in the ductwork with pitot tubes and a micromanometer. Where duct runs were long (>10 diameters) and straight, a single center line air velocity was measured and the average air velocity assumed to be 90 percent of this (Dwyer, 1980). Where duct runs were short, appropriate pitot tube traverses were made to determine the average air velocity. For the two unducted window units installed in a house #52, we used flow rate data from measurements made on an identical unit at the LBL Heat Exchanger Test Facility (Fisk, 1981).

b) Air Temperatures -- In the seven houses equipped with MVHX systems and monitored with the Aardvark, temperature measurements were made in the four airstreams of the air-to-air heat exchangers. Thermistors were installed and automatically read and recorded each one-half hour for the one week ventilated measurement period. No heat exchanger temperature measurements were made in the two houses visited by the EEB Mobile Lab.

APPENDIX B - LEAKAGE AREA MEASUREMENTS RESULTS

Effective Leakage Areas and Predicted Infiltration Rates for Rochester Houses

House #	Builder[a]	Year Built	Const. Type[b]	Total Floor Area (ft^2)	Effective Leakage Area (cm^2)	Specific Leakage Area (cm^2/m^2)	Predicted Infiltration Rates: Heating Season (ach)	Predicted Infiltration Rates: Annual (ach)
1	B	1977	2	2200	499	2.4	.37	.28
2	B	1977	2	2000	393	2.1	.30	.23
3	B	1976	2	2000	450	2.4	.36	.28
4	B	1976	3	2230	466	2.2	.42	.33
5	B	1977	4, S	2200	525	2.6	.44	.35
6	B	1977	4, S	1900	494	2.8	.42	.33
7	B	1976	2, S	1880	602	3.4	.58	.46
8	B	1977	2, S	2030	480	2.5	.41	.31
9	B	1977	3	3000	684	2.5	.44	.33
10	B	1976	2, S	1700	221	1.4	.23	.19
11	B	1977	2, S	2000	519	2.8	.43	.33
12	B	1976	3	2700	740	3.0	.56	.44
13	B	1976	3, S	2000	352	1.9	.29	.23
14	B	1977	3	2750	443	1.7	.33	.26
15	B	1975	3	2020	251	1.3	.22	.18
16	C	1978	3	2760	653	2.5	.43	.33
17	C	1979	3	3220	700	2.3	.41	.31
18	C	1979	2	2600	696	2.9	.42	.32
19	C	1980	3	2550	861	3.6	.61	.46
20	C	1979	3	2340	645	3.0	.45	.34
21	C	1978	3	3100	843	2.9	.50	.39
22	B	1979	3	2880	737	2.8	.53	.42
23	B	1979	2	2320	370	1.7	.26	.21

con't.

House #	Builder[a]	Year Built	Const. Type[b]	Total Floor Area (ft^2)	Effective Leakage Area (cm^2)	Specific Leakage Area (cm^2/m^2)	Predicted Infiltration Rates: Heating Season (ach)	Predicted Infiltration Rates: Annual (ach)
24	B	1980	4, S	1840	626	3.7	.65	.52
25	B	1980	3, S	2075	768	4.0	.70	.55
26	B	1980	3, S	2075	545	2.8	.49	.38
27	C	1978	2, NB	2800	1000	3.8	.57	.43
28	C	1979	3	2200	606	3.0	.55	.41
29	B	1980	3, S	2045	673	3.5	.61	.49
30	B	1980	4, S	2200	528	2.6	.45	.36
31	B	1980	2	2000	514	2.8	.47	.37
32	B	1980	2	2000	450	2.4	.42	.33
33	C	1979	3	2330	551	2.5	.42	.32
34	C	1978	4, S	1800	414	2.5	.46	.36
35[c]	B	1980	4, S	1900	1113	6.3	1.21	.94
36	B	1980	2	1500	760	5.5	1.00	.78
37	A	1974	2	1930	976	5.4	.92	.73
38	A	1973	3	2700	1010	4.0	.71	.54
39	A	1973	3	3050	733	2.6	.47	.35
40	B	1980	3, S	1890	593	3.4	.61	.48
41	B	1979	2, S	2080	527	2.7	.42	.33
42	A	1973	3, S	3700	1028	3.0	.51	.39
43	A	1974	3	1920	1604	9.0	1.70	1.33
44	B	1978	3	3000	637	2.3	.41	.31
45	B	1979	3	3260	606	2.0	.38	.29
46	B	1979	3, S	2075	541	2.8	.45	.35

con't.

House #	Builder[a]	Year Built	Const. Type[b]	Total Floor Area (ft^2)	Effective Leakage Area (cm^2)	Specific Leakage Area (cm^2/m^2)	Predicted Infiltration Rates: Heating Season (ach)	Predicted Infiltration Rates: Annual (ach)
47	B	1980	3, S	1630	576	3.8	.60	.46
48	A	1973	2, S	2850	951	3.6	.63	.48
49	A	1973	3	2000	653	3.5	.42	.32
50	A	1973	3	2700	1028	4.1	.71	.54
51	A	1973	3	1400	1538	11.8	2.18	1.71
52	B	1980	2	1680	225	1.4	.22	.18
53	B	1977	2	2200	593	2.9	.47	.38
54	A	1973	3	1550	978	6.8	1.16	.92
55	B	1980	2	1100	508	5.0	.87	.69
56	B	1980	2	1700	502	3.2	.56	.44
57	A	1974	2	1600	911	6.1	1.14	.89
58	A	1974	3	1400	775	6.0	1.04	.82
59	D	1967	4, S	2000	873	4.7	.82	.65
60	C	1978	3	2315	581	2.7	.47	.37

[a]A = pre-1976 Ryan Homes, B = Post-1976 Ryan Homes, C = Schantz Homes, D = private builder.

[b]Number of floor levels, S = split level, NB = no basement.

[c]House construction was not finished when measurement was taken.

APPENDIX C - ASSUMPTIONS FOR ECONOMIC ANALYSIS OF WEATHERIZATION PACKAGE

In order to evaluate the economic effectiveness of the Ryan Homes, Inc. Standard Energy Package, two standard economic analyses are applied to the data. These are net benefit analysis and cost of conserved energy. This appendix describes what assumptions were made in applying the two analyses and how each one is used. A detailed discussion of these economic analysis techniques applied to energy conservation can be found in Marshall and Ruegg, (1980) and Wright, et al., (1980).

A. Discounting Factors

In order to use these economic analyses, certain assumptions must be made about the cost of funds, alternative investment possibilities, energy price escalation, and other factors.

a) Present Worth Factor

For the purposes of this study, all costs and savings were converted to constant dollars (as opposed to nominal dollars). Present value is defined as the equivalent value of past and future dollars corresponding to a base year. To convert future dollars to a present value, both an interest rate and an inflation rate or a "real" discount rate must be taken into account through the application of a present worth factor. The present worth factor could be used to convert future costs such as replacement costs and salvage values to present values.

The present worth factor is found by the following formula:

$$PWF = \frac{1}{(1 + D)^N}$$

where

PWF is the present worth factor;
D is the real discount rate; and
N is the number of discounting periods.

In this case, the real discount rate is determined either by the costs of borrowing money or the return from alternative investments with a correction for inflation. The formula for calculating the real discount rate is:

$$D = \frac{(I - K)}{(1 + K)}$$

where

D is the real discount rate;
I is the interest rate; and

K is the inflation rate.

For example, if the interest rate is 15% and the inflation rate is 10%, the real discount rate is 4.5%. Choosing the appropriate combination of interest and inflation rates can be difficult. In order to avoid this problem, our analyses simply assume real discount rates of 3% and 5%.

b) Uniform Present Worth Factor

The uniform present worth factor is used to find the present value of a uniform series of payments that are made over N periods at a real discount rate, D. The yearly maintenance costs are multiplied by this factor in order to get the present value of the maintenance costs over the period of the investment. It is assumed that these yearly costs remain the same in constant dollars.

The uniform present worth factor is found using the following formula:

$$UPW = \frac{[1/(1 + D)]^N - 1}{1 - (1 + D)}$$

where

UPW is the uniform present worth factor;
D is the real discount rate; and
N is the number of discounting periods.

c) Energy Costs

In order to convert annual energy savings into dollars over the lifetime of an investment, the escalation rate of energy costs must be known. For this analysis a range of real energy escalation rates from 1% to 3% per year was assumed. The present energy prices must also be known in order to calculate the first year energy savings in dollars. $0.50 per therm of natural gas and $0.05 per kilowatt-hour of electricity were found to be the current average energy prices for residential customers in the Rochester, N.Y. area.

d) Energy Escalation Factor

The energy escalation factor is a modified form of the uniform present worth factor. The only difference between the two is that the energy escalation factor takes into account the rate of escalation of the periodic payment or receipt which is being discounted over N periods or years. For example, if you wish to find the present value of the energy savings (in dollars) from a conservation measure which has a useful life of N years, you would want to account for the yearly fuel price escalation rate (above and beyond inflation) in addition to discounting the yearly savings. The first year energy cost savings are multiplied by the energy escalation factor to get the present value of the energy savings over the period of the investment.

The energy escalation factor is found by the following formula:

$$EEF = \frac{[(1 + E)/(1 + D)]^N - 1}{1 - [(1 + D)/(1 + E)]}$$

where

- EEF is the energy escalation factor;
- E is the real energy escalation rate;
- D is the real discount rate; and
- N is the number of discounting periods.

B. Economic Analysis Techniques

a) Net Benefit Analysis -- Net benefit analysis allows one to determine the difference between the lifetime energy savings (in dollars) of an energy conservation investment and the lifetime costs. The analysis may be used to compare the benefits of making an investment with those of foregoing it, or it may be used to compare competing investments. An investment with a net benefit greater than zero is considered worthwhile. The formula we have utilized for calculating the net benefit is:

$$NB = EC(EEF) + TI - [P - S(PWF) + M(UPW) + R(PWF)]$$

where

- NB are the net benefits or savings;
- EC are the reductions in energy costs due to the investment;
- EEF is the energy price escalation factor;
- TI are any tax incentives applicable to the investment;
- P is the differential purchase and installation cost;
- S is the differential salvage value;
- PWF is the present worth factor;
- M are the differential maintenance and repair costs;
- UPW is the uniform present worth factor; and
- R are the differential replacement costs of any parts during the investment lifetime.

For an investment to be economically worthwhile, its net benefit must be greater than zero. Strictly speaking, for an energy conservation investment to be cost-effective, the net benefit must be greater than zero. However, due to the distribution of benefits over the period of the investment, a net benefit that is not much greater than zero may be considered marginally cost-effective. Net benefit analysis can also be used to determine the economically efficient size of a conservation investment. If the net benefit increases with additional investment, it is profitable to increase the investment. Net benefit analysis does not, however, indicate the economic return on an investment dollar. This analysis technique cannot distinguish between large and small investments that result in the same dollar savings nor can it be used to rank competing non-mutually exclusive investments because it may not indicate the highest total net benefits for a limited budget.

b) Cost of Conserved Energy -- Analysis of the cost of conserved energy allows one to determine the cost of energy saved by a conservation investment. This is done by dividing the annualized cost of the investment by the annual energy savings. A worthwhile investment is one for which the cost of conserved energy is less than the cost of supplied energy. For the homeowner, this is the average cost of energy; for the utility, it is the marginal cost of energy from new production facilities. The formula for this analysis is:

$$CCE = \frac{CRR\ [P + M(UPW)]}{ES}$$

where

CCE is the cost of conserved energy;
CRR is the capital recovery rate;
P is the purchase and installation cost of the investment;
M is the value of the yearly maintenance and repair costs;
UPW is the uniform present worth factor; and
ES are the energy savings resulting from the investment.

The capital recovery rate is a discount factor that allows one to annualize the cost of an investment made over a certain number of years. The factor is based upon a real discount rate and an amortization period. The formula for the capital recovery rate is:

$$CRR = \frac{D}{[1 - (1 + D)^{-N}]}$$

where

D is the discount rate; and
N is the number of discounting periods.

The cost of conserved energy is a useful tool because it is independent of energy costs and their associated uncertainties. As long as one knows the cost of utility supplied energy at the present or some future date, an energy price escalation rate need not be assumed (it is, however, useful to know this rate in order to determine at what point the cost of conserved energy is less than the cost of utility-supplied energy).

APPENDIX D - ASSUMPTIONS FOR ENERGY AND ECONOMIC ANALYSIS OF HEAT EXCHANGERS

A large number of assumptions were required for the energy and economic analysis of the heat exchangers. We utilized the air exchange rates with and without mechanical ventilation from Table 7, the fan power requirements from Table 3, and the heat exchanger effectiveness corrected for imbalance and fan heat from Table 13. For houses #6 and #49, no data on heat exchanger effectiveness was available, and we utilized the average effectiveness measured in the other houses with the same type of heat exchanger (67%). An indoor temperature of 72°F and a balance point temperature of 61°F were assumed (see section H). For houses #1, #33, #45, and #52, based upon the fan configuration (see Table 3), we assumed that 50% of the electrical energy consumed by the fans was delivered to the house in the form of heat. For the remaining houses, we assumed that 75% of this electrical energy consumption was delivered to the residence. For the analysis, we considered only the time period from October 31 through May 31 when the majority of the heating load occurs and we assumed that the heat exchangers operated continuously during this period. To perform the calculations, long term average weather data from the U.S. Department of Commerce for the Rochester Airport was utilized. This weather data lists on a monthly basis, the number of hours that the outside temperature falls within consecutive 5 °F temperature bins.

In addition to the energy related assumptions discussed above, a number of assumptions were required for the economic analysis. We utilized the heat exchanger purchase prices and installation costs from Table 3 and assumed a $200 incremental capital cost for construction of a low infiltration residence, an estimate provided by the home builder. A real discount rate of 5% and initial fuel prices of 0.50 per therm for natural gas and $0.05 per kilowatt hour for electricity were utilized (see Appendix C). For fuel price escalation rates, year-by-year projections by the National Energy Policy Plan that are described by Fisk and Turiel (1982) were utilized. To perform the economic analysis we also had to make assumptions for the efficiencies of the heating systems. For homes with natural gas heating, a 70% furnace efficiency was assumed and for homes with electric heat we assumed a 100% efficiency.

Some of the assumptions for this analysis are potentially a significant source of error. The heat exchanger effectiveness from Table 13 may not be representative for the entire year because freezing in the heat exchanger core could substantially reduce the effectiveness during cold weather. (Heat exchangers with freeze protection systems are commercially available; however, exchangers used for this study had no freeze protection or their freeze protection system was not utilized.) Also, the long term average effectiveness of heat exchangers under actual operating conditions is not well known. Other potentially significant sources for error are: (1) assuming that the increase in air exchange rates indicated on Table 7 are representative for the entire heating season, (2) the assumption of continuous heat exchanger operation, (3) the use of a 5% real discount rate, and (4) the fuel price escalation rates. A sensitivity analysis for many of these assumptions is described by Fisk and Turiel (1982) and indicates a high degree of sensitivity.

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Figure 28 Oblique view of the Automatic Dichotomous Air Sampler with side panels removed.

Table 1. Indoor air pollution in residential buildings

SOURCES	POLLUTANT TYPES
OUTDOOR	
Stationary Emissions	SO_2NO, NO_2, O_3, Hydrocarbons, CO, Particulates
Motor Vehicles	CO, Pb, NO, NO_2, Particulates
INDOOR	
Building Construction Materials	
Concrete, stone	Radon and other radioactive elements
Particleboard	Formaldehyde
Insulation	Formaldehyde, Fiberglass
Fire Retardant	Asbestos
Adhesives	Organics
Paint	Mercury, Organics, Pb
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	H_2O, CO_2, NH_3, Organics, Odors
Human Activities	
Tobacco smoke	CO, NO_2, HCN, Organics, Odors, Particulates
Aerosol spray devices	Fluorocarbons, Vinyl Chloride, CO_2
Cleaning and cooking products	Hydrocarbons, Odors, NH_3
Hobbies and crafts	Organics

Table 2. Physical characteristics of ten occupied houses in Rochester, New York.

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)
#1	1977	467	2.4	2	1	0	none	0
#6	1977	402	2.8	2	3	pipe	WS (not used)	0
#10	1976	357	1.4	2	0	5	none	0
#33	1979	496	2.5	2	2	0	FP, GD, GF GS, GW	<1
#37	1974	411	5.4	2	2	5	GF, GW	0
#45	1979	650	2.0	2	3	20	FP, GF, GW	<1
#49	1973	425	3.5	2	2	25	GF, GS, GW	0
#52	1980	357	1.4	2	1	0	none	17.7
#56	1981	360	3.2	2	3	0	GD, GF, GS, GW	10.2
#60	1979	493	2.7	2	2	0	GF, GW	7.0

[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 3. Physical characteristics of residential air-to-air heat exchangers installed in nine houses in Rocehster, New York.

House I.D.	Manufacturer	Model#	Core Type	Core Material	Flow Configuration	Fan[a] Configuration	Fan[b] Power (Watts)	Retail Cost $ (1981)	Installation Cost $ (1981)
1	Flakt	RDAA-1-3-1	sensible	aluminum	cross	e-draw s-draw	150	900[d]	341
6	Des Champs	79M.4-RU	sensible	aluminum	counter	e-draw s-blow	180	445	442
10	Des Champs	79M.4-RU	sensible	aluminum	counter	e-draw s-blow	180	445	395
33	Flakt	RDAA-1-3-1	sensible	aluminum	cross	e-draw s-draw	150	900[d]	653
45	Mitsubishi	LGH-50R2	sensible/ latent	treated paper	cross	e-draw s-draw	220	1400	474
49	Des Champs	79M.4-RU	sensible	aluminum	counter	e-draw s-blow	180	445	525
52	Mitsubishi	VL-1500	sensible/ latent	treater paper	cross	e-blow s-blow	56 high[c] 40 med.	330	191[e]
56	Des Champs	79M.4-RU	sensible	aluminum	counter	e-draw s-blow	180	445	252
60	Des Champs	79M.4-RU	sensible	aluminum	counter	e-draw s-blow	180	445	698

[a](e) exhaust fan, (s) supply fan, (draw) fan draws air through core, (blow) fan blows air through core.

[b]Fan power data from manufacturer's published literature.

[c]Fan power for high and medium (med.) fan speeds.

[d]This unit not currently distributed in the U.S. The retail cost of similar units available in the U.S. is approximately $900.

[e]Cost of temporary window installations of two units.

Table 4. Summary of specific leakage areas and predicted infiltration rates for three groups of houses in Rochester, New York.

Group	Sample Size	Average Specific Leakage Area[a] (cm^2/m^2)	Predicted[b] Average Heating Season (Nov.-Mar.) Infiltration Rate (ach)
Pre-1976 Ryan	12	5.5	0.97
Post-1976 Ryan	35	2.8	0.47
Schantz	11	2.9	0.48

[a]Calculated from leakage area measurements made at each house using the fan pressurization technique.

[b]Predicted average heating season infiltration rates calculated from a model of infiltration developed at LBL using the measured leakage areas of each house and monthly averaged weather data.

Table 5. Air leakage sites most commonly observed during pressurization tests of 58 Rochester, New York houses.

Leakage Site	Description
Windows	In all the houses tested, some leakage was observed around windows.
Doors	All hinged doors tested had good weather stripping and were not large leakage sites. Large leaks were found around some sliding glass patio doors.
Fireplaces	Even with the flue sealed, significant leaks were found around the edges of both pre-built and masonry fireplaces.
Attic hatches	Large cracks were found on some attic hatches prior to sealing.
Electrical outlets and light switches	Some leakage was observed around outlets and switches on both interior and exterior walls.
Dryer vents	Often not sealed around edges.
Baseboard	Unsealed gaps between the bottom of the drywall and the top of the floor deck were observed.
Structural members	Steel beams or other structural member may pass from basement through unsealed opening to garage or other unconditioned space.
Stairway walls	Openings into wall cavities were found under stairways, providing a leakage path to attic.
Ring joist	Some leakage was found at joints between foundation, sill plate, ring joist, and floor deck.
Laundry chutes and plumbing vents	May provide direct leakage path to attic.
Heating ducts in unconditioned spaces	Significant leakage was observed.
Gas appliance exhaust flue	A significant leakage area.
Gas, water, and electrical services; air conditioning and heat pump lines.	Some leakage observed where service pipes penetrated the building envelope.

Table 6. Energy performance measurements of 28 post-1976 Rochester houses.

House ID	Floor Area (m^2)	K ($W/^{o}C\text{-}m^2$)	T_{bal} (^{o}C)	R^2	Heating System[a]
1	185	1.22	14.6	.94	EFA
2	185	0.91	18.6	.98	EFA
3	186	1.12	13.9	.94	EFA
4	207	0.89	16.0	.90	HP
5	203	0.89	15.1	.97	HP
7	175	0.94	15.7	.90	HP
8	189	1.08	16.7	.99	EFA
9	279	0.74	16.3	.96	EFA
10	168	1.02	15.3	.98	EFA
11	186	0.79	18.9	.88	HP
12	251	0.95	17.2	.99	EFA
13	186	0.99	13.0	.99	EFA
14	256	0.84	16.3	.96	EB
15	188	0.99	13.9	.93	EFA
22	258	0.69	18.6	.95	GFA
23	216	0.75	14.8	.99	GFA
24	171	0.91	16.4	.94	GFA
25	193	0.86	18.9	.98	GFA
26	193	1.30	16.6	.95	GFA
29	190	0.89	15.7	.87	GFA
30	204	0.92	16.7	.97	GFA
32	186	0.79	19.1	.98	GFA
35	177	0.92	17.6	.95	GFA
40	175	1.18	17.8	.99	GFA
47	151	1.20	16.5	.85	GFA
52	164	0.81	15.1	.85	EB
53	204	1.08	16.0	.97	HP
55	204	0.79	14.8	1.00	GFA

[a]Key: (EB) electric baseboard, (EFA) electric forced air, (GFA) gas forced air, (HP) heat pump forced air.

Table 7. Energy performance measurements of 11 pre-1976 Rochester houses.

House ID	Floor Area (m^2)	K ($W/^oC-m^2$)	T_{bal} (^oC)	R^2	Heating[a] System
37	186	1.31	15.5	.98	CFA
38	251	0.94	16.6	.98	CFA
39	283	1.16	16.9	.97	CFA
42	344	0.85	16.3	.97	CFA
43	178	1.43	17.5	.96	CFA
48	265	1.42	15.9	.92	CFA
50	251	1.12	15.3	.96	CFA
51	195	1.84	17.1	.96	CFA
54	181	1.58	16.0	.98	CFA
57	177	1.77	16.1	.93	CFA
58	130	1.26	14.2	.87	CFA

[a]Key: (EB) electric baseboard, (EFA) electric forced air,
(CFA) gas forced air, (HP) heat pump forced air.

Table 8. 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	Predicted[b] Infiltration rate (ach)	Air-exchange[c] rate (ach)	Rn[d] Indoor (pCi/l)	HCHO[e] Indoor/Outdoor (ppb)		RCHO[e] Indoor/Outdoor (ppb)		NO_2[d] Indoor/Outdoor (ppb)		Relative Humidity[d] Indoor (%)
#1	12/7-15	0.37	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	0.42	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	0.23	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	0.42	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	0.92	1.17 ± .65	0.0	17	<5	26	<5	6	11	29
#45	11/13-20	0.38	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	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	0.22	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	0.56	0.50 ± .13	0.2	f	<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	0.47	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] Predicted infiltration rates calculated from a model of infiltration developed at LBL using the measured leakage areas of each house and monthly averaged weather data.

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

[d] 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).

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

[f] No HCHO for this period.

Table 9. 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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Table 10. Measurements of indoor and outdoor CO_2, CO, NO, SO_2, and O_3 at Rochester house #6.

		Sampling Location			
Parameter	Heat Exchanger	Outdoors	Kitchen	Master Bedroom	Family Room
CO_2 (ppm)	OFF	309 ± 12	810 ± 188	876 ± 204	807 ± 200
	ON	280 ± 9	535 ± 129	607 ± 174	522 ± 129
CO (ppm)	OFF	0.5 ± 0.4	0.9 ± 0.5	0.8 ± 0.5	0.8 ± 0.5
	ON	0.3 ± 0.2	0.4 ± 0.3	0.4 ± 0.2	0.4 ± 0.3
NO (ppb)	OFF	6 ± 14	16 ± 16	16 ± 16	17 ± 18
	ON	1 ± 5	3 ± 5	3 ± 5	3 ± 5
SO_2 (ppb)	OFF	12 ± 12	2 ± 2	3 ± 2	3 ± 3
	ON	7 ± 6	3 ± 5	4 ± 5	4 ± 5
O_3 (ppb)	OFF	4 ± 5	3 ± 2	3 ± 5	3 ± 2
	ON	10 ± 9	3 ± 3	2 ± 2	4 ± 1

Table 11. Measurements of indoor and outdoor CO_2, CO, NO, SO_2, and O_3 at Rochester house #49.

Parameter	Heat Exchanger	Sampling Location: Outdoors	Kitchen	Master Bedroom	Family Room
CO_2 (ppm)	OFF	312 ± 19	754 ± 251	759 ± 220	711 ± 238
	ON	302 ± 10	656 ± 251	659 ± 206	630 ± 224
CO (ppm)	OFF	0.4 ± 0.4	1.5 ± 1.3	1.3 ± 1.1	1.3 ± 1.1
	ON	0.3 ± 0.2	1.4 ± 1.2	1.3 ± 1.0	1.2 ± 1.0
NO (ppb)	OFF	3 ± 15	42 ± 45	36 ± 37	35 ± 40
	ON	1 ± 5	41 ± 51	31 ± 42	33 ± 45
SO_2 (ppb)	OFF	12 ± 9	4 ± 8	4 ± 4	4 ± 6
	ON	4 ± 8	3 ± 7	3 ± 4	3 ± 6
O_3 (ppb)	OFF	15 ± 21	10 ± 21	9 ± 22	10 ± 22
	ON	11 ± 7	4 ± 3	3 ± 2	3 ± 3

Table 12. Measurements of indoor and outdoor particulate mass in Rochester house #6.

	Heat Exchanger[b]	Indoor ($\mu g/m^3$)	Outdoor ($\mu g/m^3$)	Ratio[c]
Fine Fraction (<2.5 μ)	OFF	54 ± 18	19 ± 11	3.91 ± 2.28
	ON	31 ± 17	9 ± 5	3.89 ± 2.66
Total Mass (< 15 μ)	OFF	76 ± 22	28 ± 14	3.61 ± 1.91
	ON	49 ± 22	13 ± 5	4.16 ± 2.46
Elements (Fine particulate fraction only)				
		(ng/m^3)	(ng/m^3)	
Sulfur	OFF	1034 ± 433	2918 ± 1763	0.39 ± 0.16
	ON	952 ± 422	1663 ± 907	0.62 ± 0.14
Lead	OFF	42 ± 17	148 ± 97	0.32 ± 0.12
	ON	33 ± 10	66 ± 31	0.55 ± 0.18
Bromine	OFF	16 ± 6	37 ± 27	0.59 ± 0.32
	ON	11 ± 4	16 ± 8	0.76 ± 0.32
Zinc	OFF	178 ± 544	39 ± 14	3.88 ± 11.29
	ON	71 ± 149	20 ± 14	4.04 ± 6.68
Iron	OFF	65 ± 61	136 ± 91	0.52 ± 0.31
	ON	37 ± 23	59 ± 36	0.72 ± 0.43
Calcium	OFF	263 ± 401	59 ± 43	4.64 ± 4.95
	ON	88 ± 35	24 ± 17	4.00 ± 2.23
Potassium	OFF	15 ± 10	7 ± 2	2.32 ± 1.70
	ON	15 ± 7	6 ± 1	2.80 ± 0.17
Copper	OFF	955 ± 410	199 ± 118	6.02 ± 3.24
	ON	596 ± 385	83 ± 28	8.52 ± 6.87
Chlorine	OFF	817 ± 949	38 ± 25	33.24 ± 51.74
	ON	396 ± 375	11 ± 14	17.76 ± 10.71

[a]Air-exchange rates:

	Average ± std dev.	range	No. of measurements
Heat Exchanger OFF:	0.38 ± 0.09	0.22 – 0.55	26
Heat Exchanger ON:	0.66 ± 0.16	0.43 – 0.96	15

[b]Sampling period: Heat Exchanger OFF – 1/9 to 1/21/1981
Heat Exchanger ON – 1/22 to 2/2/1981

[c]The indoor/outdoor ratios were calculated for each day. The value given is the average of these numbers.

Table 13. Measurements of indoor and outdoor particulate mass in Rochester house #49.

	Heat Exchanger[b]	Indoor ($\mu g/m^3$)	Outdoor ($\mu g/m^3$)	Ratio[c]
Fine Fraction	OFF	38 ± 14	14 ± 7	3.93 ± 3.92
(< 2.5 μ)	ON	30 ± 12	6 ± 2	5.51 ± 4.19
Total Mass	OFF	52 ± 22	20 ± 11	4.47 ± 5.96
(< 15 μ)	ON	43 ± 18	6 ± 2	8.11 ± 6.47
Elements (Fine particulate fraction only)				
		(ng/m^3)	(ng/m^3)	
Sulfur	OFF	1335 ± 417	2445 ± 1113	0.59 ± 0.18
	ON	1058 ± 499	1215 ± 712	0.93 ± 0.24
Lead	OFF	43 ± 18	104 ± 61	0.47 ± 0.12
	ON	31 ± 17	51 ± 19	0.62 ± 0.11
Bromine	OFF	20 ± 8	26 ± 17	0.91 ± 0.35
	ON	20 ± 9	12 ± 5	2.11 ± 1.34
Zinc	OFF	18 ± 7	31 ± 20	0.69 ± 0.37
	ON	9 ± 5	12 ± 7	0.82 ± 0.30
Iron	OFF	57 ± 62	120 ± 72	1.25 ± 3.38
	ON	29 ± 18	37 ± 32	1.23 ± 1.86
Calcium	OFF	122 ± 367	56 ± 33	0.21 ± 0.21
	ON	62 ± 156	5 ± 8	0.65 ± 0.60
Potassium	OFF	598 ± 411	135 ± 74	6.87 ± 7.80
	ON	414 ± 128	41 ± 28	16.98 ± 15.10
Silicon	OFF	337 ± 342	331 ± 151	1.52 ± 2.77
	ON	181 ± 135	105 ± 59	2.09 ± 1.53

[a]Air-exchange rates:

	Average ± std dev.	range	No. of measurements
Heat Exchanger OFF:	0.42 ± .11	0.21 - .61	14
Heat Exchanger ON:	0.64 ± .17	0.34 - .93	10

[b]Sampling period: Heat Exchanger OFF 2/5 to 2/19/1981
Heat Exchanger ON 2/20 to 3/2/1981

[c]The indoor/outdoor ratios were calculated for each day. The value given is the average of these numbers.

Table 14. Measurements of flow rate and thermal performance of mechanical ventilation systems with air-to-air heat exchangers installed in nine Rochester, New York houses.

House I.D.	Supply air supply location flow into/out of HX (cfm)	Exhaust air exhaust location flow into/out of HX (cfm)	Mass balance[a] in/out	Balance ratio[b] supply/exhaust	Ventilation[c] efficiency	Cold stream[d] apparent sensible effectiveness		
						Uncorrected	Corrected for flow balance	Corrected for flow balance and fan heat
1	furnace return NA/107	basement NA/107	NA	1.00	0.64	0.49	0.49	0.45
6	furnace return 70/60	front hallway 116/111	1.09	0.54	0.60	NA		
10	furnace return 94/105	basement 114/112	0.96	0.94	0.59	0.84	0.79	0.68
33	furnace return 166/141	kitchen 153/160	1.06	0.88	0.73	0.69	0.61	0.57
45	furnace return 264/149	basement 237/210	0.92	0.71	0.60	0.69	0.49	0.44
49	furnace return 55/78	kitchen 119/92	1.02	0.85	0.60	NA		
52	living room (med)[e] 50/54	living room (med) 68/65	0.99	0.83	0.63	NA		
	basement (high)[e] 65/70	basement (high) 89/85	0.99	0.82		0.65	0.53	0.48
56	furnace return 117/104	basement 92/78	1.15	1.00	0.22	0.89	0.89	0.76
60	furnace return 87/90	2 upstairs bathrooms 85/98	0.91	0.92	0.56	0.79	0.73	0.57

[a]Mass flow rates of the two airstreams entering the heat exchanger (in) divided by the mass flow rates of the two airstreams leaving the heat exchanger (out).

[b]Mass flow rate of the airstream entering the house from the heat exchanger (supply out) divided by the mass flow rate of the airstream leaving the house from the heat exchanger (exhaust out).

[c]Calculated as the ratio of the average increase in air-exchange rate observed during the ventilated period to the predicted increase if there were perfect mixing of indoor air and no cross-stream transfer between supply and exhaust airstreams.

[d]Calculated from temperature measurements, made in the four airstreams (the temperature change of the cold airstream divided by the temperature difference between the cold and hot supply airstreams).

[e]Living room unit operated at medium fan speed; basement unit operated at high fan speed.

Table 15. Weatherization package economics analysis.

Amortization Period (years)	Discount Rate	Energy Escalation Rate	Cost of Conserved Energy ($/Therm)	Net Benefit ($)
	.05	.01	.108	2106
30	.05	.03	.108	2887
	.03	.02	.085	3382
	.05	.01	.134	1546
20	.05	.03	.134	1967
	.03	.02	.112	2212

Table 16. Results of energy and economic analysis of residential air-to-air heat exchangers in Rochester, New York.

House ID #	Heating System[a]	Capitol[b] Cost ($)	Heat[c] Exchanger Effectiveness (%)	Increase[d] in Ventilation (ft^3/min)	Ventilation[e] Heat Load Reduction (therms)	Fan Energy[f] Consumption (kwh)	Net Present[g] Benefit ($)	Benefit-[g] Cost Ratio	Discounted Payback Period (years)	Increase in[h] Ventilation Heat Load (therms)	Net Present Value of Costs ($)
1	E	1441	45	69	78	875	-779	0.67	>30	65	3490
6	E	1087	67	66	116	1050	243	1.11	16	21	2365
10	E	1040	68	65	116	1050	286	1.14	15	19	2273
33[j]	HP	1753	57	117	152	875	-851	0.68	>30	91	3562
	G	1753	57	117	152	875	-82	0.97	21	91	4023
45	G	2074	44	92	104	1283	-1511	0.54	>30	87	4567
49	G	1170	67	55	101	1050	-494	0.78	>30	14	2245
52	E	1051	48	95	103	560	345	1.20	14	94	3461
60[j]	HP	1343	57	55	89	1050	-1313	0.45	>30	25	2487
	G	1343	57	55	89	1050	-860	0.64	>30	25	2615

[a]E = electric heat with efficiency of 100%, HP = heat pump with C.O.P. = 1.7, G = natural gas heat with furnace efficiency of 70%

[b]Cost for purchase and installation of heat exchanger plus $200 estimated cost for house tightening features

[c]From Table 13.

[d]Increase in air-exchange rate multiplied by house volume (see Table 7).

[e]House where increase in ventilation is supplied by heat exchanger is compared to house with increase in infiltration.

[f]Electrical energy consumption by heat exchanger's fan system.

[g]20 year life for heat exchanger assumed.

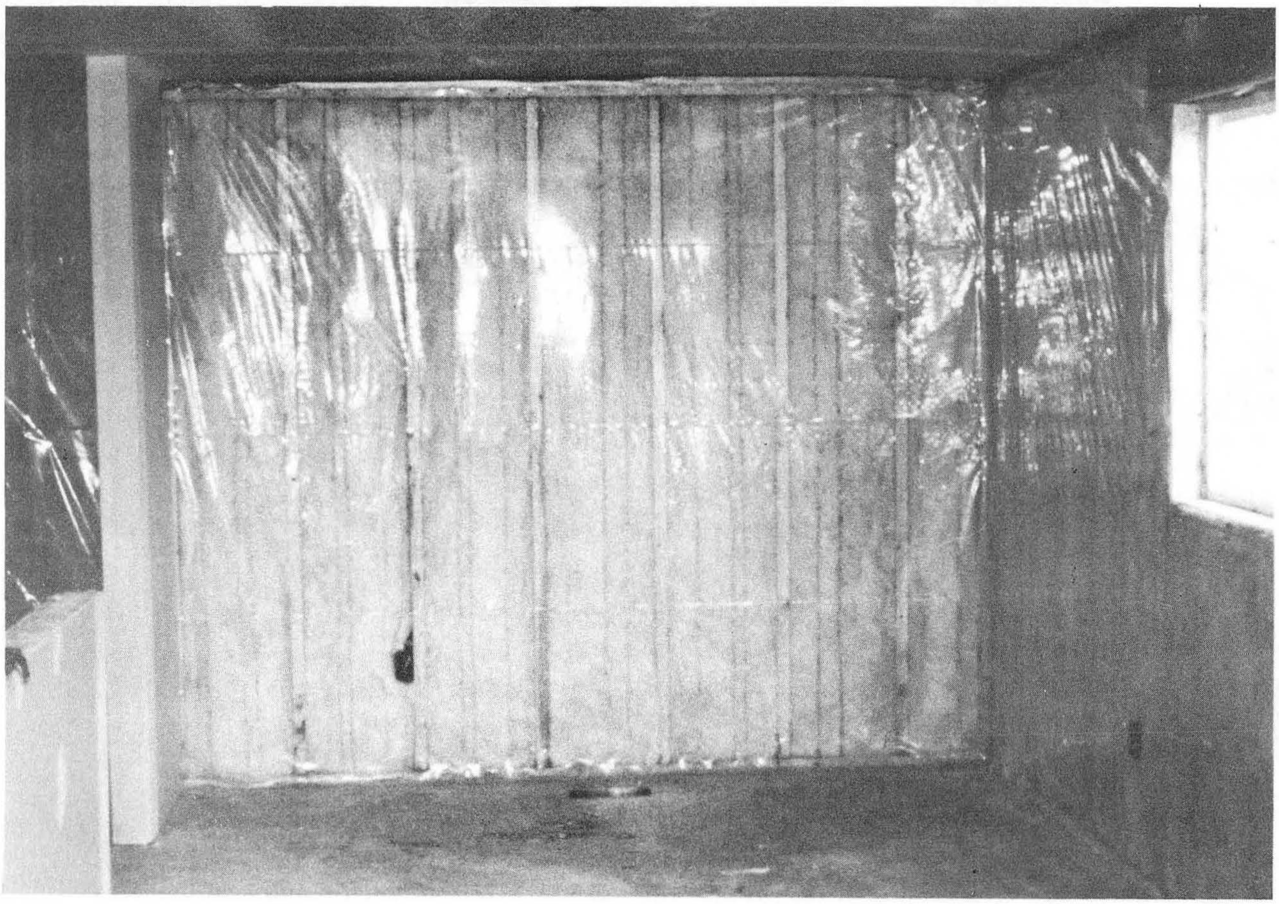
[h]House with additional ventilation supplied by heat exchanger compared to house without additional ventilation.

[i]Total cost for purchase, installation, maintenance, and operation of heat exchanger, 20 year life assumed.

[j]Home heating system is electric heat pump with natural gas assist, results are given assuming heat pump supplies all heat and assuming all heat supplied by natural gas furnace.

Table 17. **Instrumentation in the EEB Mobile Lab for Monitoring Indoor and Outdoor Air Quality Parameters**

Purpose	Method/Instrument	Manufacturer/Model
Continuous monitoring of the following parameters:		
Gases:		
CO_2	NDIR	Horiba PIR 2000
CO	NDIR	Bendix 8501-5CA
SO_2	UV fluorescence	Thermo Electron 43
NO, NO_x	Chemiluminescence	Thermo Electron 14D
O_3	UV absorption	Dasibi 1003-AH
Indoor temperature & moisture:		
Dry-bulb temperature	Thermistor	Yellow Springs 701
Relative humidity	Lithium chloride hygrometer	Yellow Springs 91 HC
Outdoor meteorology:		
Dry-bulb temperature	Thermistor	MRI 915-2
Relative humidity	Lithium chloride hygrometer	MRI 915-2
Wind speed	Generator	MRI 1074-2
Wind direction	Potentiometer	MRI 1074-2
Solar radiation	Spectral pyranometer	Eppley PSP
Infiltration	Automated controlled-flow measurement or tracer gas decay/IR absorption	LBL/Wilkes
Time-averaged monitoring of the following parameters:		
Gases:		
Radon	Electrostatic collection/ thermoluminescence	LBL
Formaldehyde/total aldehydes	Absorption (gas bubblers)/ colorimetry	LBL
Selected organic compounds	Tenax GC adsorption tubes/ GC analysis	LBL
Inhalable particulates (fine & coarse fractions)	Virtual impaction/ filtration	LBL
Data acquisition:		
	Microprocessor	Intel System 80/20-4
	Multiplexer A/D	Burr Brown Micromux Receiver MM6016 AA Remote MM6401
	Floppy disk drive	ICOM FD3712-56/20-19
	Modem	Vadic VA-317S



CBB 814-3664

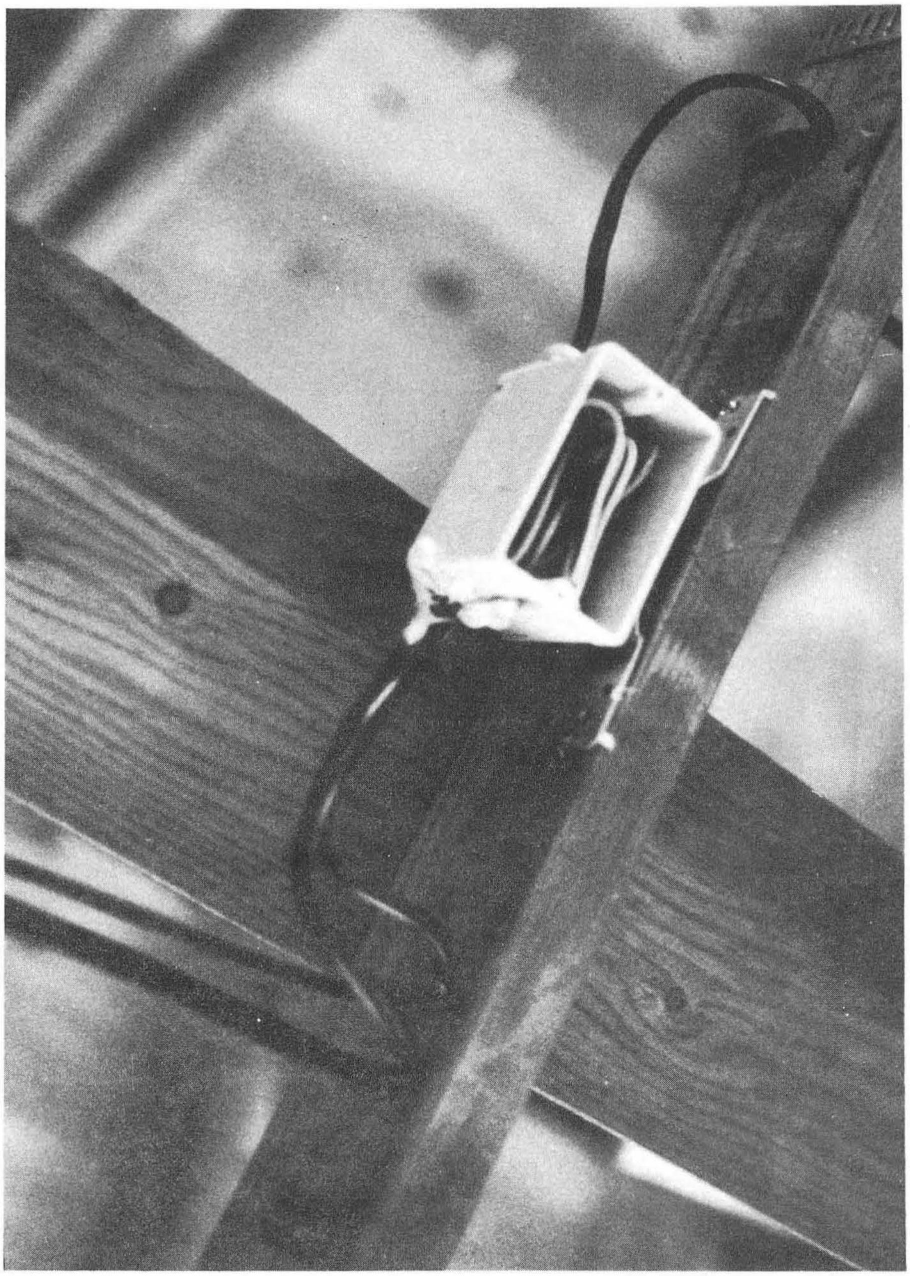
Figure 1. Photograph of a polyethylene vapor barrier installed into the stud frame of a house.

CBB 814-3668

Figure 2. Photograph of a foam gasket protruding from the joint between the sole plate and concrete foundation.

CBB 814-3696

Figure 3. Photograph of some plumbing penetrations in the process of being sealed with a polyurethane foam.



CBB 826-5295

Figure 4. Photograph of a one-piece plastic electrical conduit box installed on a joist in the ceiling of a house.

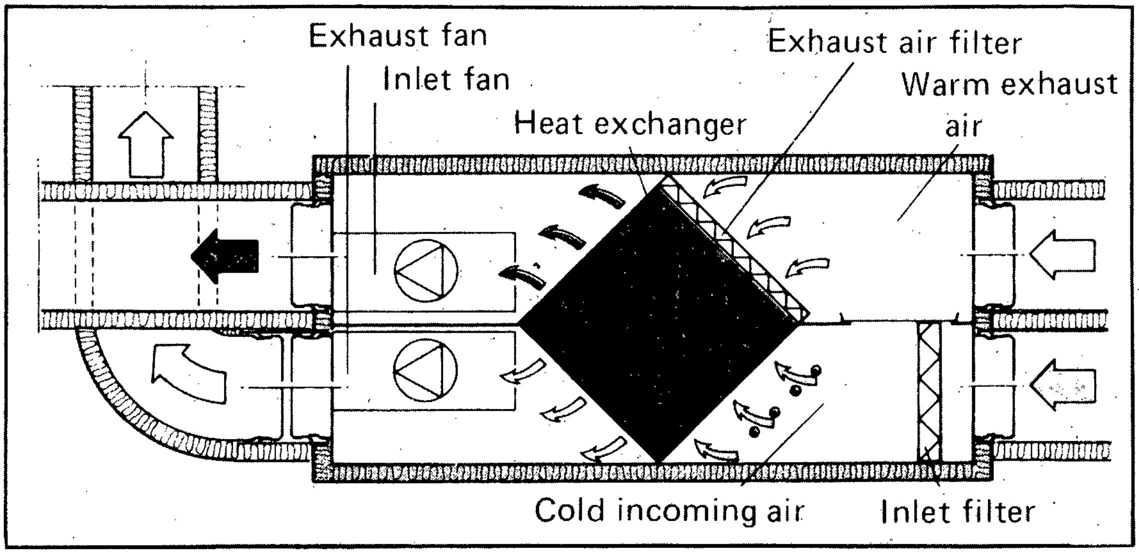
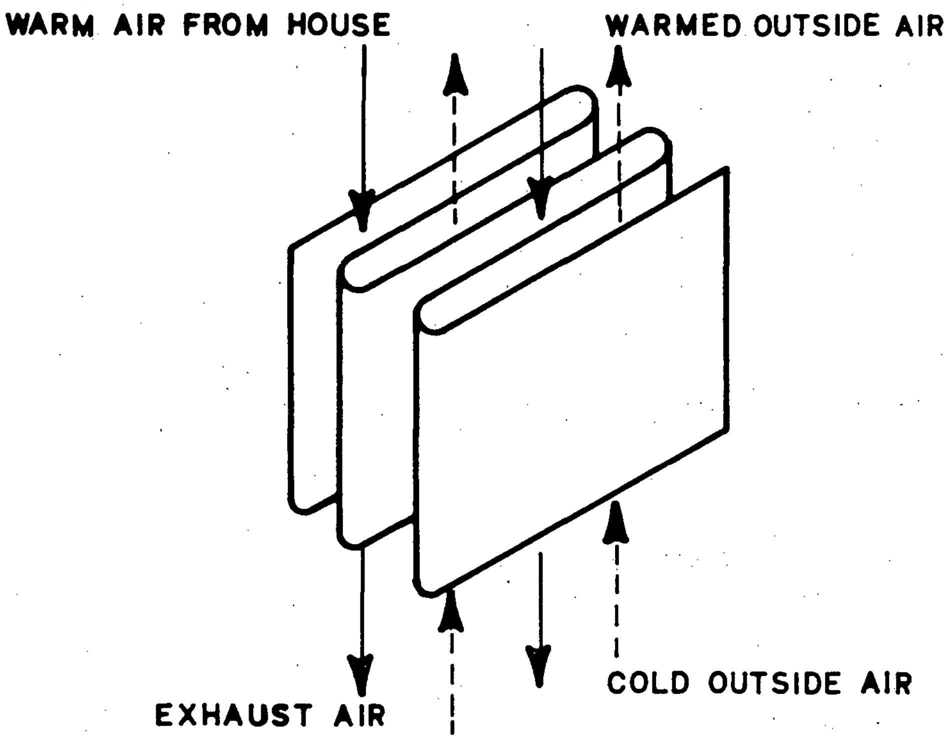
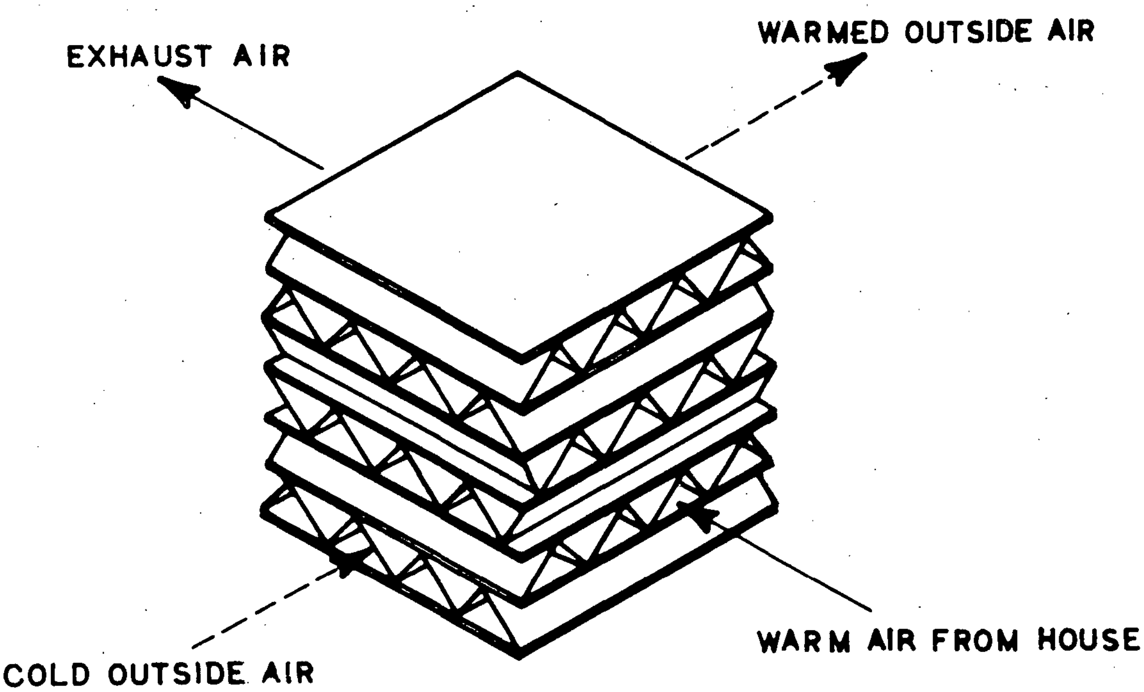


Figure 5. Schematic diagram of a mechanical ventilation system with an air-to-air heat exchanger.



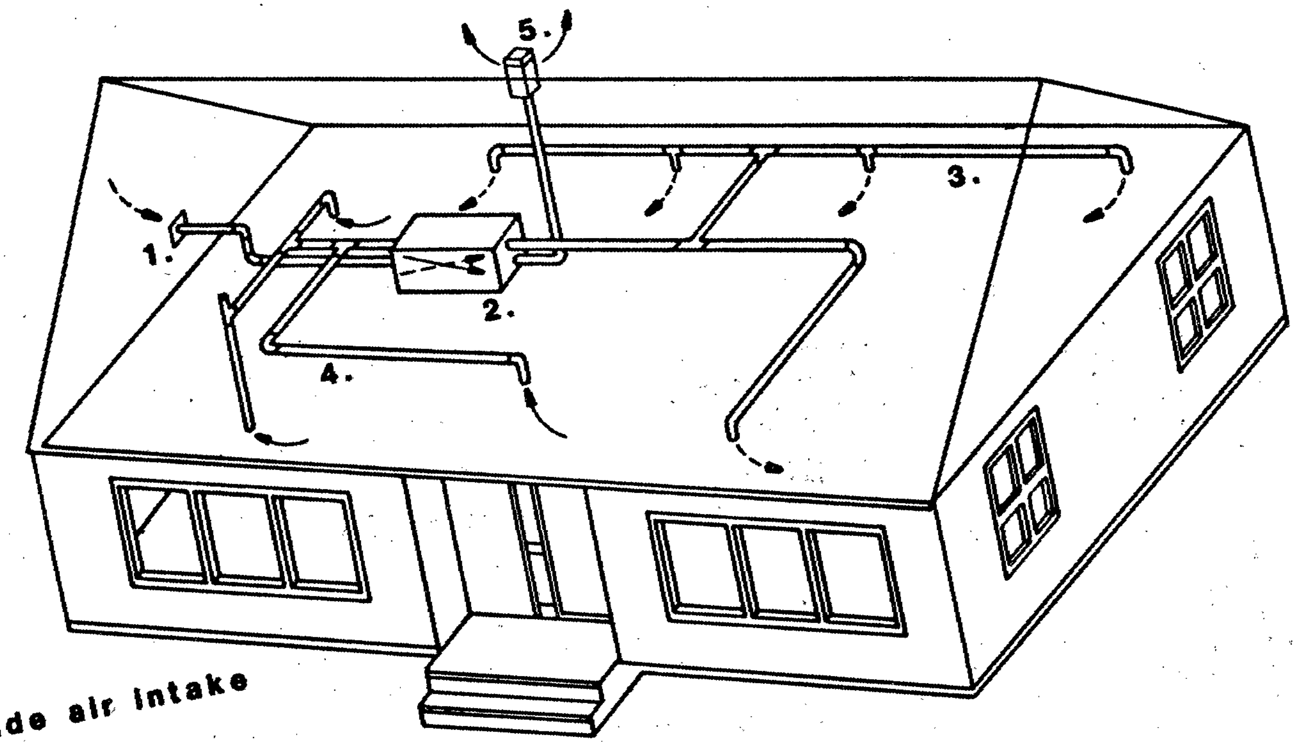
XBL 809-11957

Figure 6a. Schematic diagram of a counterflow heat exchanger core.



XBL 809-11956

Figure 6b. Schematic diagram of a crossflow heat exchanger core.



1. Outside air intake

2. Heat exchanger

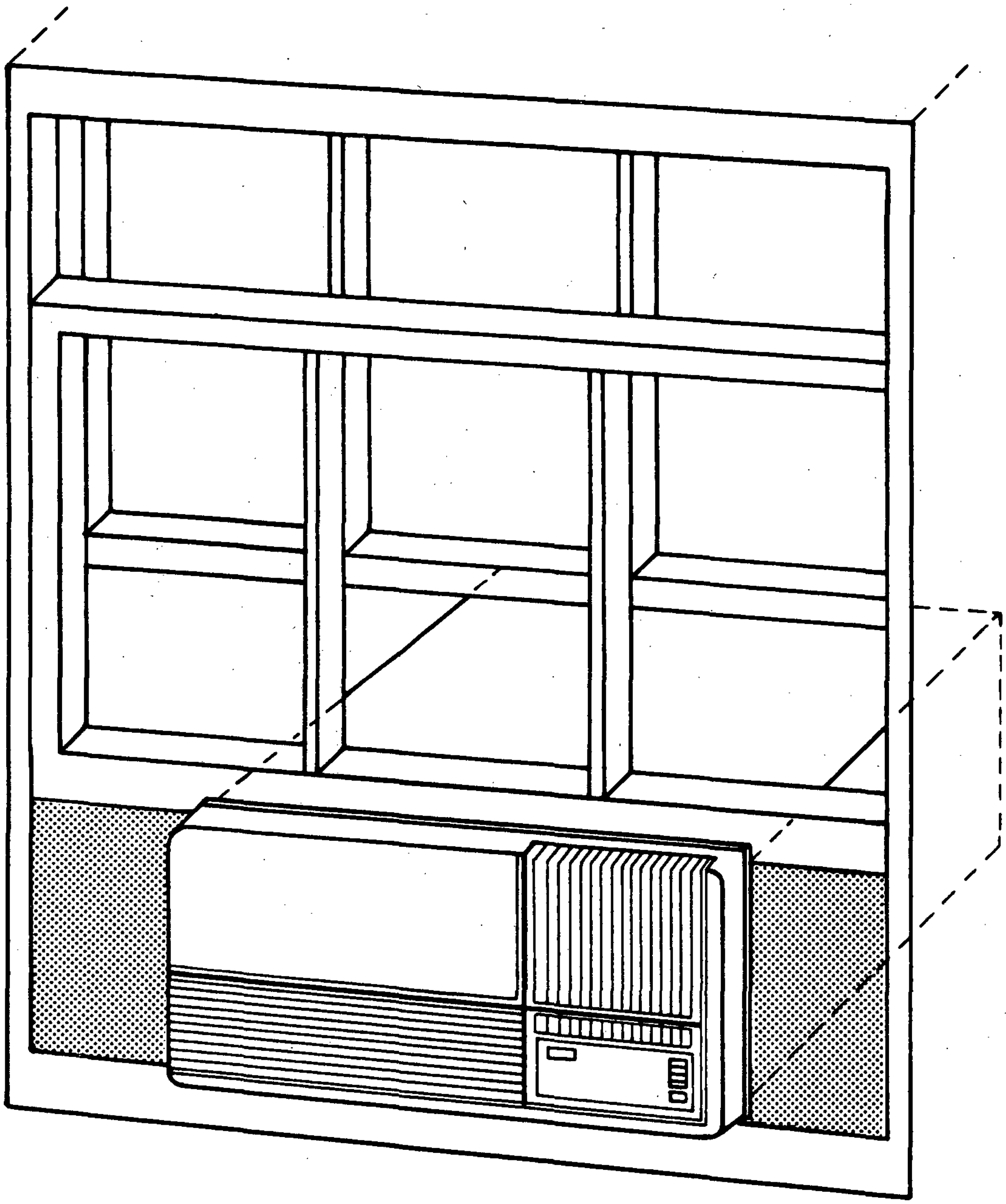
3. Air distribution duct

4. Exhaust air duct

5. Exhaust air vent

XBL 824-9286

Figure 7. Fully ducted installation of a residential mechanical ventilation system with an air-to-air heat exchanger.



XBL 824-9285

Figure 8. Window installation of a small unducted mechanical ventilation system with an air-to-air heat exchanger.

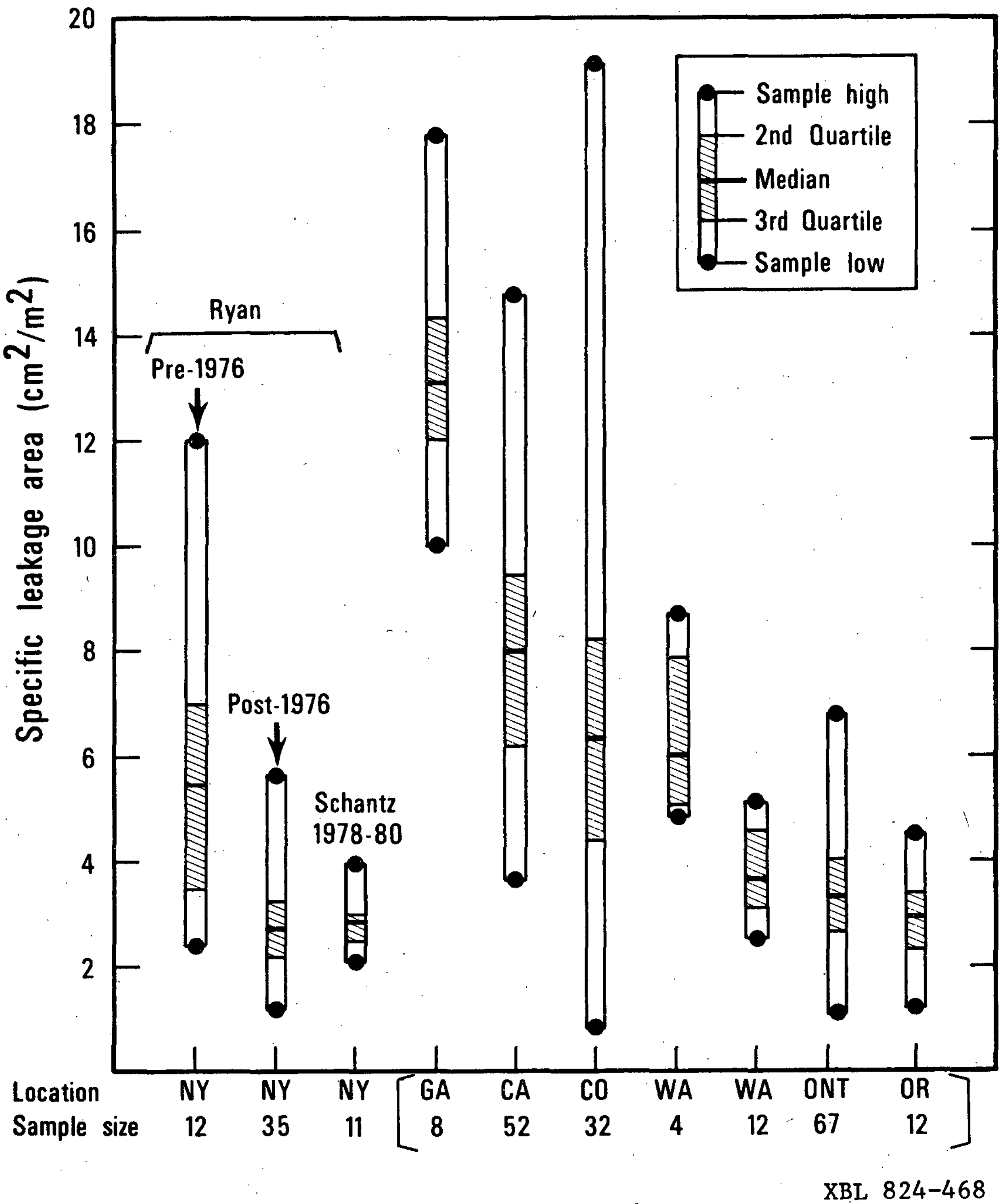
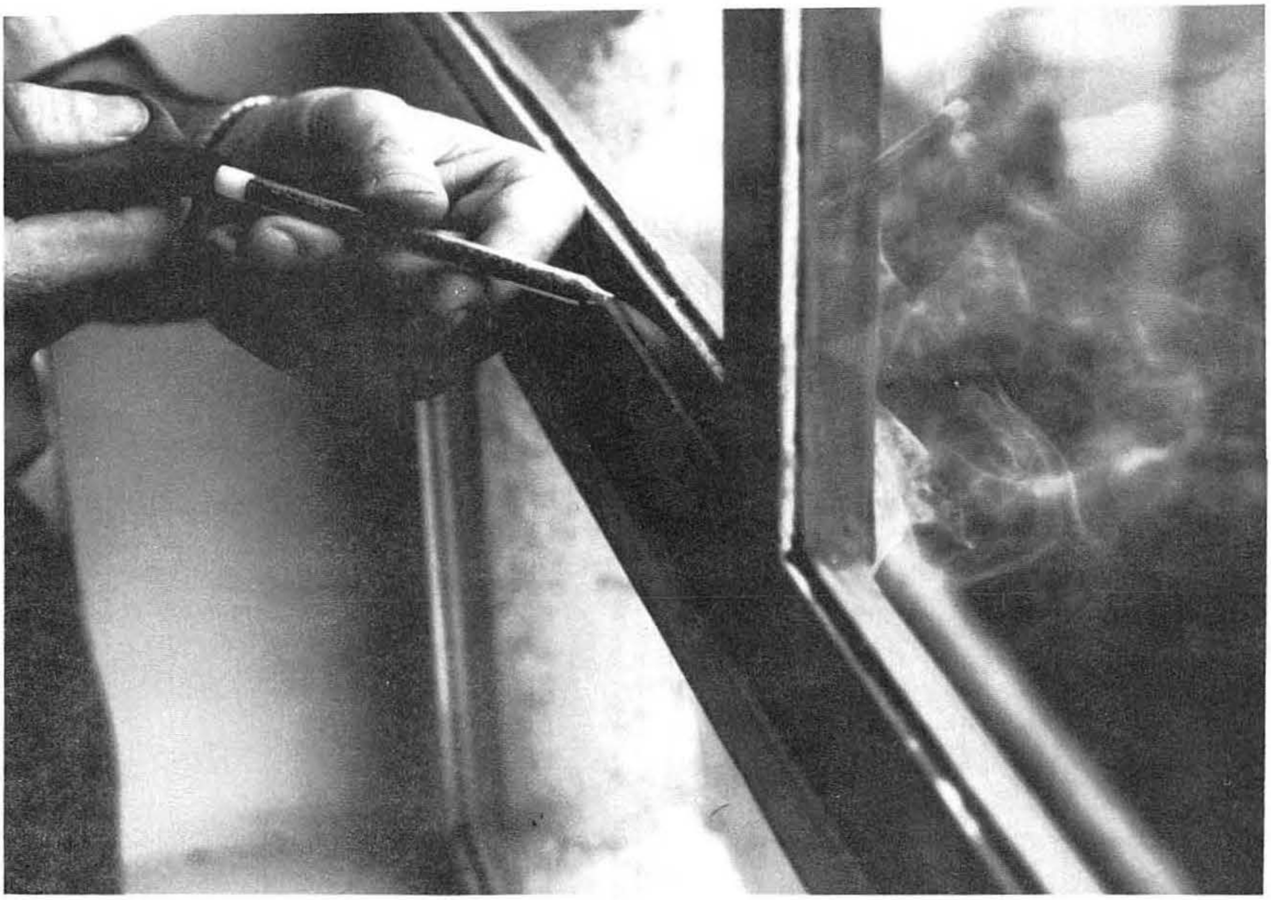
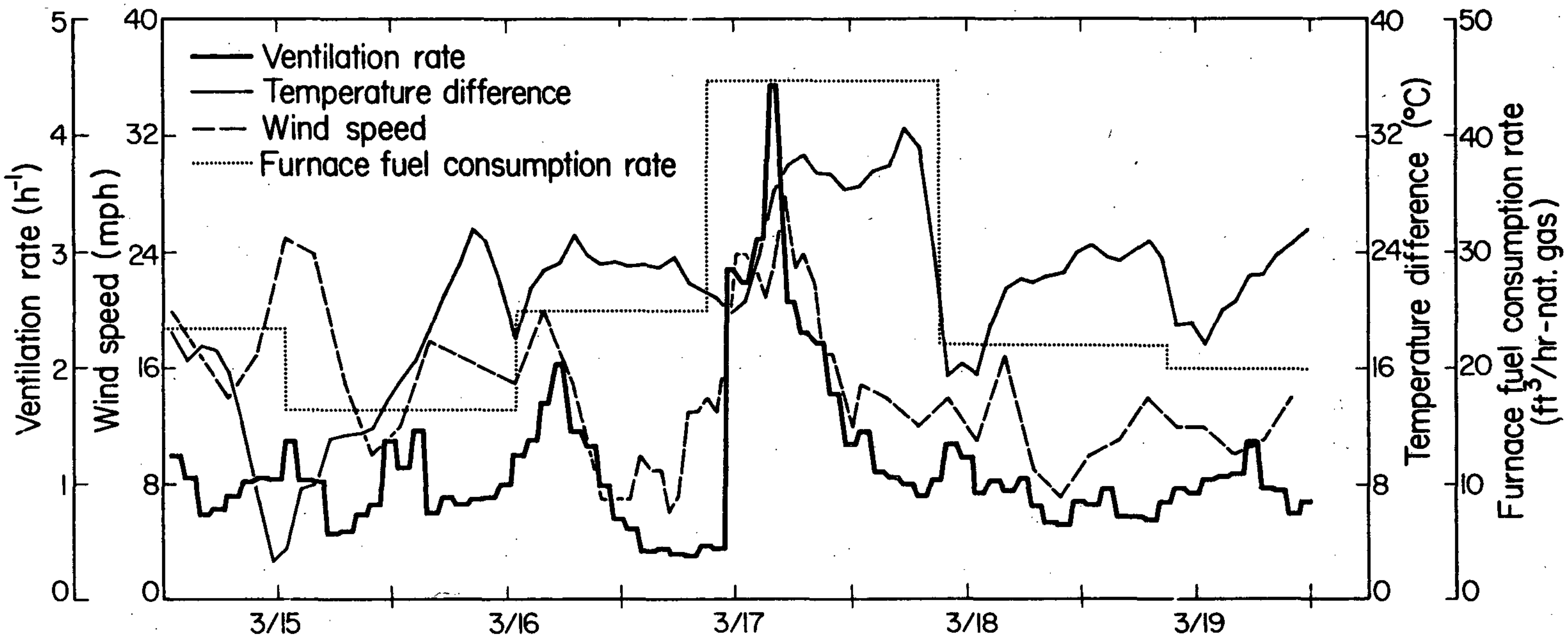


Figure 9. Comparison of specific leakage areas for three groups of houses in Rochester, N.Y. with those of other groups of houses studied in North America.



CBB 798-10925

Figure 10. Photograph of a smoke stick being used to locate the leakage sites around a window.



XBL 817-1037

Figure 11. Measurements of air-exchange rate, indoor/outdoor temperature difference, windspeed, and furnace fuel consumption versus time in Rochester house #37.

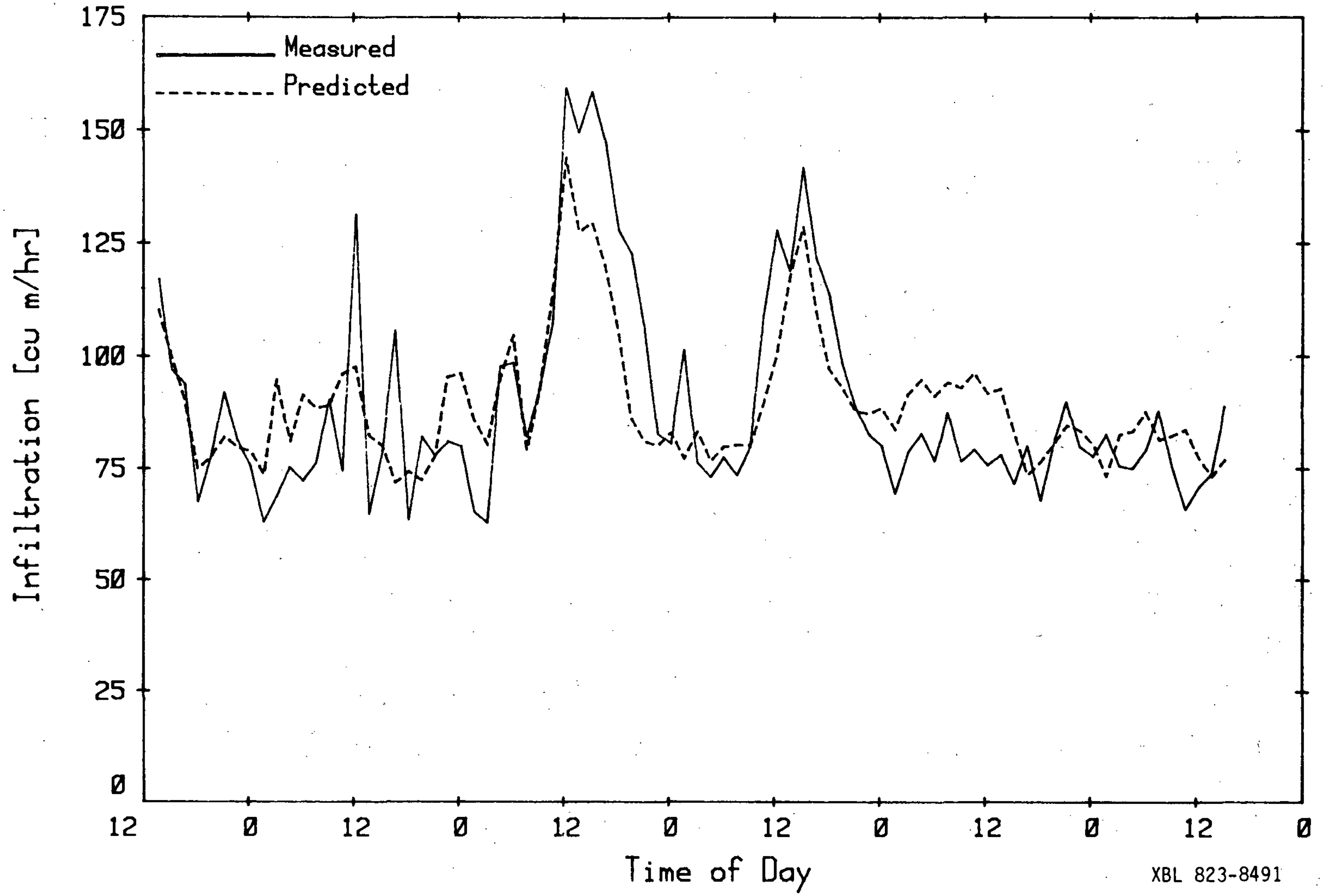


Figure 12. Comparison of measured air-exchange rate and predicted infiltration rate versus time in Rochester house #10.

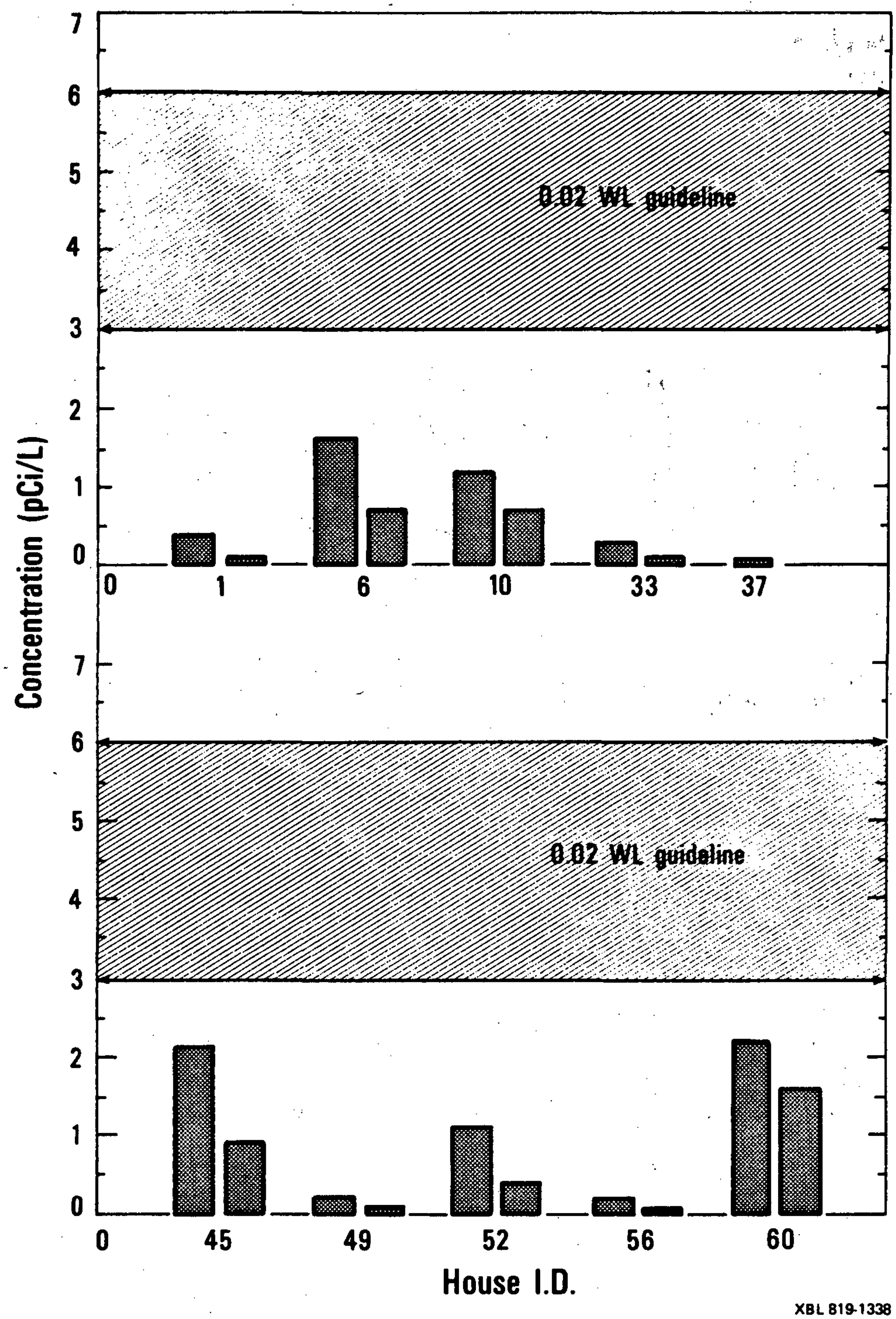


Figure 13. Average indoor concentration of radon in ten occupied houses in Rochester, N.Y. (left bar of each pair - unventilated measurement; right bar - ventilated measurement).

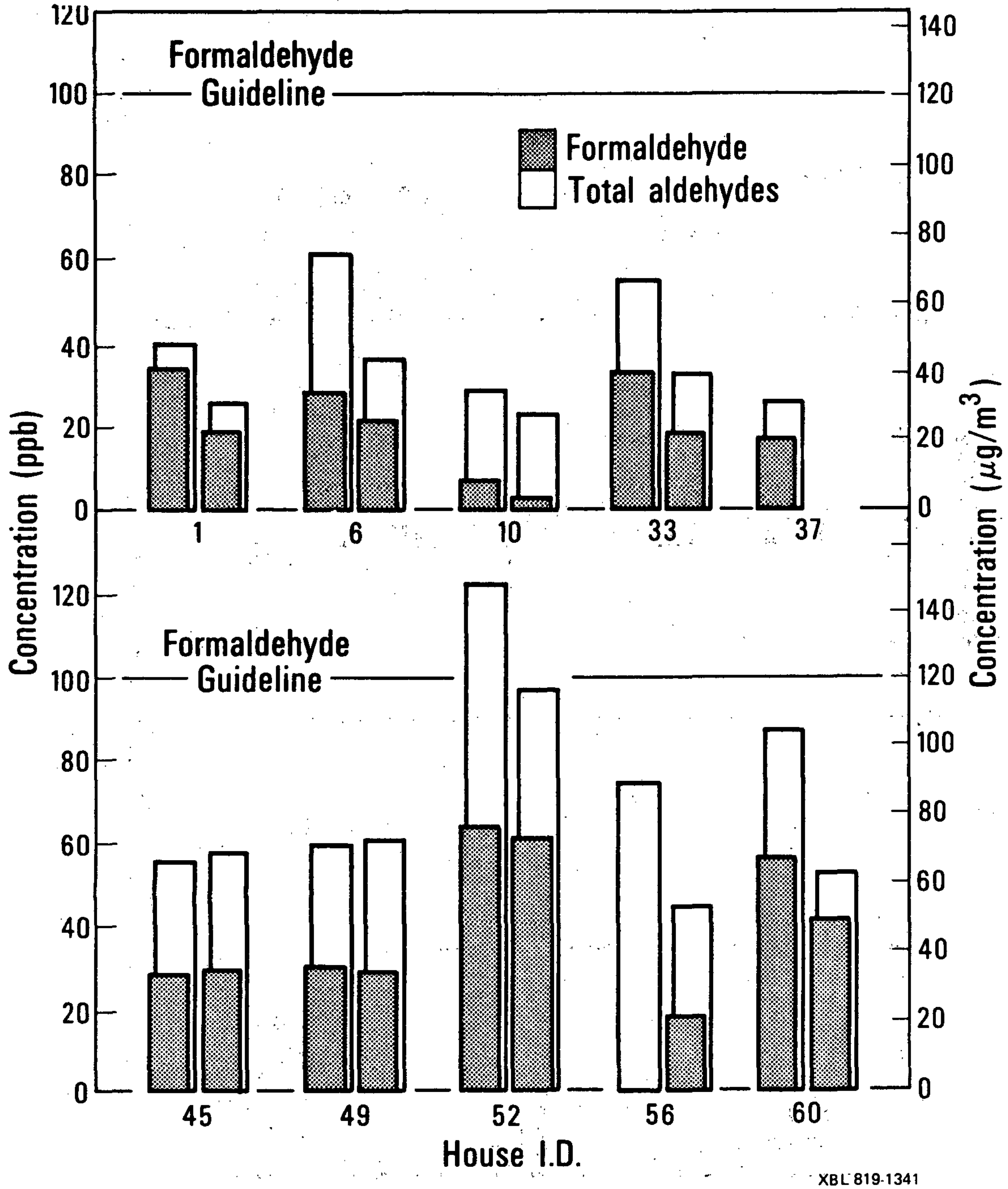


Figure 14. Average concentrations of formaldehyde and total aldehydes in ten occupied houses in Rochester, N.Y. (left bar of each pair - unventilated measurement; right bar - ventilated measurement).

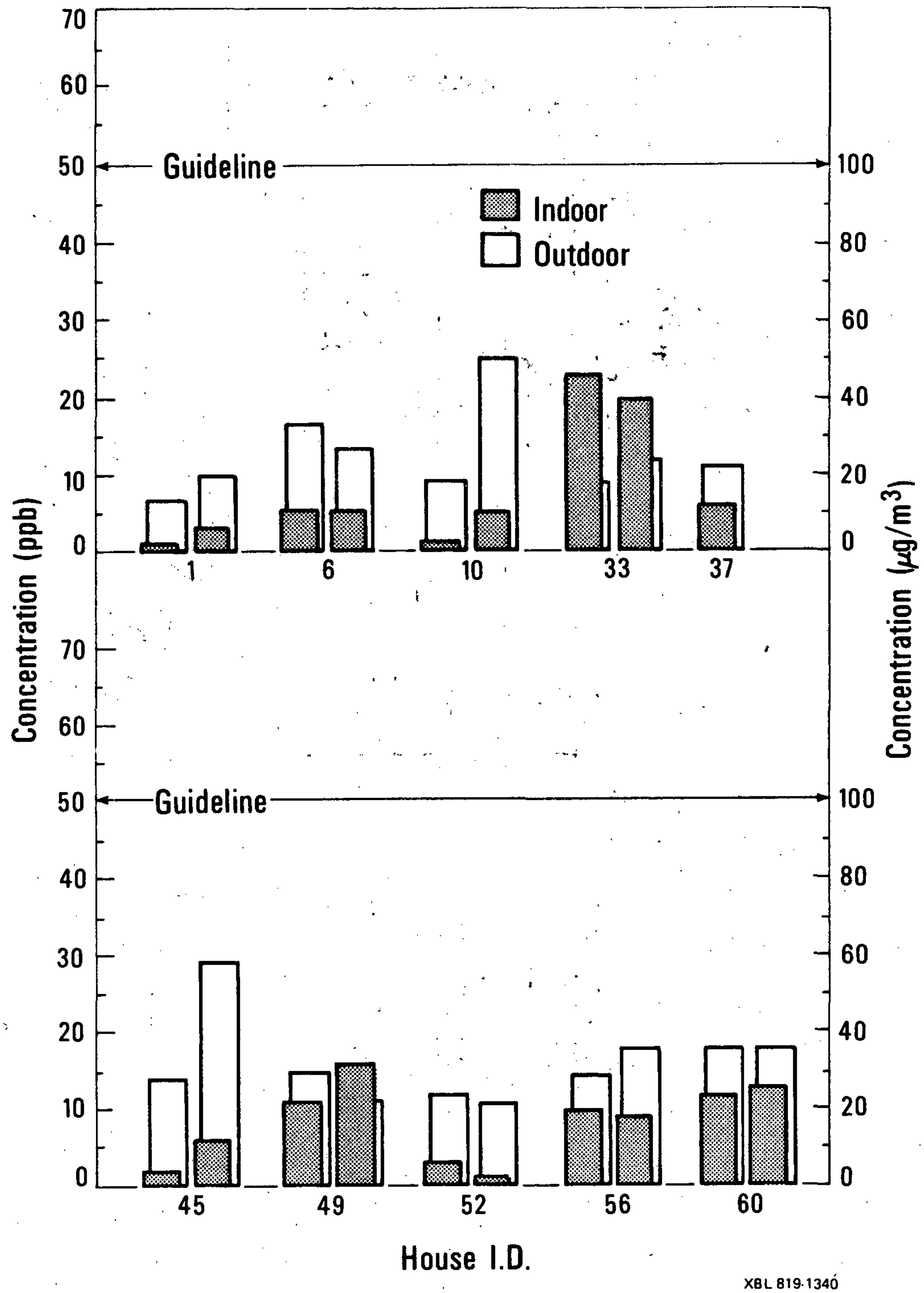


Figure 15. Average indoor and outdoor concentrations of nitrogen dioxide in ten occupied houses in Rochester, N.Y. (left bar of each pair - unventilated measurement; right bar - ventilated measurement).

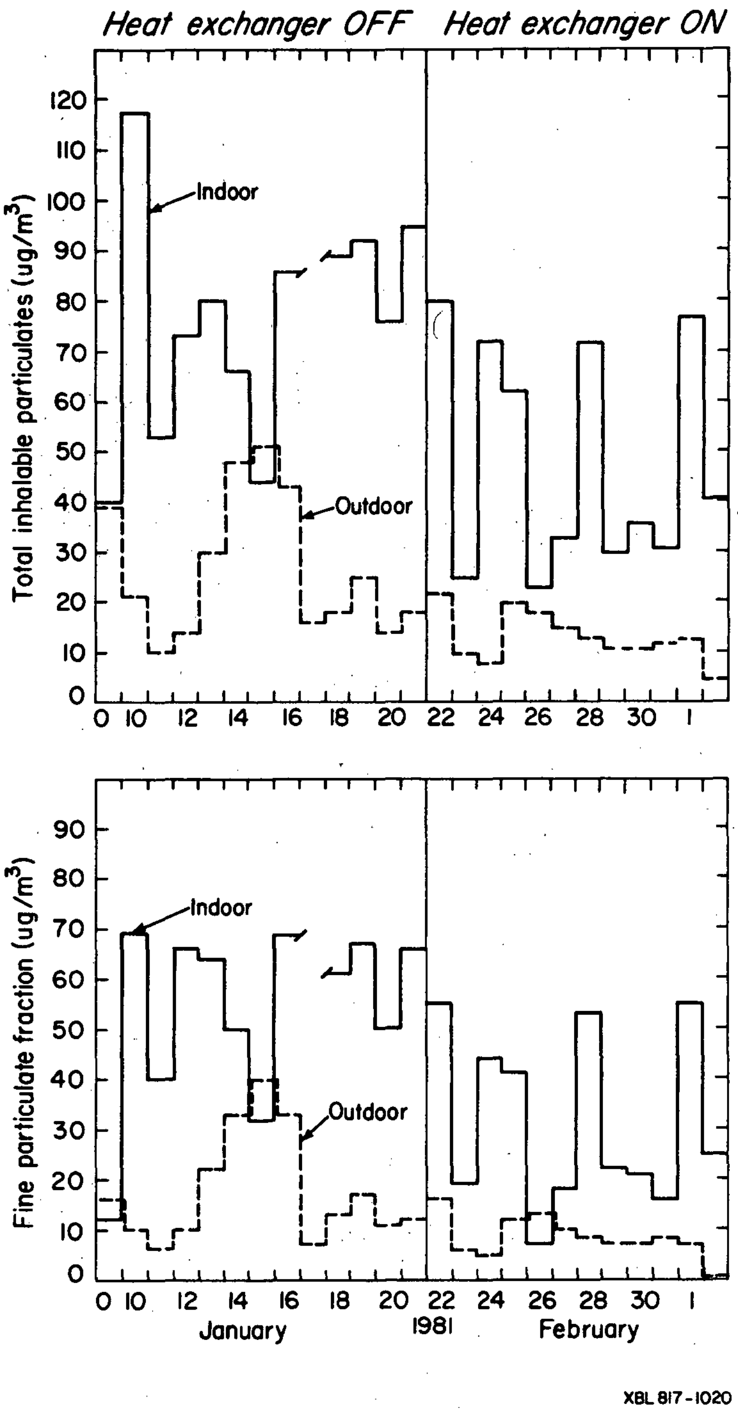


Figure 16. Indoor and outdoor concentrations of inhalable (<15 μm) and respirable (<2.5 μm) suspended particulate matter in Rochester house #6.

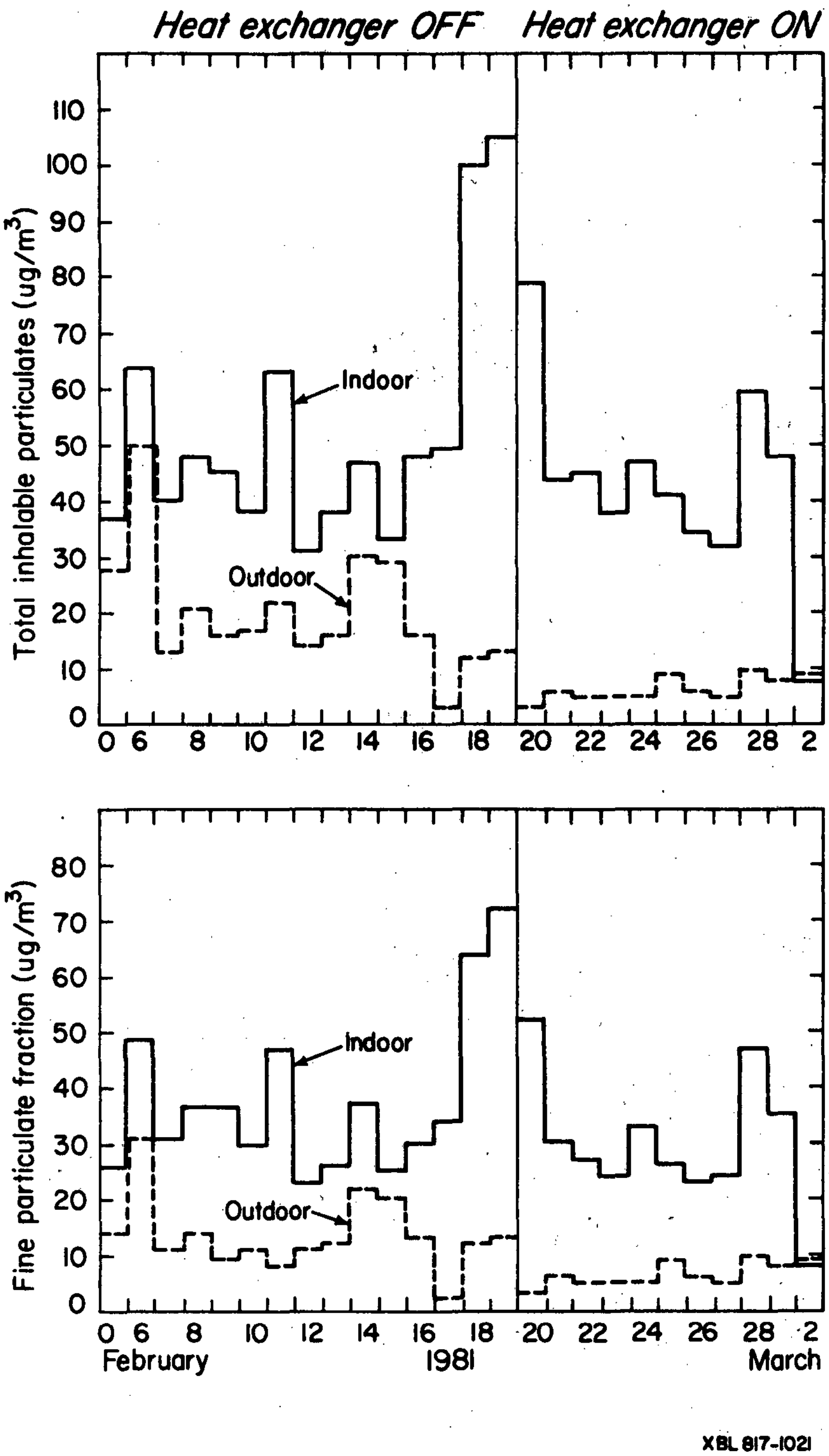


Figure 17. Indoor and outdoor concentrations of inhalable (<15 μm) and respirable (<2.5 μm) suspended particulate matter in Rochester house #49.

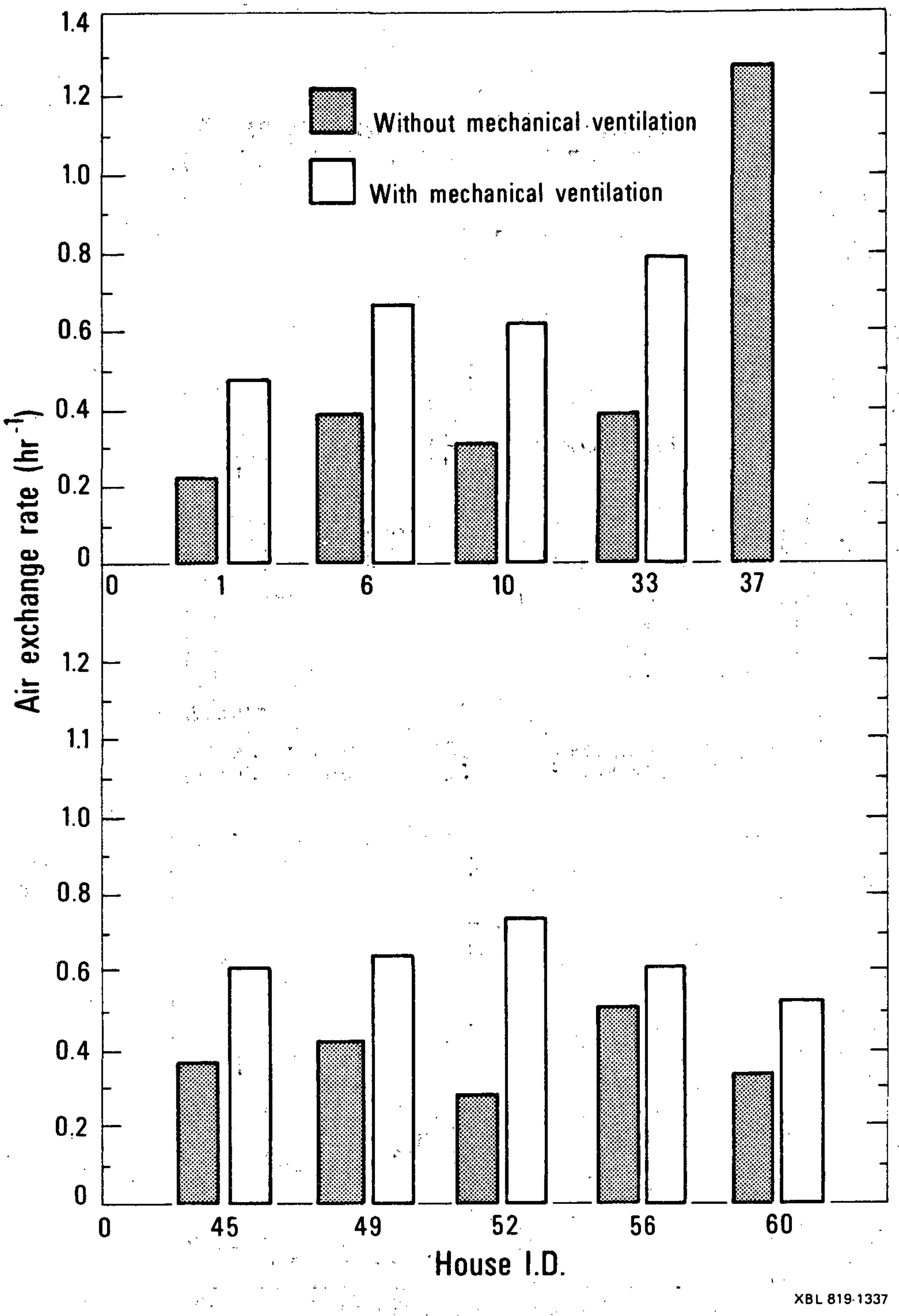


Figure 18. Average air-exchange rate of ten occupied houses in Rochester, N.Y., for a one-week period without mechanical ventilation (left bar of each pair) and a one-week period with mechanical ventilation (right bar).

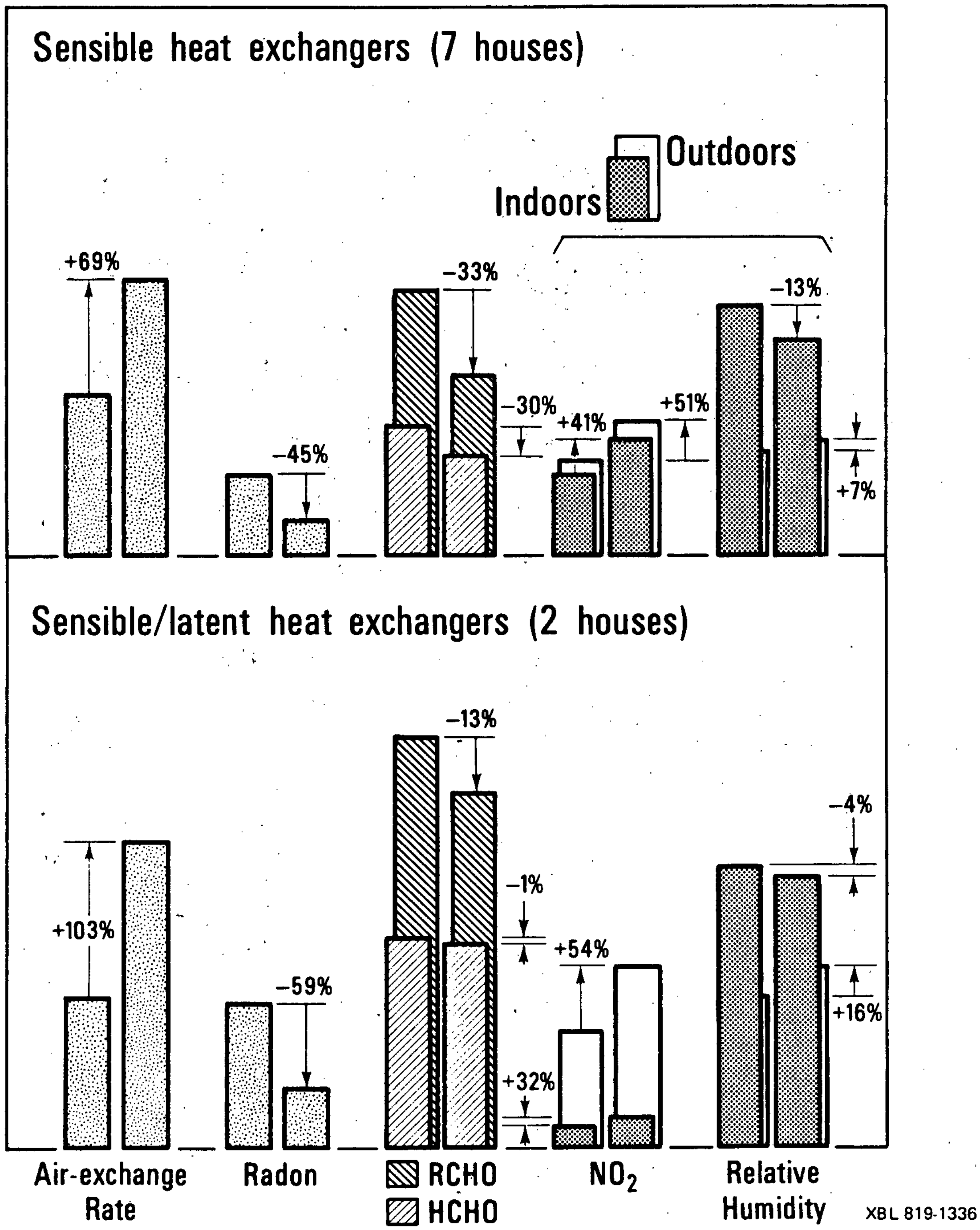
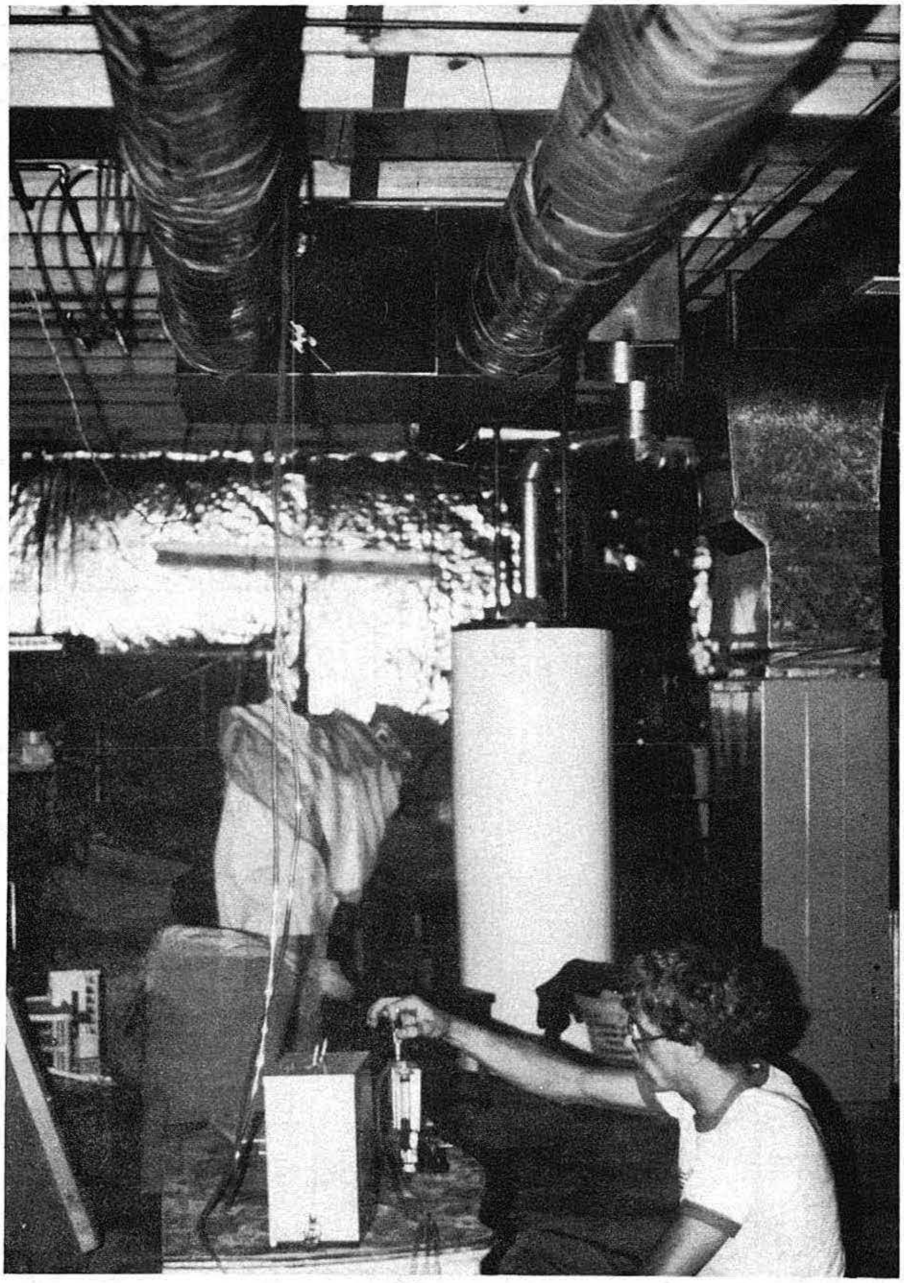


Figure 19. Comparison of changes in air-exchange rates, indoor contaminant concentrations, and humidity following ventilation with sensible-type heat exchangers (7 houses) and with sensible/latent-type heat exchangers (2 houses). (Left bar of each pair - unventilated measurements; right bar - ventilated measurements).



CBB 814-3730

Figure 20. Photograph of a researcher measuring the flow rate with a pitot tube and micromanometer in one of the insulated ducts of an installed residential air-to-air heat exchanger.

XBB 815-4519

Figure 21. Blower door installed in doorway for fan pressurization measurement of house leakage area.

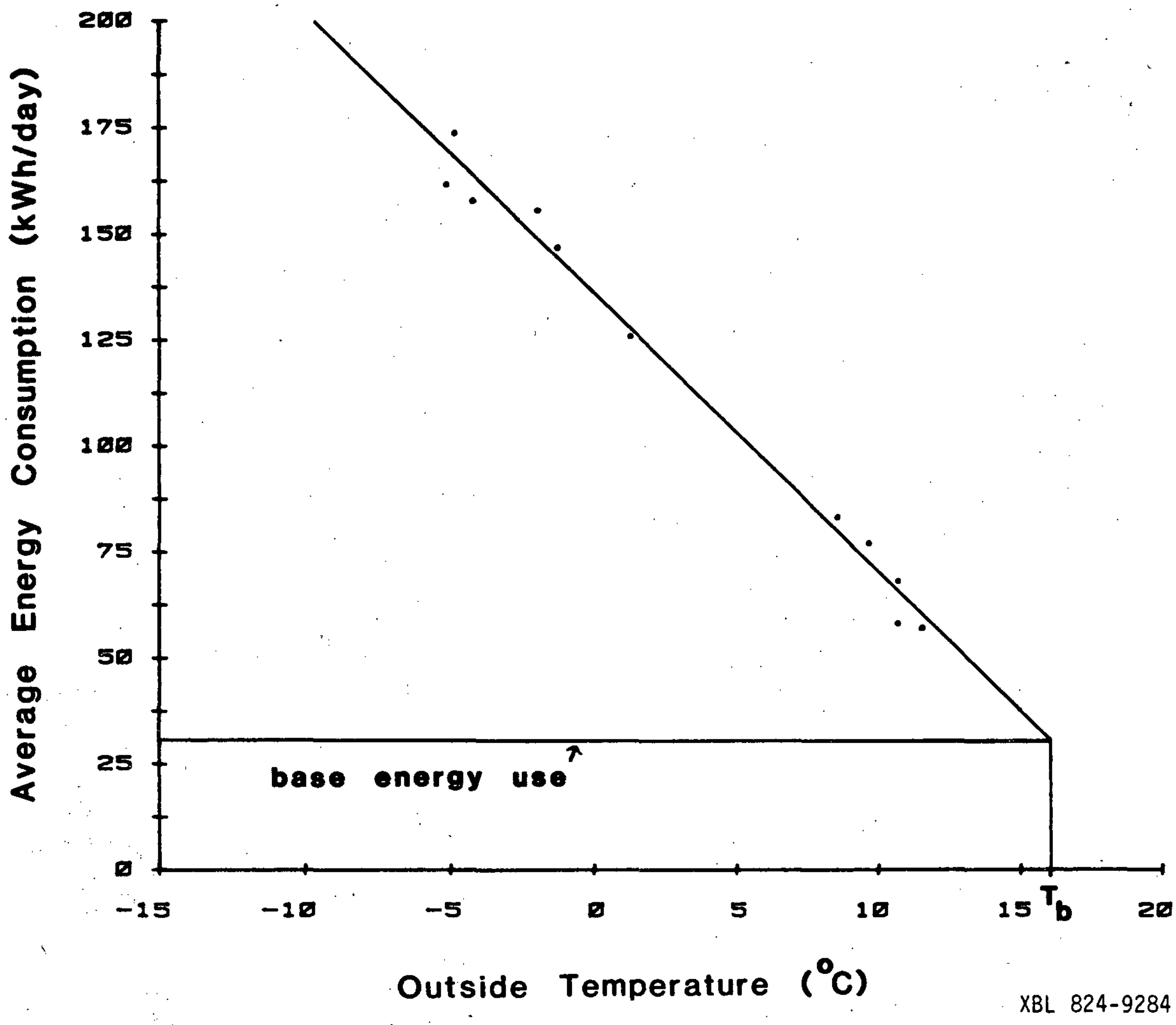
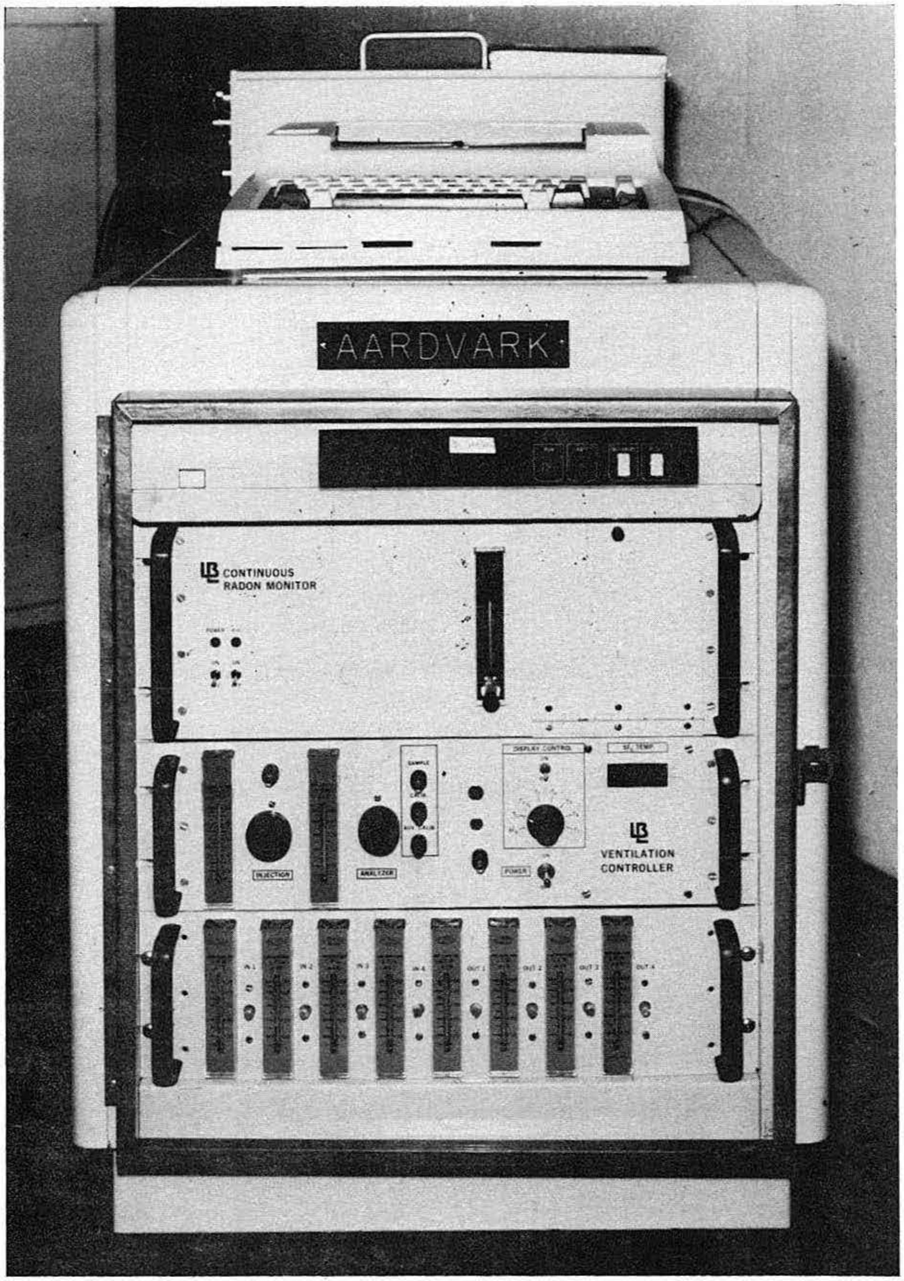


Figure 22. Energy consumption versus outside temperature for Rochester house #54.



CBB 800-12101

Figure 23. Aardvark-automated system for measuring air-exchange rates (SF_6 decay), indoor radon concentrations (scintillation counting), and seven temperatures (thermistors) in occupied houses.

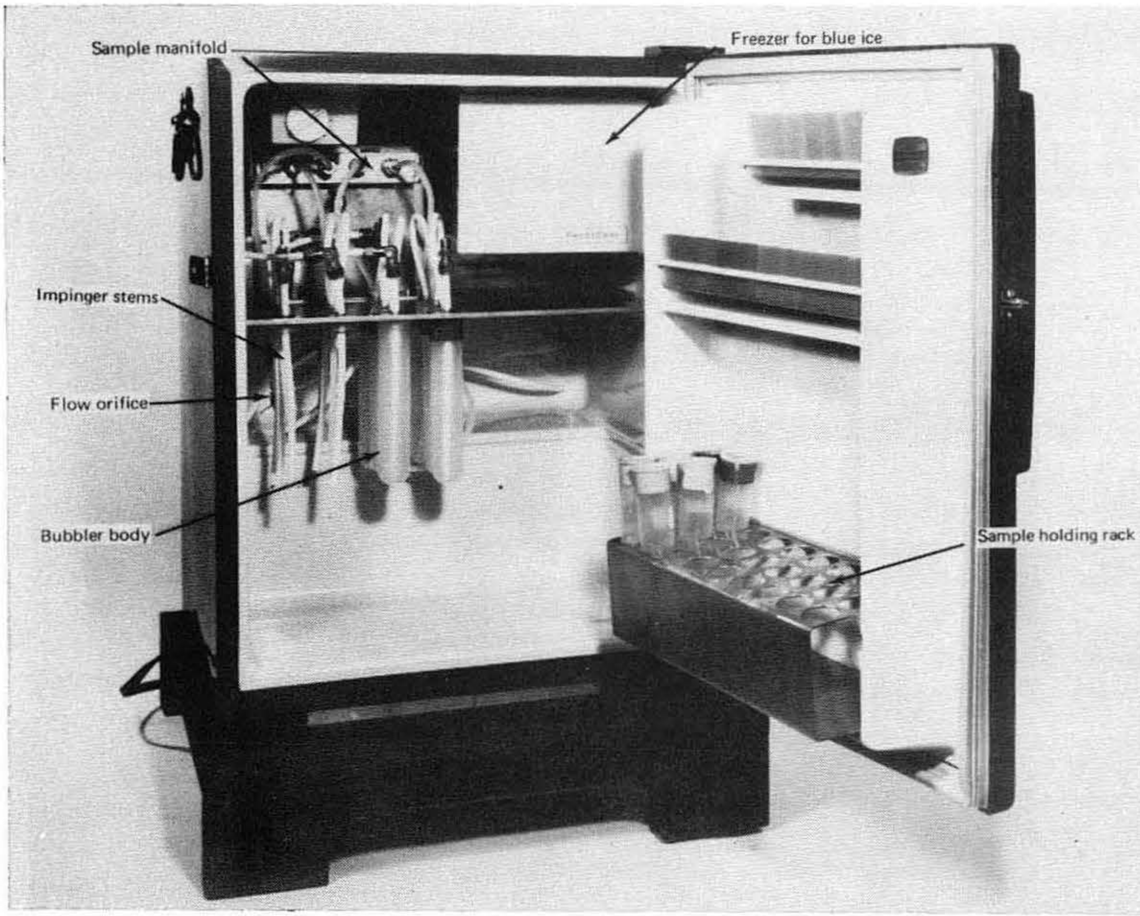
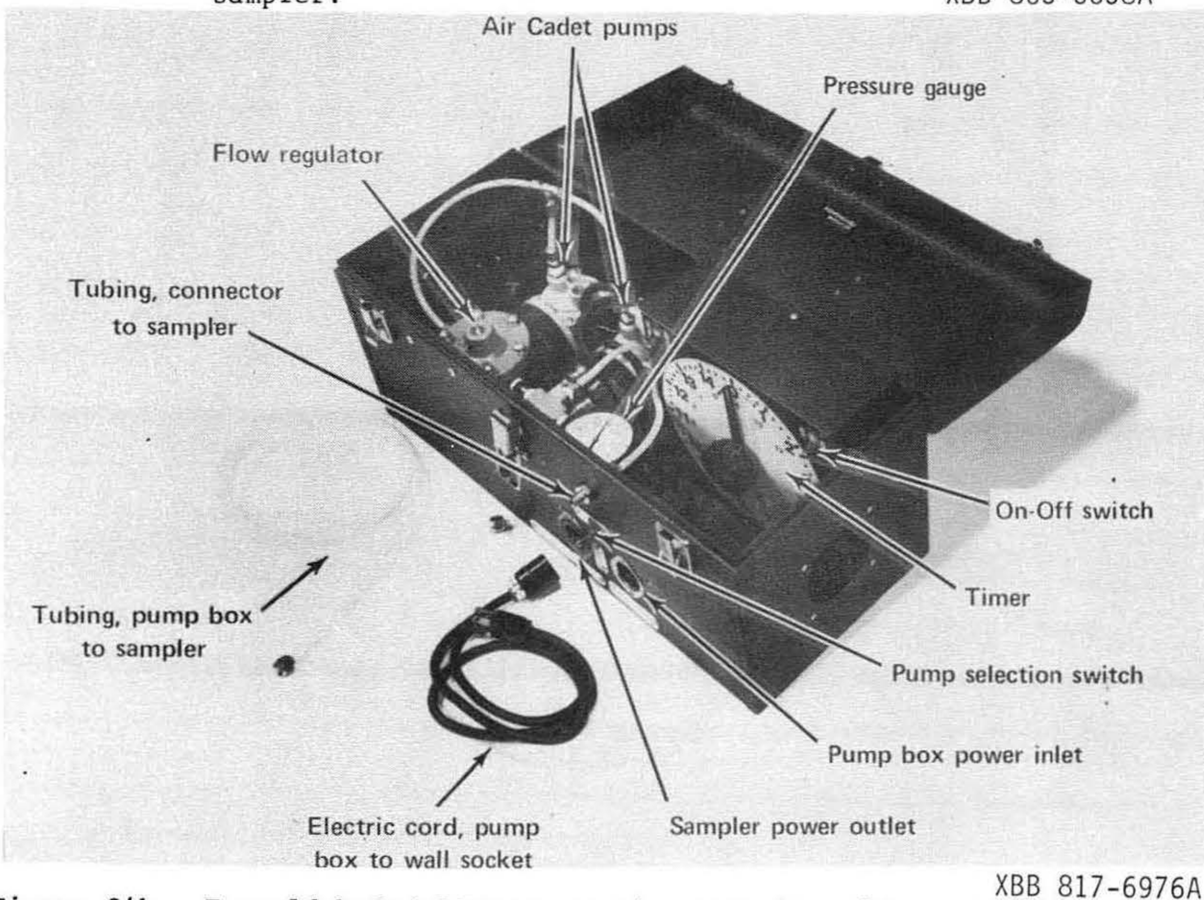


Figure 24a. Temperature- and flow-controlled formaldehyde and total aldehyde sampler. XBB 805-6058A



XBB 817-6976A

Figure 24b. Formaldehyde/aldehyde sampler pump box with connections.

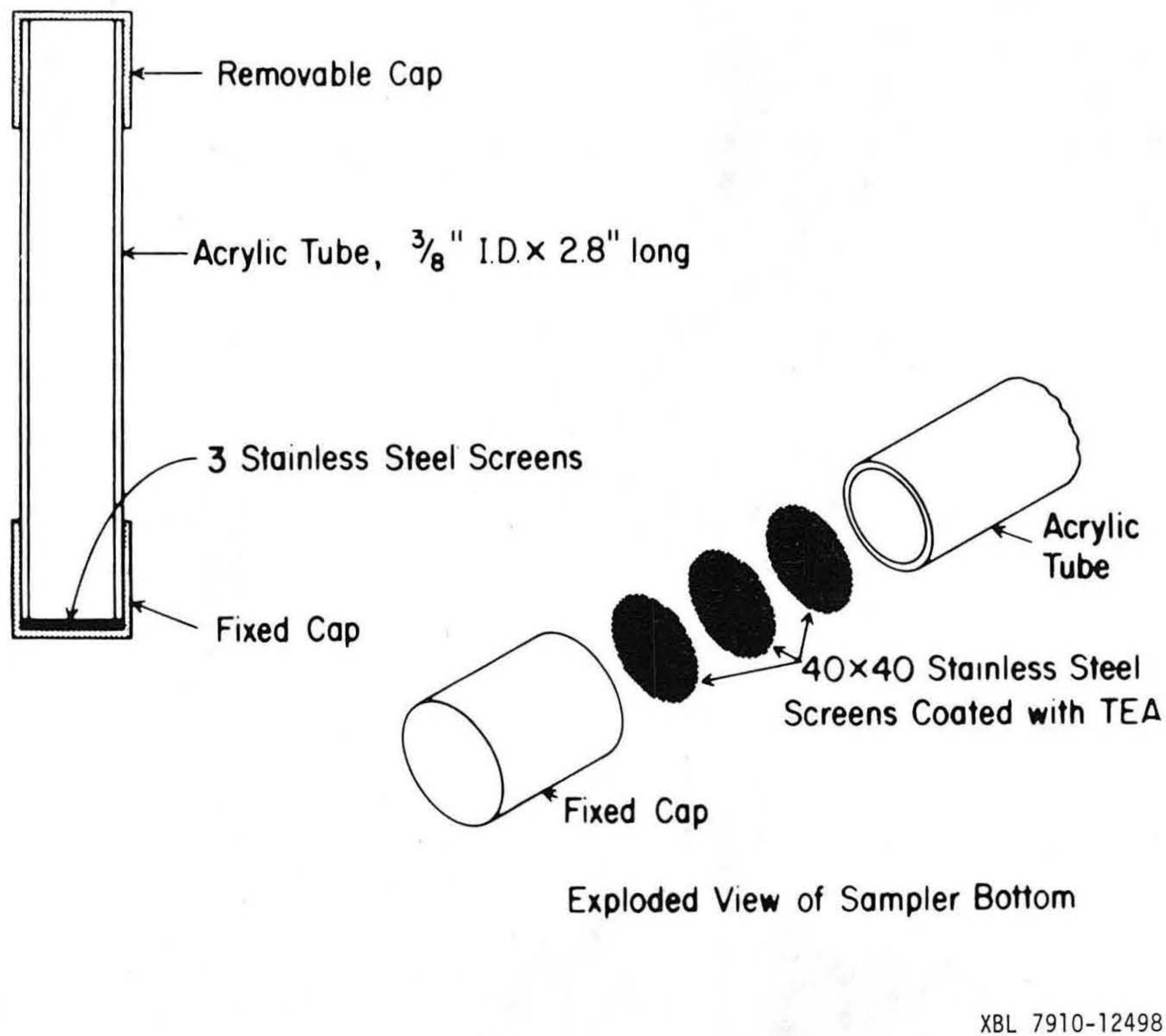
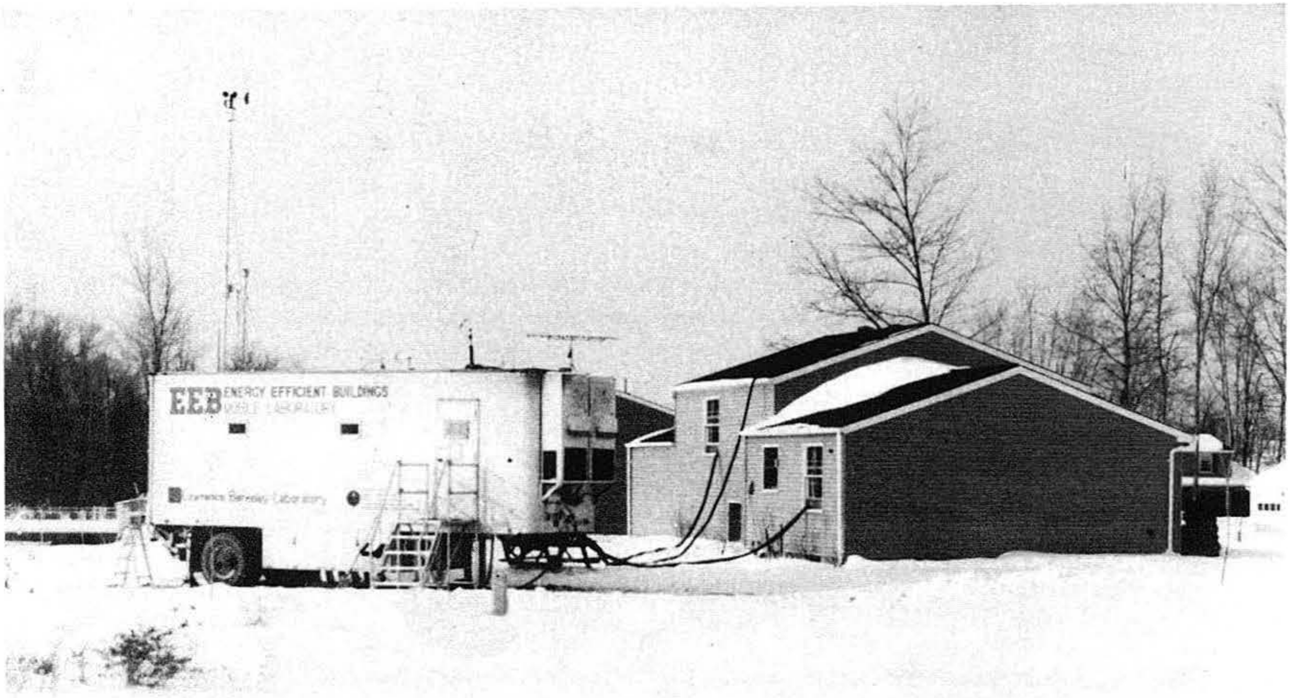
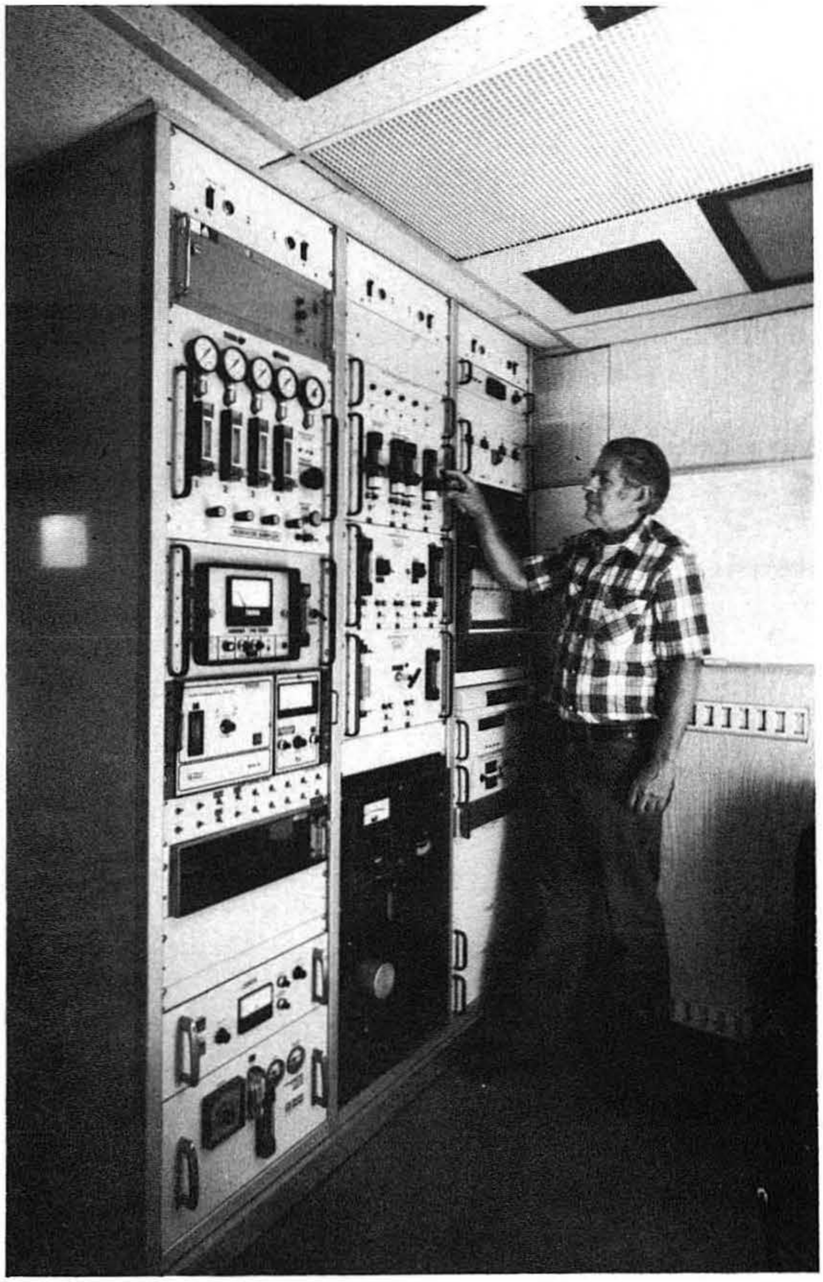


Figure 25. Schematic drawing of NO_2 passive sampler.



CBB 814-3658

Figure 26. LBL's Energy Efficient Buildings Mobile Laboratory situated behind Rochester house #6.



CBB 800-11839

Figure 27. Instrumentation panel within the Energy Efficient Buildings Mobile Laboratory.

CBB 786-7086

Figure 28. Oblique view of the Automatic Dichotomous Air Sampler with side panels removed.

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