VENTILATION STRATEGIES AND MEASUREMENT TECHNIQUES

6th AIC Conference, September 16-19 1985, Netherlands

PAPER 16

# MECHANICAL VENTILATION SYSTEM REQUIREMENTS AND MEASURED RESULTS FOR HOMES CONSTRUCTED UNDER THE R-2000 SUPER ENERGY-EFFICIENT HOME PROGRAM

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## SYNOPSIS

The R-2000 Super Energy-Efficient Home Program is a co-operative industry/government initiative sponsored by Energy, Mines and Resources Canada (EMR) and delivered by the Canadian Home Builders' Association. The program supports building industry development, training of builders and the construction of energy-efficient houses incorporating high levels of insulation, a well sealed air barrier and mechanical ventilation systems with heat recovery.

In 1983, with assistance from the Buildings Energy Conservation Sub-Committee (B.E.C.S.), EMR embarked on a field monitoring program which included air quality and ventilation system testing of approximately 300 R-2000 super energy-efficient demonstration homes and a sample of control homes that reflect conventional building practice. B.E.C.S. is responsible for general federal funds allocation in the area of energy conservation research and development.

This paper reviews the ventilation system requirements for R-2000 Homes and compares these requirements with ASHRAE Standard 62-81, the measured airflow capacities of the installed heat recovery ventilators and the average air change rates for homes using the Capillary Adsorption Tube Sampling (CATS) procedure. The CATS procedure, developed at the Brookhaven National Laboratory, uses a passive tracer gas source that emits a perfluorocarbon tracer (PFT) gas and a passive air change sampler that collects the emitted tracer gas during a 30 day test period.

The paper concludes that the response to the program is favourable; R-2000 Homes are generally performing within the tolerances of the program criteria and air quality in R-2000 Homes compares favourably with conventional homes. Formaldehyde levels in R-2000 and control homes were identical and well below the Health and Welfare Canada guideline of 0.1 ppm. The average air change rates were 42% higher in R-2000 Homes then in control homes. On average, the measured capacity of ventilation systems met program criteria but the systems generally were not balanced.

Further refinements to technical criteria and compliance requirements are under development to ensure quality assurance and to provide maximum flexibility to accommodate a variety of ventilation strategies.

## 1. INTRODUCTION

In 1980, Energy, Mines and Resources Canada in cooperation with the Canadian Home Builders' Association (CHBA) established the R-2000 Super Energy-Efficient Home (SEEH) Demonstration Program for the construction of homes to the R-2000 energy performance target and technical criteria. The initial demonstration program was recently extended to 1990.

R-2000 Homes are characterized by high levels of insulation, controlled air leakage through improved air barrier techniques, mechanical ventilation coupled with heat recovery, improved heating systems and, where possible, utilization of passive solar energy. Program emphasis was placed on industry development, training and education programs for the industry, public awareness and monitoring and evaluation.

Since 1980 the R-2000 Home Program has become an important catalyst in the evolution of energy-efficient housing technology through: the development of standard performance requirements; the development of consensus standards for products and equipment; the establishment of improved inspection and compliance procedures; the implementation of field monitoring activities; and, the support of laboratory testing of products and equipment in order to provide quality assurance for R-2000 Homes.

These activities have also provided direction for improvements to areas of housing technology that apply to conventional housing. In particular, the program has chosen to deal with ventilation and air quality issues that also apply directly to conventional housing units. Although current standards and guidelines indicate desired ventilation rates for all residential buildings, few new conventional residential buildings in Canada consistently comply with recognized ASHRAE Standard 62-81[1] minimum ventilation requirements or have the capability to provide an adequate intermittent maximum ventilation capacity when demanded by occupants. This is not surprising, since residential building codes do not require the continuous operation of whole house mechanical ventilation systems or require that ventilation air be supplied throughout the house. The R-2000 Program Technical Criteria include such requirements.

To date, there are only 400 registered R-2000 demonstration homes built across Canada despite the fact that there is considerable public interest and many builders want to build a greater number of units. Large volume construction will not proceed until adequate inspection, testing and quality assurance procedures exist throughout the industry.

## 2. TECHNICAL REQUIREMENTS FOR R-2000 HOMES

The R-2000 Program Technical Criteria[2] are basically performance-oriented and not prescriptive. The energy consumption target can result in a 50 to 80 percent reduction in energy consumption as determined by the HOTCAN computerized energy analysis program developed by the National Research Council of Canada[3]. The performance approach encourages builders to treat the whole house as a system using the best combination of features and options to suit their particular circumstance.

The technical criteria also include the requirement that the airtightness of the building envelope not exceed 1.5 air changes per hour (ACH) at 50 Pascals pressure difference when tested in accordance with the R-2000 test procedure. This procedure is based on the preliminary Canadian General Standards Board draft standard for testing the equivalent leakage area of homes[4]. This provision helps protect the building envelope from potential moisture damage and permits the efficient operation of balanced Heat Recovery Ventilators (also known as air-to-air heat exchangers).

Other specific technical criteria were established primarily for health and safety reasons. In particular, these requirements include provision for a controlled mechanical ventilation system which ensures adequate air quality; selection of combustion appliances which prevent accidental backdrafting; and, provisions to provide replacement air for appliances such as clothes dryers, central vacuums, kitchen fans and combustion equipment which exhaust air to the outside.

As the program evolves, considerable effort is being devoted to the refinement of these criteria by providing support for the establishment of consensus standards through existing national standards writing organizations such as the Canadian Standards Association (CSA) and by supporting the development of the products, equipment and skills necessary for quality assurance.

## 3. <u>VENTILATION REQUIREMENTS FOR R-2000 HOMES</u>

Given the lack of standards or experience in Canada regarding mechanical ventilation requirements for residential buildings, the Swedish standard of 0.5 ACH was adopted as the R-2000 criterion for the minimum installed mechanical ventilation system capability required in all R-2000 Homes[5].

The technical criteria require the house ventilation system to maintain a neutral pressure - neither forcing household air into the wall structure nor drawing products from the building structure into the air of the occupied space.

Although negative pressures are frequently viewed as beneficial with respect to avoiding moisture problems in structures, they can influence the diffusion of pollutants from the building structure or from soils into the basement. By operating the house close to neutral pressure and by installing a continuous air barrier, potential problems are minimized.

In order to ensure neutral pressure at all times, make-up air must be provided to replace air exhausted by central vacuum cleaners, kitchen exhaust fans, clothes dryers, and other air-exhaust appliances whose operation may induce negative pressures in the house. This must be done separately from the central mechanical ventilation system.

Figure 1 represents a recommended installation for a whole house ventilation distribution system installed in a home with perimeter radiant heating while Figure 2 illustrates a typical system using an existing forced air distribution system.

As a result of the initial field monitoring and laboratory testing of the Heat Recovery Ventilators (HRVs) which are used in virtually all R-2000 Homes, significant refinements continue to be made to the initial criteria to ensure quality assurance. Refinements under development, beyond the initial specification for a minimum installed capacity for a ventilation system, include the establishment of a minimum continuous ventilation rate of 5 l/s to be delivered to each room based on ASHRAE Standard 62-81.

Specifications are being developed for acceptable manual or automatic control strategies to increase ventilation rates to maximum capacity to handle moisture and contaminants sources when the need arises. The revised specifications would also permit greater flexibility when installing ventilation systems, including the possibility of dual or separate ventilation elements (one for continuous minimum operation and one for intermittent maximum capacity) within the system.

The Program is also considering a requirement for permanently installed airflow sensors in the ventilation system to provide a simple means for balancing, inspecting, monitoring and maintaining the ventilation system.

Recent refinements include a provision that no longer permits naturally aspirating space and water heating equipment to be installed in R-2000 Homes, in order to avoid potential problems concerning backdrafting or spillage of combustion products.

Support has also been provided to Canadian Standards Association (CSA) for the development of preliminary standards for testing and rating the performance of HRVs[6] and the development of HRV installation guidelines[7]. Support includes the testing of HRV equipment against the preliminary CSA standard by the Ontario Research Foundation (ORF)[8]. The results of both the CSA and ORF work have already been incorporated into the R-2000 Program requirements.

A national training program for installers has been developed and implemented by the Heating, Refrigerating and Air Conditioning Institute (HRAI)[5] to train contractors to design and installation of HRV systems according to the new installation guidelines.

A national technical advisory committee representing interested and concerned groups has been established to refine program criteria to ensure that R-2000 Homes continue to represent a high quality product which meets or exceeds all accepted good building practice.

The following represents a summary of results from a number of field monitoring activities related to the performance of ventilation systems installed in R-2000 Homes.

# 4. MONITORING PROCEDURES

## 4.1 Background

In 1983, Energy, Mines and Resources Canada and the Buildings Energy Conservation Sub-Committee (B.E.C.S.), which is composed of representatives from Health and Welfare Canada, National Research Council of Canada, Public Works Canada, Canada Mortgage and Housing Corporation, and Indian and Northern Affairs, established an advisory committee to review and approve funds and monitoring procedures for an extensive R-2000 field monitoring program for 1983-84 and subsequent years.

The initial monitoring program was general in scope, concentrated on indoor air quality and ventilation testing which included all R-2000 Homes and a sample of conventional control homes. Further detailed monitoring studies will be defined and undertaken during subsequent years depending on the initial results of the general field monitoring program.

The control homes were recently constructed by R-2000 builders using similar building materials as R-2000 Homes but not constructed to R-2000 insulation, airtightness and ventilation requirements.

The monitoring activities were implemented by technicians in EMR regional offices located in each province and territory in Canada. Individuals from each of these offices were trained in the specifics of air quality testing, questionnaire completion and energy metering. Laboratory and field support was provided by the Ontario Research Foundation (ORF), regional engineering firms and several laboratories in Canada and the U.S.A.

Field equipment was selected after laboratory evaluation and field testing products for ease of use, accuracy, response time and sensitivity, field durability and cost.

An extensive 200 page monitoring manual has been prepared for field technicians on all aspects of the monitoring program including administrative procedures, home occupant liaison, questionnaire completion, air quality monitoring procedures, ventilation system testing, energy metering and procedures for remedial measures.

A micro-computer based technical data base has been developed and is linked to a statistical program to analyse all program technical information.

Detailed background information for each R-2000 Home was provided by the builder upon completion of the home. This included a set of construction plans. Builder final reports described the building envelope characteristics, mechanical systems, incremental costs of construction, consumer response and attitudes, and airtightness test results. In addition, a HOTCAN computer energy analysis was performed on each home to predict monthly energy consumption for each dwelling. House surveys by regional technicians provided supplementary information during site visits. Where possible, similar information was gathered on a sample of comparative control homes.

Table 1 provides general information on the construction characteristics of both R-2000 and control homes.

## 4.2 Ventilation Compliance Testing

The required ventilation capacity for all R-2000 Homes was determined at the building plans examination stage where the interior heated volume of the house (including any basement area) was calculated and the required ventilation capacity was determined according to the program requirement of 0.5 ACH.

All R-2000 Home construction plans were reviewed and the minimum ASHRAE ventilation rate calculated based on 5 l/s per habitable room. Combined rooms such as living/dining or dining/kitchens were regarded as individual rooms. For basement and utility areas 10 l/s was used for the calculation since these areas were not specified in ASHRAE 62-81.

HRV testing included the measurement of airflow rates and static pressures to determine compliance with the R-2000 program ventilation criteria of 0.5 ACH and to identify and document installations, equipment sizing and control settings.

Airflow tests were performed on both the supply air stream and the exhaust air stream using a TSI Model 1650 Air Velocity Meter. External static pressure measurements were performed using a Dwyer 2000-0 Magnahelic Differential Pressure Gauge and Probe. These were used to derive airflows from specific fan curves for each HRV.

The HRV testing was conducted at the normal homeowner operating settings and at the high speed capacity of the unit. The measurements provided only a general approximation of the ventilation system performance and were not be used for any rating purposes concerning the thermal performance of the different HRVs.

## 4.3 Air Change Rate Monitoring

The average air change rate of the house over time was determined using a technique developed at Brookhaven National Laboratory, known as the Capilliary Adsorption Tube Sampling (CATS) procedure[10]. The technique was developed to monitor the air change rate in residential buildings over a prolonged period of time. Calibrated air change sources emit a perfluorocarbon inert tracer (PFT) gas while passive air change samplers collect the emitted tracer gas.

Four sources were installed on exterior walls and four samplers were installed on interior partition walls for a 30 day test period when all houses were operated under normal conditions. Gas chromography of the collected tracer gas was conducted upon each of the samplers and information obtained on temperature, house volumes, and wind conditions during the test period was used to determine the air change rate of the home.

Sulphur hexafluoride (SF6) measurements were completed in a limited sample of R-2000 and control homes as a further indicator of the average air change rate in the homes and as a cross reference to the CATS 30 day average air change rate measurement results. The SF6 measurement procedures conformed closely to those described by Tamura and Evans of the National Research Council of Canada[11].

The SF6 tracer gas was injected into the forced air distribution system or directly into the air space. Floor fans were utilized for tracer gas mixing to minimize the length of the test and to aid in distributing the gas.

Three sampling sites were required for each home: basement air space, ground floor main living area and second storey area (second ground floor point for bungalows). Six air samples were collected at ten minute intervals at each sample site.

The SF6 testing was conducted while the ventilation system was operating at maximum capacity and all exhaust fans/equipment operating; while the ventilation system was operating at normal setting (low speed) or exhaust fans were operating in such a manner as determined by the homeowner; and, with all ventilation and exhaust fans/equipment shut off except for furnace recirculating fans if the system was designed to operate continuously.

## 4.4 Formaldehyde Monitoring

Formaldehyde gas monitoring was performed in R-2000 and comparative control homes approximately six months following construction to determine the impact of the ventilation systems upon the concentrations and distribution of formaldehyde gas.

The EMR regional office technicians installed dosimeters purchased from Dupont de Nemours (Wilmington, Delaware) in a living and sleeping area in each of the R-2000 and control homes built by R-2000 b ilders.

The formaldehyde dosimeters were installed during the early spring months when wind induced natural ventilation is reduced and building materials are thawing (thereby possibly releasing increased quantities of moisture and formaldehyde).

Three formaldehyde dosimeters were installed in each home for seven days: one in the bedroom, one in a central location and one remaining unexposed to serve as a laboratory control unit. Temperature and humidity measurements were taken at the three installation locations to determine the initial environmental conditions of exposure. The dosimeters where then sent to I.E.C. Beak Laboratories, Mississaugua, for laboratory analysis after the seven day exposure period.

# 5. MONITORING RESULTS

## 5.1 Ventilator System Compliance Testing

The R-2000 Program requires that the house ventilation system be capable of supplying 0.5 ACH capacity. Approximately 98% of the builders selected a ventilation system with sufficient design airflow capacity to meet this specification, based on manufacturers' product information. All R-2000 Homes incorporated an HRV as the prime ventilation system. Only one comparative home had a continuous ventilation system.

Table 2 indicates that on average the measured installed ventilation capacity in R-2000 Homes did meet the program criteria. The measured mean mechanical ventilation system capacity was equivalent to 0.50 ACH for field installations.

The addition of natural air leakage of .05 ACH based on the average airtightness of 0.85 ACH at 50 Pascals for R-2000 homes increases the average ventilation capacity to beyond the program's requirement of 0.5 ACH. There was significant variation around the mean.

Generally, smaller size homes met the program requirements while some larger homes failed to meet the 0.5 ACH target. This result reflected the lack of HRVs with sufficient capacity to meet the requirement for an installed capacity of 0.5 ACH in large homes.

The mean measured capacity was 43% higher than the minimum recommended air change rate based on ASHRAE Standard 62-81 which averaged 0.35 ACH for the R-2000 Homes. The measured capacity of ventilation systems exceeded the ASHRAE minimum ventilation rate in 95% of R-2000 homes (273 out of 283 homes). The average ASHRAE recommended minimum ventilation rate for all R-2000 Homes was 50 l/s.

The results also indicated a potential conflict between the R-2000 Program requirement for 0.5 ACH capacity and the ASHRAE 62-81 per room minimum ventilation requirements. Larger homes that were sized to the 0.5 ACH capacity far exceeded the average minimum air change rate based on ASHRAE requirements of 0.32 ACH.

Proposed changes to the ventilation requirements would permit the installation of ventilation equipment for continuous minimum operation based on ASHRAE which could be separate from the equipment required to provide intermittent capacity (0.5 ACH) in large homes. The availability of improved "third generation" ventilation equipment should also resolve most problems of system capacity compliance in large homes.

Table 2 also presents comparisons of the measured ventilation capacity for R-2000 Homes heated with electricity and homes using fuel-fired heating and indicates that the results are similar. The ventilation capacity of homes with electric heating systems measured 11% higher than those with fuel-fired heating systems. The majority of the fuel-fired heating systems were forced-air gas heating systems.

The results should not be surprising since many electric baseboard heated homes used HRV equipment, ducting and installation procedures similar to those HRVs installed in homes using forced-air heating systems to distribute air.

Initially, many baseboard heated homes supplied ventilation air to the basement or to one point in the living area and relied on natural convection to distribute air throughout the house.

These strategies are no longer permitted in R-2000 homes since ventilation air must now be delivered to each room of the house in accordance with ASHRAE 62-81. This will result in more ductwork and higher external static pressures for HRVs installed in electric baseboard homes since the HRVs must now distribute air to each room of the house.

Table 3 indicates that only 16% of ventilation systems were balanced within the 10% range as required in the R-2000 technical criteria. This was determined by comparing the amount of supply air entering the ventilator to the amount of exhaust air leaving the ventilator.

It was apparent that the majority of installers did not carry out field balancing on the system. Less than 15% of the installations contained balancing dampers. This should not be surprising since most installers did not have access to balancing equipment or were not aware of potential problems due to equipment imbalance.

High negative pressure conditions could increase the level of pollutants such as radon entering the home through cracks in the building foundation, and could also induce combustion appliance backdrafting. Conversely, a high positive pressure condition may tend to force moisture into the building shell. As well, any HRV imbalance may affect the heat recovery efficiency and increase energy consumption for space heating.

Except for the issue of balancing, the above results indicate that on average the installed capacities of units are within the tolerances of the program criteria and above minimum ASHRAE ventilation requirements. However, there was considerable variation around the average values, with some homes experiencing significantly higher or lower ventilation air change rate capacities.

Monitoring activities indicate that measured results were dependent more upon the quality of the installation than the airflow capacities of many HRVs. It was evident that poor duct design, excess use of flexible duct materials and use of 125 mm diameter and smaller ducts resulted in a significant reduction in airflow in some units. Most of these problems can be attributed to lack of experienced and trained installers.

Balancing of mechanical ventilation systems would normally involve installing a simple damper in the duct with the highest airflow in order to reduce the airflow rate to balance the system. Reducing the higher airflow may result in a lowering of the system capacity below R-2000 requirements. Extensive changes may have to be made to the ventilation equipment and ductwork in order to provide minimum ventilation capacities when measures are taken to balance existing systems.

Although very few of the home occupants expressed any concern over the comfort levels experienced in their homes, steps are being taken to ensure that all units are balanced and meet minimum airflow requirements. The R-2000 monitoring program will continue to test all R-2000 homes to verify that the ventilation requirements are being provided.

The R-2000 Program is preparing revised guidelines for the installation of whole house mechanical ventilation equipment which make it mandatory to measure airflows and balance units at the time of installation. National training courses for installers will greatly improve compliance with program criteria.

## 5.2 Measured Air Change Rates

The CATS air change rate monitoring results provide information concerning the operation of the mechanical ventilation systems by occupants and the effect of air infiltration, door openings, combustion air and supplemental ventilation and air exhausting equipment operation (range hoods, clothes dryers, etc.) over a 30 day period. The results in this paper were based on 123 R-2000 homes and 40 control homes.

Since the CATS procedure is relatively new, initially, some comparisons were made between the CATS perfluorocarbon test procedure and sulphur hexafluoride (SF6) spot measurements in 9 homes.

Table 4 indicates that, on average, there was a good comparison between the SF6 and the 30 day CATS measurements even though the SF6 testing was only a spot measurement completed at the time the CATS dosimeters were installed.

Additional work is underway to validate the CATS procedure in a number of homes which are being monitored using continuous tracer gas techniques. This activity will commence in the fall of 1985.

The analysis indicates that the CATS average air change rate of .37 ACH in R-2000 homes was 26% lower than the measured capacity of the mechanical ventilation system. This is to be expected since many units were run continually at a low speed setting and since some occupants operated units intermittently (see Table 5).

The CATS average air change rate of in R-2000 homes was 42% higher than the average of .26 ACH in control homes. This is not unreasonable since measurements were taken in the spring when wind and stack effects are minimal, windows have not yet been opened and the control homes do not have mechanical ventilation systems.

A possible explanation for lower results in some control homes may have been the lack of precise information on house volumes since construction plans for control homes were not available for examination. Builders and field technicians were relied upon to supply this information.

The CATS average rate of 0.37 ACH for R-2000 Homes was slightly higher than the calculated ASHRAE air change rate of 0.35 ACH, Table 2, indicating that R-2000 Homes are performing in accordance with ASHRAE minimum requirements.

Air change rates based on ASHRAE were not available for control homes but it appears that the average CATS air change rate of .26 ACH for control homes may not meet ASHRAE minimum requirements.

Factors such as house type and size, space heating distribution systems, ventilation supply air discharge and measured air exchange rates were examined and presented in Table 5. Most analysis was conducted only on R-2000 Homes, since only one control home was equipped with a mechanical ventilation system.

Houses with volumes less than 500 m3 and homes with slab-on-grade or crawlspace foundations exhibited higher average air change rates. This is likely a reflection of the capability of the HRVs to provide a higher air change rate in smaller homes even at low speed settings.

Table 5 indicates that the mean measured CATS results for R-2000 homes heated with electricity where identical to those homes with fuel-fired systems but the CATS air change rates for control homes heated with electricity were substantially lower than for control homes with fuel-fired systems. Most of the control homes that were heated with electricity used baseboard heating systems.

R-2000 homes with electric baseboard heating had CATS average air change rates of 0.32 ACH as compared to those homes with forced-air heat distribution systems which averaged 0.39 ACH.

Control homes also exhibited much lower average air change rates for homes with electric baseboard heating with average CATS measurements of only 0.18 ACH as compared to 0.30 ACH for forced air heating systems. The lack of an active chimney flue may be a contributing factor for low air change rates in electric baseboard homes.

Analysis of the results based on the type of ventilation air discharge strategy indicates that the CATS air change rate results were 15% lower for R-2000 Homes where ventilation air was discharged into the basement rather than the living space.

Results for houses where the ventilation air was discharged into the return air duct of a forced air system were lower than expected. This may be due to to the small sample size and the possibility that many furnace fans were not operating continuously during the spring period when the measurements were conducted.

These results indicate that R-2000 homes have higher air change rates than control homes and that air distribution strategies have an impact on the whole house ventilation rates and ventilation efficiency for both R-2000 and control homes.

The CATS results will also assist in determining appropriate air change rates to be used when determining the thermal performance of R-2000 homes.

## 5.3 Preliminary Formaldehyde Results

The following formaldehyde results are based on 248 R-2000 homes and 62 control homes. The Health and Welfare Canada indoor air guideline of 0.1 ppm is used as a benchmark when comparing the results for the R-2000 Homes with the control homes.

Testing was performed in the spring months, concurrent with the CATS monitoring activity when formaldehyde offgassing is expected to be at an elevated level due to increased ambient temperatures, reduced wind induced ventilation and increased moisture content in building materials.

Table 5 presents results of measurements taken in the bedrooms of each home. Both bedroom and living area measurements were similar in R-2000 and control homes.

The test results indicate that both the R-2000 and control homes have identical average formaldehyde concentrations of 0.06 ppm. The average levels were well below Health and Welfare guideline of 0.1 ppm with only 8% of R-2000 Homes and 9% of control homes exceeding 0.099 ppm.

Relationships were hypothesized between formaldehyde levels and various contributing factors such as house type, space heating distribution systems, ventilation air discharge and measured air change rates. Most analysis was conducted only on R-2000 Homes, since only one control home was equipped with a mechanical ventilation system.

The results in Table 5 indicate little difference according to house size, volumes less than and greater than 500 m3 but slab on grade and crawlspace homes exhibit levels 26% lower than average. It should be noted that the sample size was quite small.

Baseboard electric homes on average exhibited a mean formaldehyde concentration of 0.066 ppm or a 15% higher level than those homes with forced air heating systems. This result was consistent for bedroom and living room measurements in R-2000 and control homes.

The results also indicate that formaldehyde levels in homes that simply discharged supply air into the basement and relied on natural convection to circulate air to the upper portions of the home were 0.066 ppm or 18 % higher then the average levels for houses using other ventilation air discharge strategies.

Analysis of only those homes with both CATS and formaldehyde test results, Tables 6, indicates that although the CATS air change rates were 40 % higher in R-2000 Homes, the average formaldehyde levels were not any lower then in control homes.

Preliminary formaldehyde results from repeat testing of 134 R-2000 homes and 22 control homes in the spring, 1985, indicates that control homes have average formaldehyde levels 23% higher than R-2000 homes. These new results may indeed indicate that lower air change rates are in resulting in higher formaldehyde levels in control homes. These new results will be analyzed shortly.

Table 6 also indicates that the average CATS air change rates were lower and the formaldehyde levels higher for R-2000 and control homes with electric baseboard heating systems.

R-2000 homes where ventilation air was discharged into the basement and natural ventilation was relied upon to distribute ventilation throughout the house also exhibited higher formaldehyde levels and lower air change rates than homes where the fresh air was discharged in the living area.

Additional analysis of the 17 R-2000 Homes that exceeded Health and Welfare Canada guidelines, indicates that not one home had CATS air change rates in excess of ASHRAE minimim requirements which were equivalent to 0.32 ACH for these homes. The CATS average air change rate for these homes was 0.16 ACH or 57% lower than the average of 0.37 ACH for all R-2000 Homes although the average measured capacity of the ventilation systems was 0.46 ACH.

Air distribution problems may have been a major contributing factor given that electric baseboard heating systems were in 70% of these homes and 47% discharged ventilation air into the basement. Other factors such as poor controls, intermittent operation and occupant behaviour may also be factors for such low air CATS air change rates and high formaldehyde levels.

These results indicate that both total air change rate and ventilation air distribution efficiency are major factors in controlling formaldehyde levels. Current program criteria now require that ventilation air be distributed, continuously, to each room of the house at the ASHRAE minimum of 5 l/s per room.

Measures are also being taken to reduce formaldehyde levels in the small group of homes that exceeded Health and Welfare Guidelines and formaldehyde monitoring will continue during the 1984/85 monitoring period on all R-2000 and control homes to determine if levels have dropped over time.

## 6. CONCLUSIONS

The overall response to the program is generally favourable and the R-2000 Program is showing that well-sealed homes can be constructed to provide air quality at least comparable to conventionally built homes.

The R-2000 Technical Criteria concentrate on ventilation and indoor air quality issues. The program criteria currently require a balanced mechanical ventilation system capable of 0.5 ACH and an air distribution system that supplies the ASHRAE minimum of 5 l/s per room. Installation guidelines have been established to ensure that equipment has been installed correctly and that replacement make-up air is provided for all equipment exhausting air from the house.

The monitoring program results indicate that the R-2000 homes appear to be performing within the tolerances of the program criteria. Air quality and ventilation rates compare favourably with those of conventional homes with the average formaldehyde levels identical for R-2000 and control homes and well below Health and Welfare Canada guidelines. R-2000 Homes had average air change rates that were 42% higher than control homes. On average, ventilation systems were sized to the program criteria of 0.5 ACH but the systems generally were not balanced to program requirements.

Further program refinements are being considered to ensure quality assurance for future increased numbers of R-2000 homes. These refinements include revisions to program technical requirements, inspection procedures, and national standards to address concerns or issues raised during the monitoring phase.

In particular, current requirements for ventilation system capacities and the delivery of air throughout the house need to be expanded to address issues related to system control strategies. Occupants need to be better informed about the correct operation of their ventilation systems and the systems must be designed in a manner that ensures that occupants will in fact operate them.

The R-2000 Program is supporting a large number of activities related to ventilation and air quality by including field monitoring, laboratory testing, standards development, and industry development activities. The program is at the forefront of residential ventilation and air quality activities in Canada.

## ACKNOWLEDGEMENTS

The author would like to acknowledge the contribution of Michael Lubun, Lubun Associates, in the development and implementation of the monitoring program and would like to express his appreciation to M. Lubun, Drew Perrin, Grant Courville and Barbara Tebinka for their assistance.

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FIGURE 1

HRV INSTALLATION WITH BASEBOARD HEATING

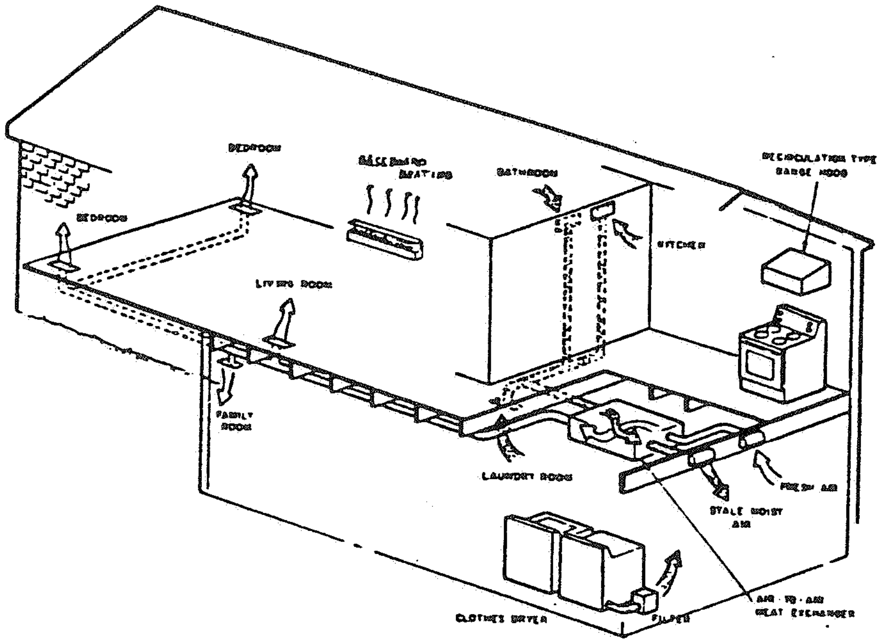
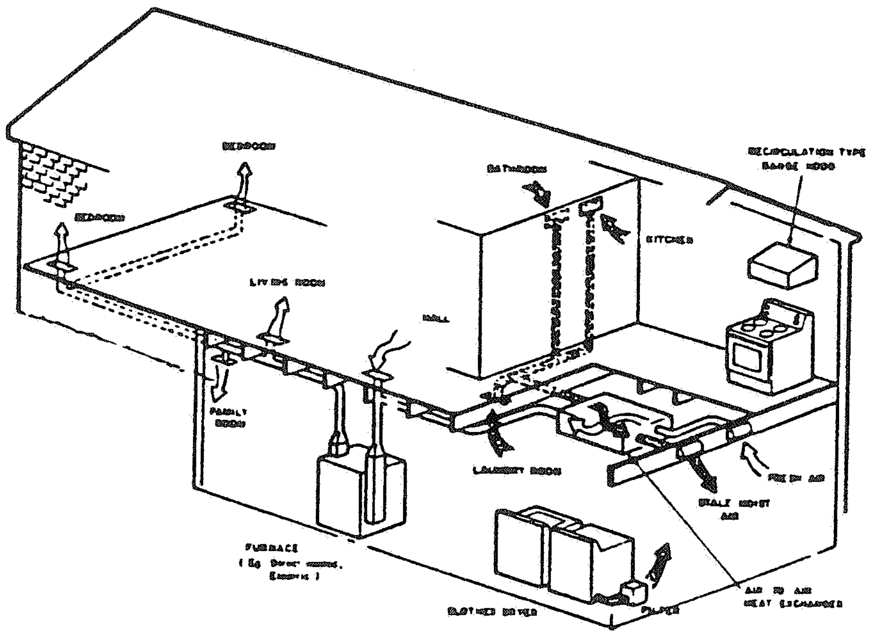


FIGURE 2

HRV INSTALLATION WITH FORCED AIR HEATING SYSTEM
WITH CONTINUAL FURNACE FAN OPERATION



## TABLE 1: GENERAL HOUSE CHARACTERISTICS

| | R-2000 HOMES | | | CONTROL HOMES | | |
|---|---|---|---|---|---|---|
| | | Mean | St. Dev. | | Mean | St. Dev. |
| HOUSE VOLUME (M3): | | 525 | 137 | | 462 | 162 |
| HOUSE TYPE AND SIZE | | No. | Percent. | | No. | Percent. |
| Slab on Grade Homes | | 15 | 0.5 | | 3 | 0.05 |
| Crawlspace Homes | | 6 | 0.1 | | 6 | 0.1 |
| All Homes: <500 M3 | | 144 | 49.6 | | 48 | 82.8 |
| All Homes: >500 M3 | | 146 | 51.4 | | 10 | 17.2 |
| Total: All Homes | | 290 | | | 58 | |
| SPACE HEATING SYSTEMS | | No. | Percent. | | No. | Percent. |
| Radiant: Electric | | 108 | 37.6 | | 26 | 34.2 |
| Radiant: Fuel-Fired | | 4 | 1.4 | | 7 | 9.2 |
| Forced Air: Electric | | 63 | 22.0 | | 7 | 9.2 |
| Forced Air: Fuel-Fired | | 112 | 39.0 | | 36 | 47.4 |
| FIREPLACES/WOODSTOVES | | 93 | 32.0 | | 21 | 27.6 |
| VENTILATION AIR DISCHARGE | | No. | Percent. | | | |
| Basement | | 86 | 31.5 | | na | na |
| Main Living Area | | 106 | 38.8 | | na | na |
| Furnace Cold Air Return | | 28 | 10.3 | | na | na |
| Near Furnace Cold Air Return | | 53 | 19.4 | | na | na |
| THERMAL CHARACTERISTICS: | | Mean | Range | | Mean | Range |
| Ceiling (RSI) | | 8.2 | 4.9 - 11.9 | | 6.1 | 3.5 - 7.0 |
| Main Walls (RSI) | | 5.5 | 3.5 - 9.6 | | 3.5 | 2.1 - 5.8 |
| Basement Walls (RSI) | | 3.9 | 1.3 - 8.8 | | 1.9 | 0.0 - 3.5 |
| Basement Floors (RSI) | | 1.1 | 0.0 - 5.0 | | 0.0 | 0.0 - 0.0 |
| Windows (RSI) | | 0.44 | 0.21- 0.56 | | 0.34 | 0.21- 0.49 |
| | Cases | Mean | Range | Cases | Mean | Range |
| AIRTIGHTNESS (50 Pascals ACH) | 259 | 0.84 | 0.03-1.49 | 4 | 4.58 | 2.0-7.1 (ACH) |

## TABLE 2: ASHRAE REQUIREMENTS AND MEASURED SYSTEM RESULTS-R-2000 HOMES

| HOUSE CHARACTERISTICS | ASHRAE REQUIREMENTS (ACH) | | | | MEASURED SYSTEM CAPACITY (ACH) | | | |
|---|---|---|---|---|---|---|---|---|
| HOUSE TYPE AND SIZE | Cases | Mean | St. Dev. | Median | Cases | Mean | St. Dev. | Median |
| Slab on Grade: | 12 | 0.43 | 0.09 | 0.44 | 10 | 0.66 | 0.21 | 0.60 |
| Crawlspace: | 6 | 0.44 | 0.09 | 0.42 | 4 | 0.55 | 0.31 | 0.51 |
| All Homes <500 M3: | 132 | 0.38 | 0.07 | 0.37 | 124 | 0.61 | 0.23 | 0.58 |
| All Homes >500 M3: | 126 | 0.32 | 0.06 | 0.32 | 135 | 0.41 | 0.14 | 0.41 |
| Total All R-2000 Homes: | 258 | 0.35 | 0.07 | 0.34 | 259 | 0.50 | 0.21 | 0.47 |
| SPACE HEATING FUEL TYPE: | | | | | | | | |
| Electricity | 155 | 0.35 | 0.07 | 0.35 | 159 | 0.52 | 0.20 | 0.50 |
| Other | 95 | 0.35 | 0.07 | 0.34 | 97 | 0.47 | 0.22 | 0.48 |
| VENTILATION AIR DISCHARGE: | | | | | | | | |
| Basement | 74 | 0.34 | 0.06 | 0.34 | 78 | 0.48 | 0.16 | 0.46 |
| Main Living Area | 92 | 0.37 | 0.08 | 0.35 | 95 | 0.56 | 0.26 | 0.52 |
| Furnace Cold Air Return | 23 | 0.32 | 0.06 | 0.32 | 25 | 0.43 | 0.16 | 0.41 |
| Near Furnace Cold Air Return | 49 | 0.35 | 0.05 | 0.35 | 49 | 0.47 | 0.18 | 0.45 |

TABLE 3

HEAT RECOVERY VENTILATOR BALANCING CHARACTERISTICS

| Heating Distribution | Airflow Imbalance | Low Speed Test | | High Speed Test | |
|---|---|---|---|---|---|
| | Percent | No. | Percent (%) | No. | Percent (%) |
| Electric Baseboard: | 0 -9% | 11 | 10 | 16 | 15 |
| | 10-25% | 12 | 11 | 40 | 37 |
| | 26-50% | 17 | 16 | 28 | 26 |
| | > 50% | 4 | 4 | 7 | 7 |
| | missing | 63 | 59 | 16 | 15 |
| Forced Air: | 0 -9% | 33 | 19 | 30 | 17 |
| | 10-25% | 44 | 25 | 66 | 38 |
| | 26-50% | 30 | 17 | 44 | 25 |
| | > 50% | 8 | 5 | 7 | 4 |
| | missing | 59 | 34 | 27 | 16 |
| Total Average: R-2000 | 0 -9% | 44 | 16 | 46 | 16 |
| | 10-25% | 56 | 20 | 106 | 38 |
| | 26-50% | 47 | 17 | 72 | 26 |
| | > 50% | 12 | 4 | 14 | 5 |
| | missing | 122 | 43 | 43 | 15 |

NOTE: The Airflow Imbalance percentages indicate the percent difference between supply and exhaust air as measured at the heat recovery ventilator. The No. value indicates the number of cases falling within the airflow imbalance range. The Percent value presents the number of cases within the range as a percentage of the total number of homes with measurements.

TABLE 4

CATS MEASURED AIR CHANGE RATES VS. SULPHUR HEXAFLUORIDE MEASURED AIR CHANGE RATES

| HOUSE TYPE | SF6 RESULTS (ACH) | | | | CATS RESULTS (ACH) | | |
|---|---|---|---|---|---|---|---|
| | Cases | Mean | St. Dev. | Median | Mean | St. Dev. | Median |
| R-2000 | 6 | 0.37 | 0.13 | 0.23 | 0.33 | 0.20 | 0.43 |
| Control | 3 | 0.22 | 0.08 | 0.20 | 0.17 | 0.09 | 0.23 |
| All Homes | 9 | 0.32 | 0.13 | 0.23 | 0.29 | 0.18 | 0.23 |

NOTE: CATS Measured House Ventilation refers to the Brookhaven National Laboratory "Capillary Adsorption Tube Sampler" method of determining average house ventilation rates over a specific time period[10].

**TABLE 5: VENTILATION AND FORMALDEHYDE TEST RESULTS**

| HOUSE CHARACTERISTICS | MEASURED VENTILATION CAPACITY (ACH) | | | | CATS MEASURED VENTILATION (ACH) | | | | FORMALDEHYDE TESTING RESULTS (PPM) Bedroom Test Results | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| HOUSE TYPE AND VOLUME RANGE | Cases | Mean | St. Dev. | Median | Cases | Mean | St. Dev. | Median | Cases | Mean | St. Dev. | Median |
| Slab on Grade: | 10 | 0.66 | 0.21 | 0.60 | 5 | 0.40 | 0.38 | 0.29 | 12 | 0.044 | 0.018 | 0.038 |
| Crawlspace: | 4 | 0.55 | 0.31 | 0.51 | 5 | 0.47 | 0.33 | 0.27 | 5 | 0.041 | 0.009 | 0.040 |
| All Homes: <500 M3 | 124 | 0.61 | 0.23 | 0.58 | 54 | 0.40 | 0.39 | 0.29 | 126 | 0.060 | 0.027 | 0.053 |
| All Homes: >500 M3 | 135 | 0.41 | 0.14 | 0.41 | 69 | 0.34 | 0.29 | 0.27 | 122 | 0.060 | 0.031 | 0.055 |
| Total All R-2000 Homes: | 259 | 0.50 | 0.21 | 0.47 | 123 | 0.37 | 0.34 | 0.28 | 248 | 0.060 | 0.029 | 0.053 |
| Total All Control Homes: | na | na | na | na | 40 | 0.26 | 0.21 | 0.20 | 62 | 0.060 | 0.033 | 0.054 |
| SPACE HEATING FUEL TYPE | | | | | | | | | | | | |
| R-2000 HOMES: | | | | | | | | | | | | |
| Electricity | 159 | 0.52 | 0.20 | 0.50 | 71 | 0.38 | 0.49 | 0.27 | 153 | 0.063 | 0.030 | 0.057 |
| Other | 97 | 0.47 | 0.22 | 0.43 | 49 | 0.38 | 0.28 | 0.30 | 95 | 0.055 | 0.026 | 0.047 |
| CONTROL HOMES: | | | | | | | | | | | | |
| Electricity | na | na | na | na | 14 | 0.20 | 0.18 | 0.14 | 27 | 0.061 | 0.029 | 0.058 |
| Other | na | na | na | na | 23 | 0.31 | 0.23 | 0.27 | 34 | 0.060 | 0.036 | 0.045 |
| SPACE HEATING DISTRIBUTION TYPE | | | | | | | | | | | | |
| R-2000 HOMES: | | | | | | | | | | | | |
| Electric Baseboard | 94 | 0.56 | 0.21 | 0.54 | 40 | 0.32 | 0.24 | 0.27 | 95 | 0.065 | 0.032 | 0.059 |
| Forced Air | 156 | 0.46 | 0.16 | 0.45 | 76 | 0.39 | 0.46 | 0.28 | 148 | 0.057 | 0.027 | 0.058 |
| CONTROL HOMES: | | | | | | | | | | | | |
| Electric Baseboard | na | na | na | na | 13 | 0.18 | 0.19 | 0.12 | 20 | 0.065 | 0.028 | 0.059 |
| Forced Air | na | na | na | na | 27 | 0.30 | 0.21 | 0.26 | 42 | 0.057 | 0.035 | 0.043 |
| VENTILATION AIR DISCHARGE (R-2000) | | | | | | | | | | | | |
| Basement | 78 | 0.48 | 0.16 | 0.46 | 36 | 0.39 | 0.56 | 0.27 | 82 | 0.066 | 0.028 | 0.059 |
| Main Living Area | 95 | 0.56 | 0.26 | 0.52 | 47 | 0.45 | 0.44 | 0.29 | 86 | 0.058 | 0.033 | 0.047 |
| Furnace Cold Air Return | 25 | 0.43 | 0.16 | 0.41 | 12 | 0.36 | 0.22 | 0.35 | 26 | 0.053 | 0.022 | 0.049 |
| Near Furnace Cold Air Return | 49 | 0.47 | 0.18 | 0.45 | 19 | 0.30 | 0.21 | 0.26 | 44 | 0.055 | 0.026 | 0.048 |

NOTE: CATS refers to the Brookhaven National Laboratory "Capillary Adsorption Tube Sampler" tracer gas (perfluorocarbon) method.

## TABLE 6: CATS AIR CHANGE RATE RESULTS FOR FORMALDEHYDE TESTED HOMES

| HOUSE CHARACTERISTICS | CATS MEASURED VENTILATION (ACH) | | | | FORMALDEHYDE TESTING RESULTS (PPM) Bedroom Test Results | | | |
|---|---|---|---|---|---|---|---|---|
| HOUSE TYPE AND VOLUME RANGE | Cases | Mean | St. Dev. | Median | Cases | Mean | St. Dev. | Median |
| Slab on Grade: | 5 | 0.40 | 0.38 | 0.29 | 5 | 0.045 | 0.023 | 0.034 |
| Crawlspace: | 4 | 0.33 | 0.16 | 0.32 | 4 | 0.041 | 0.011 | 0.040 |
| All Homes: <500 M3 | 48 | 0.35 | 0.31 | 0.28 | 48 | 0.063 | 0.028 | 0.060 |
| All Homes: >500 M3 | 61 | 0.35 | 0.30 | 0.28 | 61 | 0.062 | 0.037 | 0.049 |
| Total All R-2000 Homes: | 109 | 0.35 | 0.30 | 0.28 | 109 | 0.063 | 0.033 | 0.054 |
| Total All Control Homes: | 34 | 0.25 | 0.20 | 0.17 | 34 | 0.059 | 0.028 | 0.050 |
| SPACE HEATING FUEL TYPE | | | | | | | | |
| R-2000 HOMES: | | | | | | | | |
| Electricity | 65 | 0.39 | 0.50 | 0.27 | 65 | 0.066 | 0.035 | 0.058 |
| Other | 44 | 0.36 | 0.29 | 0.30 | 44 | 0.058 | 0.030 | 0.049 |
| CONTROL HOMES: | | | | | | | | |
| Electricity | 14 | 0.20 | 0.18 | 0.14 | 14 | 0.066 | 0.019 | 0.059 |
| Other | 19 | 0.28 | 0.22 | 0.20 | 19 | 0.055 | 0.033 | 0.042 |
| SPACE HEATING DISTRIBUTION TYPE | | | | | | | | |
| R-2000 HOMES: | | | | | | | | |
| Electric Baseboard | 39 | 0.33 | 0.25 | 0.27 | 39 | 0.069 | 0.036 | 0.062 |
| Forced Air | 67 | 0.39 | 0.49 | 0.28 | 67 | 0.060 | 0.031 | 0.054 |
| CONTROL HOMES: | | | | | | | | |
| Electric Baseboard | 13 | 0.18 | 0.19 | 0.12 | 13 | 0.063 | 0.015 | 0.058 |
| Forced Air | 20 | 0.28 | 0.21 | 0.26 | 20 | 0.057 | 0.034 | 0.042 |
| VENTILATION AIR DISCHARGE (R-2000) | | | | | | | | |
| Basement | 32 | 0.30 | 0.17 | 0.26 | 32 | 0.069 | 0.033 | 0.068 |
| Main Living Area | 37 | 0.40 | 0.39 | 0.28 | 37 | 0.062 | 0.038 | 0.046 |
| Furnace Cold Air Return | 12 | 0.36 | 0.22 | 0.36 | 12 | 0.053 | 0.026 | 0.049 |
| Near Furnace Cold Air Return | 18 | 0.31 | 0.21 | 0.27 | 18 | 0.060 | 0.033 | 0.051 |

NOTE: CATS Measured House Ventilation refers to the Brookhaven National Laboratory "Capillary Adsorption Tube Sampler" tracer gas (perfluorocarbon)method of determining average air change