INDOOR AIR QUALITY MONITORING OF THE FLAIR HOMES ENERGY DEMO/ CHBA FLAIR MARK XIV PROJECT

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SUMMARY

A comprehensive monitoring program was established to evaluate the indoor air quality of 20 new houses constructed as part of the Flair Homes Energy Demo/Canadian Home Builders Association Flair Mark XIV Project in Winnipeg. Sixteen of the houses were constructed to the R-2000 Standard and four to conventional energy conservation standards; all contained some type of mechanical ventilation system. Monitoring was carried out over a three year period from March 1986 to March 1989. Formaldehyde, radon daughter, particulate, nitrogen dioxide, carbon dioxide and relative humidity levels were measured on a regular basis along with the total air change rates.

The air quality in the R-2000 houses was found to be superior to that in the conventional structures. Mean concentrations of formaldehyde, particulates and nitrogen dioxide were lower, although not to statistically significant degrees. Geometric mean radon daughter levels and median carbon dioxide concentrations were also lower in the R-2000 houses and relative humidity levels were more frequently within the recommended winter exposure range.

The mean formaldehyde concentration in the R-2000 houses was 0.060 ppm compared to 0.068 ppm in the conventional units. Significantly higher formaldehyde levels were found in those R-2000 houses which were not operated in accordance with the R-2000 Ventilation Guidelines compared to those which were maintained in compliance with the Guidelines: 0.089 ppm vs. 0.047 ppm. It was concluded that the Action Level for formaldehyde of 0.100 ppm, established by the Federal-Provincial Advisory Committee on Environmental and Occupational Health, was readily achievable in the project houses while the Target Level of 0.050 ppm could not be reached on a consistent basis, using ventilation as the sole formaldehyde control measure.

The geometric mean radon daughter concentration in the R-2000 houses was 0.007 WL compared to 0.010 WL in the conventional houses. Only one of 123 measurements exceeded the Canadian exposure guideline of 0.100 WL. Radon daughter levels in both the R-2000 and conventional houses were well below those reported in a similar study of older, conventional houses in Winnipeg.

The mean level of particulates in houses which contained smokers averaged 44 $\mu g/m^3$ compared to 28 $\mu g/m^3$ for those without smokers. This difference was found to be statistically significant and occurred even though the houses with smokers experienced higher average air change rates. The guideline for particulates in residential environments is 40 $\mu g/m^3$.

The mean nitrogen dioxide level in the R-2000 houses was 0.0040 ppm compared to 0.0044 ppm for the conventional houses, although this difference was not statistically significant. All readings were well below the recommended exposure guideline of 0.05 ppm.

Spot measurements of carbon dioxide concentrations were made on over one thousand occasions and only one reading exceeded the recommended exposure guideline of 3500 ppm; further, 94% of the readings were below 1000 ppm. Using a sub-set of 587 carbon dioxide measurements made with high resolution samplers, the median concentration in R-2000 houses was found to be 600 ppm compared to 800 ppm in the conventional houses.

Mean relative humidity levels were more frequently within the recommended winter exposure range of 30% to 55% in the R-2000 houses compared to those in the conventional structures.

Statistical correlations between pollutant concentrations and the corresponding air change rates were found to generally be poor. In the case of formaldehyde, higher ventilation rates reduced the occurrence of extreme concentrations and thereby improved confidence in the quality of the indoor air. Nonetheless, these findings highlighted the limitations of using mechanical ventilation as the sole means of achieving acceptable air quality at the pollutant concentrations which were encountered in the study. It was concluded that greater emphasis should be placed on other control measures including source removal and isolation, pollutant entry control and improved ventilation system efficiency/effectiveness.

Homeowner intervention with the mechanical ventilation systems was a common occurrence and often resulted in lower than expected system utilization. This problem was particularly evident in the houses equipped with bathroom exhaust fans and those with central exhaust systems and make-up air ducts. It was concluded that design rates used for ventilation systems, particularly for those systems which do not have heat recovery capabilities, should be established both on the ability of the system to remove pollutants as well as the effect homeowner utilization will have on the net ventilation rate.

Recommendations were made for improving mechanical ventilation systems including suggestions regarding control systems, system capacity, homeowner-perceived operating performance and homeowner education.

RÉSUMÉ

On a mis sur pied un programme de contrôle exhaustif en vue d'évaluer la qualité de l'air à l'intérieur de 20 maisons neuves construites dans le cadre du Projet de démonstration de la maison à haut rendement énergétique/Mark XIV de l'ACCH, de Flair, à Winnipeg. Seize (16) de ces maisons étaient construites conformément à la norme R-2000 et quatre (4), conformément aux normes d'économie d'énergie classiques; toutes étaient dotées d'un type quelconque de système de ventilation mécanique. Les contrôles se sont déroulés sur une période de trois ans, soit de mars 1986 à mars 1989. On a mesuré à intervalles réguliers les taux de formadéhyde, de produit de filiation du radon, de particules, de dioxyde d'azote et d'humidité relative, de même que les taux de renouvellement d'air totaux.

La qualité de l'air dans les maisons R-2000 s'est avérée supérieure à celle des constructions classiques. Les concentrations moyennes de formaldéhyde, de particules et de dioxyde d'azote étaient plus faibles mais pas à des degrés statistiquement pertinents. Les taux de produit de filiation du radon selon la moyenne géométrique et les concentrations moyennes de dioxyde de carbone étaient également inférieurs dans les maisons R-2000, et les taux d'humidité relative dotés étaient plus fréquemment compris à l'intérieur des limites d'exposition recommandées.

La concentration moyenne de formaldéhyde était de 0,060 ppm dans les maisons R-2000 et de 0,068 ppm dans les maisons de construction classique. On a noté des taux de formaldéhyde considérablement plus élevés dans les maisons R-2000 dans lesquelles on n'avait pas observé les lignes directrices sur la ventilation des habitations à facteur d'isolation R-2000 que dans celles qui avaient été tenues en conformité avec ces lignes directrices, soit 0,089 ppm par rapport à 0,047 ppm. On en a conclu que le seuil d'intervention de 0,100 ppm établi pour le formaldéhyde par le Comité consultatif fédéral-provincial de l'hygiène du milieu et du travail pouvait être obtenu facilement dans les maisons du projet tandis que le taux cible de 0,050 ppm ne pouvait être observé avec constance, lorsque la ventilation était la seule méthode de contrôle du taux de formaldéhyde.

La concentration de produit de filiation du radon selon la moyenne géométrique était de 0,007 WL dans les maisons R-2000 et de 0,010 WL dans les maisons de type classique. Une seule des 123 mesures a dépassé le niveau de la ligne directrice canadienne établi à 0,100 WL. Dans les maisons R-2000 comme dans les autres maisons, les niveaux de produit de filiation du radon étaient bien en deçà de ceux qui avaient été notés dans une étude semblable qui portait sur des maisons de construction classique plus vieilles, menée à Winnipeg.

Le taux moyen de particules dans les maisons occupées par des fumeurs s'élevait à 44 $\mu g/m^3$, comparé à 28 $\mu g/m^3$ dans le cas des maisons qui ne comptaient pas de fumeurs. Cet écart s'est avéré statistiquement pertinent, d'autant plus que l'on note un taux de renouvellement d'air moyen plus élevé dans les maisons occupées par des fumeurs. La norme pour les taux de particules en milieux résidentiels est de 40 $\mu g/m^3$.

Le niveau moyen de dioxyde d'azote était de 0,0040 ppm dans les maisons R-2000 et de 0,0044 ppm dans les maisons classiques, mais cet écart n'est pas statistiquement pertinent. Toutes les lectures notées étaient bien en deçà de la limite d'exposition de 0,05 ppm de la ligne directrice.

Plus de 1 000 relevés ponctuels des concentrations de dioxyde de carbone ont été effectués, et une seule de ces lectures dépassait la limite d'exposition prescrite de 3 500 ppm. En outre, 94 % de ces lectures étaient inférieures à 1 000 ppm. Lorsqu'on a utilisé un sous-ensemble de 587 relevés de dioxyde de carbone effectués avec des échantillons à haute résolution, la concentration moyenne était de 600 ppm dans le cas des maisons R-2000 et de 800 ppm dans le cas des maisons de construction classique.

Les taux moyens d'humidité relative des maisons R-2000 étaient plus fréquemment compris à l'intérieur de la plage d'exposition hivernale recommandée de 30 % à 55 %.

Les corrélations statistiques entre les concentrations de polluants et les taux de renouvellement d'air correspondants se sont révélées faibles, de façon générale. Dans le cas du formaldéhyde, les taux de renouvellement d'air plus élevés réduisaient la fréquence des concentrations extrêmes et, par conséquent, amélioraient la fiabilité en termes de qualité de l'air à l'intérieur des maisons. Néanmoins, ces résultats ont confirmé les limites de l'utilisation de la ventilation mécanique comme unique moyen d'obtenir une qualité de l'air acceptable, aux concentrations de polluants relevées dans le cadre de l'étude. On en a conclu qu'il fallait mettre davantage en valeur d'autres mesures de contrôle, y compris l'élimination et l'isolation à la source, les contrôles de la pénétration des polluants et l'amélioration du rendement/de l'efficacité des installations de ventilation.

L'intervention du propriétaire parallèlement aux systèmes de ventilation mécanique s'est avérée courante et a souvent eu pour résultat un taux d'utilisation des installations plus faible que prévu. Ce problème était tout particulièrement évident dans les maisons dotées de ventilateurs d'aspiration de salle de bain et celles dotées d'un système à extraction centrale et de conduits d'air de compensation. On en a conclu que les taux de calcul utilisés pour les installations de ventilation, plus particulièrement celles qui ne sont pas dotés de caractéristiques de récupération de chaleur, devaient être fondés tant sur la capacité du système à éliminer les polluants que sur l'incidence qu'a l'utilisation du système par le propriétaire sur le taux net de renouvellement d'air.

Des recommandations ont été faites quant à l'amélioration des installations de ventilation mécanique, y compris des suggestions relativement aux systèmes de contrôle, à la capacité des installations, au rendement opérationnel tel qu'il est perçu par le propriétaire ainsi qu'à l'éducation du propriétaire.

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SECTION 1

INTRODUCTION

1.1 BACKGROUND TO THIS REPORT

In February 1989, the "Interim Report on Indoor Air Quality Monitoring of the Flair Homes Energy Demo/CHBA Flair Mark XIV Project" was released (Proskiw). It summarized the air quality surveys conducted as part of the Flair project for the period March 1986 to February 1987. This current document, the final report, incorporates the results for the full three year monitoring period, March 1986 to March 1989. Much of the information found in the Interim Report has been incorporated herein; exceptions are so noted.

1.2 RESIDENTIAL INDOOR AIR QUALITY

Indoor air quality is probably the most controversial aspect of residential building science. Since the Second World War, the product delivered by the Canadian home building industry has evolved from a leaky, draft-ridden structure which relied upon poorly understood and totally uncontrolled forces to provide ventilation, to the present-day house which often features airtight construction of the building envelope and a sophisticated mechanical ventilation system. Countering this improvement has been the increased use of numerous materials, products and systems which can threaten air quality in the modern home.

In principle, it is not difficult to construct a house which provides acceptable air quality. The difficulty is finding means to achieve this goal in a manner, and at a cost, which the average homeowner can afford and will accept. The challenge faced by the industry is to identify affordable and practical measures to safeguard indoor air quality and to develop standards and systems to permit their effective implementation.

1.3 OBJECTIVE

The purpose of this study was to survey the indoor air quality in 20 of the houses constructed as part of the Flair Homes Energy Demo/CHBA Flair Mark XIV project.

1.4 THE FLAIR HOMES ENERGY DEMO/CHBA FLAIR MARK XIV PROJECT

The work described in this report was conducted as part of the Flair Homes Energy Demo/CHBA Flair Mark XIV Project. This project was created in 1985 to provide a demonstration of various energy conservation technologies, products and systems which might be suitable for the Canadian home building industry. The specific objectives of the project were:

1. To demonstrate and evaluate the performance of various low energy building envelope systems.

2. To demonstrate and evaluate the performance of various space heating, hot water heating and mechanical ventilation systems.

3. To transfer the knowledge gained in the project to the Canadian home building industry.

Support for the project was provided by Energy, Mines and Resources Canada under the Energy Demo Program and by Manitoba Energy and Mines under the Manitoba/Canada Conservation and Renewable Energy Demonstration Agreement (CREDA). Project management was the responsibility of Flair Homes (Manitoba) Ltd. Project monitoring and reporting were performed by UNIES Ltd., consulting engineers, of Winnipeg.

The project was also designed to provide technical support to the R-2000 Home Program, which is funded by Energy, Mines and Resources Canada and administered by the Canadian Home Builders Association (CHBA). The CHBA's "Mark XIV" designation was acquired when a major portion of the research priorities identified by the CHBA's Technical Research Committee was incorporated into the work plan.

To meet the project's objectives, 24 houses were constructed in Winnipeg by Flair Homes Ltd. and independently monitored for periods of up to three years. Energy conservation levels ranged from those of conventional houses to those which met or exceeded the R-2000 Standard.

1.5 DESCRIPTION OF THE PROJECT HOUSES

Indoor air quality monitoring was carried out in Houses #1 to #20. Built in 1985 and 1986 these houses were divided into 10 pairs with each pair possessing a unique combination of envelope features and mechanical systems. A summary of the houses is provided in Table 1 and more detailed descriptions are given in Proskiw (1992).

The 20 houses were all detached bungalows with similar floor plans, full basements and main floor areas ranging from 60 m^2 to 85 m^2 (646 ft^2 to 915 ft^2). Sixteen were constructed to the R-2000 Standard with the remaining four built to conventional conservation standards. All were equipped with mechanical ventilation systems ranging from small-capacity bathroom exhaust fans to Heat Recovery Ventilators (HRVs) designed to run on a continuous basis and provide fresh air distribution to all zones of the house. Sixteen of the ventilation systems used multi-speed controls which permitted flow rates to be automatically or manually adjusted. Ventilation rates for the R-2000 houses were established in accordance with the R-2000 Home Program Design and Installation Guidelines for Ventilation Systems (1986) which required a minimum continuous mechanical ventilation rate of 0.35 air changes per hour (ac/hr).

TABLE 1
DESCRIPTION OF PROJECT HOUSES

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HOUSE	BUILDING ENVELOPE					MECHANICAL SYSTEMS		YEAR COMPLETED	ENERGY STANDARD
	WALL CONSTRUCTION	EXTERIOR WALL FINISH	BASEMENT CONSTRUCTION	CEILING/ATTIC CONSTRUCTION	WINDOWS	SPACE HEATING SYSTEM	VENTILATION SYSTEM		
1-6	38x140 (2x6), Rigid Glass Fibre Insulated Sheathing (Reversed) c/w SBPO Air Retarder	Stucco with Wood or Brick Siding	Cast Concrete	Cathedral & Truss Ceilings	Triple-Glazed; Fixed, Awning & Casement	Electric Forced Air Furnace	Heat Recovery Ventilator	1985	R-2000
7,8	38x140 (2x6)	Stucco with Wood Siding	Cast Concrete	Cathedral & Truss Ceilings	Triple-Glazed; Fixed, Awning & Casement	Electric Forced Air Furnace	Central Exhaust with Make-Up Air Duct	1985	Conventional
9,10	38x140 (2x6)	Stucco with Stone & Wood Siding	Cast Concrete	Cathedral & Truss Ceilings	Triple-Glazed; Fixed, Awning & Casement	Gas Forced Air Furnace	Bathroom Exhaust Fan	1985	Conventional
11-14	38x140 (2x6), Rigid Glass Fibre Insulated Sheathing c/w SBPO Air Retarder	Stucco with Wood, Brick or Stone Siding	Cast Concrete	Truss Ceiling	Triple-Glazed; Fixed, Awning & Casement	Electric Baseboards or Forced Air Furnace	Exhaust-only Heat Pump or Heat Recovery Ventilator	1986	R-2000
15,16	Double Wall	Stucco with Wood Siding	Cast Concrete	Truss Ceiling	Triple-Glazed; Fixed, Awning & Casement	Air-to-Air Heat Pump	Integrated with Space Heating System	1986	R-2000
17,18	Double Wall	Stucco with Brick, Wood or Stone Siding	Cast Concrete	Truss Ceiling	Triple-Glazed; Fixed, Awning & Casement	Electric Baseboards	Heat Recovery Ventilator	1986	R-2000
19,20	38x89 (2x4), Rigid Extruded Polystyrene Sheathing	Stucco with Wood & Brick Siding	Cast Concrete	Truss Ceiling	Triple-Glazed; Fixed, Awning & Casement	Electric Baseboards	Heat Recovery Ventilator	1986	R-2000

Several other features were incorporated into the ventilation systems to improve their performance. For example, ten of the houses used high sidewall supply registers to minimize the cool drafts which can be created by continuous operation of the air distribution system. These introduce the heating/ventilation air close to the ceiling in a horizontal plume thereby preventing direct impingement of the air jet on the occupants. The 14 houses which used forced air heating systems also had individual room return air registers to improve air circulation.

All 20 houses, including the conventional structures, were constructed with tight building envelopes to minimize natural air infiltration. Airtightness levels, measured in accordance with CAN/CGSB Standard 149.10-M86 (1986), ranged from 0.40 to 1.77 air changes per hour at 50 Pascals (ac/hr_{50}) when tested in March 1989.

1.6 OVERVIEW OF THE MONITORING PROGRAM

The indoor air quality monitoring program extended over a three year period from March 1986 to March 1989 and included monitoring of the following pollutants:

- Formaldehyde
- Radon daughters
- Particulates
- Nitrogen dioxide
- Carbon dioxide
- Relative humidity

In addition, total air change rates (i.e. natural and mechanical) were measured on several occasions, coincident with the pollutant surveys. Indoor dry bulb temperatures were monitored using recording thermohygrographs installed at central locations in the living/dining areas. Additional quantitative and qualitative information on house performance and occupancy was obtained through regular contact with the homeowners.

Various statistical comparisons were made between observed pollutant concentrations, air change rates, environmental conditions, etc. using two-sided t or z-tests (for small and large sample sizes respectively) with a 5% level of significance.

Sections 2 through 7 of this report summarize and discuss the pollutant surveys. Section 8 reviews the air change rate measurements and Section 9 considers the implications of the study results with respect to indoor air quality and mechanical ventilation.

SECTION 2

FORMALDEHYDE

2.1 INTRODUCTION

Formaldehyde (HCHO) is colourless gas with a pungent odour that is found in both the indoor and outdoor environments. Although formed naturally outdoors, most of the formaldehyde found indoors originates from manufactured goods and materials within the home. In new houses, the major sources are particleboard, medium density fibreboard and hardwood plywood panelling. Some consumer products and household chemicals also use it as a constituent of glues or coatings. Cigarette smoke is known to contain formaldehyde.

For a home builder, formaldehyde which originates from construction materials is a particular concern since he can exercise some control over material selection and use. Emission rates from construction products are known to vary substantially with time and ambient conditions. For example, they have been shown to increase with temperature and with increased absolute humidity (Godish and Rouch 1986). Conventional wisdom states that emission rates decrease with time as the chemical is depleted from the exposed surfaces of the material, although this process may extend over several years.

Emission rates from manufactured products are also thought to be affected by the concentration of formaldehyde in the ambient air, although the evidence is somewhat contradictory. Nelms et al (1986) studied emission rates from commercially produced particleboard using varying ventilation rates and material loadings in test chambers and found increased emission rates at lower ambient concentrations. However, Godish and Rouch (1987) investigated formaldehyde source interactions in both houses and test chambers and were unable to reproduce chamber results in the houses, so the applicability of the chamber studies is unclear.

Formaldehyde is a suspected carcinogen and is also acknowledged as a sensory irritant, primarily affecting the respiratory and nasal passages and the eyes. As is the case with most pollutants, people demonstrate varying tolerances to formaldehyde with some individuals, especially those with chemical sensitivities, being strongly affected by its presence.

The following residential exposure guidelines have been established for formaldehyde by the Federal-Provincial Advisory Committee on Environmental and Occupational Health (1989) (the concentrations are expressed in parts per million):

0.050 ppm as a Target Level
0.100 ppm as an Action Level

The concept of a "Target Level" was created as the long term objective which could be aimed at whereas the "Action Level" was considered a guideline which could be attained with current technology. Prior to the release of these guidelines, 0.100 ppm, as suggested by ASHRAE 62-81 (1981), had generally been accepted for long-term exposures.

2.2 RELATED STUDIES

The R-2000 Program monitored formaldehyde levels in both R-2000 and conventional houses beginning in 1984. Piersol and Mijailovic (1987) found formaldehyde levels in R-2000 houses to be lower than those in conventional structures. Annual mean levels in the R-2000 houses ranged from 0.045 ppm to 0.069 ppm whereas those in the conventional houses ranged from 0.057 ppm to 0.070 ppm. The primary reason for the elevated levels was attributed to problems with the ventilation systems, specifically inadequate ventilation rates or distribution systems. As a consequence, the R-2000 Guidelines were altered in 1986 to provide better control of these factors. Ventilation systems in the 1984/85 houses were subsequently upgraded to the revised Guidelines and the resulting air quality was reported as being comparable to newer R-2000 houses (Riley 1988). Formaldehyde levels measured in R-2000 houses constructed in 1986 and 1987 were lower than those of the earlier houses, with mean values equal to, or less than the 0.050 ppm Target Level. Standard deviations also declined - a desirable characteristic from a quality control perspective. These improvements were attributed to the Guideline changes and their more rigorous enforcement.

A multi-year monitoring project was also conducted by the Ontario Ministry of Energy on 22 R-2000 and five conventional new houses (Buchan, Lawton, Parent Ltd. 1986). Results from the 1986 tests indicated that approximately 1% of all formaldehyde measurements exceeded 0.100 ppm while approximately 40% exceeded 0.050 ppm, even though some of the R-2000 units were not operated in accordance with the R-2000 Guidelines.

Formaldehyde levels were also monitored during 1989 in 48 new, conventional houses as part of a cross-country survey of merchant-built housing (Hamlin et al 1990). The mean reported concentration was 0.071 ppm with a standard deviation of 0.028 ppm.

2.3 MONITORING PROCEDURES

Formaldehyde levels in the Flair project were measured on 141 occasions using Air Quality Research Inc. PF-1 passive diffusion dosimeters. Two dosimeters were installed during each test: one in the main bedroom and the second in the living/dining room area. Exposure periods were approximately one week. Laboratory analysis was performed by ORTECH International.

2.4 RESULTS

The formaldehyde data is summarized in Table 2 and a more complete data set is attached in Appendix A. Mean formaldehyde levels for each house were calculated as the mean of the two measurements made in each house during each survey.

Table 3 contains a reduction of the data for the R-2000 houses based on the structures' compliance with the R-2000 Ventilation Guidelines. During the routine site visits, several of the HRV systems were found to not be operating in accordance with the Guidelines, as determined through measurement of their air flow rates. Data in the first row of Table 3 shows the mean formaldehyde levels for the R-2000 houses which initially appeared to meet the Guidelines, based on a single set of HRV flow rate measurements. This data was sub-divided into two categories, A and B, based on the PFT air change rate measurements (discussed in Section 8) conducted during the formaldehyde monitoring. This provided independent determination of the air change rate and, after an allowance had been made for natural infiltration, permitted the mechanical ventilation rate to be estimated. Category A houses were defined as those in which reasonable agreement was found between the HRV flow rates and the PFT data and it could therefore be concluded that the ventilation systems were operated in accordance with the Guidelines. Category B houses were those which initially appeared to meet the Guidelines, based on the single HRV flow rate measurement, but whose PFT measurements indicated that this had not been the case due to homeowner intervention or mechanical failures.

2.5 DISCUSSION

R-2000 vs. Conventional Houses

A total of 110 sets of formaldehyde measurements were made in the R-2000 houses and 31 in the conventional structures. Except for two survey periods which had small sample sizes, the R-2000 houses displayed lower mean formaldehyde levels than the conventional houses, 0.060 ppm vs. 0.068 ppm. However, a statistical comparison made to evaluate the significance of the difference between these two sample means (using a two-sided z test and a 5% level of significance) indicated that the difference was not statistically significant. The observed formaldehyde concentrations for the conventional houses were similar to those reported by Hamlin for 48 conventional new houses (1990).

Another method of comparing formaldehyde levels between groups is to examine the percentage of measurements which exceed the Target and Action Levels of 0.050 ppm and 0.100 ppm respectively. As shown in Table 2, 57% of the measurements in the R-2000 houses exceeded the Target Level versus 81% in the conventional houses; 8% and 10%, respectively, exceeded the Action Level.

TABLE 2

FORMALDEHYDE LEVELS - FLAIR HOUSES

CATEGORY	NO. OF HOUSE MEASUREMENTS	MEAN (ppm)	STANDARD DEVIATION (ppm)	MEASUREMENTS >0.050 ppm TARGET LEVEL		MEASUREMENTS >0.100 ppm ACTION LEVEL	
				NUMBER	%	NUMBER	%
R-2000 HOUSES							
March 1986	6	0.060	0.016	4	67	0	0
August 1986	16	0.058	0.023	10	63	1	6
October 1986	16	0.080	0.028	16	100	2	13
February 1987	16	0.057	0.021	9	56	1	6
August 1987	4	0.123	0.077	3	75	2	50
October 1987	16	0.048	0.016	7	44	0	0
January 1988	16	0.052	0.018	8	50	1	6
September 1988	4	0.118	0.084	3	75	2	50
January 1989	16	0.039	0.014	3	19	0	0
Cumulative	110	0.060	0.034	63	57	9	8
CONVENTIONAL HOUSES							
March 1986	4	0.078	0.029	3	75	1	25
August 1986	4	0.066	0.014	4	100	0	0
October 1986	3	0.089	0.021	3	100	1	33
February 1987	4	0.067	0.019	4	100	0	0
August 1987	2	0.065	0.029	1	50	0	0
October 1987	4	0.073	0.036	3	75	1	25
January 1988	4	0.056	0.017	3	75	0	0
September 1988	2	0.071	0.010	2	100	0	0
January 1989	4	0.052	0.015	2	50	0	0
Cumulative	31	0.068	0.022	25	81	3	10
VENTILATION SYSTEM							
Bathroom Fan	18	0.079	0.022	16	89	3	17
Central Exhaust & Make-Up Air Duct	13	0.052	0.010	9	69	0	0
HRV	110	0.060	0.034	63	57	9	8
HEATING SYSTEM (R-2000 ONLY)							
Forced Air	70	0.064	0.039	41	59	8	11
Baseboard	40	0.054	0.021	22	55	1	3
PRESENCE OF SMOKERS							
Non-Smokers	60	0.060	0.020	41	68	3	5
Smokers	81	0.064	0.038	47	58	9	11

TABLE 3

EFFECT UPON FORMALDEHYDE LEVELS OF APPARENT AND ACTUAL COMPLIANCE WITH THE R-2000 VENTILATION GUIDELINES

	NUMBER OF HOUSE MEASUREMENTS	MEAN (ppm)	STANDARD DEVIATION (ppm)	MEASUREMENTS >0.05 ppm TARGET LEVEL		MEASUREMENTS >0.10 ppm ACTION LEVEL	
				NUMBER	%	NUMBER	%
Houses which Appeared to Meet the R-2000 Ventilation Guidelines as Determined by a Single Measurement of HRV Flow Rates	37	0.064	0.041	21	57	5	14
CATEGORY A Houses Actually Operated in Compliance with the R-2000 Ventilation Guidelines, as Verified using the PFT Data	22	0.047	0.017	9	41	0	0
CATEGORY B Houses Not Operated in Compliance with the R-2000 Ventilation Guidelines, as Determined using the PFT Data	15	0.089	0.051	12	80	5	33

From the perspective of air quality and ventilation standards, the Action Level of 0.100 ppm was found to be readily achievable, given the presence and use of a good quality mechanical ventilation system. However, the Target Level of 0.050 ppm could not be reached on a consistent basis although mean levels were often close to this value. These results suggest that to achieve the Target Level on a reliable basis would require additional control measures. However, as will be discussed in Section 8, the variation in formaldehyde levels decreased significantly at higher total air change rates thereby reducing the probability of unusually high levels and, in effect, lowering the risk of an air quality problem.

It should also be stressed that the R-2000 results includes data from houses not operated in compliance with the Ventilation Guidelines. From Table 3, it can be seen that a (statistically significant) difference was found between levels in the Category A and Category B houses with sample mean concentrations of 0.047 ppm and 0.089 ppm respectively. Further, 41% of the Category A measurements exceeded the Target Level versus 80% of the Category B measurements; corresponding percentages for the Action Level were 0% and 33%, respectively. Most houses were classified as Category B because of homeowner intervention with the system. Many occupants adjusted speed control settings to reduce flow rates or disconnected the power supply to the HRV. Houses operated in "nominal" compliance with the Ventilation Guidelines were those with measured minimum mechanical ventilation rates of 0.35 ac/hr. The independently measured air change rates indicated that this ventilation rate had not been maintained during approximately one-third of the formaldehyde sampling periods.

Based on these experiences, homeowner intervention with the ventilation system was highlighted as a significant problem, especially from a codes and standards perspective. Homeowners in the Flair houses received detailed instructions on the purpose and use of the systems, including the need to maintain continuous operation. However, they frequently reduced ventilation rates to cut energy costs, control noise or reduce ventilation system drafts.

Type of Ventilation System

The formaldehyde data was analyzed on the basis of the type of ventilation system. As shown in Table 2, houses with HRVs had lower mean levels than those with simple bathroom fans, to a statistically significant degree. However, the mean observed level in houses with central exhaust systems and make-up air ducts was lower than that in houses with HRVs, although the difference was not statistically significant.

Type of Heating System (R-2000 Houses)

Formaldehyde levels in the R-2000 houses equipped with baseboard heating were lower than those in R-2000 houses with forced air heating systems, but not to a statistically significant degree. Figure 1 shows the measured bedroom

FIGURE 1(a)

FORCED AIR HEATING SYSTEMS

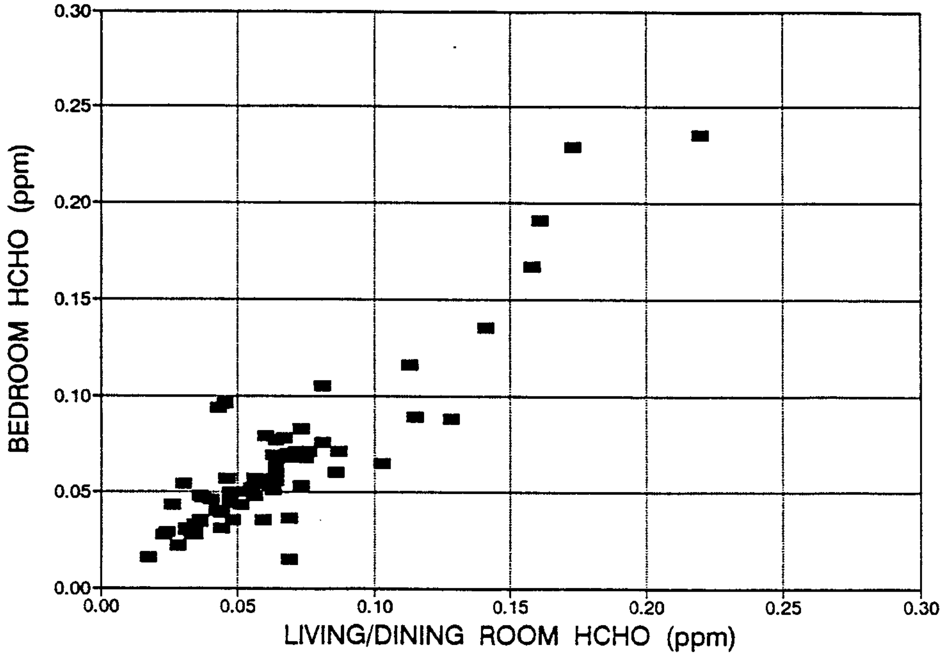
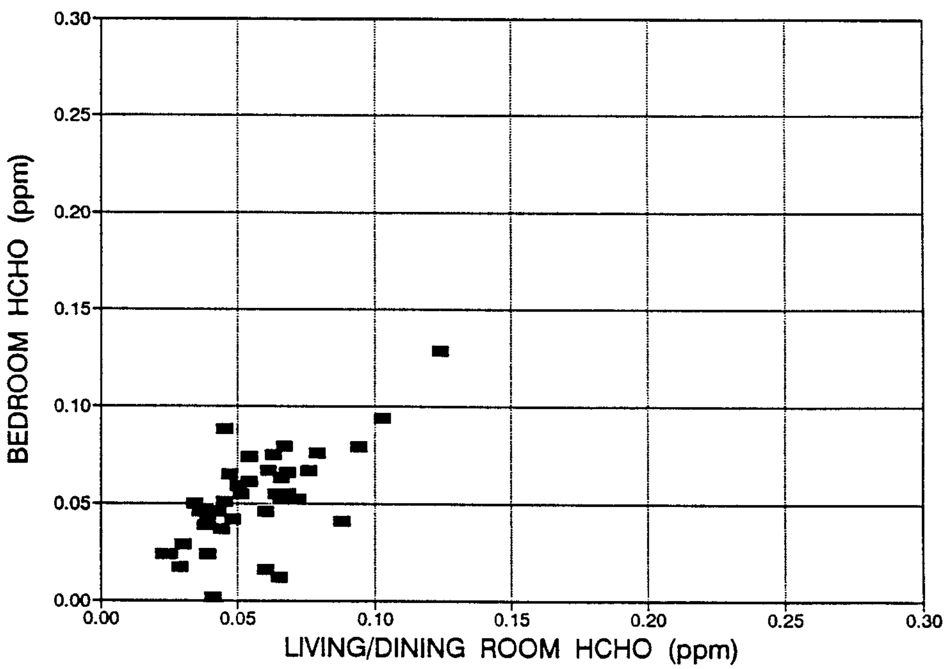


FIGURE 1(b)

BASEBOARD HEATING SYSTEMS



formaldehyde levels plotted against the living/dining room levels for the two types of heating systems. The scatter about the line of perfect correlation (i.e. the 45° line) illustrates the ability of the ventilation systems to mix the interior air (the lower the scatter, the better the mixing). The forced air systems produced better mixing than the baseboard systems which used a dedicated ductwork system to distribute the outdoor air. Correlation coefficients were 0.90 and 0.67, respectively, for the two types of systems.

Presence of Smokers

Mean formaldehyde levels were slightly higher in houses which contained a smoker, although not to a statistically significant degree even though houses with smokers had higher air change rates, 0.40 ac/hr vs. 0.32 ac/hr (see Section 8).

Formaldehyde Source Strength

An analysis was also conducted to study the behaviour of the apparent formaldehyde source strength. The indoor concentration of a pollutant can be expressed as:

$$C_i = C_o + N/V_t \qquad (1)$$

where:
C_i = Indoor concentration, $\mu g/m^3$
C_o = Outdoor concentration, $\mu g/m^3$
N = Source emission rate, $\mu g/s$
V_t = Total (natural and mechanical) air change rate, m^3/s.

Mass units can be used to express the pollutant concentration and Eq. 1 can be reorganized to give:

$$N = V_t(C_i - C_o), \text{ or} \qquad (2)$$

$$N = [(ac/hr)(V)(C_i - C_o)]/(3600)$$

where:
ac/hr = Air changes per hour
V = House volume, m^3.

To reduce the effect of house size, Eq. 2 can be divided by a suitable size parameter, such as floor area (A), to produce:

$$N_a = [(ac/hr)(V)(C_i - C_o)]/[(3600)(A)] \qquad (3)$$

where:
N_a = Unit area source strength, $\mu g/s \cdot m^2$.

N_a provides a convenient parameter to express the emission rate of a pollutant independent of house size and air change rate.

Outdoor air formaldehyde levels (C_o) were measured on two occasions during the winter of 1989 at the project site using the National Institute of Occupational Safety and Health (NIOSH) Method #P&CAM125.

To minimize extraneous interactions from smokers and sources of formaldehyde introduced after construction, the formaldehyde data was edited to remove all results in which a smoker was present or in which new furnishings or interior renovations had been introduced within the preceding six months. Figures 2 and 3 show N_a as a function of indoor temperature and absolute humidity, respectively, for the edited data. Both parameters have been suggested as factors which influence indoor formaldehyde levels. Correlations in both instances were poor, with correlation coefficients of 0.09 and 0.27, respectively. In contrast, Godish and Rouch (1986) were able to demonstrate a strong dependence between formaldehyde levels and temperature in a single unoccupied mobile home, with other variables held constant, using indoor temperatures ranging from 20 °C to 30 °C.

Figure 4(a) shows the formaldehyde source strength for each monitoring period and as evident, no clear trend is initially apparent. However, when this data was edited to include only seasonally coincident measurements from a common group of houses, Fig. 4(b), a steady reduction in the source strength was observed with N_a declining by 48% between February 1987 and February 1989.

For reference purposes, the density of potential building product formaldehyde sources was estimated for the study houses and found to be lower than published values for typical houses. The product loading, defined as the area of potential emitters per unit of house volume, was estimated to range from 0.1 m^2/m^3 to 0.2 m^2/m^3 for the 20 houses, exclusive of furniture. Nelms et al (1986) give a typical residential formaldehyde product loading for particleboard of 0.4 m^2/m^3.

FIGURE 2

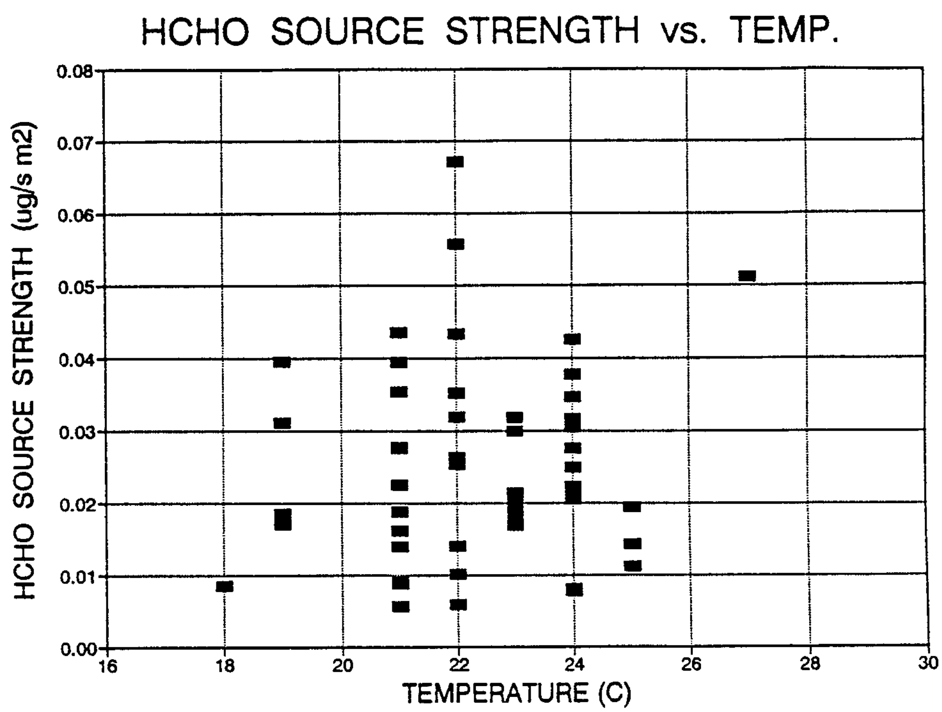


FIGURE 3

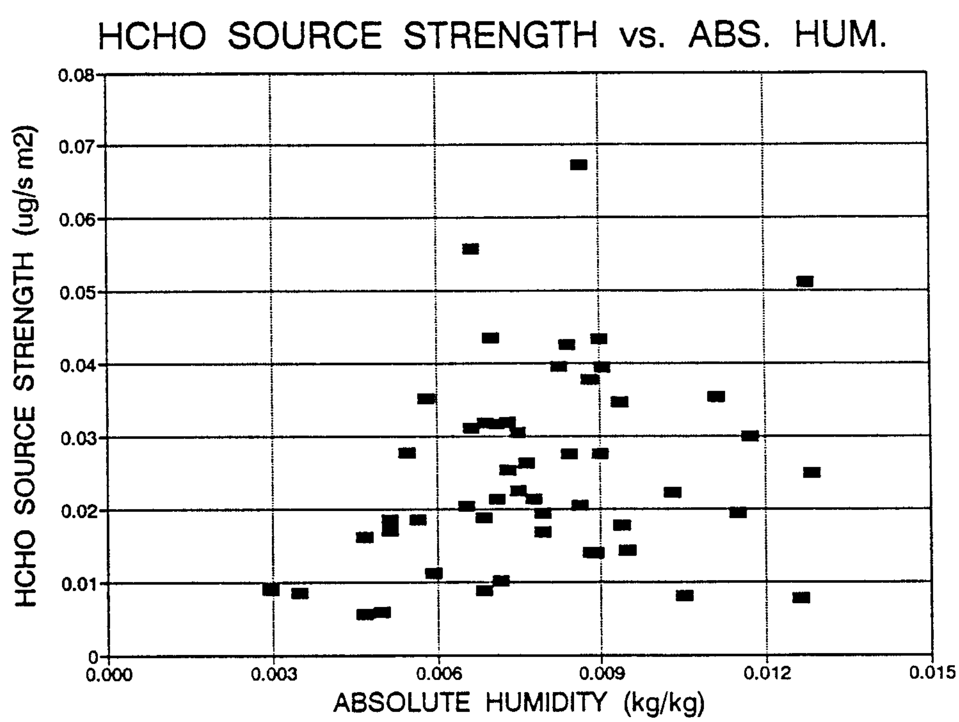


FIGURE 4(a)

HCHO SOURCE STRENGTH

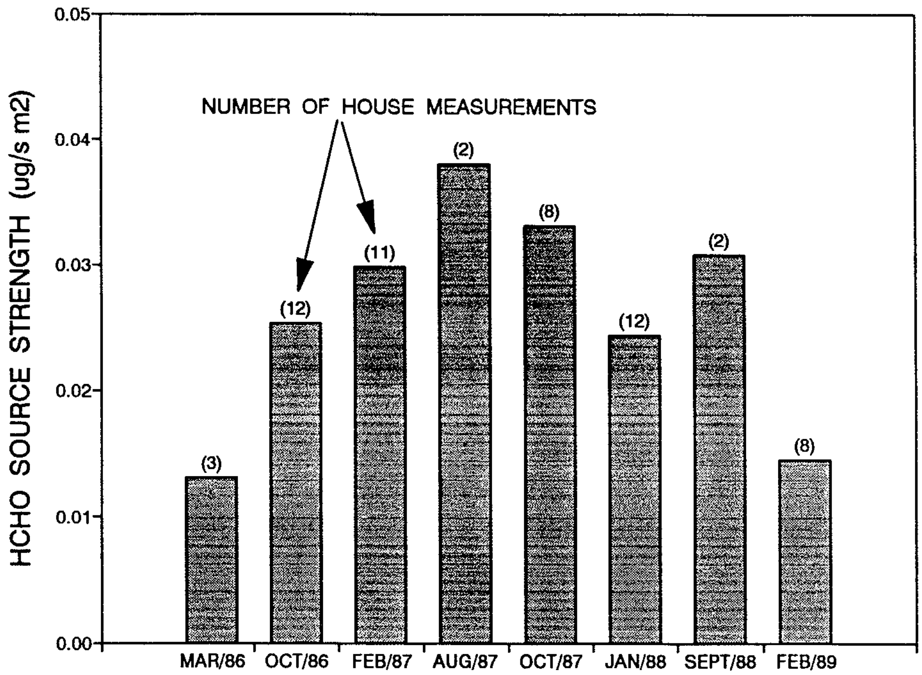
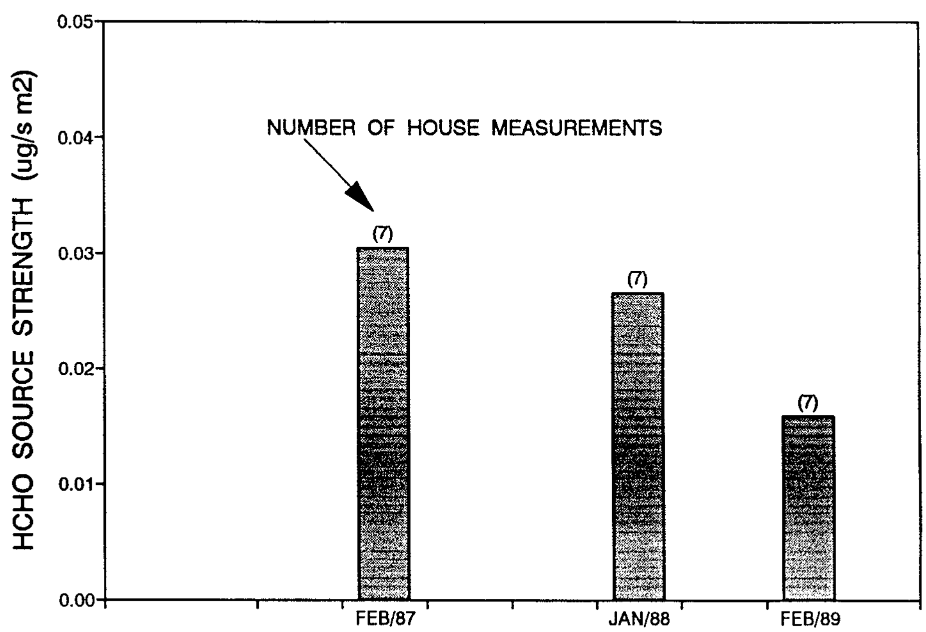


FIGURE 4(b)

SEASONALLY-COINCIDENT
HCHO SOURCE STRENGTH



SECTION 3

RADON DAUGHTERS

3.1 INTRODUCTION

Radon is an inert, colourless gas which occurs naturally as part of the Uranium-238 decay chain. Originating in underlying geological formations and soils, the gas enters buildings primarily by airborne transport through physical openings between the soil and the structure, specifically those portions of the envelope below grade level. Radon has been detected in houses in all parts of Canada, although concentrations vary widely with location.

Radon gas decays to four radioactive daughters which have a tendency to affix themselves to airborne particulates. Upon inhalation, these particulates can become lodged within the human respiratory tract. As a result exposure to radon gas is acknowledged as a contributor to an increased incidence rate of lung cancer.

Common radon control methods include ventilation and source control (to reduce entry from the soil); the latter consists of increasing the airtightness of the below-grade/surface portions of the structure. Other measures which have been successfully demonstrated include sub-slab depressurization and positive pressurization of the basement (Nitschke et al).

Assessment of the health risk due to prolonged exposures is difficult to determine because the primary effect, lung cancer, has a very high incidence rate relative to other causes, most notably smoking. In addition, the effects of prolonged exposures to low level radiation may not become evident for several years or decades. Nonetheless, it is generally acknowledged that exposure to radiation, at any level, constitutes a health risk. For the general public, the primary exposure to radiation has been reported as that resulting from the inhalation of radon daughters (George 1985).

The problem of assessing the health risk has made the establishment of exposure standards very difficult and as a result, different countries have set varying exposure limits. The Canadian guideline developed by the Federal-Provincial Advisory Committee on Environmental and Occupational Health (1989) for residential air recommends that action be taken if the annual, average radon level exceeds 800 Becquerels per cubic metre, equivalent to 0.100 Working Levels (WL). The term Working Level is a measure of the potential alpha energy concentration and was originally developed for application to uranium miners. It is defined as any combination of radon daughters in one litre of air such that the decay to Lead-210 results in the emission of 130,000 MeV of alpha energy. The current American guideline, established by the Environmental Protection Agency, is 0.020 WL (1988). Swedish guidelines vary depending on the type of structure: 0.108 WL for existing dwellings, 0.054 WL for renovated buildings and 0.019 WL for new dwellings (Swedemark and Mjones 1984).

3.2 RELATED STUDIES

Radon daughter monitoring in new R-2000 and conventional houses was carried out by Energy, Mines and Resources Canada commencing in 1985. Buchan, Lawton, Parent Ltd. (1986) studied radon levels in 22 R-2000 and five conventional houses in Ottawa and reported average levels of 0.010 WL. (The BLP data was expressed in terms of the gas concentration and was converted to Working Levels using an equilibrium ratio of 0.5 - the "equilibrium ratio" describes the state of equilibrium existing between radon and radon daughters.) The highest reported reading in the Ottawa study was 0.026 WL.

If one considers the physical process by which radon enters a structure, and the ageing characteristics of houses, it is apparent that significant differences can exist between concentrations in new houses relative to those in older dwellings. An existing house, because of the type of foundation or the damage which it has experienced, may have significantly higher entry rates. For example, the highest radon daughter levels found by Piersol (1987) in R-2000 houses were those recorded in the Maritimes. However, a major study of 14,000 older, conventional houses in 18 Canadian cities found that four of the five cities with the highest levels were on the Prairies (Letourneau et al 1983).

Another study of older houses, conducted in the same city as the Flair project, was described by Yuill (1987). Radon levels were measured during the summer and fall of 1987 in 70 randomly distributed Winnipeg houses. Measurements were conducted over one week periods using passive dosimeters. The houses were constructed between 1902 and 1980 and were considered representative of older, conventional housing stock in the city.

3.3 MONITORING PROCEDURES

Radon daughter levels in the Flair study were monitored using Surveymeters manufactured by R.A.D. Service and Instruments Ltd. This is an active time-integrating, track registering sampler which uses a small pump to draw controlled amounts of air across a detecting surface. Analysis of the exposed detector heads was performed by R.A.D. Ltd. The Surveymeters were installed in the house basements for approximately one week. The basement was chosen to provide consistency with other field surveys and to identify the maximum exposure levels to which homeowners might be subjected given significant residency in the basement such as would occur with a bedroom located in the basement.

An investigation was also conducted in one of the project house to examine the impact of house pressurization upon radon daughter levels and a further study was conducted on two project houses to examine the impact of sub-slab depressurization. Both are described in the Interim Report (Proskiw 1989).

3.4 RESULTS

The radon daughter results are summarized in Table 4 and a more complete data set is attached in Appendix A. Geometric means were used to describe the average concentration because radon daughter populations typically follow log-normal distributions.

3.5 DISCUSSION

R-2000 vs. Conventional Houses

A total of 95 radon daughter measurements were made in the R-2000 houses and 28 in the conventional houses. For each of the seven monitoring periods, the mean radon daughter levels were found to be lower in the R-2000 houses. Only one of the 123 measurements exceeded the 0.100 WL guideline. With respect to average values for the full study period, the geometric mean levels in the R-2000 and conventional houses were 0.007 WL and 0.010 WL respectively. Comparing levels based on house type and the percentage of measurements which exceeded the Canadian and American guidelines, 0.100 WL and 0.020 WL respectively, gives similar results.

The observed radon daughter concentrations in the R-2000 houses were similar to those reported by Piersol for his 1985 results while the conventional, new houses in the Flair study experienced higher levels than the corresponding structures in the 1985 study. The R-2000 results also displayed greater variations than the conventional structures with the highest concentrations occurring in the summer.

One significant observation was the difference in radon daughter working levels in the Flair houses compared to those reported by Yuill (1987) for older, conventional houses in the same city. The geometric mean for the older houses was 0.017 WL vs. 0.007 WL and 0.010 WL respectively for the R-2000 and conventional houses in the Flair study. Twenty-eight of the 70 older houses, or 40%, exceeded the EPA Guideline of 0.020 WL, compared to 5% and 7% respectively for the two house types in the Flair study. However, monitoring of the older structures was conducted in the summer and fall, periods during which the highest concentrations were recorded in the Flair study. These results may be explained in part by the differences in below-grade airtightness. The average airtightness of the 70 older houses was reported as 6.78 ac/hr_{50} whereas the corresponding figures for the R-2000 and conventional houses were 1.07 ac/hr_{50} and 1.62 ac/hr_{50} respectively. (A slight difference was found between the airtightness testing protocols used in the two studies which would have produced slightly elevated ac/hr_{50} values for the older, conventional houses). Winnipeg is located in an area of moisture-susceptible soils which react to variations in moisture content by swelling or shrinking, often resulting in differential foundation

TABLE 4

RADON DAUGHTER LEVELS - FLAIR HOUSES

CATEGORY	NO. OF HOUSE MEASUREMENTS	GEOMETRIC MEAN (WL)	MEASUREMENTS >0.020 WL U.S. EPA GUIDELINE		MEASUREMENTS >0.100 ppm CDN. GUIDELINE	
			NUMBER	%	NUMBER	%
R-2000 HOUSES						
March 1986	6	0.004	0	0	0	0
August 1986	14	0.007	1	7	0	0
October 1986	16	0.009	1	6	0	0
February 1987	14	0.004	0	0	0	0
October 1987	14	0.007	1	7	0	0
January 1988	15	0.006	0	0	0	0
January 1989	16	0.008	2	13	1	6
Cumulative	95	0.007	5	5	1	1
CONVENTIONAL HOUSES						
March 1986	4	0.009	0	0	0	0
August 1986	4	0.011	0	0	0	0
October 1986	4	0.010	2	50	0	0
February 1987	4	0.007	0	0	0	0
October 1987	4	0.008	0	0	0	0
January 1988	4	0.007	0	0	0	0
January 1989	4	0.018	0	0	0	0
Cumulative	28	0.010	2	7	0	0
VENTILATION SYSTEM						
Bathroom Fan	14	0.009	1	7	0	0
Central Exhaust & Make-Up Air Duct	14	0.010	1	7	0	0
HRV	95	0.007	5	5	1	1
HEATING SYSTEM (R-2000 ONLY)						
Forced Air	61	0.005	3	5	0	0
Baseboard	34	0.009	2	6	1	3

movement and subsequently foundation distress and cracking. Older dwellings are particularly vulnerable because their foundations often lack the structural integrity of those built in recent years and are more likely to suffer damage which would reduce below-grade airtightness and permit increased infiltration of radon-bearing air. However, the variation observed in radon daughter levels for houses located in the same city suggests that geographic location, by itself, may not be a reliable parameter for predicting indoor radon concentrations, thereby necessitating actual measurement to establish exposure levels with confidence.

Type of Ventilation System

Analysis of the data based on the type of ventilation system parallels the results based on house type; houses containing bathroom fans or central exhaust systems with make-up air ducts (i.e. conventional houses) showed higher radon daughter levels than houses with HRVs (i.e. R-2000).

Type of Heating System (R-2000 Houses)

Geometric mean radon daughter levels in the R-2000 houses using baseboard heating systems were nearly double those found in houses with forced air heating systems. This may have occurred because of plate-out of the attached radon daughters on the ductwork, blowers, filters, etc. in the forced air system houses. Based on measurements performed in a single house equipped with a balanced ventilation system, furnace operation did not have significant effect upon basement pressurization (relative to the outdoors) so it does not appear the lower levels in the forced air system houses were attributable to positive pressurization of the basement.

SECTION 4

PARTICULATES

4.1 INTRODUCTION

Particulates are materials suspended in the air in a physical or chemical state, the most common example is household dust although many types and sizes are found in residential air. Major sources include tobacco smoke, construction materials (especially those originating from the cutting or installation of fibrous materials such as insulation), household products, humans, pets, plants, clothing and carpeting materials, mould, fungi, algae, wood smoke and outdoor sources such as automobile exhausts and wind borne dust. Airborne particulates vary in size from 0.005 μm to 100 μm although those between 0.1 μm and 10 μm are the most significant from a health perspective.

The health effects of particulates vary depending on the type, duration and intensity of exposure. While the effects of tobacco smoke are well known, typical reactions to other types include irritation of the respiratory and digestive tracts, skin irritation from man-made fibres and allergic reactions in some individuals to organic matter such as pollens and animal dander.

The current Canadian guideline for long-term residential exposure to fine particulate matter (less than or equal to 2.5 μm) is 40 $\mu g/m^3$ (Federal-Provincial Advisory Committee on Environmental and Occupational Health 1989).

4.2 RELATED STUDIES

No published investigations of particulate concentrations in R-2000 houses were identified.

4.3 MONITORING PROCEDURES

Total Suspended Particulate concentrations were monitored using Millipore type AA mixed cellulose ester filters with a pore size of 0.8 μm. These were installed in the R.A.D. Surveymeters used for radon daughter monitoring. Pre and post-exposure filter weights were determined and the change related to the air volume sampled by the Surveymeter. Sampling was performed in the basements with exposure periods of approximately one week.

4.4 RESULTS

The results are summarized in Table 5 and the complete data set is attached in Appendix A.

4.5 DISCUSSION

R-2000 vs. Conventional Houses

A total of 92 particulate level measurements were made in the R-2000

TABLE 5

PARTICULATE LEVELS - FLAIR HOUSES

CATEGORY	NO. OF HOUSE MEASUREMENTS	MEAN ($\mu g/m^3$)	STANDARD DEVIATION ($\mu g/m^3$)	MEASUREMENTS >40 $\mu g/m^3$ GUIDELINE	
				NUMBER	%
R-2000 HOUSES					
March 1986	5	34.6	24.7	2	40
August 1986	14	43.4	29.2	5	36
October 1986	15	18.9	14.5	2	13
February 1987	14	20.1	15.3	1	7
October 1987	14	40.4	19.8	3	21
January 1988	14	29.0	19.2	4	29
January 1989	16	41.8	35.1	5	31
Cumulative	92	32.5	24.9	22	24
CONVENTIONAL HOUSES					
March 1986	4	27.3	14.0	1	25
August 1986	4	40.0	18.7	2	50
October 1986	4	23.8	20.4	1	25
February 1987	4	50.0	64.3	1	25
October 1987	4	29.5	16.1	1	25
January 1988	4	67.3	63.0	2	50
January 1989	4	30.8	9.5	1	25
Cumulative	28	38.4	34.9	9	32
VENTILATION SYSTEM					
Bathroom Fan	14	49.8	44.7	7	50
Central Exhaust & Make-Up Air Duct	14	26.9	13.0	2	14
HRV	92	32.5	24.9	22	24
HEATING SYSTEM (R-2000 ONLY)					
Forced Air	59	36.1	27.7	18	31
Baseboard	33	26.0	17.2	4	0
PRESENCE OF SMOKERS:					
Non-Smokers	73	27.5	23.0	10	14
Smokers	47	43.7	31.2	21	45

houses and 28 in the conventional houses during seven monitoring periods. Mean concentrations over the full monitoring period were found to be 33 $\mu g/m^3$ and 38 $\mu g/m^3$ respectively, this difference was assessed as not statistically significant. The percentages of readings exceeding the 40 $\mu g/m^3$ guideline were 24% and 32% respectively.

Type of Ventilation System

The lowest particulate concentrations were recorded in houses equipped with central exhaust systems and make-up air ducts (27 $\mu g/m^3$) and the highest in houses with bathroom exhaust fans (50 $\mu g/m^3$). Average values in houses containing HRVs were similar to those found in houses containing central exhaust systems with make-up air ducts (33 ug/m^3). The analysis indicated that the difference between the mean values for the HRV and bathroom exhaust fan houses was statistically significant while the difference between the means for the HRV and central exhaust system houses was not.

Type of Heating System (R-2000 Houses)

The type of heating system in the R-2000 houses had a major impact upon particulate levels. Houses with forced air systems averaged 36 $\mu g/m^3$ compared to 26 $\mu g/m^3$ in baseboard heated houses, a statistically significant difference, despite a lower incidence of smokers in the forced air houses, 27% compared to 39% for the baseboard houses. It is possible that the high recirculation rates helped to maintain airborne suspension of the particulate matter. However, it appears that the furnace filters, standard low efficiency types, had little beneficial impact.

Presence of Smokers

Particulate levels in houses which contained smokers averaged well above those which were smoker-free. Mean concentrations for the two groups were 44 $\mu g/m^3$ and 28 $\mu g/m^3$ respectively, the difference being statistically significant. Forty-five percent of the smoker houses exceeded the 40 $\mu g/m^3$ guideline versus 14% of the non-smoker houses. As previously noted, total air change rates were higher in houses which contained smokers.

SECTION 5

NITROGEN DIOXIDE

5.1 INTRODUCTION

Nitrogen dioxide is a colourless gas which is odourless in the concentrations normally encountered in residential environments. It is formed as a combustion by-product and major indoor sources include unvented gas stoves and other combustion appliances (including wood stoves and fireplaces) as well as tobacco smoke. There are numerous outdoor sources including vehicle exhaust and other combustion processes. Outdoor levels in urban environments may exceed those found indoors. Increased risk of respiratory illness is believed to result from prolonged exposures.

The current long-term exposure guideline for nitrogen dioxide in residential environments is 0.05 ppm (Federal-Provincial Advisory Committee on Environmental and Occupational Health 1989).

5.2 RELATED STUDIES

Nitrogen dioxide monitoring was conducted by Energy, Mines and Resources in the spring of 1985 in a limited number of R-2000 and conventional houses (Riley 1986). Measured concentrations in both types of houses were generally similar and all were below the exposure guideline.

5.3 MONITORING PROCEDURES

A small number of nitrogen dioxide measurements were made in the Flair houses using AQRI passive dosimeters installed in the basement and main floor areas of four project houses (#2, #3, #9 and #10). The first two were electrically heated R-2000 houses while #9 and #10 were conventional structures which used naturally aspirated gas furnaces and hot water tanks. Exposure periods were approximately one week. Monitoring was conducted on three occasions during the study. Dosimeter analysis was performed by ORTECH International.

5.4 RESULTS

The results are summarized in Table 6 and the complete data set is attached in Appendix A.

5.5 DISCUSSION

R-2000 vs. Conventional Houses

Observed nitrogen dioxide concentrations were slightly lower in the R-2000 houses compared to the conventional structures (0.0040 ppm vs. 0.0044 ppm), although the difference was not statistically significant. For both house types, the observed concentrations were well below the exposure guideline and none of the individual measurements approached this limit. Similar

TABLE 6

NITROGEN DIOXIDE LEVELS - FLAIR HOUSES

CATEGORY	NO. OF HOUSE MEASUREMENTS	MEAN (ppm)	STANDARD DEVIATION (ppm)	MEASUREMENTS >0.05 ppm GUIDELINE	
				NUMBER	%
R-2000 HOUSES					
March 1986	2	0.0026	0.0008	0	0
October 1986	2	0.0025	0.0000	0	0
February 1987	2	0.0070	0.0007	0	0
Cumulative	6	0.0040	0.0024	0	0
CONVENTIONAL HOUSES					
March 1986	2	0.0056	0.0037	0	0
October 1986	2	0.0025	0.0000	0	0
February 1987	2	0.0050	0.0000	0	0
Cumulative	6	0.0044	0.0022	0	0
VENTILATION SYSTEM					
Bathroom Fan	6	0.0044	0.0022	0	0
HRV	6	0.0040	0.0024	0	0
PRESENCE OF SMOKERS					
Non-Smokers	3	0.0053	0.0029	0	0
Smokers	9	0.0038	0.0020	0	0

concentrations were measured in the basements and main floors of the R-2000 houses while basement concentrations in the conventional houses were slightly higher than those on the main floor. None of the houses contained gas stoves, fireplaces, wood stoves or combustion appliances other than the furnaces and hot water tanks in the conventional houses. The results generally paralleled those reported by Riley (1986).

Presence of Smokers

Higher nitrogen dioxide levels were found in the houses which did not contain smokers relative to those which did, although the difference was not assessed as statistically significant.

SECTION 6

CARBON DIOXIDE

6.1 INTRODUCTION

Carbon dioxide is a colourless, odourless gas present in both indoor and outdoor air. It is produced as a by-product of metabolic processes such as human respiration and by the combustion of fossil fuels. Unvented gas stoves and kerosene heaters have been identified as major potential sources and can dramatically increase indoor concentrations. Outdoor levels average around 320 ppm although significant variations occur with time and location.

From a health perspective, carbon dioxide can affect the rate and depth of respiration and produce feelings of fatigue, headaches and a general sense of discomfort.

The Canadian guideline for long-term exposure in residential environments is 3500 ppm (Federal-Provincial Advisory Committee on Environmental and Occupational Health 1989). ASHRAE 62-89 suggests a level of 1000 ppm, not as an indicator of health risk, but as a surrogate for human comfort (1989).

6.2 RELATED STUDIES

Carbon dioxide concentrations were monitored in 22 R-2000 houses in Ontario on a monthly basis in a study by Buchan, Lawton, Parent Ltd. (1986) and found to be well below the guideline of 3500 ppm. Average readings were reported to vary between 500 and 800 ppm with peak concentrations occurring in the January/February period.

6.3 MONITORING PROCEDURES

Spot measurements, using a sampling time of a few minutes, were made in the Flair houses during the monthly site visit using gas detection tubes which produced a colourmetric indication of exposure. Measurements were made in the basement and on the main floor.

Detection tubes, manufactured by Draeger, were used for the monitoring between March 1986 and August 1987. These tubes have a minimum detection limit of 1000 ppm. They were subsequently replaced with tubes manufactured by Gastec Corp., which have a minimum detection limit of 300 ppm.

6.4 RESULTS

The results are summarized in Table 7.

TABLE 7

CARBON DIOXIDE LEVELS - FLAIR HOUSES

ALL DATA (1065 MEASUREMENTS)							
HOUSE TYPE	CARBON DIOXIDE (ppm)						
	<1000	1001 - 1500	1501 - 2000	2001 - 2500	2501 - 3000	3001 - 3500	>3500
R-2000	94.7%	3.9%	1.0%	0.1%	0.1%	0.0%	0.1%
Conventional	93.0%	7.0%	0.0%	0.0%	0.0%	0.0%	0.0%

LOW CONCENTRATION DETECTION TUBES ONLY (587 MEASUREMENTS)								
HOUSE TYPE	CARBON DIOXIDE (ppm)							
	<301	301 - 500	501 - 700	701 - 900	901 - 1100	1101 - 1300	1301 - 1500	>1500
R-2000	5.1%	42.3%	19.2%	19.4%	8.1%	1.1%	2.6%	2.1%
Conventional	0.0%	26.1%	10.9%	37.8%	21.0%	1.7%	2.5%	0.0%

VENTILATION SYSTEM	MEDIAN CONCENTRATION
Bathroom Exhaust	725 ppm
Central Exhaust & Make-Up Air Duct	800 ppm
HRV	600 ppm

6.5 DISCUSSION

R-2000 vs. Conventional Houses

Typical concentrations in both R-2000 and conventional houses were well below the exposure guideline of 3500 ppm with only one reading out of 1065 exceeding this value. Further, 94% of the measurements were below 1000 ppm, the minimum detection limit of the Draeger tubes (this also precluded determination of median values). Frequency distributions are shown in Fig. 5.

The data collected using the Gastec tubes, consisting of 587 measurements spanning a period of approximately 19 months, was analyzed separately, as shown in Table 7 and Fig. 6.

The median concentration in the R-2000 houses was lower than the conventional houses, 600 ppm vs. 800 ppm respectively. None of the houses contained gas stoves, kerosene heaters or other major sources of carbon dioxide. Average occupancy levels were typically two adults and one child per house.

Type of Ventilation System

Small differences in the median concentrations were found among houses, depending on the type of ventilation system which they contained. Houses with HRVs, central exhaust systems with make-up air ducts and bathroom exhaust fans had median carbon dioxide concentrations of 600 ppm, 725 ppm and 800 ppm respectively.

FIGURE 5(a)

CO2 LEVELS
R-2000 HOUSES

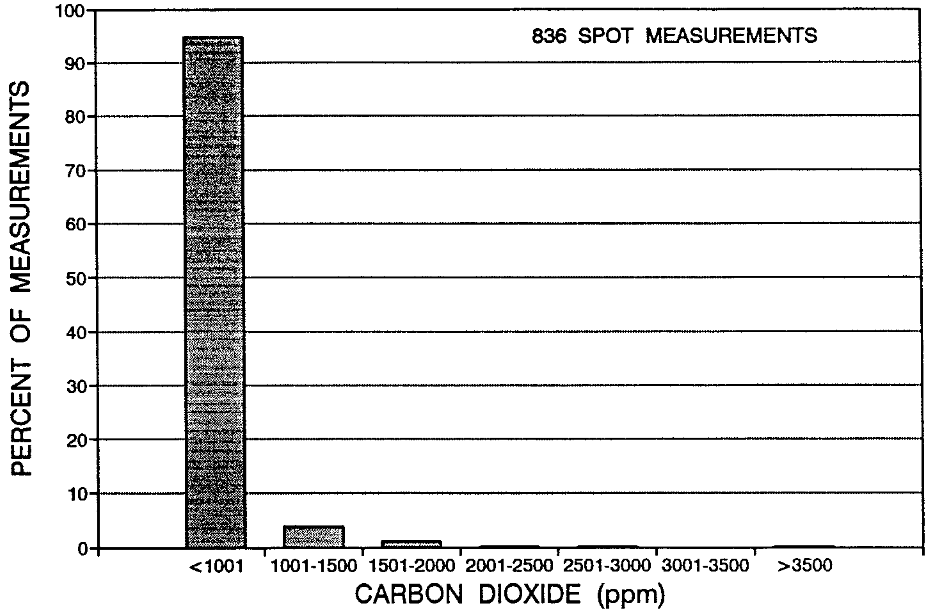


FIGURE 5(b)

CO2 LEVELS
CONVENTIONAL HOUSES

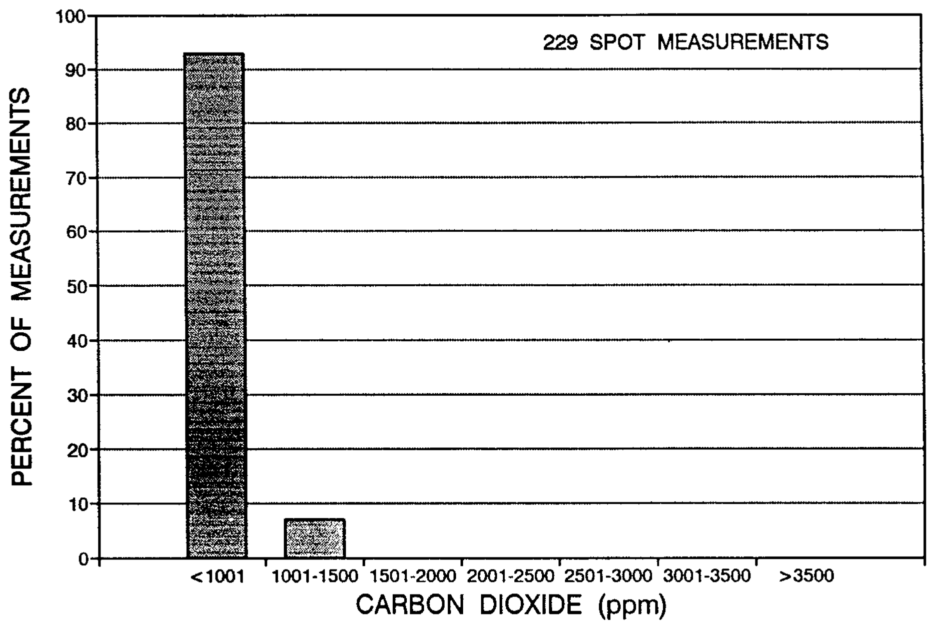


FIGURE 6(a)

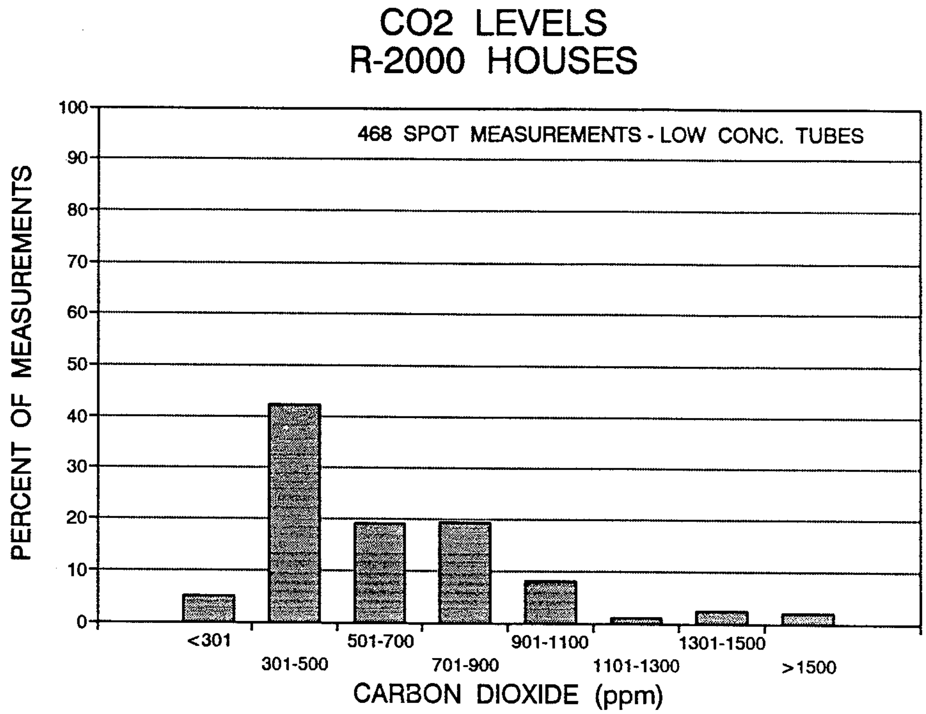
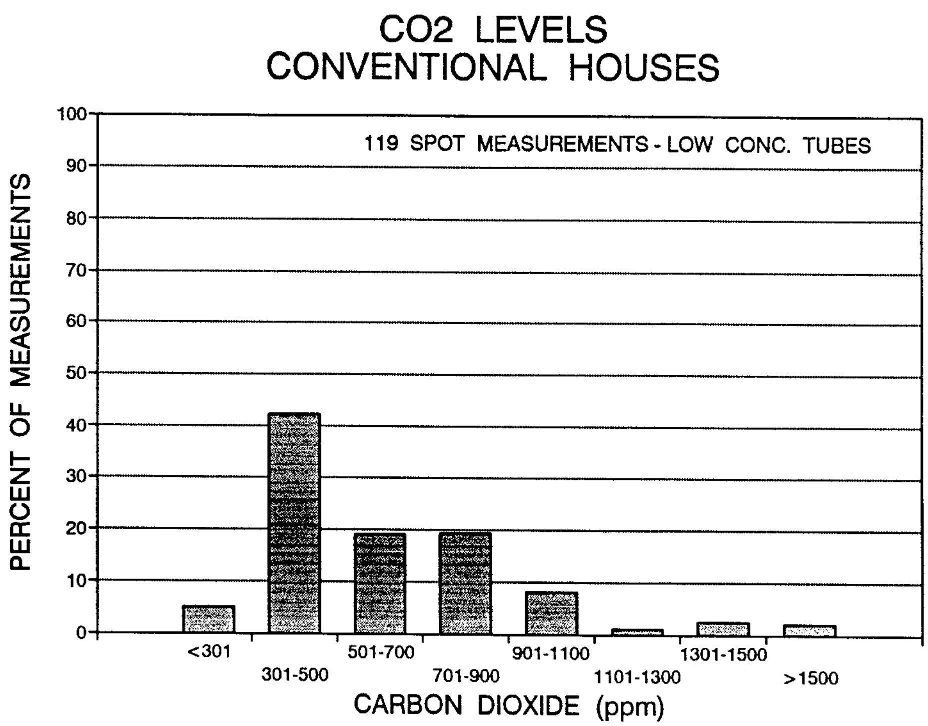


FIGURE 6(b)



SECTION 7

RELATIVE HUMIDITY

7.1 INTRODUCTION

Moisture in the indoor air is seldom viewed as a pollutant, however if present in either small or large quantities, it can create adverse effects upon the occupants and the structure. Water vapour originates from several sources including: personal activities (bathing, cooking, cleaning, respiration, etc.), outdoor air (whose moisture content varies significantly during the year), and the surrounding soil (from which water can move into the house through direct leakage or vapour diffusion). In newer construction, i.e. under about a year in age, significant quantities of moisture is released from construction materials, particularly concrete and wood framing members.

Houses and their furnishings have the capacity to store moisture during periods of high relative humidity and release it during dry periods, such as in the winter. Large amounts can be absorbed by exposed wood surfaces and then released during the fall and winter as humidity levels drop and the wood attempts to reestablish equilibrium. This phenomenon tends to dampen normal moisture level fluctuations.

Prolonged exposure to low relative humidity can increase the frequency of respiratory infections and the drying of skin and mucous membranes. Conditions of high humidity and high temperature can lead to excess sweating and, in extreme cases, heat exhaustion. High humidity will also accelerate growth of moulds, mildew, fungi and mites which can increase allergic reactions. This condition will also raise the probability of mould and fungal growth on the surfaces of potential food sources, such as wood and drywall. Extreme humidity levels can create feelings of discomfort.

The Canadian exposure guidelines for residential environments recommend that relative humidity levels be maintained between 30% and 80% in summer and 30% and 55% in winter (unless constrained by window condensation). A range of 40% to 50% is suggested to minimize upper respiratory infections (Federal-Provincial Advisory Committee on Environmental and Occupational Health 1989).

7.2 RELATED STUDIES

No published references on moisture levels in R-2000 houses were identified. The Federal-Provincial Advisory Committee on Environmental and Occupational Health (1989) notes that relative humidities in Canadian homes have been found to range from 21% to 68%.

7.3 MONITORING PROCEDURES

Relative humidity levels were measured using Casella London T9420 thermohygrographs with sampling periods of approximately one month. The units were installed on the main floor in a central location away from obvious drafts and sources of heat or sunlight.

7.4 RESULTS

A summary of the relative humidity data is given in Table 8 and a more complete data set is attached in Appendix A.

7.5 DISCUSSION

R-2000 vs. Conventional Houses

A total of 89 relative humidity (R/H) surveys were performed in the R-2000 houses and 26 in the conventional structures. Mean R/H levels were found to be slightly lower in the R-2000 houses, 46% vs. 52%, with the difference assessed as statistically significant. R/H levels in the R-2000 houses were also more frequently within the recommended winter exposure range of 30% to 50%. Maximum R/H levels were measured in the summer months.

Type of Ventilation System

Relative humidity levels were highest in the houses with bathroom exhaust fans, followed by houses equipped with central exhaust systems and make-up air ducts and then HRVs (55%, 49% and 46% respectively). The difference between means for the bathroom exhaust and HRV house levels was found to be statistically significant whereas that between the central exhaust and HRV houses was not.

Type of Heating System (R-2000 Houses)

Mean R/H levels in those R-2000 houses which used forced air heating systems were the same as in those which used baseboard heating.

TABLE 8

RELATIVE HUMIDITY LEVELS - FLAIR HOUSES

CATEGORY	NO. OF HOUSE MEASUREMENTS	MEAN (%)	STANDARD DEVIATION (%)	MEASUREMENTS <30% GUIDELINE		MEASUREMENTS >55% GUIDELINE	
				NUMBER	%	NUMBER	%
R-2000 HOUSES							
March 1986	6	42	4	0	0	0	0
October 1986	14	54	8	0	0	5	36
February 1987	13	44	6	0	0	0	0
August 1987	14	60	6	0	0	10	71
October 1987	15	49	7	0	0	3	20
January 1988	14	41	6	0	0	0	0
January 1989	13	28	7	8	62	0	0
Cumulative	89	46		8	9	18	20
CONVENTIONAL HOUSES							
March 1986	4	46	5	0	0	0	0
October 1986	4	58	9	0	0	3	75
February 1987	4	50	7	0	0	1	25
August 1987	4	65	1	0	0	4	100
October 1987	4	56	10	0	0	2	50
January 1988	4	47	8	0	0	0	0
January 1989	2	34	6	0	0	0	0
Cumulative	26	52		0	0	10	38
VENTILATION SYSTEM							
Bathroom Fan	13	55	9	0	0	6	46
Central Exhaust & Make-Up Air Duct	13	49	11	0	0	4	31
HRV	89	46	12	8	9	18	20
HEATING SYSTEM (R-2000 ONLY)							
Forced Air	56	46	11	5	9	11	20
Baseboard	33	46	12	3	9	7	21

SECTION 8

TOTAL AIR CHANGE RATES

8.1 INTRODUCTION

The development of control strategies for indoor air quality requires an understanding of the relationship between pollutant behaviour and the total air change rate created by natural infiltration and mechanical ventilation. "Inadequate ventilation " is frequently identified as the reason for many air quality problems, although this assessment is often in error. Ventilation, particularly that achieved by mechanical means, is often seen as the only, or at least the most significant, variable affecting the quality of the indoor environment.

The 1985 National Building Code (1985) included a requirement that houses be equipped with mechanical ventilation systems capable of providing 0.5 ac/hr of outdoor air to the dwelling, although the system was not required to operate on a continuous basis. The 1990 National Building Code (1990) altered this requirement to 0.3 ac/hr. Neither document includes requirements for distribution of the ventilation air.

The most recent development has been the release of CSA Standard F326, "Residential Mechanical Ventilation Systems" (1991) which contains requirements for system capacity, air distribution, house pressurization/depressurization and methods to verify system compliance. Experience to date with F326 has been limited.

The R-2000 Program ventilation requirements were, at the time the Flair houses were designed, were based on ASHRAE 62-81 with additional requirements for ventilation air distribution and house pressurization (Energy, Mines and Resources Canada 1986). This included a requirement for continuous ventilation, with the rate calculated based on the type and number of rooms and expressed using "litres per second" as the rate parameter. To prevent over-ventilation of houses with many rooms, an upper limit of 0.45 ac/hr was specified. No lower limit was stipulated although, for energy modelling purposes, 0.35 ac/hr was assumed. Requirements were also included for additional ventilation capacity to handle peak loads; this permitted automatic control without excessive continuous operation.

In late 1991, the R-2000 Program adopted CSA F326 as its ventilation standard.

8.2 PHYSICAL MODEL

Recalling Eq. 1, the relationship between the concentration of a pollutant and the total air change rate can be expressed as:

$$C_i = C_o + N/V_t \qquad (1)$$

This formula was developed on the basis of a simple mass balance for a single compartment and assumes perfect mixing of the indoor air. The source term, "N", is assumed to be independent of pollutant strength and air change rate. As previously noted, this generalization is not necessarily valid for all contaminants, formaldehyde and relative humidity being notable examples.

Equation 1 has been found to reasonably describe the behaviour of a given structure with a constant source strength and outdoor pollutant concentration. For example, Rector el al (1985) found a good relationship between air change rate and both radon and radon daughter concentrations in two unoccupied houses.

However, when discussing a population of houses, as opposed to a single structure, the assumptions of equal outdoor concentrations and source strengths will seldom be valid. For such applications, the terms C_o' and N', can be used to describe the representative effective values for the entire group. This approach can be employed to predict the general behaviour of a house population and is useful in the development of codes and standards. Equation (1) thus becomes:

$$C_i = C_o' + N'/V_t \qquad (4)$$

8.3 RELATED STUDIES

Thirty day average total air change rates were monitored in 123 R-2000 and 25 control houses in the spring of 1984 (Riley 1986). Reported mean values were 0.37 ac/hr and 0.34 ac/hr respectively with the majority of the measurements falling between 0.20 ac/hr and 0.80 ac/hr. The extreme values were reported as possibly being caused by homeowner intervention or improperly designed and installed ventilation systems.

Total air change rates were measured in 50 conventional houses in 1989 as part of a cross-country survey of new housing (Hamlin 1990). The reported mean air change rate was 0.20 ac/hr with a standard deviation of 0.15 ac/hr.

8.4 MONITORING PROCEDURES

Average total air change rates (i.e. natural plus mechanical) were measured using the capillary adsorption tube sampling technique developed by Brookhaven National Laboratory (BNL) (Dietz and Cote 1982) which uses an inert perfluorocarbon tracer (PFT). This technique was used by EMR in their 1984 study and has demonstrated good agreement against the constant concentration sulphur hexafluoride technique when the air change rate is relatively constant (Piersol and Mayhew 1987).

The technique uses four calibrated sources located around the house close to exterior walls to emit a tracer which is adsorbed by samplers positioned at central locations on each level. The total air change rate is related to the amount of tracer adsorbed by the samplers as determined using gas chromatographic/mass spectrophotometry analysis. Monitoring periods for the Flair study were approximately one week and were conducted simultaneously with the pollutant measurements. Sampler analysis was performed by BNL.

8.5 RESULTS

The total air change rate results are summarized in Table 9 and a more complete data set is attached in Appendix A. Figures 7 to 11 show pollutant concentrations against the simultaneously measured total air change rate using both air changes per hour and litres per second as the ventilation rate parameter.

8.6 DISCUSSION

R-2000 vs. Conventional Houses

Ninety-three total air change rate measurements were made in the R-2000 houses and 28 in the conventional structures. For each of the eight monitoring periods, the largest total air change rates were found in the R-2000 houses with mean values for the two groups of 0.39 ac/hr and 0.24 ac/hr respectively, the difference being assessed as statistically significant. Results for the conventional houses were similar to those reported by Hamlin for 50 new conventional structures measured during the cross-country survey (1990).

For the first two monitoring periods, the air change rates were lower than normal in the R-2000 houses because of homeowner intervention with the ventilation systems or mechanical problems (motor burn-outs, control malfunctions, etc.). By February 1987, after the homeowners had been asked to refrain from excessive intervention, the mean rose to 0.43 ac/hr.

Table 9 also shows the percentage of measurements which fell outside the range of 0.40 ac/hr to 0.50 ac/hr. This is the approximate range an R-2000 house would experience if operated within the R-2000 Ventilation Guidelines to which the houses were designed and was calculated using the specified mechanical ventilation range of 0.35 ac/hr to 0.45 ac/hr with 0.05 ac/hr added for natural infiltration; the latter value is typically assumed as a gross heating season average for modelling purposes for houses which pass the R-2000 airtightness test. As evident, the measured air change rate data suggests that most of the mechanical systems were not operated in compliance with the Ventilation Guidelines. Only 17% of the R-2000 measurements and 0% of the conventional house measurements met the design ventilation rates. Looking solely at the winter means for the R-2000 houses (Feb/87, Jan/88 and Jan/89), there was a slow reduction in air change rates, possibly indicating reduced usage of the mechanical system by the homeowners.

TABLE 9

TOTAL AIR CHANGE RATES - FLAIR HOUSES

CATEGORY	NO. OF HOUSE MEASUREMENTS	MEAN (ac/hr)	STANDARD DEVIATION (ac/hr)	MEASUREMENTS <0.40 ac/hr		MEASUREMENTS >0.50 ac/hr	
				NUMBER	%	NUMBER	%
R-2000 HOUSES							
March 1986	6	0.28	0.18	5	83	1	17
October 1986	16	0.30	0.16	11	69	2	13
February 1987	15	0.43	0.13	4	27	4	27
August 1987	4	0.48	0.41	2	50	2	50
October 1987	16	0.54	0.19	3	19	10	63
January 1988	16	0.38	0.14	11	69	4	25
September 1988	4	0.42	0.36	2	50	2	50
January 1989	16	0.31	0.14	12	75	2	13
Cumulative	93	0.39	0.20	50	54	27	29
CONVENTIONAL HOUSES							
March 1986	4	0.16	0.05	4	100	0	0
October 1986	4	0.15	0.05	4	100	0	0
February 1987	4	0.20	0.07	4	100	0	0
August 1987	2	0.48	0.28	1	50	1	50
October 1987	4	0.34	0.23	3	75	1	25
January 1988	4	0.26	0.05	4	100	0	0
September 1988	2	0.28	0.13	2	100	0	0
January 1989	4	0.21	0.07	4	100	0	0
Cumulative	28	0.24	0.14	26	93	2	7
VENTILATION SYSTEM							
Bathroom Fan	16	0.26	0.13	15	94	1	6
Central Exhaust & Make-Up Air Duct	12	0.22	0.15	11	92	1	8
HRV	93	0.39	0.20	50	54	27	29
HEATING SYSTEM (R-2000 ONLY)							
Forced Air	60	0.33	0.17	39	65	11	18
Baseboard	33	0.49	0.19	11	33	16	48
PRESENCE OF SMOKERS							
Non-Smokers	68	0.32	0.18	46	68	11	16
Smokers	53	0.40	0.21	30	57	18	34

FIGURE 7(a)

HCHO vs. TOTAL AC/HR

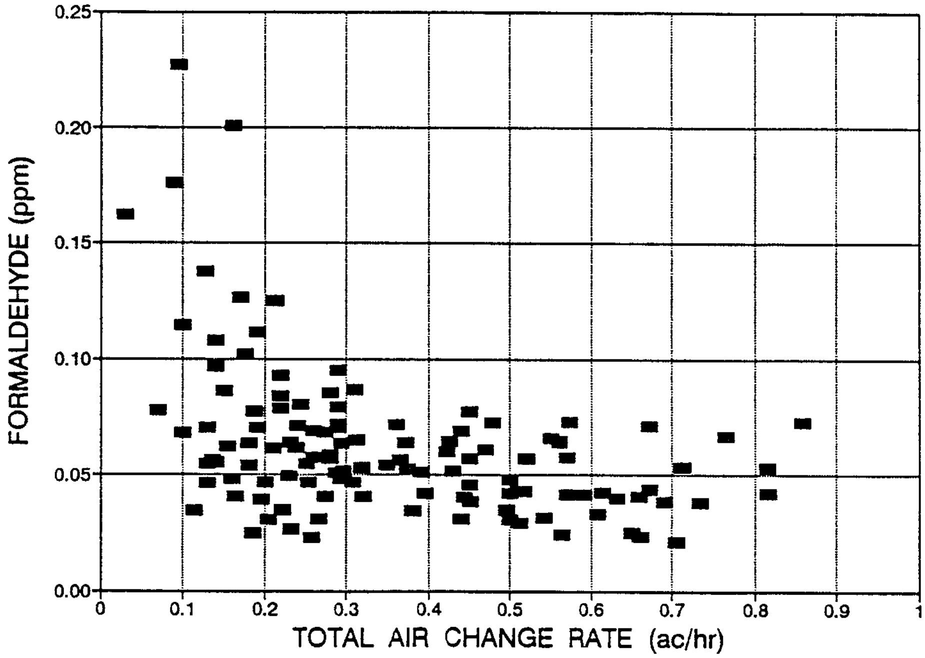


FIGURE 7(b)

HCHO vs. TOTAL L/S

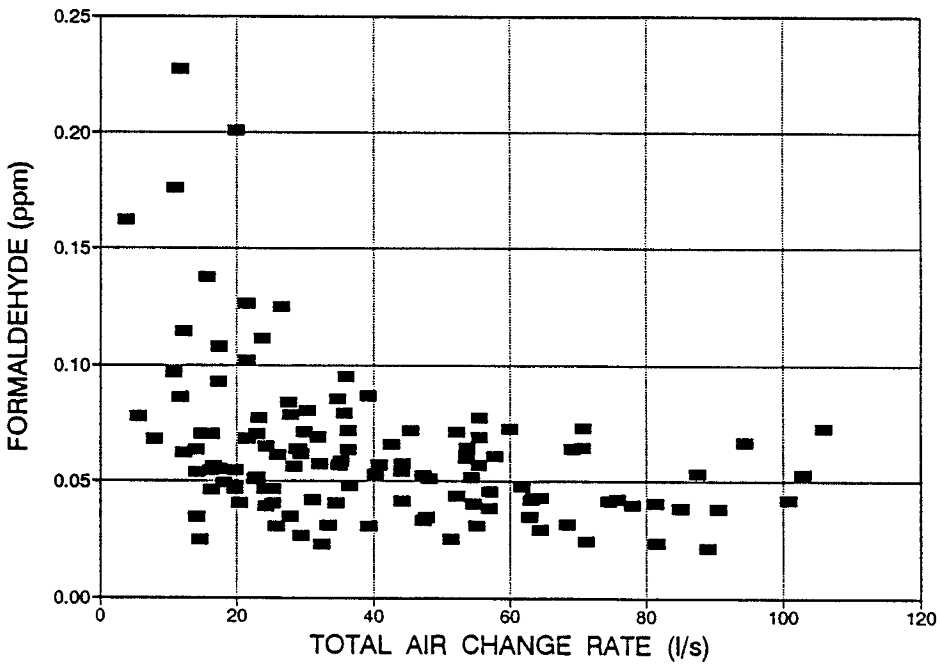


FIGURE 8(a)

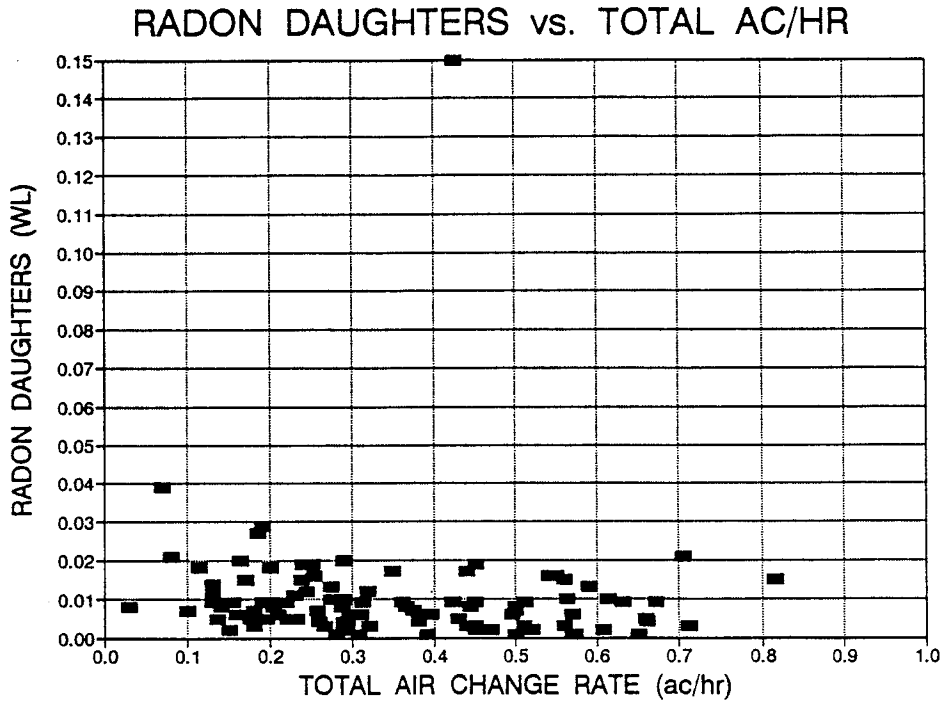


FIGURE 8(b)

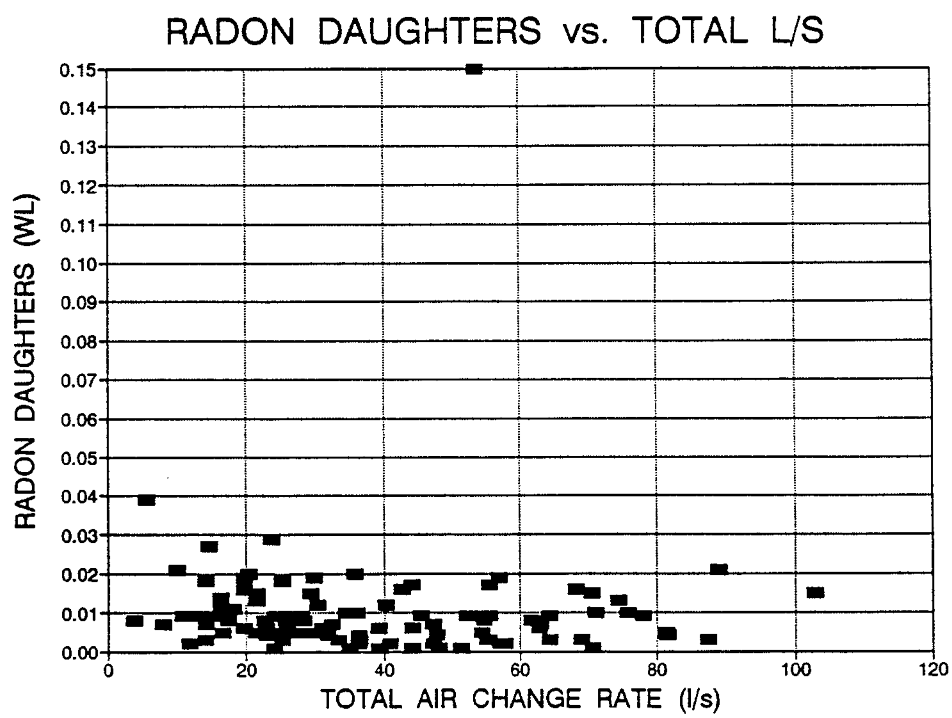


FIGURE 9(a)

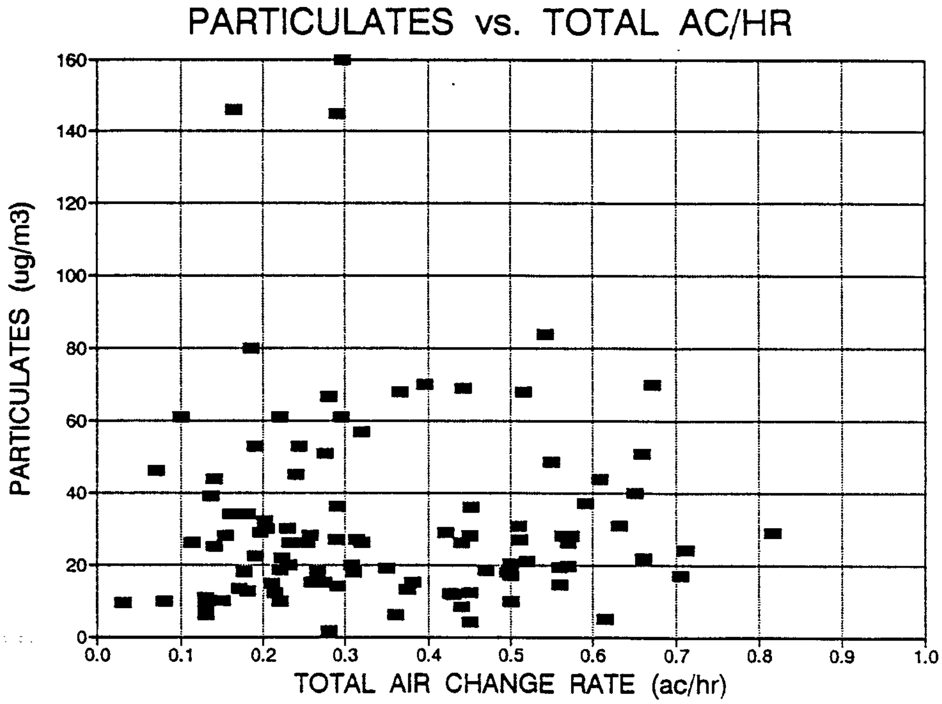


FIGURE 9(b)

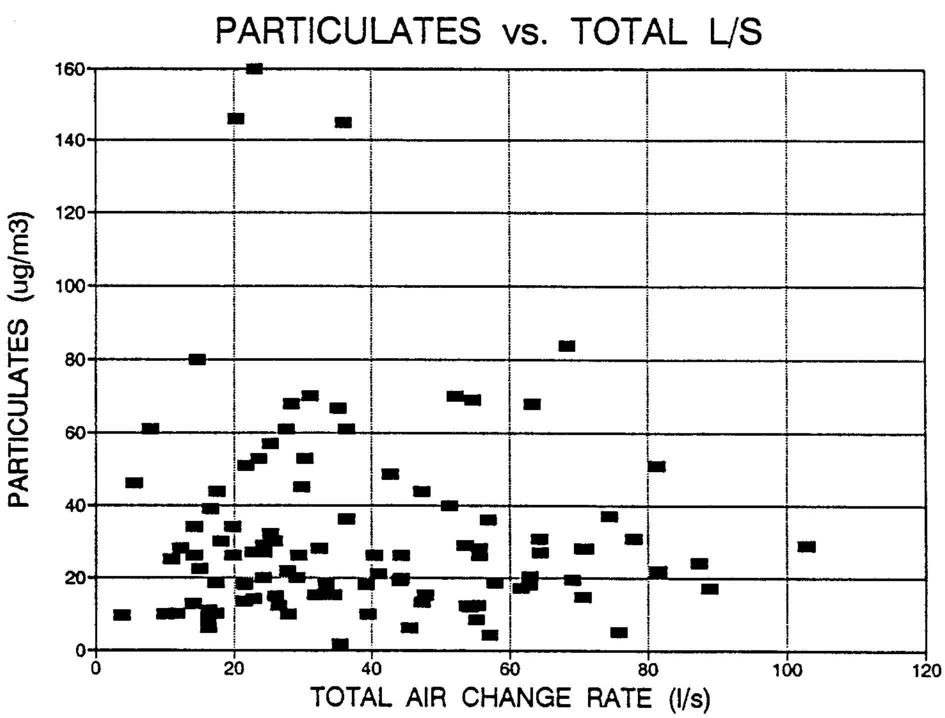


FIGURE 10(a)

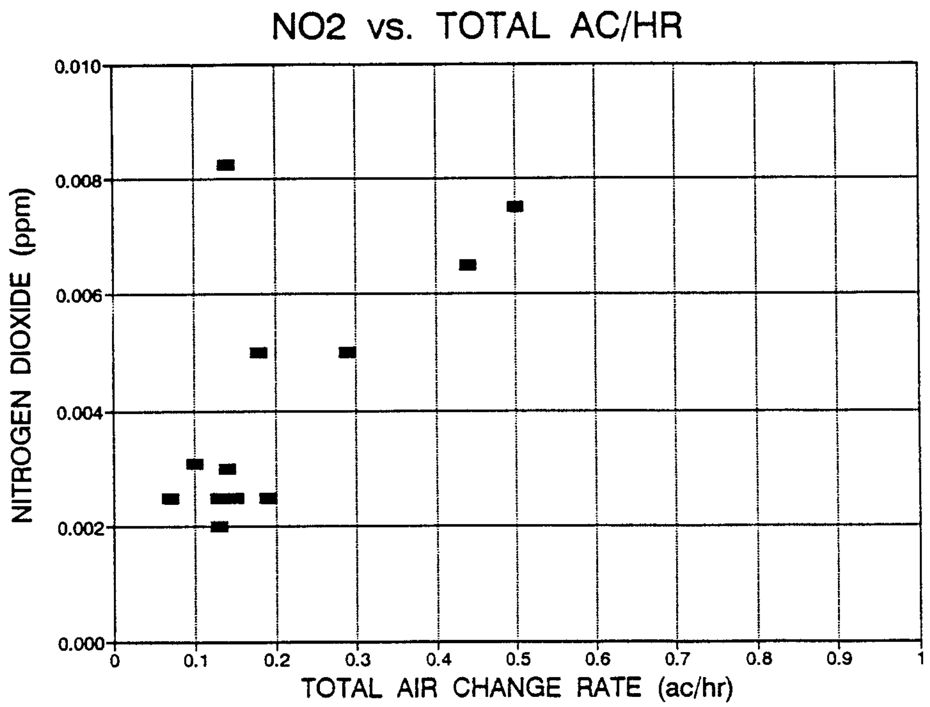


FIGURE 10(b)

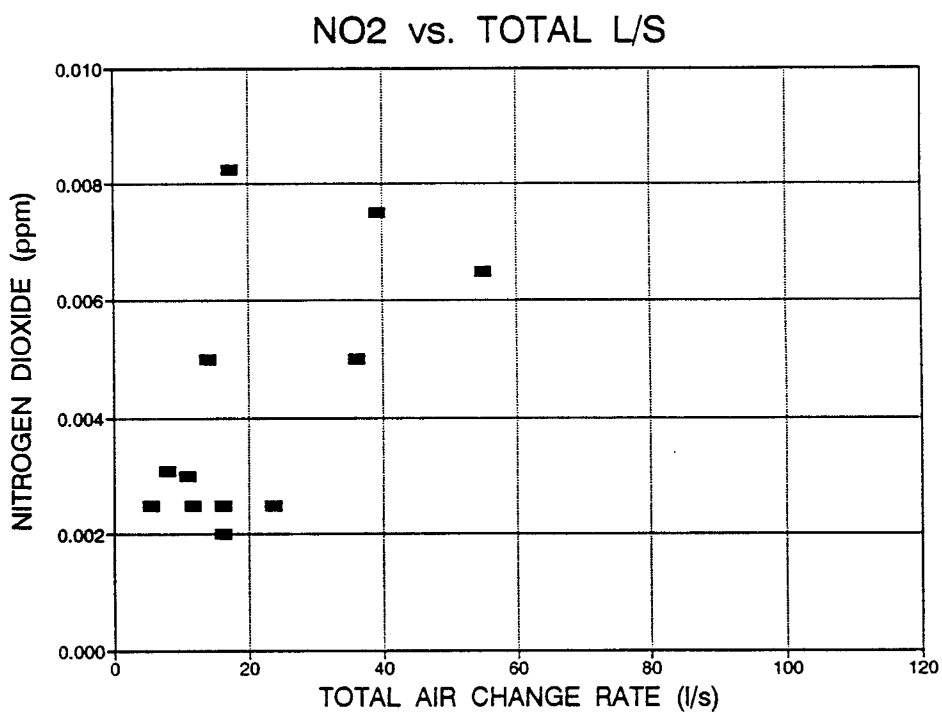


FIGURE 11(a)

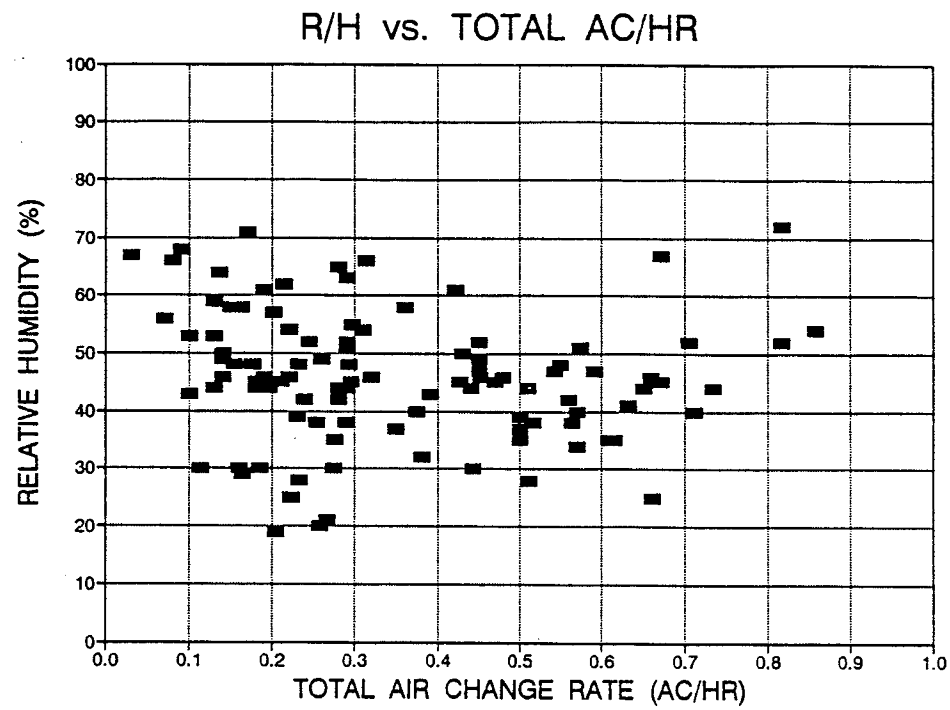
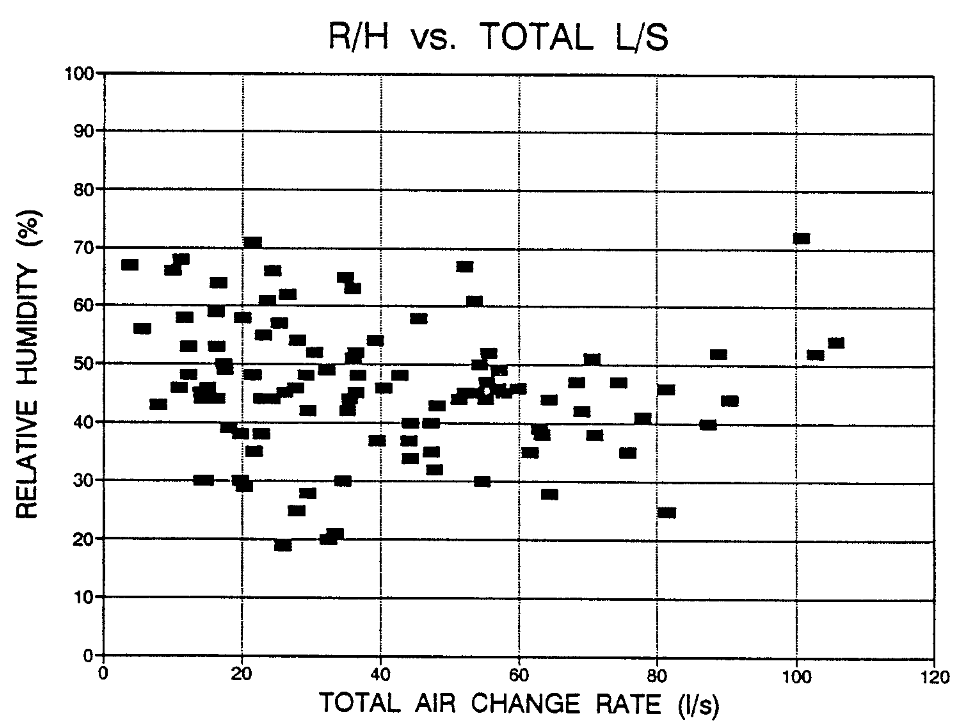


FIGURE 11(b)



Type of Ventilation System

Houses equipped with bathroom fans or central exhaust systems with make-up air ducts experienced total air change rates which were lower, to statistically significantly levels, than houses with HRVs. In fact, none of the former group's values were within the desired range of 0.40 ac/hr to 0.50 ac/hr. Most of the air change in the two houses with bathroom fans was is believed to have been provided by the open vents of the naturally aspirated heating systems. The three houses with central exhaust systems were also equipped with make-up air ducts to the furnace's return air plenum. However, the make-up air flow rates were found to be relatively minor in one case and negligible in the other two houses.

Type of Heating System (R-2000 Houses)

Baseboard heated R-2000 houses experienced a statistically significant higher mean air change rate than R-2000 houses using forced air heating systems, 0.33 ac/hr vs. 0.49 ac/hr. This may have occurred because homeowners in the former group were more inclined to turn off the HRV since another "air moving device", i.e. the furnace blower, was present. In houses with baseboard heating, the HRVs were the only air circulation devices so their non-use may have been more noticeable.

Presence of Smokers

The presence of a smoker in the household appears to have increased utilization of the ventilation systems. Mean air change rates were 0.32 ac/hr and 0.40 ac/hr in non-smoker's houses and smoker's houses respectively, the difference being assessed as statistically significant.

Correlations Between Pollutant Concentrations and Total Air Change Rates

Regression equations of the form shown in Eq. 4 were fitted to the five pollutant vs. total air change rate data sets shown in Figs. 7 to 11. The results, including the correlation coefficients (r), are summarized in Table 10 using both air changes per hour and litres per second as the rate parameter.

Correlations between pollutant concentrations and total air change rates were generally found to be poor. The only contaminant which displayed even a moderate dependency was formaldehyde, with correlation coefficients of 0.54 and 0.47, depending on the rate parameter. The greatest benefit of increased ventilation, with respect to formaldehyde, was its ability to reduce the occurrence of peak concentrations. When the total air change rate exceeded approximately 0.35 ac/hr, or roughly 0.30 mechanical, the variation in concentrations declined significantly indicating reduced risk and a lower probability of unusually high levels.

Although the nitrogen dioxide results had moderate correlation coefficients, the computed regression equations had negative coefficients for the independent variable, i.e. the least squares fit curve indicated that pollutant concentrations

TABLE 10

REGRESSION DATA

EQUATION: $C_i = C_o + \frac{N'}{ac/hr}$

POLLUTANT (C_i)	C_o	N′	NO. OF DATA POINTS	CORRELATION COEFFICIENT (r)
Formaldehyde (ppm)	0.03967	0.005504	120	0.5361
Radon Daughters (WL)	0.009352	0.0002500	104	0.0603
Nitrogen Dioxide (ppm)	0.6590	-0.0003629	12	0.5608
Particulates ($\mu g/m^3$)	34.52	-0.4845	101	0.0655
Relative Humidity (%)	42.35	0.8384	103	0.2822

EQUATION: $C_i = C_o + \frac{N'}{l/s}$

POLLUTANT (C_i)	C_o	N′	NO. OF DATA POINTS	CORRELATION COEFFICIENT (r)
Formaldehyde (ppm)	0.04476	0.4705	120	0.4739
Radon Daughters (WL)	0.009250	0.02909	104	0.0660
Nitrogen Dioxide (ppm)	0.005901	-0.02398	12	0.5110
Particulates ($\mu g/m^3$)	32.97	-11.61	101	0.0147
Relative Humidity (%)	42.75	80.82	103	0.2531

increased with air change rate.

With respect to formaldehyde, the regression equations predicted outdoor concentrations of 0.040 ppm and 0.045 ppm. These exceeded the 0.010 ppm to 0.030 ppm range suggested by Bowen et al (1981) for urban environments (although higher levels are noted as possible in areas of heavy traffic) or predicted by Figley (1985) in a study of formaldehyde levels in Winnipeg houses. The values of 0.040 ppm and 0.045 ppm are not considered representative of actual outdoor concentrations since several indoor levels were found below these values and because the two outdoor measurement performed in March 1989 (discussed in Section 2) found outdoor levels below 0.005 ppm. Reasons for this include the assumptions used in the creation of Eq. 4, i.e. constant source strength and outdoor levels. As noted by Nelms (1986), the emission rate of formaldehyde from particleboard and, by inference, other manufactured products containing formaldehyde, occurs by a diffusion mechanism which is a function of the indoor concentration. At higher air change rates and hence lower formaldehyde concentrations, the diffusion concentration gradient and thus the emission rate may increase. This would increase the source strength, N', in Eq. 4.

The dependence of relative humidity upon total air change rate was also found to be poor although this is somewhat an artificial result since relative humidity and air change rate are not totally independent. Undesirable R/H levels will induce homeowner reactions to restore a more comfortable condition.

SECTION 9

MECHANICAL VENTILATION AND INDOOR AIR QUALITY

9.1 INTRODUCTION

The preceding sections of this report have reviewed the indoor pollutant levels in the 20 study houses over the three year monitoring period. Contaminant concentrations have been compared to exposure guidelines developed on the basis of health considerations. In a broad sense, these exposure guidelines can be described as performance targets. The difficulty lies in determining how they can be best met. This section considers the relationship between mechanical ventilation and indoor air quality.

9.2 OBSERVED CORRELATION BETWEEN MECHANICAL VENTILATION AND INDOOR AIR QUALITY

The statistical correlations between the five measured pollutants and their corresponding total air change rates were found to generally be poor. While these five contaminants represent only a small sample of the vast number of pollutants found in residential environments, they are generally regarded as some of the more important. With the possible exception of formaldehyde, air change rate was not observed to be a good predictor of pollutant concentration. With respect to formaldehyde, high concentrations (those over the Action Level of 0.100 ppm) only occurred at very low air change rates, below about 0.20 ac/hr. However, a well-defined cut-off point could not be established beyond which an acceptable low level (those under the Target Level of 0.050 ppm) could be achieved with confidence.

Since the project houses were constructed to minimize natural air leakage, the major component of the total air change rate was provided by mechanical ventilation. As a result, the statistical correlations between the pollutant concentrations and mechanical ventilation can also be considered as poor.

In the Interim Report (Proskiw 1989), it was suggested that little practical benefit was achieved in the project houses when total air changes exceeded about 0.35 ac/hr, which corresponded to a mechanical ventilation rate of roughly 0.30 ac/hr (assuming a natural infiltration rate of 0.05 ac/hr). With the additional data available, it is worth revisiting this comment.

First, it should be stressed that mechanical ventilation was necessary to achieve good indoor air quality in the study houses. Those operated at very low mechanical ventilation rates were more likely to suffer from elevated indoor contaminant levels, particularly formaldehyde, and to a lesser extent, relative humidity. However, pollutant levels, for the study population, did not respond in a highly predictable fashion to increased ventilation rates. Given that the houses were similar with regards to many of the factors which influence air quality (size, location, outdoor pollutant concentrations, construction materials, etc.), it is probable that a larger, more random sample of houses would demonstrate an even poorer dependence between mechanical ventilation rate and indoor air quality. The study findings do not suggest that mechanical ventilation is not an important component of an effective indoor air quality control strategy, but rather that additional measures would generally be required. Mechanical ventilation appears to be best suited to controlling extreme concentrations of pollutants, as occurred with formaldehyde when the air change rates were very low. However, to reduce concentrations further would require other control measures such as source removal and isolation, prevention of pollutant entry from outdoors and improvements in ventilation efficiency/effectiveness.

Similar arguments have been put forward in other studies. Nero et al (1983) investigated the relationship between radon concentrations and air infiltration rates in 98 conventional and energy efficient houses and concluded that no clear correlation existed between the two parameters even though each varied over a wide range. Harris (1987) compared radon and formaldehyde concentrations as a function of ventilation rates for 820 conventional and energy efficient houses in four northwest American states and concluded: "First, low air exchange rates do not cause or even indicate high radon or formaldehyde concentration. Second, a high air exchange rate is no guarantee of low pollutant concentrations." Fisk (1986) reviewed indoor air quality control techniques and observed that maintaining ventilation rates in accordance with ASHRAE 62-81 did not guarantee that pollutant concentrations would be kept acceptably low. Harrje and Gadsby (1986) argued that source control should be seen as the first line of defence to protect indoor air quality.

9.3 TYPE OF VENTILATION SYSTEM

Table 11 summarizes the mean pollutant concentrations on the basis of ventilation system type. Note that the houses with bathroom exhaust fans also contained naturally aspirated furnaces and hot water tanks which provided additional air exchange capability.

The lowest contaminant levels were typically those in the HRV-equipped houses although levels in houses with central exhaust system and make-up air ducts were similar. The poorest air quality occurred in the conventional houses equipped with bathroom exhaust systems.

9.4 HOMEOWNER UTILIZATION OF THE MECHANICAL VENTILATION SYSTEMS

Homeowner intervention with the mechanical ventilation systems was found to be a common occurrence, resulting in utilization rates lower than expected. Homeowners, including those in houses with state-of-the-art HRVs, frequently reduced air flow rates by adjusting the speed control or disconnecting the power

TABLE 11

EFFECT OF VENTILATION SYSTEM UPON POLLUTANT CONCENTRATIONS

TYPE OF VENTILATION SYSTEM	FORMALDEHYDE (ppm)		RADON DAUGHTERS (WL)	PARTICULATES ($\mu g/m^3$)		NITROGEN DIOXIDE (ppm)		RELATIVE HUMIDITY (% OUTSIDE RECOMMENDED RANGE)
	MEAN	STD. DEV.	GEOMETRIC MEAN	MEAN	STD. DEV.	MEAN	STD. DEV.	
Bathroom Fan	0.079	0.022	0.009	50	45	0.0044	0.0022	46%
Central Exhaust & Make-Up Air Duct	0.052	0.010	0.010	27	13	--	--	31%
HRV	0.060	0.034	0.007	33	25	0.0040	0.0024	29%

supply to the unit. This occurred even though the HRVs were located in the basement and were therefore inconvenient to adjust. A separate study of ventilation system utilization in the Flair houses found an average annual utilization of 19.3 hr/day for HRVs and 0.62 hr/day for central exhaust systems (Proskiw 1992). These HRVs were designed for continuous service whereas the central exhaust systems were controlled by a dehumidistat which, it was assumed, would result in relatively heavy usage. However, it was discovered during the numerous site visits that the dehumidistats were generally adjusted to settings well above the existing relative humidity levels indicating that the homeowners were deliberately not using them. This suggests that the conventional dehumidistat, at least when used with non-HRV ventilation systems, will not be properly operated by homeowners and that a better design, coupled with improved homeowner education, is warranted. Reasons given by homeowners for not using their ventilation systems on a continuous basis included concerns that the ventilation rate was excessive thereby wasting energy (despite the heat recovery capability of the HRVs), noise (particularly on the first generation units) and discomfort caused by cold drafts at the registers (mainly on systems which did not use high sidewall supply grilles).

These findings were interpreted to mean that the design rates used for mechanical ventilation systems should be established both on the ability of the system to remove pollutants as well as the impact the design ventilation rate will have on homeowner utilization of the system. In fact, ventilation systems with large installed capacities are likely to be used less frequently because of homeowner perceptions of increased energy costs, noise or discomfort. These comments are directed primarily at systems without heat recovery since they introduce a greater space heating liability, are more likely to create discomfort problems and are often noisier.

9.5 IMPROVED VENTILATION SYSTEM DESIGN AND UTILIZATION

While the primary objective of this study was to survey the air quality in the project houses, the findings have suggested some opportunities for improving residential mechanical ventilation systems:

Control Systems - Alternative control systems need to be developed and field proven to increase utilization of mechanical ventilation systems. Conventional wisdom has taken a narrow perspective of how homeowners control ventilation systems, assuming that while they might turn the system off for (say) the summer, they would dutifully activate it during the winter and shoulder seasons when natural ventilation was less practical. Unfortunately, the results of this study suggest that a significant percentage of homeowners may never bother to use the system after the first year or two, particularly if it has a large system capacity (which could increase negative perceptions by the homeowners). An alternative control system might be one which provided infinitely variable speed control, with a minimum setting, which would lessen the likelihood of the system being turned completely off. It could also utilize remote controls similar to those used on televisions (a concept now available on some room air conditioners).

System Capacity - Given the generally poor correlations between contaminant levels and ventilation rates, coupled with the potentially negative effects of a high installed capacity (increased homeowner intervention, furnace backdrafting, increase radon entry, etc.), it was concluded that system capacities should not be set excessively high. Desires to err on the high side (i.e a large installed capacity), could result in degraded air quality as systems are disabled or not used by the homeowner.

Perceived System Performance - Every effort should be made to improve the homeowner's perception of the ventilation system's performance. Noise levels have to be kept to a minimum, mixing and distribution of ventilation air must be done so as to not create drafts and the system must generally be perceived as unobtrusive by the occupants. The concern about energy wastage will be a difficult problem to address with non-HRV systems but can be partially handled through improved homeowner education.

Homeowner education - Improvements are needed to increase the understanding by homeowners as to the function of the ventilation system, why it should not be turned off for extended periods of time (unless natural ventilation is being used), how it can be effectively used, maintenance requirements, etc. Several of the study homeowners reported that they did not understand what their HRVs did, even after three years of occupancy, possession of operating manuals and the guidance from the testing technician. One method which has been suggested is to supplement the written homeowner manual with short videos covering the same material. Videos are becoming increasingly popular while written manuals are increasingly ignored.

SECTION 10

CONCLUSIONS

10.1 COMPARATIVE AIR QUALITY IN R-2000 AND CONVENTIONAL HOUSES

- o The air quality in the R-2000 houses was found to have been superior to that in the conventional houses. Mean levels of formaldehyde, particulates and nitrogen dioxide were lower in the R-2000 houses, although not to statistically significant degrees. Lower mean radon daughter levels and median carbon dioxide concentrations were also observed in the R-2000 houses while relative humidity levels were more frequently within the recommended winter exposure range.

10.2 FORMALDEHYDE

- o The mean formaldehyde concentration in the R-2000 houses was 0.060 ppm compared to 0.068 ppm for the conventional structures, although the difference was not statistically significant. However, levels in the R-2000 houses were more frequently below the recommended Target Level of 0.100 ppm and the Action Level of 0.050 ppm.

- o Formaldehyde levels in the R-2000 houses which were not operated in accordance with the R-2000 Ventilation Guidelines averaged 0.089 ppm compared to 0.047 ppm for houses operated in compliance with the Guidelines. The difference was statistically significant.

- o The Federal-Provincial Advisory Committee on Environmental and Occupational Health Action Level for formaldehyde of 0.100 ppm was found to be readily achievable while the Target Level of 0.050 ppm could not be reached on a consistent basis. Mechanical ventilation was the only formaldehyde control measure used in the project houses.

- o Mean formaldehyde levels in houses with smokers were slightly higher than those in houses which did not contain smokers, although the difference was not statistically significant. However, the mean total air change rate in the smoker houses was also higher.

- o The formaldehyde source strength in a sub-group of seven houses was measured for three consecutive winters and found to decline by 48% over this period.

10.3 RADON DAUGHTERS

- o Geometric mean radon daughter levels were 0.007 WL in the R-2000 houses and 0.010 WL in the conventional structures. Only one of the 123 measurements conducted in the study exceeded the Canadian exposure guideline of 0.100 WL.

o The geometric mean radon daughter levels in both the R-2000 and conventional houses were well below those reported in a similar study of older, conventional houses in the same city. This large difference for houses in the same city suggests that geographic location, by itself, may not be a reliable parameter for predicting indoor concentrations.

o Radon daughter levels were nearly twice as high in houses which used baseboard heating systems compared to those which used forced air heating systems.

10.4 PARTICULATES

o Particulate levels were nearly 60% higher in houses which contained smokers relative to those which did not (44 $\mu g/m^3$ vs. 28 $\mu g/m^3$), even though air change rates were higher in the houses with smokers; the difference in particulate levels was assessed as statistically significant.

10.5 NITROGEN DIOXIDE

o The mean nitrogen dioxide level in the R-2000 houses was 0.0040 ppm compared to 0.0044 ppm for the conventional houses, although the difference was not statistically significant. All of the measurements were well below the recommended exposure guideline of 0.05 ppm.

10.6 CARBON DIOXIDE

o Spot measurements of carbon dioxide concentrations were made on 1065 occasions and only one reading exceeded the recommended exposure guideline of 3500 ppm. Also, 94% of the readings were below 1000 ppm.

o Using a sub-set of 587 carbon dioxide measurements performed with high resolution detection tubes, the median concentration in R-2000 houses was found to be 600 ppm compared to 800 ppm in the conventional houses.

10.7 RELATIVE HUMIDITY

o Mean relative humidity levels were more frequently within the recommended winter exposure range of 30% to 55% in the R-2000 houses than in the conventional houses.

10.8 MECHANICAL VENTILATION AND INDOOR AIR QUALITY

o Statistical correlations between formaldehyde, radon daughter, particulate, nitrogen dioxide and relative humidity levels, and the corresponding air change rates were generally found to be poor. However, with respect to formaldehyde, pollutant concentrations were found to be more consistent, with fewer extreme levels recorded when the mechanical air change rate exceeded about 0.30 ac/hr.

- The study highlighted the limitations of using mechanical ventilation as the sole indoor air quality control measure. It concluded that greater emphasis should be placed on other measures including source removal and isolation, pollutant entry control and improved ventilation system efficiency/effectiveness.

- Homeowner intervention with the mechanical ventilation systems was found to be a common occurrence, particularly on those systems without heat recovery capabilities. Intervention usually occurred due to homeowner perceptions of noise, energy waste and discomfort and resulted in lower than expected utilization rates. It was also concluded that the design rates used for mechanical ventilation systems, particularly for systems without heat recovery, should be established both on the ability of the system to remove pollutants as well as the effect homeowner utilization of the system will have on the net ventilation rate.

- Recommendations were made to improve mechanical ventilation system performance including suggestions for improved control systems, system capacity and homeowner education.

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APPENDIX A

MONITORING DATA

DATE	HOUSE	FORMALDEHYDE (ppm)			RADON DHTRS. (WL)	PARTIC-ULATES (ug/m3)	NITROGEN DIOXIDE (ppm)			TEMP. (C)	R/H (%)	HUMIDITY RATIO (kg/kg)	TOTAL ac/hr
		BDRM.	L/R	MEAN			MAIN	BSMT.	MEAN				
MARCH 1986	1	0.077	0.064	0.071	0.004	14.0				24	44	0.0082	0.29
	2	0.046	0.047	0.047	0.011	11.0	0.0020	0.0020	0.0020	21	44	0.0069	0.13
	3	0.068	0.068	0.068	0.007	61.0	0.0060	0.0002	0.0031	22	43	0.0072	0.10
	4	0.065	0.103	0.084	0.009	61.0				22	46	0.0077	0.22
	5	0.039	0.044	0.042	0.001	26.0				20	34	0.0049	0.57
	6	0.057	0.046	0.052	0.001					22	43	0.0072	0.39
	7	0.063	0.036	0.050	0.011	30.0				25	39	0.0077	0.23
	8	0.068	0.043	0.056	0.008	10.0				19	50	0.0068	0.14
	9	0.109	0.085	0.097	0.009	25.0	0.0010	0.0050	0.0030	24	46	0.0086	0.14
	10	0.110	0.106	0.108	0.008	44.0	0.0040	0.0125	0.0083	23	49	0.0087	0.14
AUGUST 1986	1	0.071	0.076	0.074	0.018	31.0							
	2	0.031	0.044	0.038	0.005	36.0							
	3	0.035	0.036	0.036	0.014	29.0							
	4	0.050	0.051	0.051	0.005	88.0							
	5	0.047	0.037	0.042	0.007	30.0							
	6	0.079	0.060	0.070	0.032	122.0							
	7	0.062	0.065	0.064	0.008	54.0							
	8	0.049	0.052	0.051	0.015	21.0							
	9	0.088	0.083	0.086	0.007	27.0							
	10	0.069	0.063	0.066	0.020	58.0							
	11	0.046	0.043	0.045	0.005	32.0							
	12	0.061	0.054	0.058	0.010	28.0							
	13	0.088	0.128	0.108	0.009	18.0							
	14	0.053	0.073	0.063	0.008	47.0							
	15	0.016	0.017	0.017									
	16	0.054	0.030	0.042	0.003	14.0							
	17	0.055	0.064	0.060	0.005	27.0							
	18	0.094	0.103	0.099									
	19	0.088	0.045	0.067	0.005	54.0							
	20	0.065	0.047	0.056	0.004	52.0							

DATE	HOUSE	FORMALDEHYDE (ppm) BDRM.	L/R	MEAN	RADON DHTRS. (WL)	PARTIC -ULATES (ug/m3)	NITROGEN DIOXIDE (ppm) MAIN	BSMT.	MEAN	TEMP. (C)	R/H (%)	HUMIDITY RATIO (kg/kg)	TOTAL ac/hr
	1	0.105	0.081	0.093	0.009	18.5							0.22
	2	0.096	0.045	0.071	0.014	6.1	0.0020	0.0030	0.0025	22	53	0.0088	0.13
	3	0.083	0.073	0.078	0.039	46.1	0.0020	0.0030	0.0025	24	56	0.0105	0.07
	4	0.068	0.075	0.072	0.002	36.3				22	52	0.0087	0.29
	5	0.069	0.063	0.066	0.016	48.6				24	48	0.0090	0.55
	6	0.071	0.087	0.079	0.020					22	63	0.0105	0.29
	7	0.080	0.061	0.071	0.009	22.4				25	46	0.0091	0.19
	8				0.021	9.7				20	66	0.0097	0.08
	9	0.078	0.094	0.086	0.002	10.0	0.0030	0.0020	0.0025	25	58	0.0115	0.15
OCT. 1986	10	0.121	0.102	0.112	0.029	53.0	0.0030	0.0020	0.0025	24	61	0.0115	0.19
	11	0.067	0.076	0.072	0.009	6.0				21	58	0.0091	0.36
	12	0.041	0.088	0.065	0.015	14.6							0.56
	13	0.167	0.158	0.163	0.008	9.4				24	67	0.0126	0.03
	14	0.058	0.064	0.061	0.002	18.5				24	45	0.0084	0.47
	15	0.048	0.056	0.052	0.005	11.8				24	50	0.0094	0.43
	16	0.076	0.081	0.079	0.009	9.6				21	54	0.0084	0.22
	17	0.129	0.124	0.127	0.015	13.3				21	71	0.0111	0.17
	18	0.052	0.066	0.059	0.010	1.6				22	44	0.0073	0.28
	19	0.055	0.068	0.062	0.006	14.9				23	45	0.0080	0.21
	20	0.076	0.079	0.078	0.009	28.0				22	52	0.0087	0.45
	1	0.051	0.063	0.057	0.002	20.9							0.52
	2	0.031	0.031	0.031	0.003	8.2	0.0060	0.0070	0.0065	21	44	0.0069	0.44
	3	0.030	0.031	0.031	0.001	9.8	0.0070	0.0080	0.0075	23	37	0.0065	0.50
	4	0.055	0.059	0.057	0.001	66.7				22	42	0.0070	0.28
FEB. 1987	5	0.057	0.058	0.058	0.006	19.7				25	40	0.0079	0.57
	6	0.053	0.062	0.058						22	49	0.0082	0.26
	7	0.052	0.056	0.054	0.007	33.9				23	44	0.0078	0.18
	8	0.054	0.056	0.055	0.009	8.6				18	59	0.0074	0.13
	9	0.059	0.068	0.064	0.003	12.5	0.0050	0.0050	0.0050	23	45	0.0080	0.18
	10	0.089	0.101	0.095	0.010	145.0	0.0050	0.0050	0.0050	23	51	0.0090	0.29

DATE	HOUSE	FORMALDEHYDE (ppm)			RADON DHTRS. (WL)	PARTIC -ULATES (ug/m3)	NITROGEN DIOXIDE (ppm)			TEMP. (C)	R/H (%)	HUMIDITY RATIO (kg/kg)	TOTAL ac/hr
		BDRM.	L/R	MEAN			MAIN	BSMT.	MEAN				
	11	0.046	0.040	0.043	0.003	30.7				22	44	0.0073	0.51
	12	0.075	0.063	0.069	0.017	26.2							0.44
	13	0.116	0.113	0.115						23	53	0.0094	0.10
	14	0.056	0.058	0.057	0.003	12.3				24	47	0.0088	0.45
FEB. 1987	15	0.048	0.036	0.042	0.007	20.2				23	39	0.0069	0.50
	16	0.044	0.047	0.046	0.002	4.0				19	49	0.0066	0.45
	17	0.079	0.094	0.087	0.006	17.8				22	54	0.0090	0.31
	18	0.042	0.048	0.045	0.010	8.6							
	19	0.051	0.045	0.048	0.008	17.1				22	35	0.0058	0.50
	20	0.074	0.054	0.064	0.003	19.2				21	42	0.0065	0.56
	1												
	2									21	63	0.0099	
	3									25	52	0.0103	
	4												
	5									25	50	0.0099	
	6									24	62	0.0117	
	7									25	65	0.0129	
	8									20	64	0.0094	
	9	0.045	0.043	0.044						25	67	0.0134	0.67
AUGUST 1987	10	0.086	0.085	0.086						26	65	0.0136	0.28
	11									24	60	0.0113	
	12									23	63	0.0112	
	13	0.191	0.161	0.176						24	68	0.0128	0.09
	14	0.229	0.173	0.201						27	58	0.0128	0.16
	15									24	53	0.0100	
	16									21	60	0.0094	
	17									22	60	0.0100	
	18									22	64	0.0107	
	19	0.050	0.034	0.042						19	72	0.0098	0.82
	20	0.079	0.067	0.073						26	54	0.0113	0.86

DATE	HOUSE	FORMALDEHYDE (ppm) BDRM.	FORMALDEHYDE (ppm) L/R	FORMALDEHYDE (ppm) MEAN	RADON DHTRS. (WL)	PARTIC-ULATES (ug/m3)	NITROGEN DIOXIDE (ppm) MAIN	NITROGEN DIOXIDE (ppm) BSMT.	NITROGEN DIOXIDE (ppm) MEAN	TEMP. (C)	R/H (%)	HUMIDITY RATIO (kg/kg)	TOTAL ac/hr
OCT. 1987	1	0.015	0.069	0.042	0.006	70.0							0.40
	2	0.043	0.051	0.047	0.018	32.0				21	57	0.0089	0.20
	3	0.028	0.023	0.026	0.001	40.0				23	44	0.0078	0.65
	4	0.078	0.067	0.073						21	46	0.0072	0.48
	5	0.071	0.071	0.071	0.009	70.0				25	45	0.0089	0.67
	6	0.060	0.086	0.073	0.001	28.0				21	51	0.0080	0.57
	7	0.078	0.047	0.063	0.009	28.0				25	48	0.0095	0.15
	8	0.032	0.050	0.041	0.005	51.0				19	46	0.0062	0.66
	9	0.066	0.064	0.065	0.009	27.0				23	66	0.0117	0.31
	10	0.127	0.123	0.125	0.009	12.0				25	62	0.0123	0.21
	11	0.024	0.039	0.032	0.016	84.0				21	47	0.0073	0.54
	12	0.012	0.065	0.039	0.019	36.0				25	46	0.0091	0.45
	13	0.054	0.059	0.057	0.005	39.0				25	64	0.0127	0.14
	14	0.052	0.055	0.054	0.003	24.0				22	40	0.0066	0.71
	15	0.035	0.048	0.042	0.013	37.0				23	47	0.0083	0.59
	16	0.056	0.064	0.060	0.009	29.0				19	61	0.0083	0.42
	17	0.055	0.051	0.053	0.015	29.0				22	52	0.0087	0.82
	18	0.002	0.041	0.022	0.021	17.0				16	52	0.0054	0.71
	19	0.041	0.039	0.040	0.009	31.0				19	41	0.0055	0.63
	20	0.016	0.060	0.038						25	44	0.0087	0.73
JAN. 1988	1	0.035	0.059	0.047	0.001	20.0							0.31
	2	0.043	0.026	0.034	0.004	15.0				23	32	0.0056	0.38
	3	0.094	0.043	0.069	0.013	51.0				21	35	0.0054	0.27
	4	0.050	0.047	0.049	0.003					21	48	0.0075	0.29
	5	0.033	0.034	0.034	0.002	44.0				25	35	0.0069	0.61
	6	0.063	0.064	0.064	0.004	61.0				21	45	0.0070	0.29
	7	0.047	0.055	0.051	0.008	27.0				24	38	0.0071	0.29
	8	0.043	0.036	0.040	0.005	29.0				20	44	0.0064	0.20
	9	0.050	0.054	0.052	0.006	160.0				24	55	0.0103	0.30
	10	0.067	0.094	0.081	0.012	53.0				25	52	0.0103	0.24

DATE	HOUSE	FORMALDEHYDE (ppm)			RADON DHTRS. (WL)	PARTIC -ULATES (ug/m3)	NITROGEN DIOXIDE (ppm)			TEMP. (C)	R/H (%)	HUMIDITY RATIO (kg/kg)	TOTAL ac/hr
		BDRM.	L/R	MEAN			MAIN	BSMT.	MEAN				
JAN. 1988	11	0.067	0.061	0.064	0.005	20.0				21	48	0.0075	0.23
	12	0.059	0.050	0.055	0.017	19.0				25	37	0.0073	0.35
	13	0.089	0.115	0.102	0.005	18.0				24	48	0.0090	0.18
	14	0.046	0.040	0.043		68.0				24	38	0.0071	0.52
	15	0.036	0.069	0.053	0.007	13.0				24	40	0.0075	0.37
	16	0.034	0.036	0.035	0.006	18.0							0.50
	17	0.046	0.060	0.053	0.012	26.0				22	46	0.0077	0.32
	18	0.024	0.025	0.025	0.010	28.0				19	38	0.0051	0.56
	19	0.047	0.038	0.043	0.010	5.0				21	35	0.0054	0.62
	20	0.052	0.072	0.062	0.015					23	42	0.0074	0.24
SEPT. 1988	1												
	2												
	3												
	4												
	5												
	6												
	7												
	8												
	9	0.064	0.064	0.064									0.37
	10	0.084	0.071	0.078									0.19
	11												
	12												
	13	0.135	0.141	0.138									0.13
	14	0.235	0.220	0.228									0.10
	15												
	16												
	17												
	18												
	19	0.039	0.038	0.039									0.69
	20	0.066	0.068	0.067									0.77

DATE	HOUSE	FORMALDEHYDE (ppm)			RADON DHTRS. (WL)	PARTIC-ULATES (ug/m3)	NITROGEN DIOXIDE (ppm)			TEMP. (C)	R/H (%)	HUMIDITY RATIO (kg/kg)	TOTAL ac/hr
		BDRM.	L/R	MEAN			MAIN	BSMT.	MEAN				
	1	0.040	0.042	0.041	0.003	57.0							0.32
	2	0.034	0.036	0.035	0.005	22.0				23	25	0.0044	0.22
	3	0.022	0.028	0.025	0.027	80.0				22	30	0.0050	0.19
	4	0.028	0.034	0.031	0.003	18.0				18	21	0.0026	0.27
	5	0.057	0.056	0.057	0.008	68.0							0.37
	6	0.040	0.042	0.041	0.020	146.0				24	29	0.0054	0.16
	7	0.060	0.050	0.055	0.019	26.0							0.25
	8	0.028	0.041	0.035	0.018	26.0				21	30	0.0047	0.11
	9	0.046	0.048	0.047	0.016	26.0				19	38	0.0051	0.25
FEB.	10	0.070	0.072	0.071	0.019	45.0							0.24
1989	11	0.046	0.036	0.041	0.010	15.0				21	30	0.0047	0.27
	12	0.017	0.029	0.023	0.007	28.0				20	20	0.0029	0.26
	13	0.070	0.068	0.069	0.004	15.0							0.26
	14	0.050	0.047	0.049	0.006	34.0				25	30	0.0059	0.16
	15	0.028	0.033	0.031	0.008	30.0				21	19	0.0029	0.20
	16	0.029	0.024	0.027	0.005	26.0				18	28	0.0035	0.23
	17	0.063	0.066	0.065	0.150	12.0				21	45	0.0070	0.43
	18	0.029	0.030	0.030	0.009	27.0				22	28	0.0046	0.51
	19	0.024	0.023	0.024	0.004	22.0				22	25	0.0041	0.66
	20	0.037	0.044	0.041	0.008	69.0				24	30	0.0056	0.44