Ventilation and Air Quality Testing in Electrically Heated Housing

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NOTE: DISPONIBLE AUSSI EN FRANÇAIS SOUS LE TITRE:

ESSAIS DE VENTILATION ET DE QUALITÉ DE L'AIR DANS DES MAISONS CHAUFFÉES À L'ÉLECTRICITÉ

DISCLAIMER

Acknowledgment

This report is the compilation of an enormous amount of work carried out by the technical staff at LTEE, by the volunteers and their families who allowed us into their homes and faithfully recorded the needed information, and by other staff responsible for the field work and laboratory testing.

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Executive Summary

The objectives of this field study were to determine if there is a correlation between measured airtightness and ventilation, as well as indoor air quality, and to investigate the main factors which determine indoor humidity levels in the fall and winter. This information is required to determine if there is a range of building airtightness, within which there are no indoor air quality or high humidity problems. The expectation is that buildings in the upper level of the range could be safely air-tightened. Test results of measurements of source strength of various indoor air pollutants in thirty houses in Québec are presented and compared with similar data obtained from houses in Ontario. This information permits estimating the minimum ventilation required to keep the levels of the various pollutants within acceptable levels.

Additional observations were also made in eight of these houses to study the effects of living habits and of various ventilation systems on the quality of indoor air and on indoor humidity levels, and to estimate the actual ventilation rates under various operating conditions. The AQ1 model was used to predict the natural ventilation rate in several houses. The findings indicate that the correlation between measured airtightness and natural ventilation (and indoor air quality) must take into account many factors including the use of combustion equipment, building characteristics and living habits. Most houses experience periods of time during which the amount of natural ventilation is low enough that certain air pollutants rise above the maximum recommended levels.

The report concludes that the correlation between indoor air quality and measured airtightness is poor, and that leaky houses as well as airtight houses can experience excessive indoor pollution levels. Certain activities of the occupants strongly influence the production of certain air contaminants. The limiting pollutants in the group of houses tested were fairly evenly distributed among the following three contaminants: Formaldehyde, RSP's and Carbon Dioxide.

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RESULTS OF FIELD TESTS

The objectives of the study were to determine the correlation between measured airtightness and ventilation in a sample of houses in Quebec, and to investigate the effects of ventilation on the levels of indoor air contaminants and humidity.

1. Sample Selection and Test Procedure

A total of 30 houses in the Trois-Rivières area were selected on the basis of their air leakage determined via a blower door test at 50 Pa. By design, a sample selection was made so as to have a similar distribution of air leakage as the houses in the Éval-Iso Program. The distribution of air leakage determined during the Éval-Iso Program is representative of the air leakage of the houses in the province of Québec. The following Table 1.A lists the distribution of house leakage determined during the Éval-Iso Program, and the distribution of leakage in the thirty selected houses.

Table 1.A Distribution of air leakage of houses in Québec and number selected in our sample (Air changes per hour at 50 Pa.)

AC/H_{50}	Distribution in Québec (%)	Sample
1.25	0.1	0
1.75	2.2	1
2.25	6.9	2
2.75	9.7	3
3.25	11.2	3
3.75	11	3
4.25	12.5	4
4.75	7.6	2
5.25	5.4	2
5.75	6.2	2
6.25	4.6	1
6.75	4.4	1
7.25	1.4	0
7.75	2.2	1
8.25	1.8	1
8.75	1.8	1
9.25	2.5	1
9.75	0.3	0
10.25	1.6	1
10.75	1.1	0
11.25	0	0
11.75	4.5	1
16.25	1	0
	Total	**30**

A brief description of the test protocol follows: The thirty houses selected were within a short distance from one another and also within a few kilometers of a monitored weather station in order to have the same weather conditions in all test houses at the same time. Air quality measurements were carried out in each of the houses for a period of one week. A sub-group of eight houses was selected for continuous, much more detailed monitoring for about one year. These eight houses were selected because they had ventilation systems of interest and were fairly airtight.

Measurements made in the 30 houses

The physical size and shape of each house was noted, and during a one week period between December and March, air sampling kits were installed in each of houses for a period of one week to determine level of the following variables:

Variable	Sampling System
Average air change rate	PFT tracer method. This method uses 1, 2, or 3 sources and several samplers per house for a 7-day period. The materials and analysis a carried out by Brookhaven National Labs in Long Island.
Indoor air particulates	Pumped occupational hygiene filter cassette for 7-day period (micrograms per cu.m)
Total VOC's:	Pumped special multi-absorption tube for 3-hour period (will identify 6 major components in percent of toluene equivalent)
Formaldehyde:	AQRI passive Dosimeter (tube with a lid) with +/- .02 ppm resolution
Radon:	Canadian Institute for Radiation Safety (CAIRS) pumped filter sampler for 7-day period
Carbon Dioxide and Water Vapour	YES 203 recorder in living room

The average contaminant levels along with the house volume and average ventilation rate for the week were used to calculate the "source strength" of each airborne contaminant.

Continuous, long-term recording in the group of 8 houses:

The indoor air quality (carbon dioxide and moisture level) in eight houses was monitored continuously during the first few weeks in the fall, to help plan changes in the ventilation system of some of these houses. Before the end of December changes were made to the ventilation systems in five of the houses. The systems were energized and operated in various modes as will be indicated later. Three of the eight houses were used as a control or "Reference", and no changes were intended to be made in their equipment or operation during the year. In this manner, changes in the variables observed which were related to the weather could be identified and tracked, and an attempt could be made to separate weather effects from the effects of the new ventilation equipment on indoor air quality.

Data collected from the eight test houses which underwent continuous monitoring have been organized and processed in a manner which permits reviewing and comparing the results on a 10-minute basis. Appropriate weather variables were also summarized and presented along with these data.

The data collected from each of the eight houses were as follows:
On a ten-minute average basis, all year:

Carbon Dioxide level (in the master bedroom)
Total house kWh consumption
Inside-outside pressure difference in Pascals
Outdoor Temperature
Indoor Absolute Humidity in the master bedroom, (derived from recorded indoor RH and temperature)
Outdoor absolute humidity (derived from recorded outdoor RH and temperature)
Wind speed
Wind Direction

On a ten minute basis, for one week:
Carbon dioxide level (in the living room)
Absolute humidity in the living room (derived)
Carbon dioxide level (in the basement of some houses)

Occupant - controlled variables recorded throughout the year were:
Cigarette consumption (per day)
Window opening (hours and size of opening per day)
Occupancy (person-hours per day)
Exhaust fan operation (hours per week)
Clothes Dryer (hours per week)
Amount of wood burned (per day)
Number of candles burned (per day)

In order to present the vast amount of data efficiently, the 10-minute data was averaged for each 24-hour period starting at midnight, and the results were entered into a set of spreadsheets. See Appendix 1. These data summaries were used as a "navigation" tool to identify specific periods of time or events where meaningful comparisons in air quality could be made, such as use or non-use of a ventilation system, large gatherings of people, absence from home, closing bedroom doors versus not closing, use of fireplace versus non-use, as well as detect gradual changes in air quality over time. The eight houses selected for the detailed recording are described in Table 1.B. A total of four ventilation systems were installed as described in the footnote following Table 1.B. A fifth type of ventilation system had been previously installed in two of the houses, system "E". The records were collected weekly and entered into a data base. The records were then plotted and also summarized on a daily basis (midnight to midnight)

Table 1.B. Summary Description of Test Houses

House #	# 1	# 2	# 3	# 4	# 5	# 6	# 7	# 8
Purpose	Reference	Test	Test	Test	Test	Reference	Reference	Test
Test System	Turbine "E"	Turbine "E"	"A"	"B"	"C"	None *	None	"D"
Storeys	1	1	1	1	1	1	1	2
Wood Fire and Use	Fireplace Occasional	none	Fireplace Occasional	Firepl.,occas W/S, often	Fireplace occasional	Fireplace not used	Fireplace Slow fire	Fireplace often
Location	basement		bsmt	bsmt	first	first fl	bsmt	first fl
Bsmt Door		n	y	y	n	y	n	y
Turbine	y	y	n	n	n	n	n	n
Bath fan	n	1	1	1	1 bsmt	n*	n	n
Smoker	2	1	n	n	n	1	n	n
Win open	occasionally	y	y	n	n	n	occasion	y
Remark		Plug Tubine.						AirExchang
Occ day	1 dog	2	1 cat	3 + 1cat	0	2 + cat	2	2+ dog
Occ night	4+ dog	4	2 + 1 cat	4 + 1 cat	5	3 + cat	3	4+ dog
ACH50	3.66	4.69	3.04	2.81	2.28	3.27	3.44	2.52

* A through-the-wall fan was installed in mid-winter as an additional system "A" for use in the spring.

Test systems:

"A" = Exhaust only, plug basement leaks (radon mitigation)

"B" = 2 fans through the floor, unbalanced

"C" = Replace exhaust fan with quiet model, add fresh air /tempering system

"D" = Retrofit balanced air intake, exhaust and ventilation system

"E" = Turbine System, natural chimney effect via a 6" diameter duct

The recommended maximum levels for the contaminants of interest for continuous exposure[1] are presented in Table 1.C. For most contaminants, two levels are given: the acceptable long-term exposure range (ALTER), is that concentration range to which it is believed from existing information that a person may be exposed over a lifetime without undue risk to health, and the acceptable short term exposure (ASTER) is that concentration range to which it is believed from existing information that a person may be exposed over the specified time period without undue risk to health. For certain contaminants such as radon, Health Canada recommends an "action level" above which action should be initiated to reduce the ambient level.

[1]Health Canada, "Exposure Guidelines for Residential Indoor Air Quality", A Report of the Federal-Provincial Advisory Committee on Environmental and Occupational Heath, revised July 1989.

Table 1.C Recommended Maximum Levels Of Airborne Contaminants

Contaminant	Acceptable Long Term Exposure Range	Acceptable Short-term Exposure Range
Respirable Solid Particles < 2.5 µm mass median aerodynamic diameter	40 µg/cu m	100 µg/cu m (1 hour)
Total Volatile Organic Compounds	0.2 mg/cu m for no irritation* 3 mg/cu m and above results in complaints from occupants*	
Radon	2.7 pCi/L (Europe) 4 pCi/L (EPA, USA)	800 Bq/cu m (Health Canada Action Level) 21.6 pCi/L
Formaldehyde	60 µg/cu m (0.05 ppm)	120 µg/cu m (0.10 ppm)
Carbon Dioxide	3500 ppm (Health Canada) 1000 ppm (ASHRAE Std 62-1989) 650 ppm (Europe, 90% satisfied)	
Maximum RH (winter) Maximum RH (summer)	55% 65%	

* Molhave, L. Volatile Organic Compounds, Indoor Air Quality and Health, *Indoor Air* 1(4): 357 - 76, 1991

2. Results

2.1 Average Air Contaminant Levels - 30 Houses - One Week Test

The test results of the week-long sampling of the air contaminants of interest in the thirty houses are presented on Table 2.1.A. This table contains the average natural air change rate as well as the average contaminant concentrations recorded during the week of the test. Since these observations are averaged over one week, we cannot determine whether the readings are representative for the year or what the variance is from hour to hour or from day to day. The numbers which exceed the Health Canada acceptable long term exposure guidelines during the 1-week test period have been highlighted (***bold, Italic***) on the same Table.

Table 2.1.A. Summary of Average Pollutant Concentrations - 1-Week Test

House #	Volume	RSP	VOC's	Formald.	Radon	CO_2	Occup'cy	AC/H natural	AC/H 50pa
Units:	cu m	µg/ cu m	mg/cu m	ppm	pCi/L	ppm	m-hr/day	per hr	per hr.
1*	444	***83***	0.4	0.054	0.2	910	102	0.12	3.66
2*	306	***76***	0.4	0.046	0.2	994	89	0.31	4.69
3	486	27	0.7	***0.094***	0.6	956	39	0.11	3.04
4***	505	20	1.7	***0.099***	0.4	1118	83	0.14	2.81
5	515	38	0.7	***0.082***	1.0	1300	77	0.1	2.28
6*	517	***74***	0.3	***0.083***	0.8	949	69	0.1	3.27
7	487	23	0.4	***0.056***	0.6	723	55	0.1	3.44
8**	737	35	2.3	0.042	0.6	903	83	0.13	2.52
9	478	19	0.3	0.037	0.4	903	82	0.21	5.08
10	371	17	0.3	***0.070***	0.6	784	69	0.08	4.24
11*	513	***60***	0.7	***0.071***	0.2	784	74	0.24	5.50
12	412	25	<0.1	0.035	0.4	1266	63	0.2	2.86
13	504	26	0.2	0.021	0.6	592	121	0.58	6.81
14*	548	***74***	0.2	0.054	0.4	919	69	0.15	2.44
15	429	26	0.5	0.043	0.2	676	40	0.19	4.13
16	478	18	0.5	0.049	0.2	1234	96	0.2	2.46
17	387	19	0.6	0.043	0.2	665	125	0.37	7.14
18	397	35	0.4	0.033	0.4	825	32	0.38	8.30
19	325	26	0.7	0.034	1.8	1507	39	0.14	3.17
20	519	11	0.7	0.014	0.6	890	101	0.22	9.96
21*	270	11	0.7	***0.066***	0.4	792	39	0.2	10.06
22*	426	21	0.4	0.046	1.0	1069	90	0.33	3.32
23*	441	***43***	2.5	0.024	1.4	758	80	0.18	4.18
24*	221	26	0.7	0.032	0.6	966	69	0.38	8.55
25	748	10	0.3	0.021	0.4	570	69	0.28	5.63
26*	444		0.4	0.030	0.8	579	24	0.22	3.49
27*	231	***42***	0.3	0.038	0.8	878	74	0.38	11.35
28	456	22	0.2	0.025	0.2	840	90	0.5	3.45
29*	418	33	0.3	0.045	4.4	1034	59	0.17	3.65
30*	455	92	1.0	0.051	3.4	1491	99	0.15	1.72
Means	449	35.6	0.63	.048	.79	929	73	.23	4.77

* House where smoking takes place

** House with attached garage (House #10 has interconnecting door to garage)

*** Epoxy resin used in basement

Bold figures indicate where the Health Canada levels are exceeded

2.2 Source Strength Evaluation for Québec Houses

The "Source Strength" of an airborne contaminant in a house of known volume can be estimated by measuring the average level of the contaminant of interest and the average rate of air infiltration over the same period of time. The source strength S is:

S = house volume (cu. m.) x avge. contaminant level (mg/cu. m.)
x air change rate (AC/H)

Using the indicated units, S would be defined in units of mg/hr.

The average air change rate for each house during the test week was determined using the PFT tracer method. The tests in the 30 houses were conducted sequentially in small groups due to the limited number of instruments available. Therefore the weather conditions during the determination of average air change rates would not have been identical for the group of tests.

The results of pollutant level measurements therefore provide a snapshot in time for each house, but not under identical weather conditions. The test results are tabulated on Table 2.2.A. On this table, the natural air change rate is expressed in litres/second.

The source strength of each contaminant is useful for determining the contaminant levels in each house under various ventilation conditions (by natural infiltration or by forced ventilation). The accuracy of the estimate will be affected by the uniformity of diffusion of airborne pollutants throughout the entire building, and by the stability of the source strength of each contaminant over time.

Since the sample of 30 houses selected for the tests has a similar distribution of airtightness as houses in Québec, we expect the results of source strength determinations to be representative of the population of existing houses. The observations tabulated on Table 2.1.A were used to calculate the source strength of the air contaminants of interest, which are presented on Table 2.2.A.

The source strength calculation for carbon dioxide assumes that outdoor air contains 350 ppm of CO_2, and this amount was subtracted from the recorded levels in the houses. The source strength for water vapour was calculated by taking the difference in absolute humidity between indoor and outdoor air averaged over the test week. For VOC's, formaldehyde and radon source strength calculations, a zero level of pollutant was assumed for outdoor air.

Table 2.2.A. Source Strength of Airborne Contaminants in 30 Québec Houses

House #	Vol	Nat. Air Change	Occu-pancy	RSP	VOC's	Form.	Radon	CO_2	Mois-ture.
Units:	cu m	L/s	M-Hr/ day	mg/ hr	mg/hr	mg/hr	µCi/hr	g/hr	g/hr
1*	444	14.8	102	4.42	21	3.54	11	59	259
2*	306	26.4	89	7.21	38	5.37	19	120	488
3	486	14.9	39	1.44	37	6.18	32	64	295
4***	505	19.6	83	1.41	120	8.61	28	107	
5	515	14.3	77	1.96	36	5.19	52	96	358
6*	517	14.4	69	3.83	16	5.28	41	61	342
7	487	13.5	55	1.12	19	3.35	29	36	239
8**	737	26.6	83	3.35	220	4.95	57	104	332
9	478	27.9	82	1.91	30	4.57	40	109	
10	371	8.2	69	0.50	9	2.56	18	25	
11*	513	34.2	74	7.39	86	10.75	25	105	
12	412	22.9	63	2.06	7	3.55	33	149	
13	504	81.2	121	7.60	58	7.55	175	139	
14*	548	22.8	69	6.08	16	5.46	33	92	
15	429	22.6	40	2.12	41	4.31	16	52	
16	478	26.6	96	1.72	48	5.76	19	166	
17	387	39.8	125	2.72	86	7.57	29	89	
18	397	41.9	32	5.28	60	6.12	60	141	
19	325	12.6	39	1.18	32	1.90	82	104	
20	519	31.7	101	1.26	80	1.97	69	121	
21*	270	15.0	39	0.59	38	4.38	22	47	
22*	426	39.1	90	2.95	56	7.95	141	199	
23*	441	22.1	80	3.41	198	2.34	111	64	
24*	221	23.3	69	2.18	59	3.31	50	102	
25	748	58.2	69	2.09	63	5.41	84	91	
26*	444	27.1	24		39	3.6	78	44	
27*	231	24.4	74	3.69	26	4.10	70	91	
28	456	63.3	90	5.02	46	7.01	46	220	
29*	418	19.7	59	2.34	21	3.93	313	96	
30*	455	19.0	99	6.35	68	4.28	232	153	
Means	449	27.6	73	3.21	55.9	5.03	67.1	102	330

* House where smoking takes place
** House with attached garage
*** Epoxy resin used in basement

Please note that the natural ventilation is expressed in L/s rather than in AC/H, to reflect the fact that it is the L/s (along with source strength) that determines the ultimate level of indoor pollutants. The ventilation rate was first measured in the first eight houses in late fall, and the others were tested later in the winter.

2.2.1 Respirable Solid Particles

There was a significant difference in levels of RSP's between houses with smokers and non-smokers. The houses where smoking takes place (more than 4 cigarettes per week) are indicated by an asterisk. The average levels of RSP's in houses with smokers was 52.9 μg/cu.m. and in houses with non-smokers was 23.3 μg/cu.m.

In some of the houses where there is a significant amount of use of the fireplace or wood stove, the source strengths of particulates appears to be elevated. Table 2.2.1.A lists the thirty houses along with the average RSP levels, the RSP source strengths, and an indication of the amount of smoking and fireplace use in each. Houses #13 and #18, where there is no tobacco used, have among the highest recorded RSP source strengths of the group (5.3 and 7.6 mg/hr), probably attributable to the continuous use of the wood-stove and fireplace. Houses #2 and #11, with no fireplace in use, have similarly elevated RSP source strengths over 7 mg/hr, probably caused by the heavy use of tobacco.

Note also that some houses where wood burning was most frequent have the lowest RSP concentrations and so, RSP production is not necessarily correlated with wood use, but is dependent upon the appliance installed and the operator's skill in avoiding spillage.

Table 2.2.1.A Respirable solid Particles

House #	Volume	RSP Concentrat	RSP Source Str.	Smoking	Candles	Wood Burning	Usage of Wood
Units:	cu m	microgram /cu. m	mg/hr	# Cigs. weekly	# per week	Fireplace/ wood stove	Hours per Week
1	444	*83*	4.42	175		FP	21
2	306	*76*	7.21	112		none	0
3	486	27	1.44	0	4	FP	3
4	505	20	1.41	0		FP + WS	35
5	515	38	1.96	0		FP	0
6	517	*74*	3.83	129		FP	0
7	487	23	1.12	3		FP	10
8	737	35	3.35	0	5	FP	20
9	478	19	1.91	0	23	none	0
10	371	17	0.50	4		none	0
11	513	*60*	7.39	150		none	0
12	412	25	2.06	0		WS	0
13	504	26	7.60	0		WS	144
14	548	*74*	6.08	74		FP	65
15	429	26	2.12	0		none	0
16	478	18	1.72	0		FP	15
17	387	19	2.72	0		FP	48
18	397	35	5.28	10		FP	168
19	325	26	1.18	0		none	0
20	519	11	1.26	0		FP	0
21	270	11	0.59	225		none	0
22	426	21	2.95	93		none	0
23	441	*43*	3.41	110		FP	0
24	221	26	2.18	151		none	0
25	748	10	2.09	0		FP	0
26	444			72		none	0
27	231	*42*	3.69	175		none	0
28	456	22	5.02	4		none	0
29	418	33	2.34	140		FP	0
30	455	92	6.35	220		none	0

2.2.2 Volatile Organic Compounds.

Molhave[2] reported that there are usually no problems with irritation when TVOC levels are below 0.2 mg/cu m. As the levels increase towards 3 mg/cu m., complaints occurred in all buildings where occupants experienced symptoms. There is no specific maximum recommended level of VOC's for Canada. The observed concentrations in the 30 houses are presented on Table 2.1.A. The average level of total VOC's for the sample was 0.63 mg/cu m. The source strengths of TVOC calculated for each of the houses are presented

[2]Molhave,L. Volatile Organic Compounds, Indoor Air Quality and Health, *Indoor Air* 1(4): 357-76, 1991

on Table 2.2.2.A. The levels of Total VOC's ranged between 0.2 and 2.5 mg/cu.m. Houses #8 and #10 have attached garages, and house #10 has an interconnecting door to the garage. Only house #8 had an elevated TVOC level. The cause may be seepage of fumes from the garage into the house. Cars with carburetors are more likely to give off more gasoline vapours than cars with fuel injection, however, this level of detail was not pursued.

On Table 2.2.2.A is presented a summary of the measured TVOC levels and source strengths, along with data on the amount of paints and solvents stored in the houses. There is no apparent correlation.

Table 2.2.2.A Total Volatile Organic Compounds

House #	Volume	VOC's	VOC's	Solvents	Attached
Units:	cu m	mg/cu.m	mg/hr	# of Cans	Garage
1	444	0.4	21	10	no
2	306	0.4	38	4	no
3	486	0.7	37	8	no
4*	505	1.7	120	?	no
5	515	0.7	36	20	no
6	517	0.3	16	?	no
7	487	0.4	19	8	no
8	737	2.3	220	10	yes
9	478	0.3	30	0	no
10	371	0.3	9	0	yes(door)
11	513	0.7	86	3	no
12	412	0.1	7	4	no
13	504	0.2	58	50	no
14	548	0.2	16	?	no
15	429	0.5	41	0	no
16	478	0.5	48	10	no
17	387	0.6	86	7	no
18	397	0.4	60	6	no
19	325	0.7	32	4	no
20	519	0.7	80	10	no
21	270	0.7	38	0	no
22	426	0.4	56	0	no
23	441	2.5	198	8	no
24	221	0.7	59	2	no
25	748	0.3	63	10	no
26	444	0.4	39	5	no
27	231	0.3	26	0	no
28	456	0.2	46	8	no
29	418	0.3	21	0	no
30	455	1.0	68	4	no

* Epoxy is used in the basement workshop

2.2.3 Formaldehyde

The main sources of formaldehyde in houses are binders in carpeting, furniture and in certain building materials such as particleboard and plywood, and cigarette smoke. ***The average level of formaldehyde in the sample was 0.048 ppm***

Table 2.2.3.A Formaldehyde Levels

House #	Volume	Formaldehyde Level	Formaldehyde Source Strength	Fraction covered by carpets	# of Cigarettes Weekly
Units:	cu m	ppm	mg/hr		
1	444	0.054	3.54	0.25	175
2	306	0.046	5.37	0.15	112
3	486	***0.094***	6.18	0.8	0
4	505	***0.099***	8.61	0	0
5	515	***0.082***	5.19	0.25	0
6	517	***0.083***	5.28	0.33	129
7	487	***0.056***	3.35	0.33	3
8	737	0.042	4.95	0	0
9	478	0.037	4.57	0.6	0
10	371	***0.07***	2.56	0.75	4
11	513	***0.071***	10.75	0.8	150
12	412	0.035	3.55	0	0
13	504	0.021	7.55	0.05	0
14	548	0.054	5.46	0.3	74
15	429	0.043	4.31	0.1	0
16	478	0.049	5.76	0.1	0
17	387	0.043	7.57	0.32	0
18	397	0.033	6.12	0.1	10
19	325	0.034	1.90	0.1	0
20	519	0.014	1.97	0.05	0
21	270	***0.066***	4.38	0	225
22	426	0.046	7.95	0.4	93
23	441	0.024	2.34	0.6	110
24	221	0.032	3.31	0.05	151
25	748	0.021	5.41	0.9	0
26	444	0.03	3.60	0.25	72
27	231	0.038	4.10	0	175
28	456	0.025	7.01	0.05	4
29	418	0.045	3.93	0	140
30	455	0.051	4.28	0	220

The source strengths ranged between 1.9 and 10.75 mg/hour. On Table 2.2.3.A is presented a summary of the formaldehyde concentrations and source strengths, along with the fraction of the floors which are covered by carpeting, and the amount of smoking in each house. There is no obvious relationship among the observed levels of formaldehyde and the other factors. The amount of carpeting in a house does not appear to be a significant factor determining the source strength of formaldehyde. The type and age of the carpet, age of the building and the presence of other materials may be more important factors.

2.2.4 Radon

The radon levels recorded in the thirty houses were well below the Canadian action level of 800 Bq/cu m, equivalent to 21.6 pCi/L. The radon concentration ranged between 0.2 and 4.4 pCi/L. The average level of radon for the group was 0.79 pCi/L. See Table 2.1.A.

The source strength of radon ranged between 11 and 313 μCi/hr, with a mean of 67.1 μCi/hr. See Table 2.2.A

2.1.5 Carbon Dioxide

Since the main source of CO_2 is expired air from the occupants, and this gas diffuses throughout most of the house, it was decided to place the CO_2 recorder in the living room to determine the average level during the week of interest. At the same time, the level of carbon dioxide was recorded continuously in the master bedroom in eight of the houses, as part of the long-term testing of this sub-group. Comparison of records in the master bedroom, living room and basement indicated that in most houses, the level in the living room is representative of the level that occupants are exposed to in the house. The notable exception is in houses where the occupants sleep with the bedroom door closed. The difference in levels of CO_2 between living room and master bedroom (while the door between zones was open) was normally the same within 200 and 300 ppm, the level being higher in the zone where the occupants were present. With the bedroom door closed, levels of CO_2 could be higher by over 3000 ppm by early morning before opening the door.

The average daily level of CO_2 as recorded in the living rooms of the houses during the test week ranged between 570 and 1507 ppm., with an average for the group of 929 ppm. See Table 2.1.A. The CO_2 source strength in the 30 houses ranged between 25 and 220 g/hour, and averaged 102 g/hr. See Table 2.2.A.

2.2.6 Water Vapour

The equivalent source strength of moisture generation was evaluated for the first eight houses by first calculating the rise in moisture content by recording indoor and outdoor relative humidity and temperature, calculating the absolute humidities, and subtracting outdoor moisture content from indoor air moisture content. The house volume and average air change rates were then used as described in Section 2.2 to calculate the source strengths. Moisture content in g of moisture per kg of dry air were converted to g/cu m by multiplying by 1.293, the density of dry air. The values ranged between 259 and 342 g/hour, with an average of 330 g/hr. It is expected that the source strength evaluation may yield different results in fall than in spring due to the movement of moisture out of the building materials in the fall, and into the materials in the spring. Please refer to Table 2.2.A

Since the drying process involves diffusion through solid materials, the process is slow, and its time constant is in the order of days. We expect that the results of the one-week test at the beginning of the winter may be somewhat biased towards a higher moisture production rate due to the house being in the process of drying out after the summer season, releasing some stored moisture into the air. The capacity of the house contents and of the building materials to absorb and release moisture to the air tends to moderate and delay changes in moisture content of indoor air. Building materials such as wood, drywall and concrete absorb water vapour from the air during humid periods, and release moisture to the air during dry periods.

Table 2.2.6.A presents a summary of the factors which may affect the moisture level in houses, including occupancy, ventilation equipment and practices, and building leakage characteristics. Note that some of the potential moisture sources (e.g. damp basements and drying firewood indoors) were not recorded and are not part of this analysis. The last two columns report some of the moisture problems recalled by the customers when they were asked the questions during the Éval-Iso project and later again in the fall of 1993. The correlations among these variables are not straightforward nor obvious.

Table 2.2.6.A Factors which may affect Moisture Levels in Houses

House #	Vol.	Occupancy	Mechanical Ventilation	Natural Ventilation Opening	Duration	Natural AC/H	AC/H at 50 Pa	Moisture mid-winter **	Moisture spring **
Units:	cu m	M-H/day		cm sq	hr/week				
1	444	102	turbine	0	0	0.12	3.66	0	0
2	306	89	turbine	0	0	0.31	4.69	2	0
3	486	39	0	door	.25	0.11	3.04	1	3
4	505	83	0	0	0	0.14	2.81	0	?
5	515	77	0	0	0	0.10	2.28	2	3
6	517	69	0	54/30	168/72	0.10	3.27	2	2,3
7	487	55	0	0	0	0.10	3.44	0	0
8	737	83	†	335	1	0.13	2.52	1-2	1
9	478	82	turbine	0	0	0.21	5.08	3	1
10	371	69	†	0	0	0.08	4.24	3	1
11	513	74	turbine	0	0	0.24	5.50	0	0
12	412	63	0	0	0	0.20	2.86	0	0
13	504	121	0	0	0	0.58	6.81	0	0
14	548	69	†	0	0	0.15	2.44	2	0
15	429	40	0	0	0	0.19	4.13	1	2
16	478	96	turbine	0	0	0.20	2.46	0	0
17	387	125	0	0	0	0.37	7.14	2	2*
18	397	32	0	0	0	0.38	8.30	0	0
19	325	39	†	0	0	0.14	3.17	0	3
20	519	101	0	0	0	0.22	9.96	0	1
21	270	39	0	0	0	0.20	10.1	0	0
22	426	90	†	0	0	0.33	3.32	0	0
23	441	80	0	0	0	0.18	4.18	0	0
24	221	69	0	0	0	0.38	8.55	0	0
25	748	69	0	0	0	0.28	5.63	0	0
26	444	24	0	1125/1500	.5/.75	0.22	3.49	0	0
27	231	74	0	0	0	0.38	11.4	0	0
28	456	90	0	300	.5	0.50	3.45	0	0
29	418	59	0	0	0	0.17	3.65	3	3
30	455	99	0	0	0	0.15	1.72	0	0

† Built-in ventilation system with fresh air supply and exhaust
* summer only
** Moisture Conditions:

0 = none
1 = high humidity, window condensation
2 = condensation on walls
3 = mould growth

2.2.7 Comparison with Ontario Data

Results from measurements of indoor air contaminant levels and simultaneous average air change rate determinations on 62 houses in Ontario[3] were used to derive the ***source strength*** of formaldehyde, radon, RSP's and TVOC's. The data used and the resulting calculated source strengths are presented in Appendix 2. A summary of the average concentrations and calculated source strengths of the Ontario and Quebec data presented below on Table 2.2.7.A:

Table 2.2.7.A. Summary of Québec and Ontario Average Air Contaminant Concentrations and Source Strengths

Contaminant	Avge Concentration and Source Strength (units)	Québec Houses	Range	Ontario Houses	Range
Formaldehyde	(ppm) (mg/hr)	0.048 5.03	1-10	0.036 10.2	2-33
Radon	(pCi/L) (µCi/hr)	0.79 67.1	10-300	1.2 285	10-1300
RSP	(µg/cu m) (mg/hr)	36 3.07	0.5-7	25.2 6.7	1-20
TVOC's	(mg/cu m) (mg/hr)	0.63 55.9	5-200	2.05 352	60-500
CO_2	(g/hr)	102			
Moisture	(g/hr)	330			

One must keep in mind that the level of indoor pollution is partly determined by the source strength of the contaminant and partly by the average infiltration rate. Building volume also comes into play to affect contaminant levels when the contaminant sources are intermittent, such as RSP, CO_2 and VOC generation. Comparing source strengths between Ontario and Québec homes provides only part of the picture of relative levels of indoor air quality in Ontario and Quebec homes. It is also necessary to compare average ventilation rates and house volumes in order to compare *average indoor air quality levels*. It is interesting to note that although the average source strength of formaldehyde and RSP's are twice as high in Ontario than in Quebec, the average levels of these pollutants were somewhat higher in Quebec houses. The reasons may include different weather conditions during the time of the test, differences in house volumes, and different air leakage characteristics between the two groups.

[3] Indoor Environment Study, Ontario Hydro Report No. PTA-90-92, Oct. 1990

2.3 Required Minimum Air Change Rates

The source strength estimates can be used to determine the minimum ventilation required in order to maintain the air contaminant levels within the recommended maximum levels in all houses. The level of an airborne pollutant of source strength S is:

Airborne pollutant level = S (mg/hr) / average air change rate (cu.m/hr)
(answer in mg/cu.m)

Using the above formula, we can calculate for each source strength the required air change rate in order to be below the Health Canada guidelines. Taking the ***highest source strengths measured*** in the thirty houses in the Québec sample,

the (minimum) air change rate required = highest source strength measured / Health Canada guideline

For source strength in mg/hr and the guidelines in mg/cu m, the answer would be in cu m per hr.

For each pollutant of interest and for each house, the minimum fresh air required to satisfy the Health Canada guidelines have been calculated using the above procedure, and the results are presented in Table 2.3.A

Table 2.3.A Minimum Ventilation Required to Control Pollutants to within Recommended Levels

House #	RSP	VOC	Formald.	Radon	CO2 *	CO2 **	Limiting
Units	**L/s**	**L/s**	**L/s**	**L/s**	**L/s**	**L/s**	**Pollutant**
1	*31*	1.9	17	0.0	2.8	13	RSP
2	*50*	3.3	25	0.5	5.2	26	RSP
3	10	3.3	*29*	0.5	2.8	14	Formald.
4	10	11	*40*	0.5	4.7	23	Formald.
5	14	3.3	*24*	0.9	4.2	21	Formald.
6	*26*	1.4	25	0.5	2.8	13	RSP
7	7.6	1.9	*16*	0.5	1.4	7.6	Formald.
8	*23*	20	*23*	0.9	4.7	23	RSP/Form.
9	13	2.8	21	0.5	4.7	*24*	CO2 **
10	3.3	0.9	*12*	0.5	0.9	5.7	Formald.
11	*51*	8.0	50	0.5	4.7	23	RSP
12	14	0.5	17	0.5	6.6	*32*	CO2 **
13	*53*	5.2	35	2.4	6.1	30	RSP
14	*42*	1.4	26	0.5	4.2	20	RSP
15	15	3.8	*20*	0.0	2.4	11	Formald.
16	12	4.2	26	0.5	7.6	*36*	CO2 **
17	19	8.0	*35*	0.5	3.8	19	Formald.
18	*37*	5.7	29	0.9	6.1	30	RSP
19	8.0	2.8	9.0	0.9	4.7	*22*	CO2 **
20	8.5	7.6	9.0	0.9	5.2	*26*	CO2 **
21	4.2	3.3	*20*	0.5	1.9	9.9	Formald.
22	20	5.2	37	1.9	9.0	*43*	CO2 **
23	*24*	18	11	1.4	2.8	14	RSP
24	15	5.7	15	0.5	4.7	*22*	CO2 **
25	15	5.7	*25*	0.9	4.2	19	Formald.
26		3.8	*17*	0.9	1.9	9.4	Formald.
27	*26*	2.4	19	0.9	4.2	20	RSP
28	35	4.2	33	0.5	9.9	*47*	CO2 **
29	16	1.9	19	4.2	4.2	*21*	CO2 **
30	*43*	6.1	20	3.3	6.6	33	RSP
Mean	**22**	**5.2**	**23**	**0.9**	**4.5**	**22**	
Std Dev	**14.6**	**4.5**	**9.5**	**1.0**	**2.1**	**10**	

* Assuming the current Health Canada guideline of 3,500 ppm
** Assuming the current ASHRAE recommended level of 1,000 ppm

As can be seen from the above table, the levels of RSP's, Formaldehyde and Carbon Dioxide are the determining factors for the minimum amount of ventilation required in Québec houses. Usually one of these pollutants dominates and determines the amount of minimum ventilation required. It is interesting to note that each of these three pollutants (including CO_2 at 1000 ppm maximum) was the determining factor in about one third of the houses. The mean minimum ventilation is 30.5 L/s; the standard deviation is 11.3 L/s (95% confidence level) and the standard error is 2.1

Looking at the houses with the ***highest source strengths in the sample***, the minimum amount of ventilation required in these houses is listed in the following Table 2.3.B.

Table 2.3.B Calculated Fresh Air Requirements to Control Pollutants in Houses with the Highest Source Strengths in Québec

Pollutant	Highest Source Strength	Allowable Level	Calculated Fresh (or dry) Air Required
CO_2	220 g/hr	(a) Health Canada: 3500 ppm or 6.9 g/cu.m. (b) ASHRAE: 1000 ppm or 2 .0 g/cu.m.	(a) 9.9 x 1.1* = 10.9 L/s (b) 47.2 x 1.53**= 72.2 L/s
RSP	7.6 mg/hr	40 μg/cu. m.	52.9 L/s
Formaldehyde	10,750 μg/hr	60 μg/cu m	49.6 L/s
VOC	220 mg/hr	3 mg/cu m (limit before complaints)	20.3 L/s
Moisture	488 g/hr	55% RH (11.6 g/cu m)	11.7 L/s (assumes "dry" air)
Radon	313,000 pCi/hr	20,000 pCi/ cu. m	4.2 L/s

* increased by 10% to account for atmospheric carbon dioxide
** increased by 53% to account for atmospheric carbon dioxide

The ventilation requirements for the house with the highest source strength of carbon dioxide were calculated for two target levels: 3500 ppm (the Health Canada guideline) and 1000 ppm (the ASHRAE comfort guideline). Since outdoor air contains about 350 ppm of carbon dioxide, the ventilation rate must be increased accordingly to dilute the carbon dioxide in the house. These adjustments were included in the table. The ventilation required for maintaining an average of 3,500 ppm of CO_2 is 10.9 L/s, considerably lower than the amount of ventilation required to control the other pollutants. For maintaining an average of 1000 ppm of CO_2, about seven times more ventilation is required, 72.2 L/s.

The amount of ventilation required by the house with the highest source strength of RSP's was 52.9 L/s. As can be seen from the above table, the control of RSP's is the factor determining the minimum ventilation in about one third of the houses. The results are not surprising, since a large portion of the households have both main sources of particulates, cigarette smoking and wood burning fireplaces and stoves.

The amount of ventilation required by the house with the highest formaldehyde source strength was 49.6 L/s. The main source of formaldehyde is outgassing from carpeting, plywood and other building materials. Cigarette smoking also generates a small amount of formaldehyde. The amount of outgassing depends on humidity and temperature, on the ambient level of formaldehyde, and on the amount left in the material which diffuses out gradually over a very long time.

The houses with the highest source strengths of VOC's, moisture and radon require 20 L/s or less ventilation to remain within the acceptable guidelines of air quality.

Since renovations may include the installation of new building and finishing materials including new carpeting (most of which may outgas formaldehyde and VOC's), the ventilation required ***after*** renovations or air-tightening will have to be sufficient to look after the new sources as well as the old.

The control of moisture by ventilation with outdoor air relies on outside air being dryer than indoor air. During the fall, the drying effect of ventilation is highest during cool weather, when outdoor air contains little water vapour. The amount of fresh air required to remove indoor moisture decreases as the weather turns colder and the contents of the house dry out. The 11.7 L/s estimated in Table 2.3.B assumes that the outside air is dry. In practice, outside air contains some moisture, and the amount of ventilation will have to be increased accordingly. In addition, there may be a considerable amount of moisture stored in the building at the beginning of the fall which needs to be removed by ventilation before the really cold weather arrives.

The pollutant levels in individual houses are determined by the level of the source strength and by the actual ventilation rate that takes place. Window openings, the operation of exhaust fans, the operation of a wood stove, and the use of a ventilation turbine can affect the ventilation rate of a house to some degree. On the following Table 2.3.C is presented a summary of the measured ventilation (one-week average ventilation recorded during the PFT test, starting on the indicated date) and the ventilation required according the Health Canada guidelines and ASHRAE recommended level for CO_2.

As can be seen on the table, the first ten houses were tested during December while the weather was reasonably mild, and the balance were tested during the much colder period of January and February. Eighty percent of the houses in the first group had insufficient natural ventilation, and the indoor pollutant levels exceeded the recommended levels. Only house #8 and 9 had adequate ventilation levels during the test week.

Fifty-five percent of the houses in the second group of houses tested during the colder period had inadequate ventilation during the test week. It is interesting to note that the houses with the highest leakage area (#21 with AC/H_{50} =10.06, and #27 with AC/H_{50} = 11.35) had inadequate ventilation during the test week, while other houses with smaller leakage as low as AC/H_{50} = 3.49 had adequate ventilation.

These results are consistent with the expectation that natural ventilation is higher during colder weather and lower during milder weather, and that the amount of ventilation required to maintain an acceptable air quality varies according to the pollutant source strength.

Table 2.3.C Comparison Between Minimum Ventilation Required and Actual Ventilation Measured During a 1-week test

House #	Start Date of 1-week test	Natural Ventilation (1-week avge) L/s	Minimum Ventilation required L/s	Building Leakage (AC/H, 50 Pa.)	Limiting pollutant*
1	9-Dec	14.6	30.7	3.66	RSP
2	9-Dec	26.4	50.0	4.69	RSP
3	1-Dec	14.6	28.8	3.04	Formald.
4	30-Nov	19.8	39.6	2.81	Formald.
5	1-Dec	14.6	24.1	2.28	Formald.
6	8-Dec	14.6	26.4	3.27	RSP
7	7-Dec	13.7	15.6	3.44	Formald.
8	2-Dec	26.9	23.1	2.52	
9	14-Dec	27.8	23.6	5.08	
10	15-Dec	8.5	11.8	4.24	Formald.
11	10-Jan	34.0	51.4	5.50	RSP
12	11-Jan	22.7	32.1	2.86	CO2 **
13	12-Jan	81.2	52.9	6.81	
14	13-Jan	22.7	42.0	2.44	RSP
15	17-Jan	22.7	19.8	4.13	
16	18-Jan	26.9	35.9	2.46	CO2 **
17	19-Jan	39.6	34.9	7.14	
18	20-Jan	42.0	36.8	8.30	
19	24-Jan	12.7	22.2	3.17	CO2 **
20	25-Jan	31.6	26.0	9.96	
21	26-Jan	15.1	20.3	10.06	Formald.
22	27-Jan	39.2	42.9	3.32	CO2 **
23	31-Jan	21.7	23.6	4.18	RSP
24	1-Feb	23.1	22.2	8.55	
25	2-Feb	58.0	25.0	5.63	
26	3-Feb	27.4	16.5	3.49	
27	7-Feb	24.5	25.5	11.35	RSP
28	8-Feb	63.2	47.2	3.45	
29	9-Feb	19.8	20.8	3.65	CO2 **
30	10-Feb	18.9	43.4	1.72	RSP

* Limiting pollutant according to Health Canada Guidelines
** Assuming ASHRAE's recommended level of 1000 ppm for CO_2

2.4 Results of Continuous Monitoring of AQ Variables in 8 Houses

2.4.1 Carbon Dioxide Dynamics Between Zones

Air contaminants produced by occupants such as carbon dioxide tend to move to other parts of the building by diffusion, by natural air movement between zones, or by forced means such as air distribution systems and fans. Observations were made in several houses in the following locations to note the differences in the levels of this pollutant in different parts of the building at the same time:

1. Simultaneous recording of CO_2 levels at different heights in an occupied bedroom
2. Simultaneous recording of CO_2 in a house living room and occupied bedroom with the bedroom door open and closed.
3. Simultaneous recording of CO_2 in the basement and on the main floor in an occupied house

Stratification within a Room

The records indicate that there is a small difference in CO_2 levels between the floor and the ceiling while the room was occupied, the readings near the ceiling being higher by about 200 ppm while people were present in the room. Readings at table height were nearly identical to those near the ceiling. CO_2 levels were much higher while the room was occupied and the door was closed, and the amount of the difference at the three levels remained about the same. (House #4, Nov 21-29, 1993) Please refer to Figure 2.4.1.A. After occupants leave the area, stratification disappears within about 20 minutes.

Difference in Levels Between Rooms on Same Floor

Simultaneous records of CO_2 levels in the living room and master bedroom of House #3 (on the same floor) with the door open indicate a difference of 300 to 400 ppm only during the sleeping hours. The rest of the time, while the occupants are moving about the house or are away, the levels are within about 50 to 100 ppm. (House #3, Dec 4 - 8, 1993). Please refer to Figure 2.4.1.B. In House #6, the difference in levels of CO_2 recorded simultaneously in the bedroom and living room varies by 200 to 300 ppm only during the night. The balance of the time, the levels are within the range of 100 to 150 ppm (Nov 15 to 20, 1993). Please refer to Figure 2.4.1.C

In House #5, where the bedroom door is closed regularly during the night time, the difference in CO_2 levels between the bedroom and living room increases steadily during the night to about 3600 ppm until the door is opened in the morning. Once the bedroom door is opened in the morning, it takes approximately 30 minutes for the CO_2 levels in the bedroom and living room to equalize . During the day, while the occupants move about the house or are away, the levels in the bedroom and in the living room are essentially the same. The differences in CO_2 levels vary with the length of time that the door is closed,

Figure 2.4.1.A Stratification of CO2 in Master Bedroom, House #4

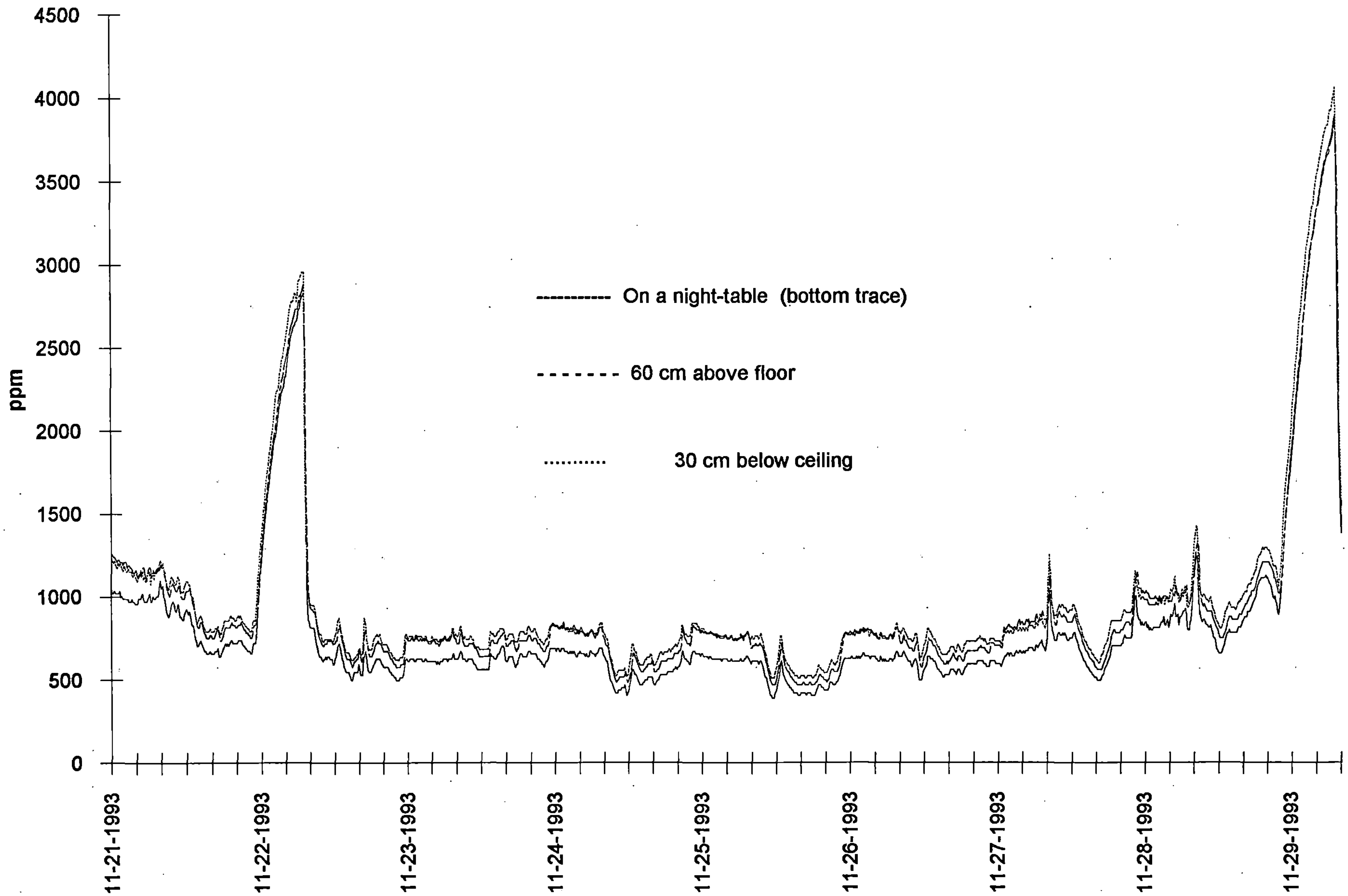


Figure 2.4.1.B Difference in CO2 Levels Between Rooms on Same Floor, House #3

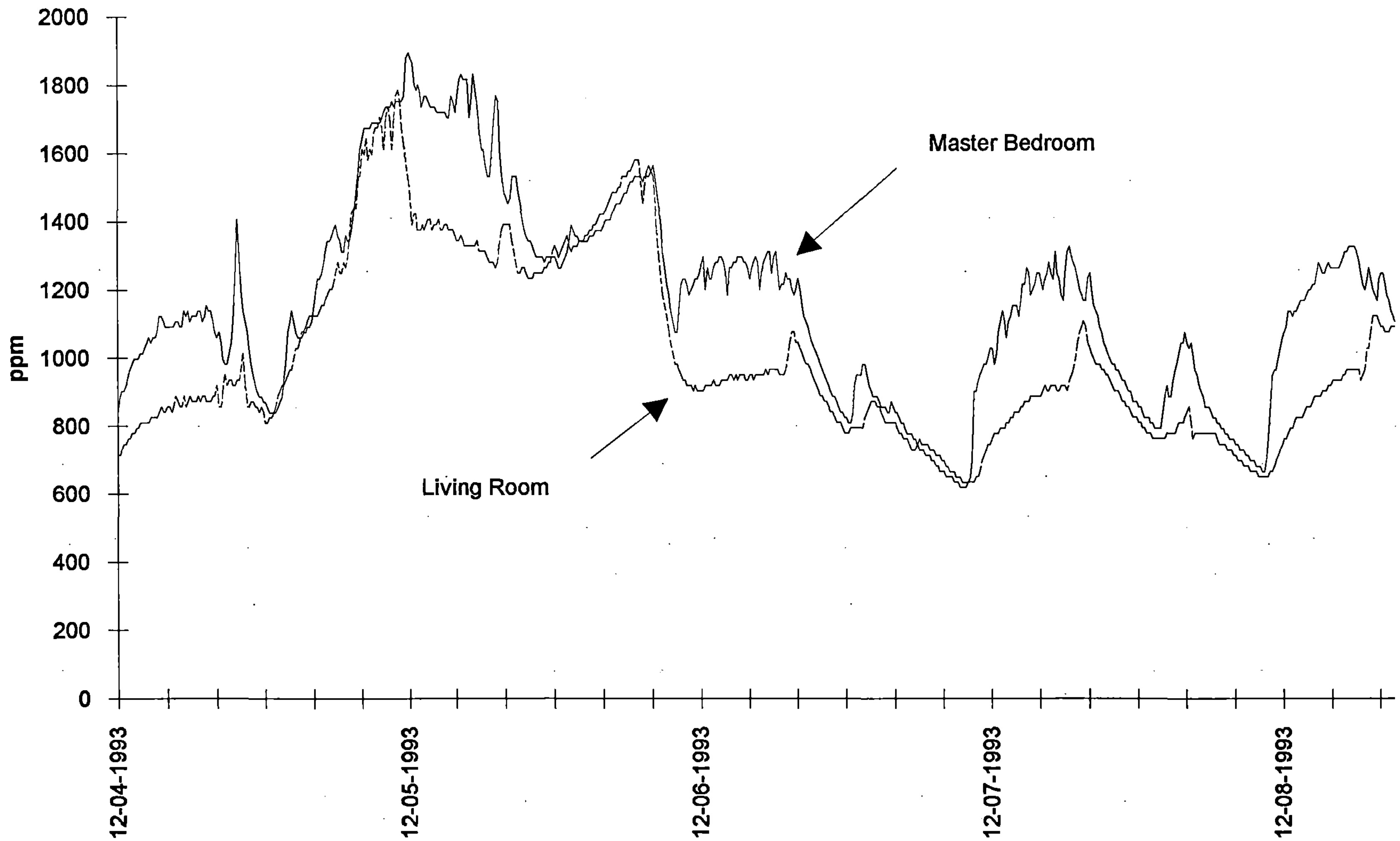
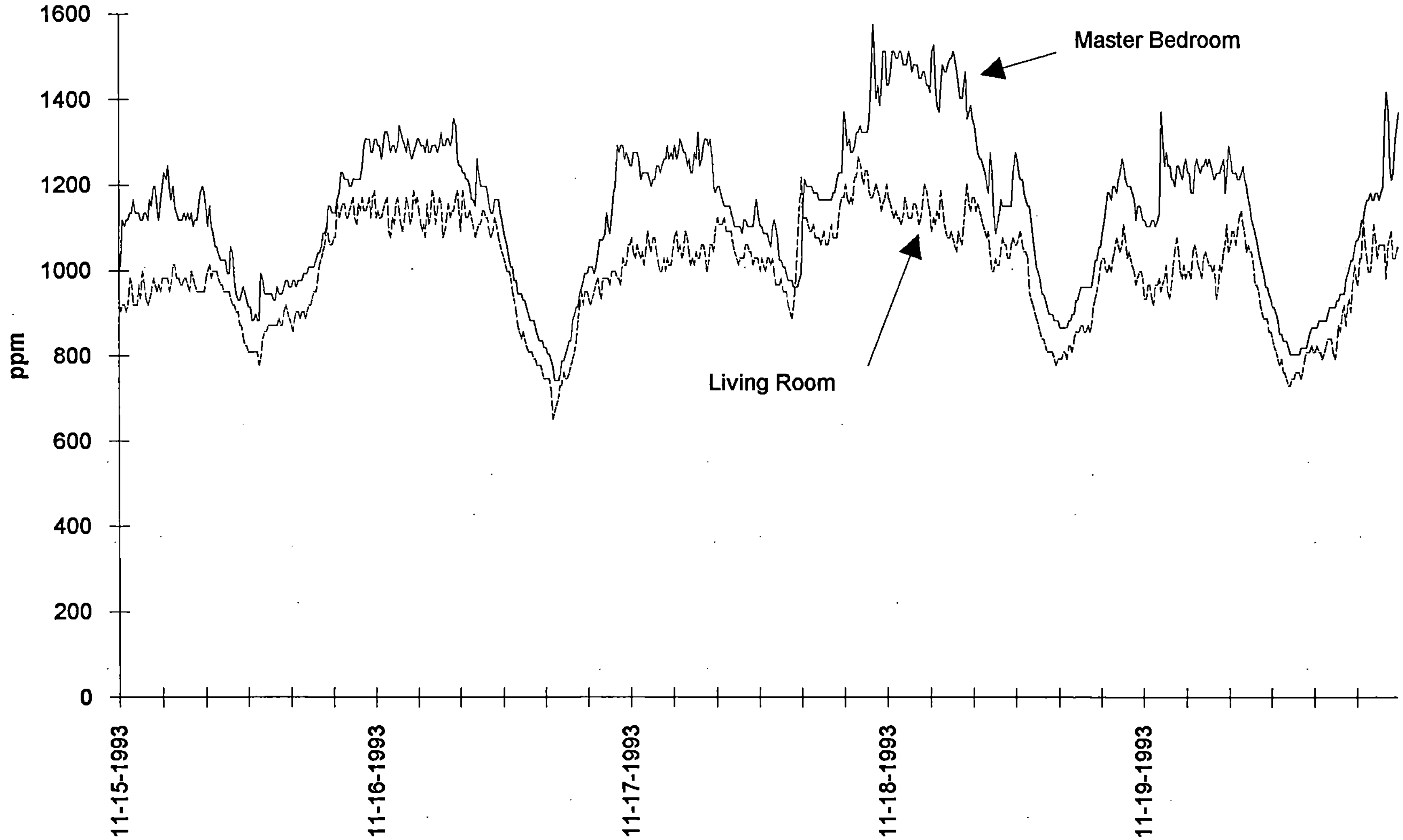


Figure 2.4.1.C Difference in CO2 Levels between Rooms on same Floor, House #6



and from day to day, possibly related in a minor way to differences in the weather. Please refer to Figure 2.4.1.D

Difference In Levels Between Basement And Main Floor

In houses where a new ventilation system had been installed, the carbon dioxide levels were recorded in the master bedroom, in the living room and in the basement for a period of several days. The daily average carbon dioxide level was calculated from the 10-minute recorded data and the results were plotted.

In House #4, where there is a pair of fans installed through the basement ceiling to mix the air between the main and basement levels, there was an indistinguishable difference in carbon dioxide levels among the bedroom, living room and basement while the fans were operating. Please refer to Figure 2.4.1.E.

In House #5, a new ventilation and air mixing system was ducted to each bedroom and to the hallway. In this house, the occupants normally sleep with the bedroom door closed. While the system was operating, there was a small difference of between 100 and 200 ppm in the levels of CO_2 recorded in the bedroom, living room and basement. Please refer to Figure 2.4.1.F. The difference went to zero while the house was unoccupied on December 30. When the ventilation system was turned off, the bedroom level climbed by about 600 ppm above the living room level, while the difference between the basement and main floor remained about the same at 100 ppm.

In house #8, where a balanced fresh air supply and exhaust system normally operates, the average levels of CO_2 in the basement, bedroom and living room were observed for one week with the ventilation system off, and the door to the basement in the normal "closed" position. The average CO_2 level in the basement was always lower than the levels on the main floor. The recorded (daily average) CO_2 levels in the bedroom, living room and basement during one week are presented on Figure 2.4.1.G. The difference between upper level and basement ranged between 300 and 600 ppm. The difference in levels between the bedroom and living room were indistinguishable.

Highest Recorded Level of CO_2

The level of CO_2 in the air in a room increases gradually when a person enters. CO_2 is produced at a fairly steady and predictable rate by the occupants and is not absorbed nor stored by surfaces. When the door to the room is closed, if there is no forced ventilation, the rate of increase of the level of CO_2 will depend on the room size as well as on the rate of natural infiltration of outside air (which normally contains 350 ppm of CO_2). The rate of increase varies directly with the source strength and inversely with the volume of the room and inversely with ventilation with outside air. The ultimate level of CO_2 in an occupied room is dependent on the length of time that the occupants remain in the room with the door closed, as well as on the rate of infiltration. During the study it was observed that CO_2 levels reached higher values on week-ends when the occupants tended

Figure 2.4.1.D Difference in CO_2 Levels between Rooms on Same Floor, House #5

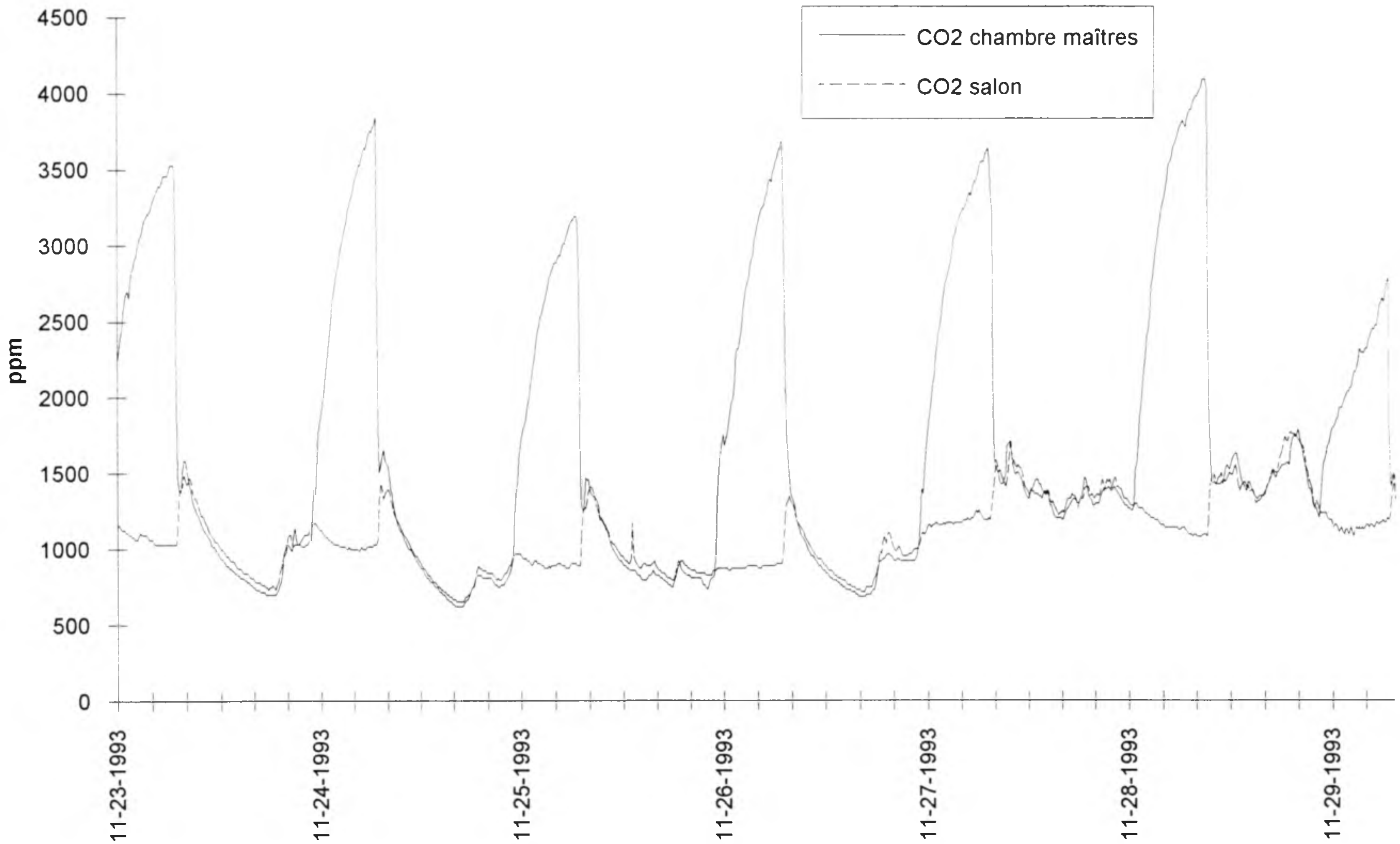


Figure 2.4.1.E Difference in CO_2 Levels between Main Floor Rooms and Basement, (mixing fans operating) House #4

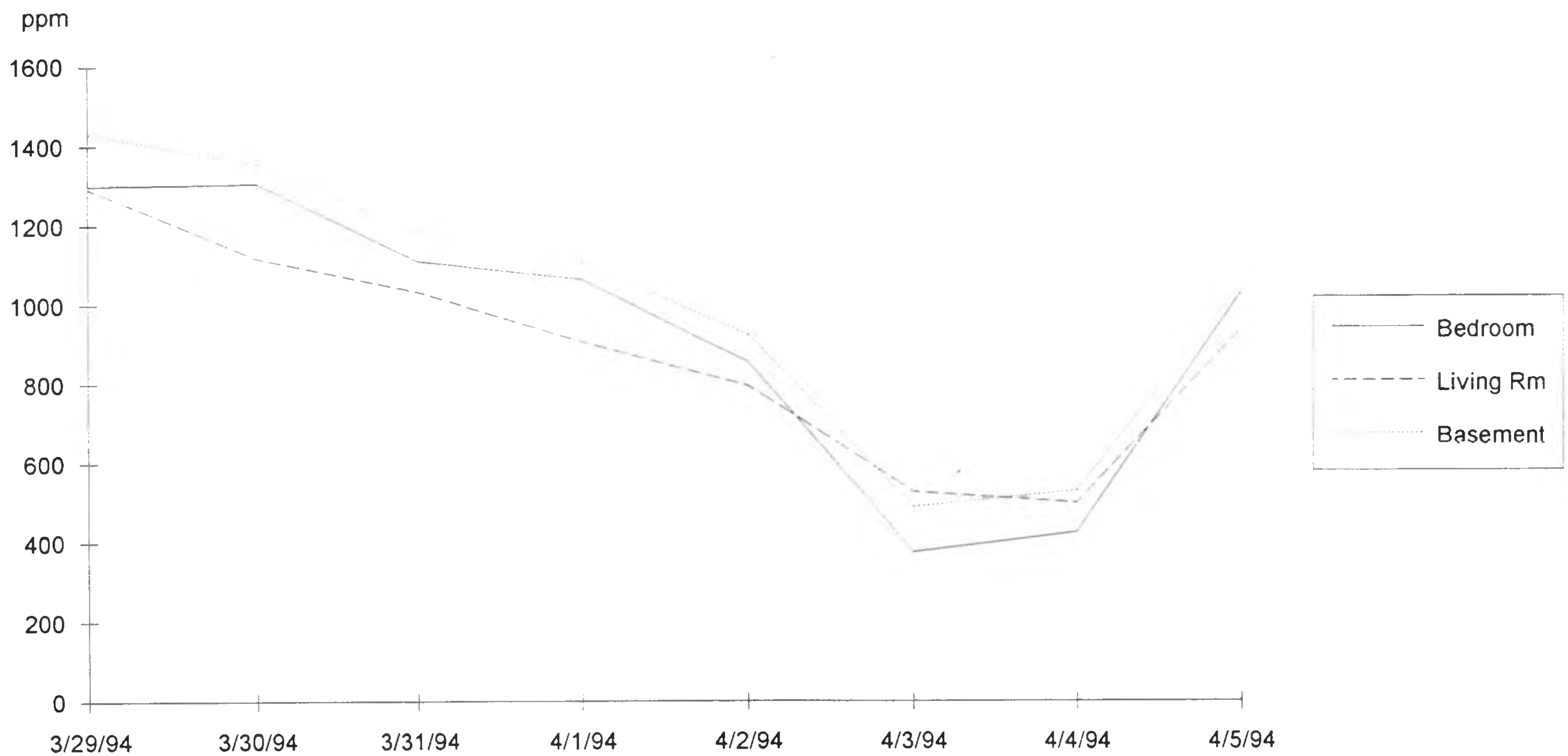


Figure 2.4.1.F Difference in CO_2 Levels between Main Floor Rooms and Basement, (Ventilation system operating and not operating) House #5

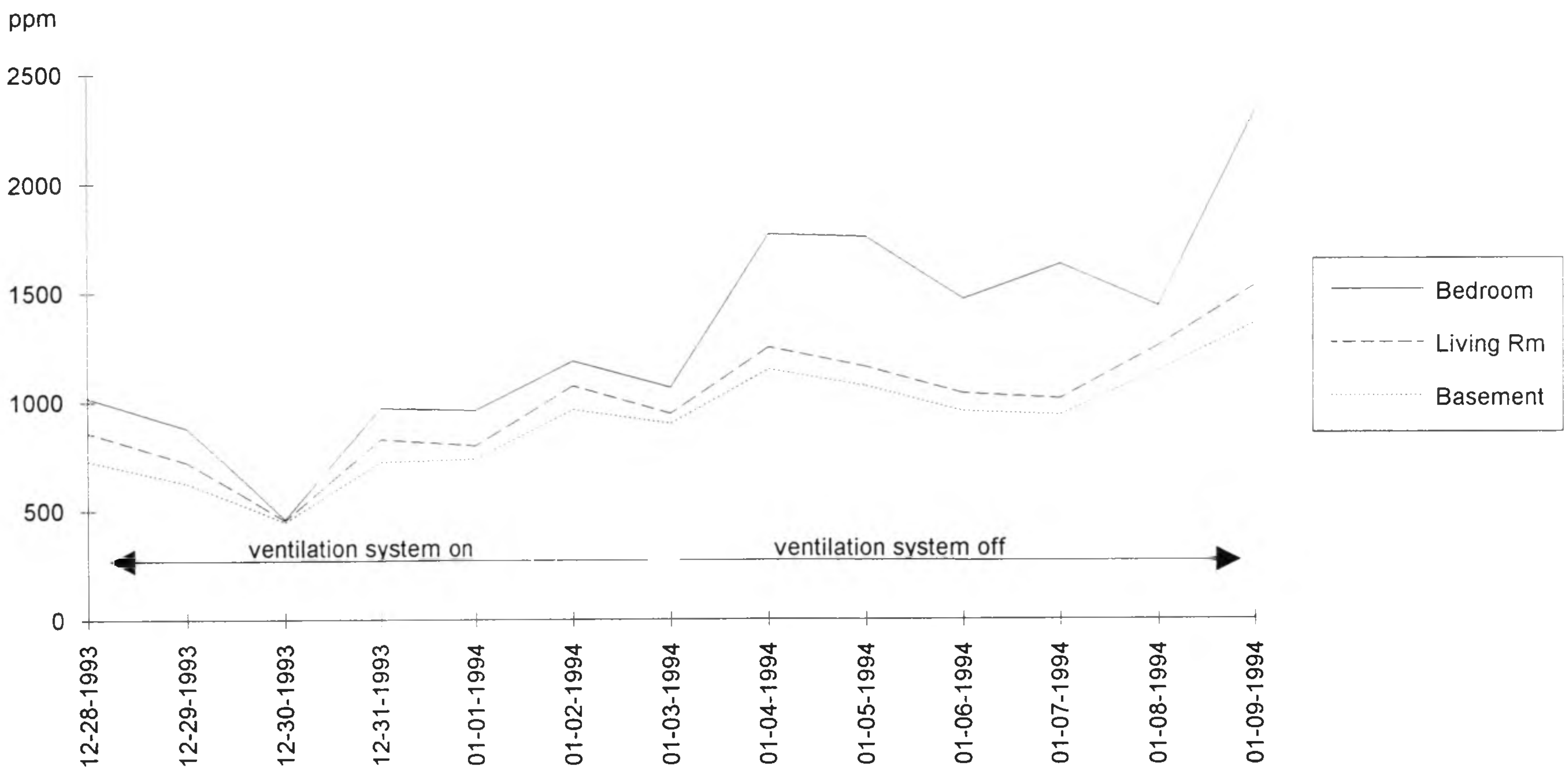
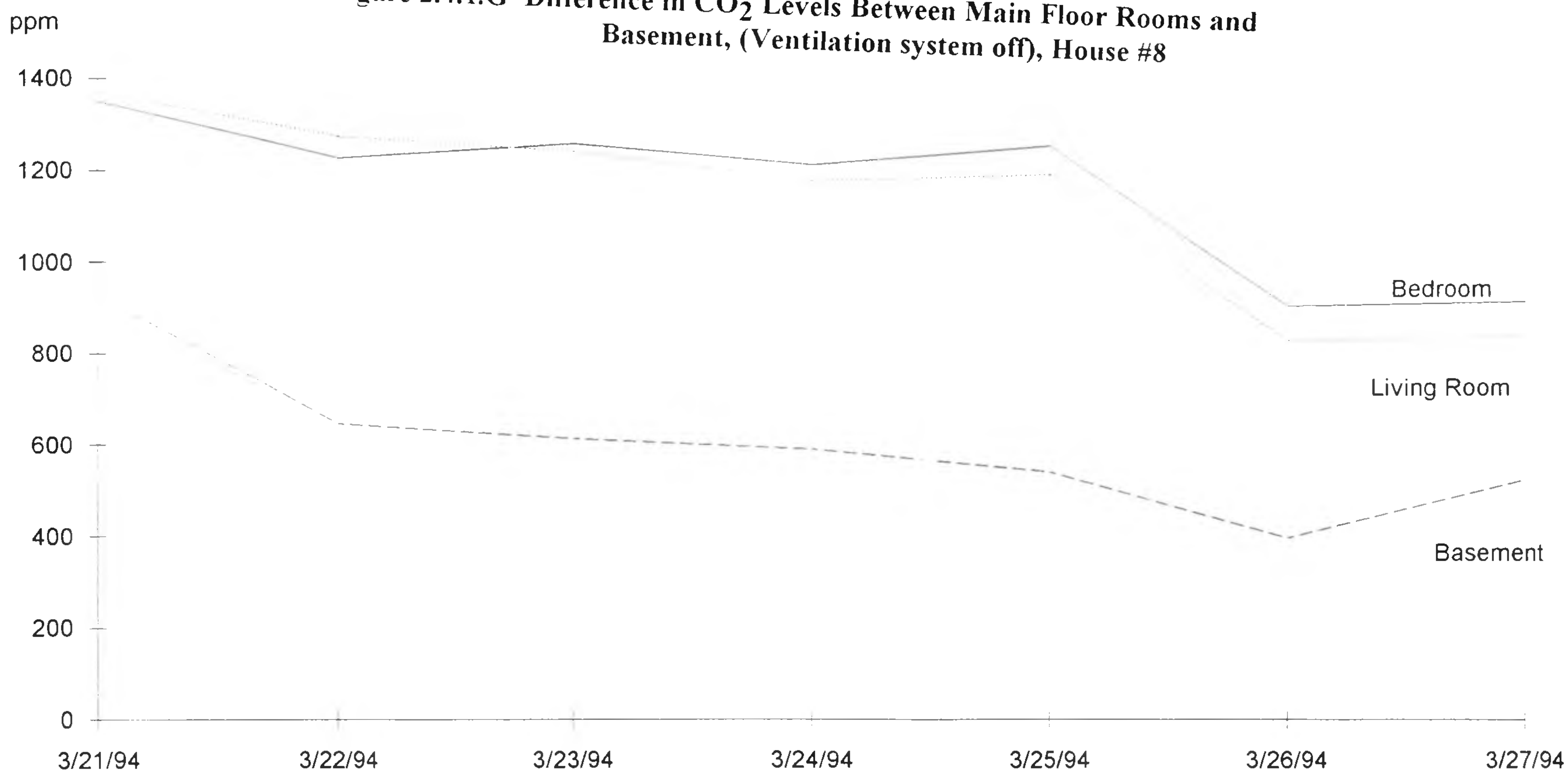


Figure 2.4.1.G Difference in CO_2 Levels Between Main Floor Rooms and Basement, (Ventilation system off), House #8



to sleep longer, and occupied the house for more hours. In houses with teen-agers or adults, the tendency is to sleep with the bedroom door closed, and in houses with small children, to sleep with the door open. The level of CO_2 in an occupied bedroom is strongly dependent on whether the door is open or closed.

The highest level recorded in a master bedroom during winter was in house #5, 4671 ppm[4] on December 4, 1993. The occupants normally sleep with the bedroom door closed. On the same day, the minimum level was 1423 ppm, (door was open at the time) and the mean for the day was 2476 ppm. The average level of CO_2 in the living room is normally lower than in the bedroom due to the nightly peaks resulting from closing the door.

Carbon dioxide is also produced by pets, by cigarette smoking, by the use of candles, by the active brewing process of beer and wine, and by plants during the night. In Appendix 3 are listed the estimated generation of CO_2 by various sources.

Summary of Observations:

The relatively small differences in CO_2 concentrations in open areas indicates that there is a fairly high rate of diffusion and mixing of carbon dioxide from room to room on the same level of a house when the door between zones is kept open. When doors between zones are closed, the CO_2 level in the occupied zone rises, and little diffusion to other parts of the building takes place (when there is no air distribution system in operation). In houses where the bedroom doors are kept open, the level of CO_2 in the living room is a good indicator of the average level in the upper levels of the house. Basement CO_2 levels may be lower than in the upper levels of the house, and circulating this volume of preheated air could be used to dilute point sources of air contaminants in the rest of the house. The use of a wood burning stove is equivalent to adding mechanical ventilation. Occupancy also affects the level of CO_2 in a house. When occupants leave the house, the CO_2 level drops within hours to the outdoor level. In order to maintain indoor CO_2 levels between 800 and 1000 ppm, it is estimated from the observations that each additional person in a household requires approximately 5 L/s of fresh air. This figure takes into account the amount of time away from home and the house volume.

2.4.2 Seasonal Variation in Humidity Levels

The variation in indoor humidity in the eight houses from November until April is best illustrated by the following graph of indoor absolute humidity as a function of time for a pair of houses (a test house, #5 and a similar "control" house, #8) with similar characteristics. An absolute humidity above 8.2 g moisture /kg dry air represents a relative humidity above 55% at air temperatures below 21C. Thus we can draw a

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[4]The calibration of the recorders was checked afterwards at high levels of carbon dioxide, and it was found that at levels above 2000 ppm, the recorders have a non-linear response, understating the levels by the following amount: 2000 ppm, 0 error; 4000 ppm reading corresponds to 5000 ppm; 5000 ppm reading corresponds to 6500 ppm. The readings of CO_2 above 2000 ppm in this report have not been adjusted.

horizontal line across 8 g/kg as a dividing line between problem and no problem periods of time. Please refer to Figures 2.4.2.A.

House #5 is the tightest house of the sub-group, and House #8 has the ventilation system with a fresh air intake and exhaust. The new ventilation system was installed in House #5 and operated from the middle of December onwards, except for the first two weeks in January. The humidity level in this house dropped gradually until Dec. 31. Another significant difference between the houses is that in house #5, the occupants sleep with the bedroom door closed. The humidity and CO_2 recorder is installed in the bedroom, and the result of closing the door during the night, is a somewhat elevated humidity and CO_2 levels recorded in house #5. Severe condensation on windows was reported in house #5 in the fall prior to the start-up of the ventilation system.

In the detailed recordings of humidity in this house, the relative humidity was seen to climb steadily during the night and then saturate, probably as condensation on the bedroom windows started to take place. The condensation problem is indicative of insufficient ventilation, of excessive moisture generation, or both. This phenomenon was observed regularly in a bedroom with two occupants and the door closed (House # 5, Nov 21 - Nov 25, 1993). The RH in the room is seen to saturate shortly after the bedroom door is closed. Please refer to Figure 2.4.2.B. The maximum (saturation) RH reached in the room from day to day also follows the outside temperature: 64% at -8 C, and 61% at -12 C.

Fall Condensation Problem: A Special Case

Severe condensation problems occur in many houses in Québec during early fall, when the outdoor temperature suddenly drops from warm summer conditions to the freezing point overnight. The condensation builds up on windows and may drip down walls and floors creating a nuisance and occasionally causing minor surface damage. As the house dries out over several weeks, the condensation problem diminishes and may disappear.

The problem is caused by warm, humid air from summer which is trapped in the house during a sudden cold spell, as well as by moisture absorbed by walls and floors (especially in basements) during the summer. When summer air comes in contact with basement cold surfaces, condensation may take place on surfaces, and the water may be absorbed into the materials. As the cold weather arrives, doors and windows are closed, trapping the moisture already in the building. Houses are built to resist the migration of water vapour across the walls and ceilings. Cold outside air causes interior surfaces such as windows and doors to drop in temperature below the dew point of indoor air, causing condensation to build up on these surfaces.

The only effective ways of lowering the indoor moisture level are by controlling sources and by ventilating with drier outside air. During the tests, we observed the following methods being used by people to control the humidity and indoor air quality:

Figure 2.4.2.A Daily Indoor Absolute Humidity, Houses #5 and #8

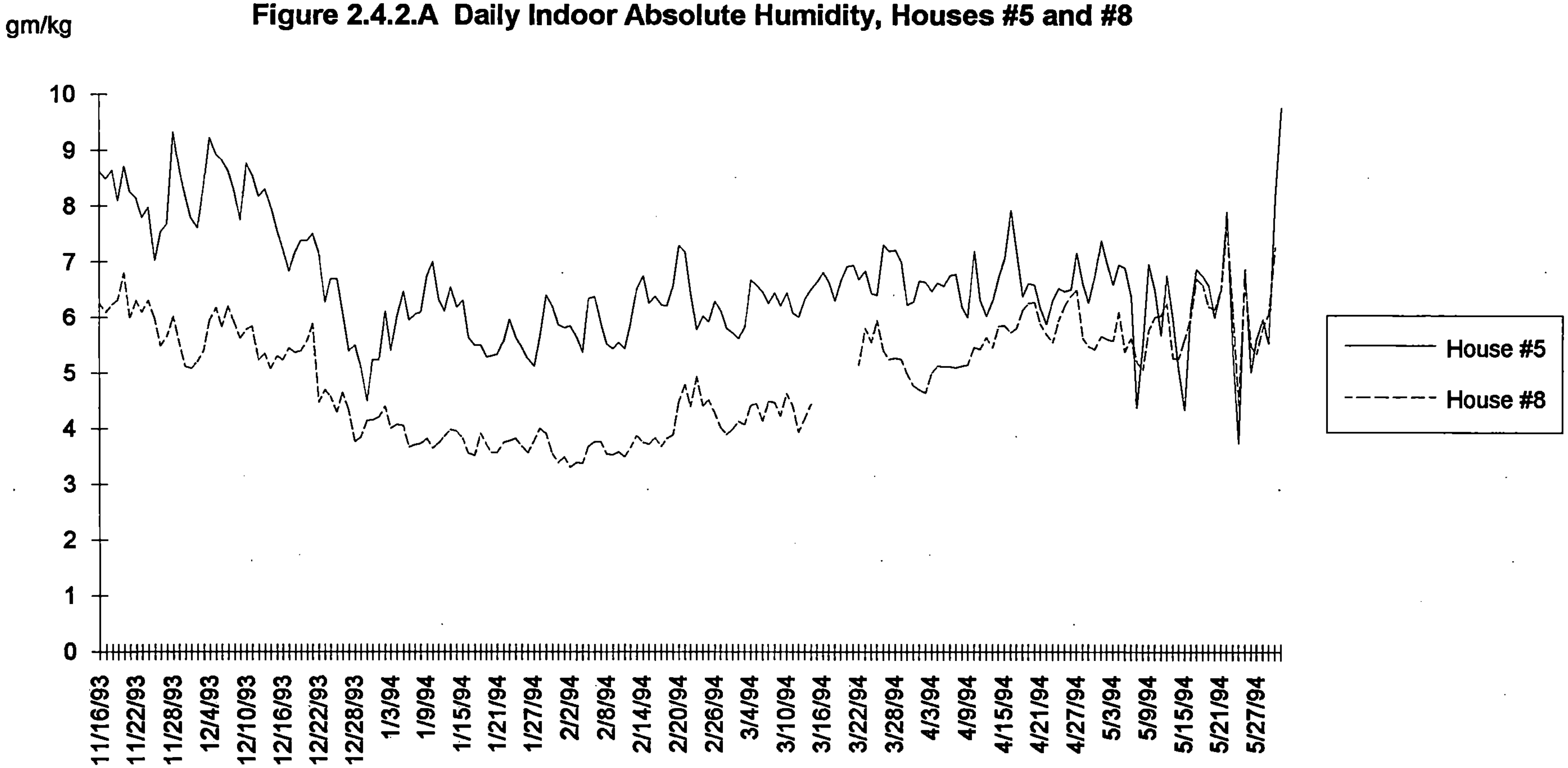
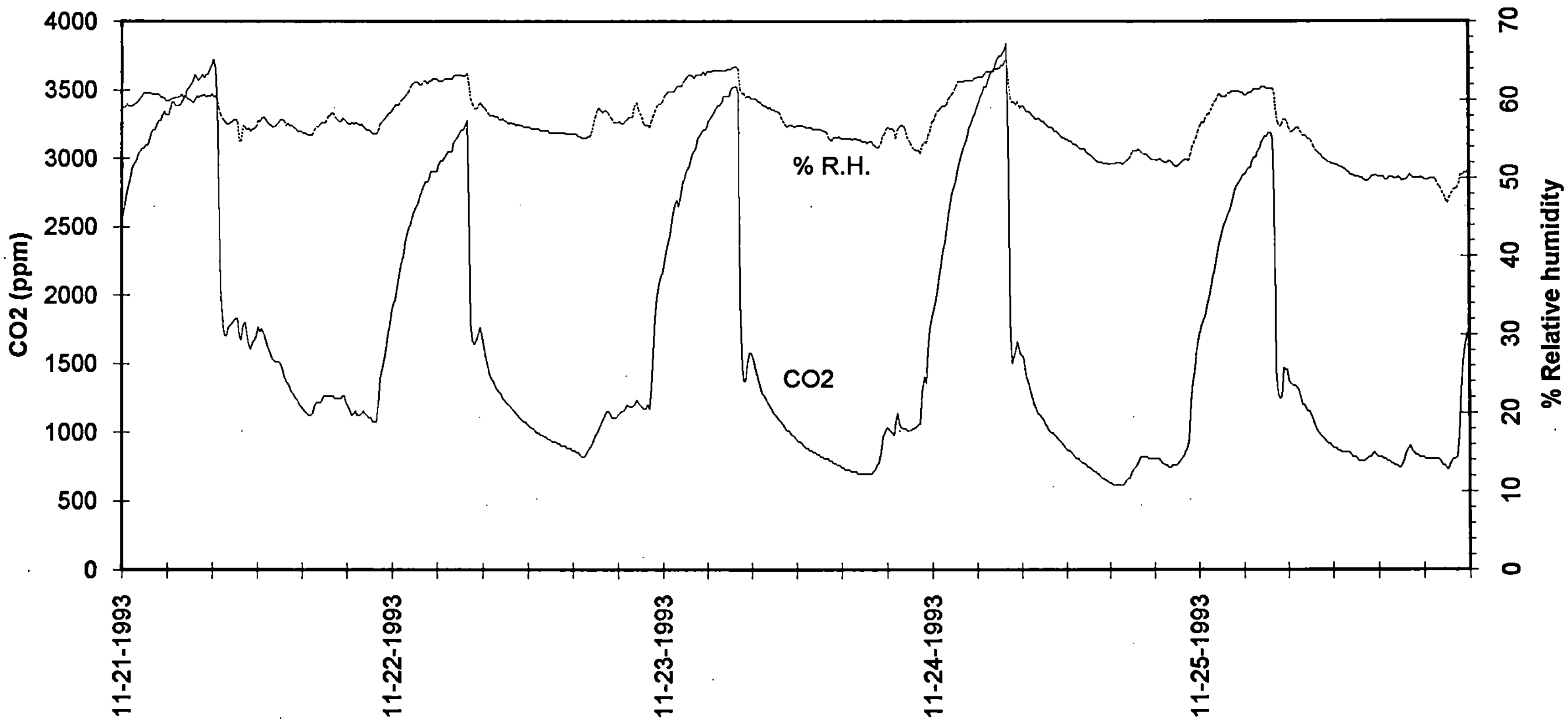


Figure 2.4.2.B CO2 and Relative Humidity In Master Bedroom, House #5



- Opening windows for long periods of time
- Operation of a wood-fired stove
- Opening the fireplace damper in the fall
- Operation of a ventilation system with fresh air intake.
- Installation of a turbine ventilation system

Exhaust fans in bathrooms (where installed) in the monitored houses are used on the average 0.5 to 1.5 hours per day. Fans in kitchens are used on average 15 to 45 minutes per day. Clothes dryers which exhaust approximately 30 L/s of indoor air, are used on the average 45 minutes to 2 3/4 hours per day. With this low level of use, their operation will not have a significant effect on indoor humidity. Mechanical exhaust contributes less than 5 L/s of ventilation on the average.

The fall condensation problem will be studied in detail during the fall of 1994 in the same group of eight houses. The results will be presented in a follow-up report.

2.5 Estimated Average Daily Ventilation Rate

The carbon dioxide generated by the occupants can be used as a "tracer gas" to estimate the ventilation rate of each of the houses. Appendix 3 presents the details of the method used to make the estimates, and discusses the possible error associated with these estimates. The method uses house volume, the measured average daily carbon dioxide levels and an estimate of occupancy, amount of smoking and of candle use. The expected error in these estimates is fairly large due to the variability of carbon dioxide production by humans and pets, the transient nature of the occupancy, and the uneven distribution of carbon dioxide within the house volume. Nevertheless, these estimates provide additional insights into natural ventilation of houses such as the wide range of average daily ventilation. The contributions of smoking and the use of candles were included as adjustments to the occupancy for houses #1, #3 and #8. The impact of pet occupancy on CO_2 generation is less than 3% in most houses and was neglected.

In the same Appendix are presented histograms of the estimated ventilation rates in winter. Table 2.5.1 summarizes the mode and range of the average daily ventilation histogram for each house.

Table 2.5.1 Estimated Ventilation Rate Based on CO_2 Measurements and Occupancy.

House #	Mode (L/s)	Range (L/s)
1	4	2 - 6
2	19	8 - 72
3	9	2 - 59
4	30	9 - 72
5*	13	9 - 42
5**	19	19 - 72
6	8	4 - 28
7	9	4 - 15
8	21	11 - 43

* Ventilation system off
** Ventilation system on (10 L/s fresh air)

2.6 Effects of Ventilation Systems on the Indoor Environment

In this section will be described the five different ventilation systems used during the field tests, and the effects on indoor humidity and carbon dioxide levels. The first eight test houses were selected on the basis that they were equipped with the ventilation equipment of interest, or that the equipment could be easily installed. Observations of humidity levels and carbon dioxide levels were made during periods when the ventilation systems were operating and other periods when the equipment was shut down and sealed closed, in an attempt to isolate the effects on indoor air quality of the operation of the ventilation equipment. Other houses were retrofitted as indicated in Table 2.6.A below.

Table 2.6.A Summary of Ventilation Equipment Tested

House #	Equipment	Ventilation provided
1	Turbine (System E)	exhaust only, natural forces
2	Turbine (System E)	exhaust only, natural forces
3	Exhaust fan with outdoor 'stat* (System A) Retrofit	exhaust only during mild periods, (approximately 21 L/s)
4	2 circulating fans through basement floor (System B) Retrofit	continuous mixing (42-57 L/s) between basement and main floor and minor pressurization of basement (unbalanced flow)
5	Air distribution system in attic to bedrooms & hall, plus bathroom exhaust with outdoor 'stat* (System C) Retrofit	9 L/s fresh air, tempered by mixing with bedroom air, plus exhaust during mild periods
6	Exhaust fan with outdoor motor and motorized cover with indoor relative humidity sensor (System A, Retrofit)	approximately 28 L/s exhaust during of high indoor humidity above the set-point
7	none	natural
8	Air distribution system drawing air from hallways with balanced air exchanger (fresh air supply and exhaust) (System D)	18 L/s fresh air and equal exhaust, tempered by mixing with indoor air

* Outdoor thermostat set to turn on between 2C and 18C

The observations made on each of the system types are described in the following sections

2.6.1 Turbine Ventilation Systems (System E)

The owners of Houses 1 and 2 had previously installed turbine ventilation systems in order to alleviate condensation problems. There were no complaints of remaining condensation problems or of back drafting of the ceiling register during cold weather. House #1 has two ducts connected via a "Y" fitting to the turbine on the roof, one connected to a register on the main floor ceiling, and the other to a register on the basement ceiling. House #2 has a single 6" dia duct connecting a ceiling register on the main floor to the turbine on the roof. The occupants of house #1 make use of a wood-burning fireplace located in the basement. The turbine in house #2 was closed off for one week (January 7 to 14) to observe the difference in house environments and other variables being recorded. The flow of air through each turbine ventilation system was recorded during the heating season, and the energy content of the replacement air was also calculated. The instrumentation used is described in more detail in Appendix 4.

Turbine behaviour will be described with the aid of the following charts. During the month of December, the turbines in both houses were observed to exhaust on the average 10 to 21 L/s. As time went on, there was a noticeable gradual drop in flow, which was later traced to the build-up of a surface coating and lint on the flow transducers. The flow probes in house #1 and #2 were left undisturbed until May and April respectively. An attempt was made to correct the recorded data for House #2 by applying a linear correction to the flow rate ranging from 1.0 to 4.0 from December 10 to April 18. The result is plotted on Figure 2.6.1.A. As expected, the highest flows occur during the coldest period, around January.

The behaviour of the CO_2 levels in the two houses is illustrated on Fig. 2.6.1.B:

- When house #1 is left unoccupied, the CO_2 level drops within a few hours to the outdoor level. (January 3-7, house #1).
- On the same Figure it can be seen that when additional people are present, the CO_2 level in house #2 increases (Jan 4 and Jan 9)
- On the same Figure it can also be noticed that when the turbine in house #2 was closed between January 7 and 14, the CO_2 level rose by approximately 200 ppm.

The behaviour of the humidity levels in house #1 and #2 is presented on Figure 2.6.1.C.

- The humidity levels in both turbine houses also follow a similar pattern as the CO_2 levels, but there is a noticeable delay in the changes, due to the storage effect of the house materials and furnishings. During the time that house #1 was unoccupied (Jan 3-7) the absolute humidity levels are seen to gradually drop over the first three days.
- During the time that the turbine in house #2 was closed (Jan 7-14) the absolute humidity is seen to increase gradually. After the turbine was opened, the humidity remains higher in house #2 than in house #1 for several days.

The relationship between daily average turbine flow, wind speed and outdoor temperature was investigated next.

An attempt was made to determine the relationship between turbine flow and weather factors:

- Scatter plots of *daily average turbine flow* versus wind on a daily average basis show a wide scatter, caused in part by the transducer fouling problem. The problem was detected after it was noticed that there was a noticeable downward trend in flow as time went on. See Figures 2.6.1.D.

Figure 2.6.1.A Corrected Turbine Flow, House #2

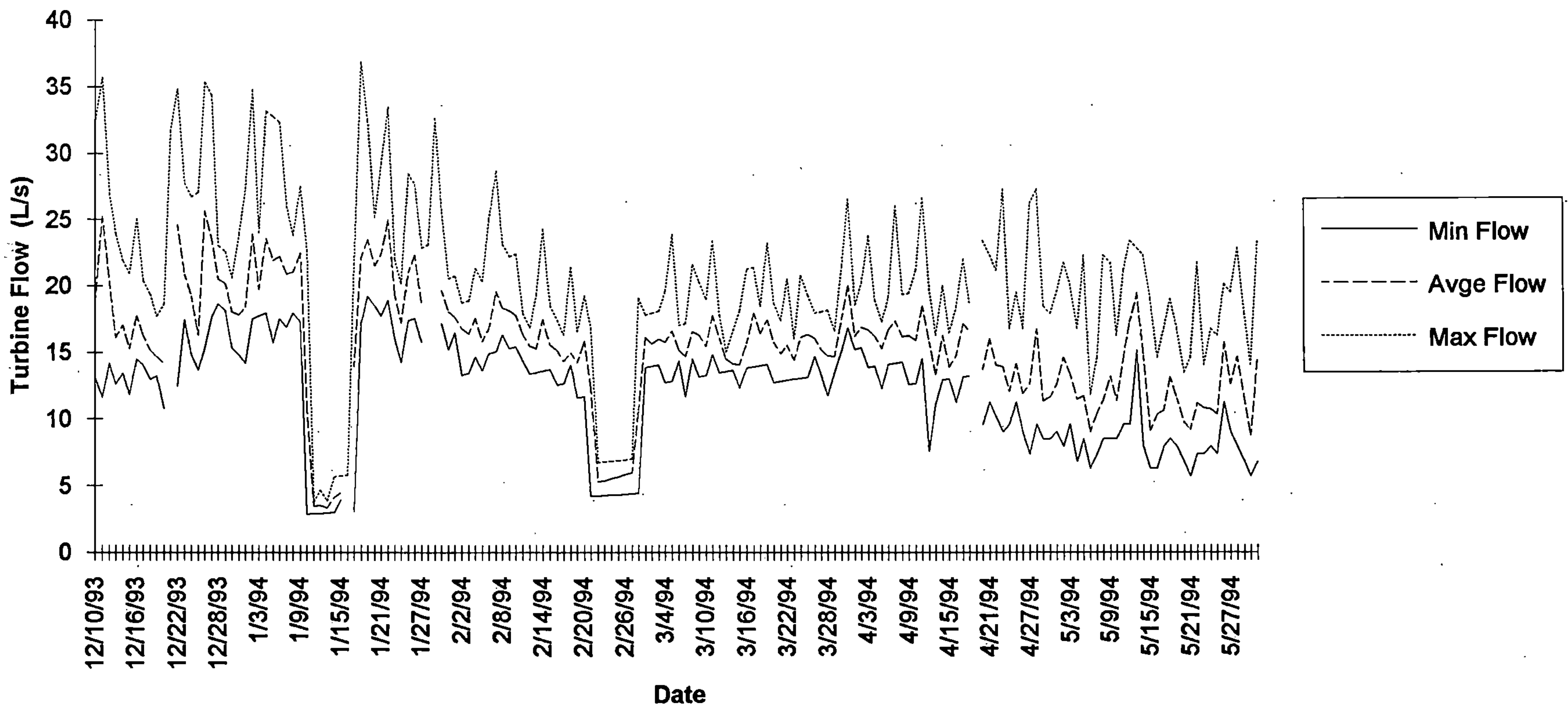


Figure 2.6.1.B **CO_2 Levels in Turbine Houses #1 and #2**

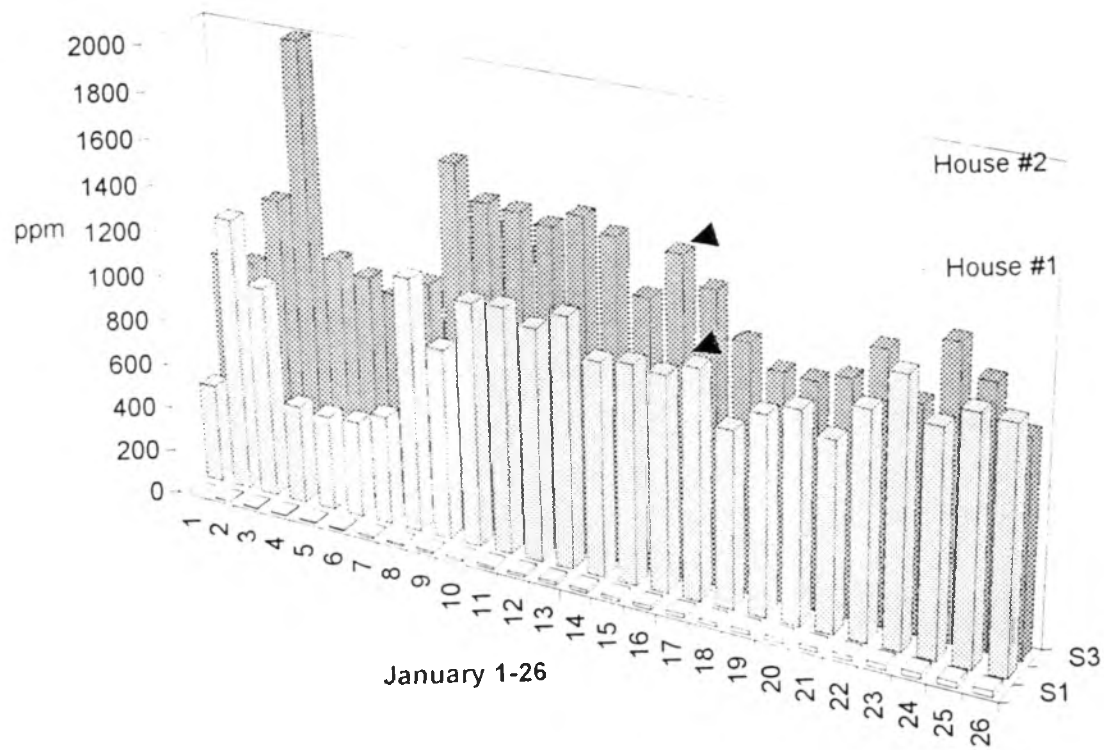


Figure 2.6.1.C **Absolute Humidity Levels in Turbine Houses #1 and #2**

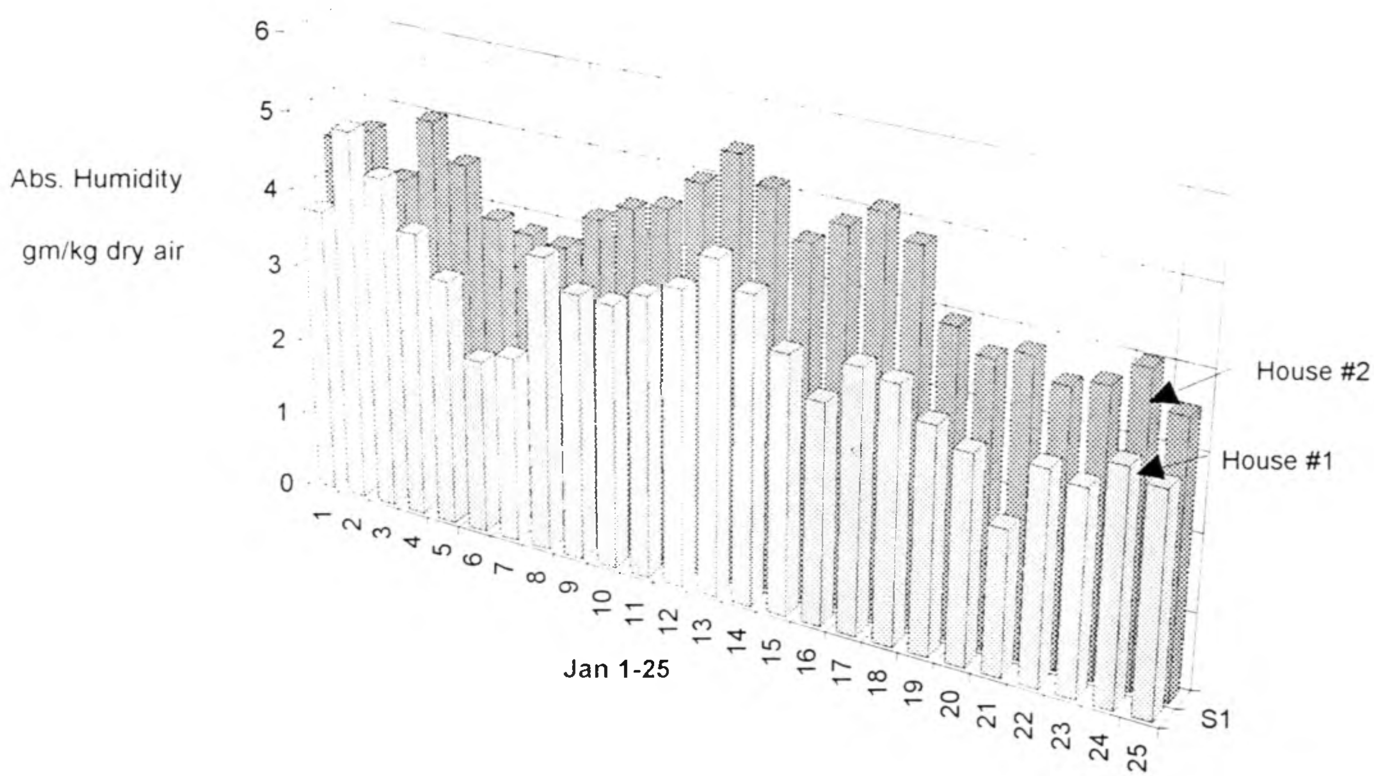
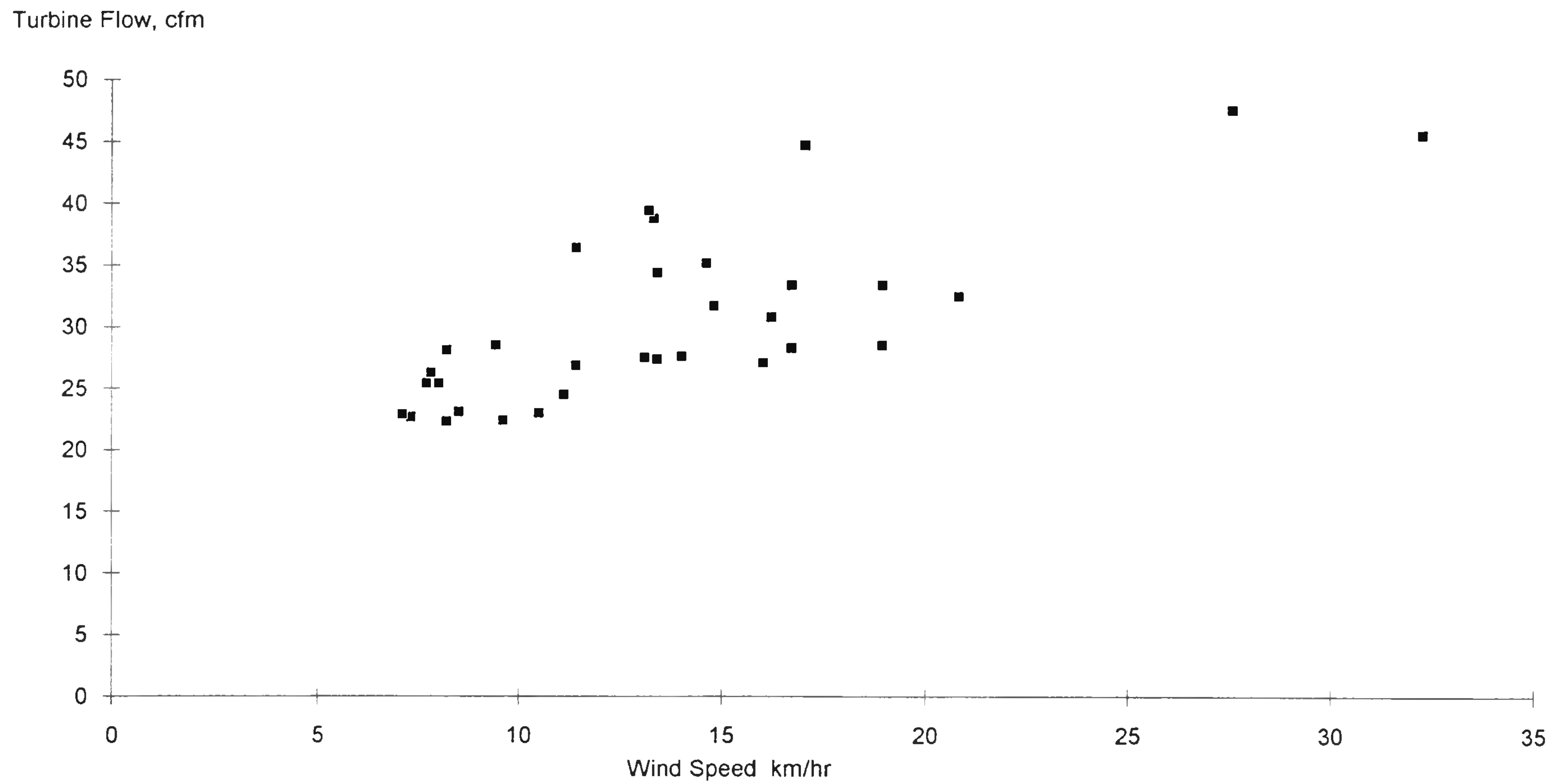


Figure 2.6.1.D **Turbine Flow vs Wind Speed, House #1 (1 day average data)**



- A plot of *daily average turbine flow* versus wind speed during different days at the same temperature (-15C) is presented for house #1 and #2 on Figure 2.6.1.E. The dependence of flow on outdoor temperature is not as strong, as demonstrated by a plot of turbine flow versus outdoor temperature during different days when the wind speed was 7 km/h; please refer to Figure 2.6.1.F. Wind speed appears to have a stronger effect on turbine flow than indoor-outdoor temperature difference, but the scatter is large.

- The relationship between turbine flow and outdoor temperature and between turbine flow and wind speed was investigated further by looking at the *detailed 10-minute data* near the beginning of the recording period, while the effect of fouling (which became evident later on in the season) on the transducer was minimal. The detailed results are presented in Appendix 4. The conclusions are that the relationship between turbine flow and wind speed even at the 10-minute level of detail has a fairly large variance during periods of time while the temperature was constant within 2 degrees, and that the relationship between flow and temperature was also not very pronounced and it also had a wide variance.

The energy content of the air exhausted by the turbine depends on the product of flow rate and indoor-outdoor temperature-difference. As the flow transducers fouled up during the winter, the error in the velocity readings increased, therefore the calculated energy losses will be underestimated by an increasing amount towards April.

- The energy content of the air exhausted by the turbine from mid-December to the end of February ranges between 5 and 30 kWh per day, representing 7% to 24% of the total electricity consumed by house #1, and represents about 12.5% of the total electrical energy consumed during this period. Note that the flow figures include an increasing error after the first few weeks of operation due to the fouled flow transducers. Please refer to Figures 2.6.1.G for an example. For house #2, the energy content of exhausted air ranges between 4 and 25 kWh per day, and represents 7% to 22% of the daily electrical energy consumed, and represents 10% of the energy consumed by the house during the same period.

2.6.2 Exhaust Only System (System A)

In House #3, a 21.5 L/s replacement exhaust fan was installed in the bathroom. An outdoor thermostat was set to run the exhaust fan between the outdoor temperatures of 18C and 2C. The fan would be off during very cold periods and also during warm periods while windows would probably be open. The operation of the control was verified by checking the fan's record of operation. In House #6, a through-the-wall fan with a motorized cover was installed in late winter on an

Figure 2.6.1.E **Turbine Flow vs Wind Speed, T = - 15C**

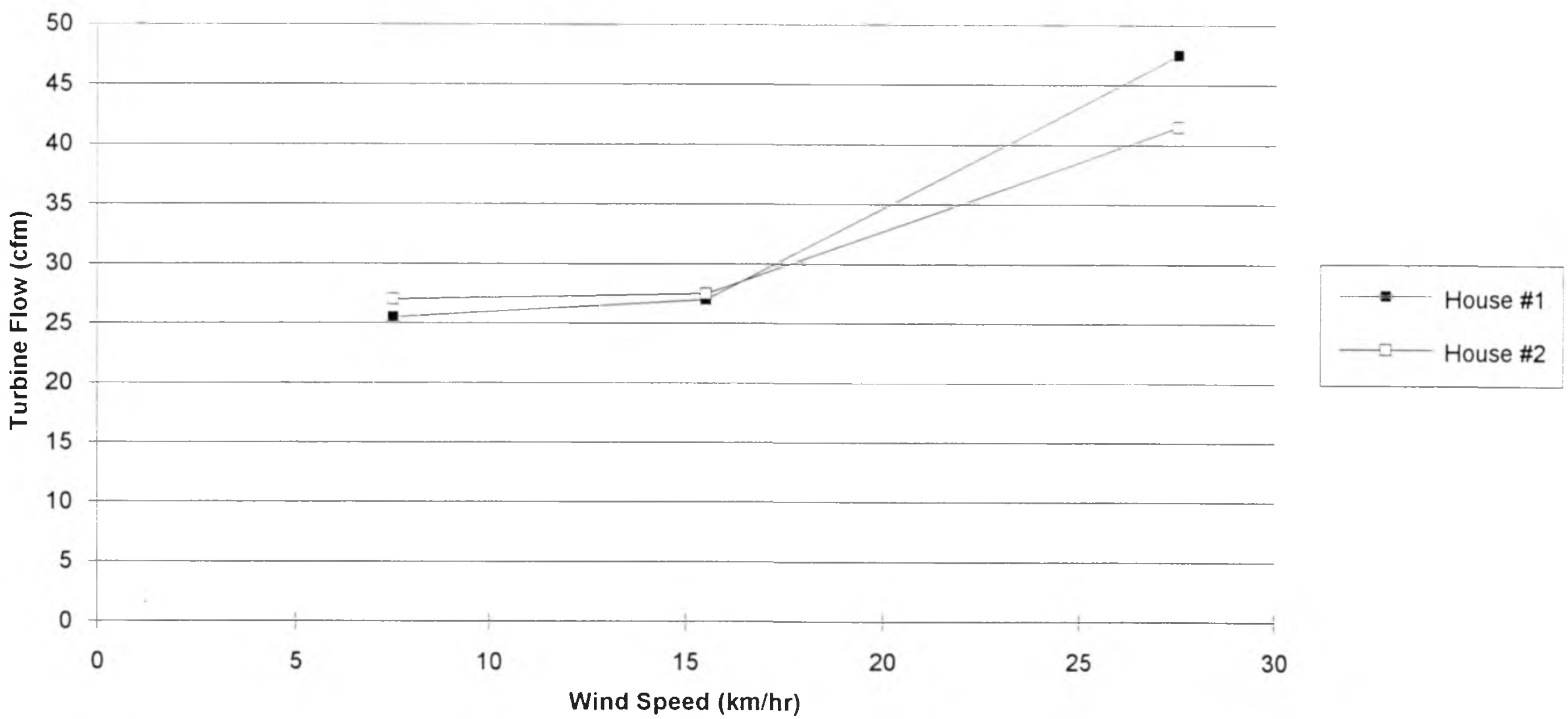


Figure 2.6.1.F **Turbine Flow vs Outdoor Temperature Wind Speed = 7 km/hr**

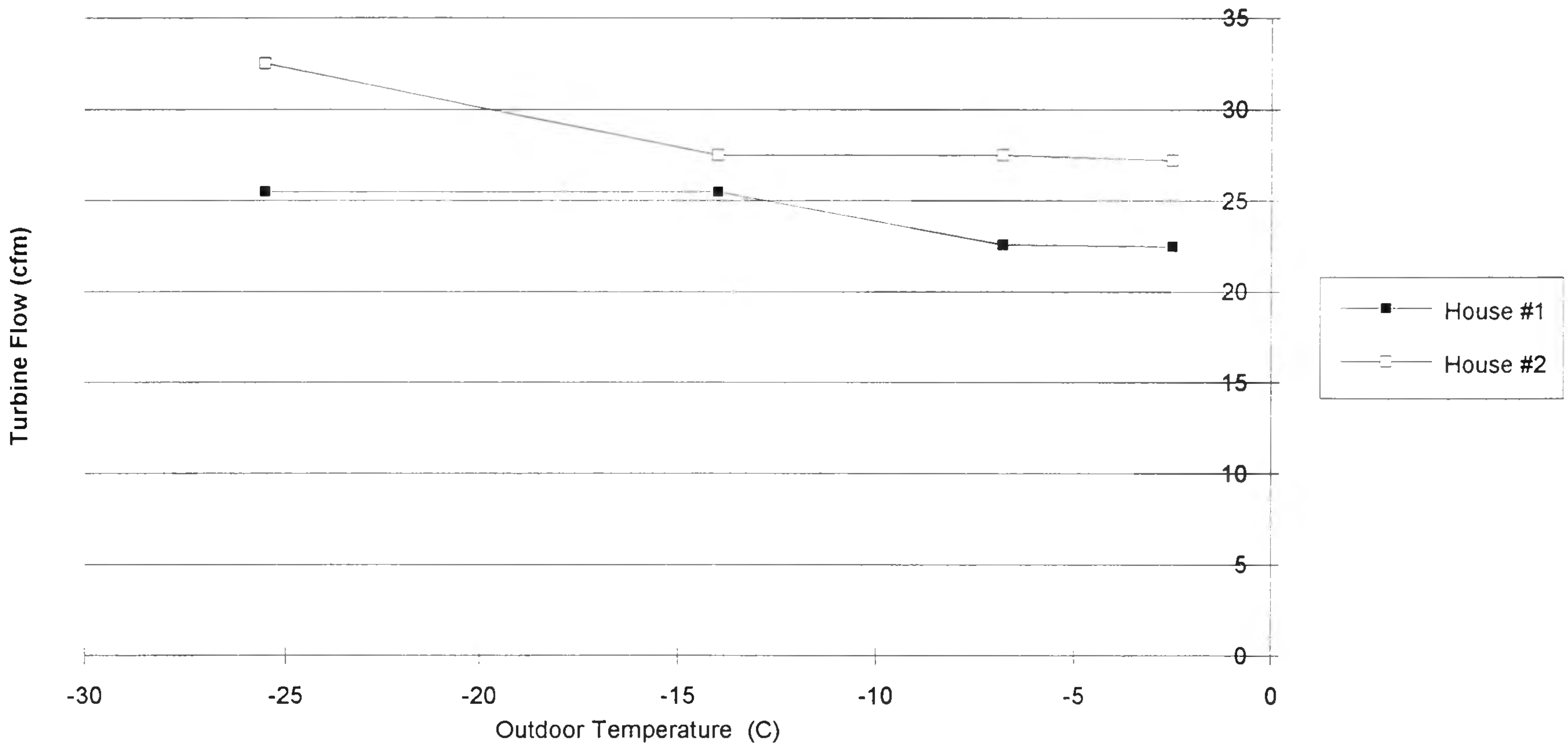
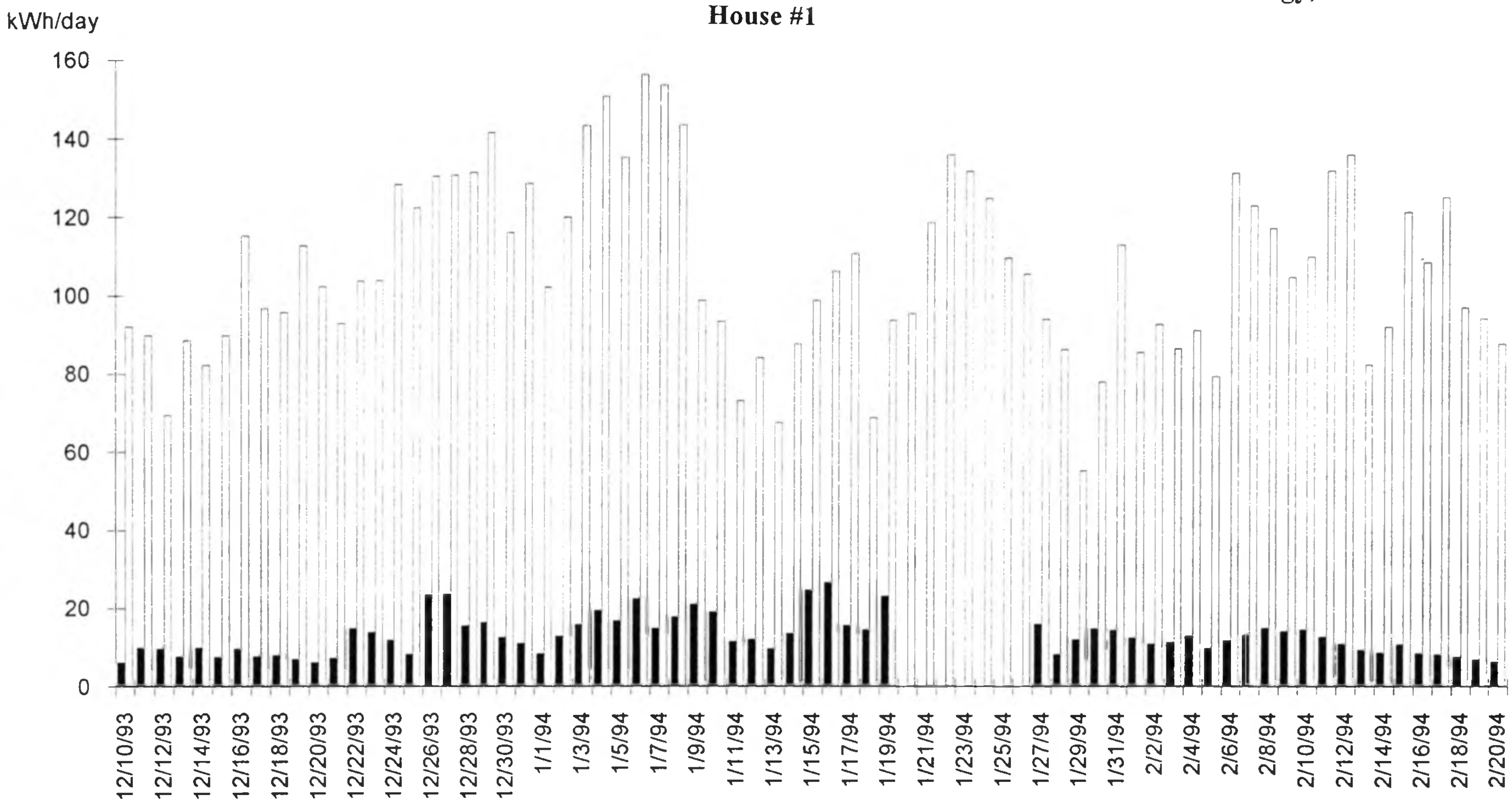


Figure 2.6.1.G **Total House Energy Consumption and Turbine Exhaust Energy, House #1**



outside wall, and was controlled by an indoor humidity sensor (45% or 55% RH). The customer found the system was too noisy, and turned it off. The drop in humidity in House #3 in spring is attributed to the operation of the exhaust fan.

By the time these controls were installed in late fall and winter, the outdoor temperatures were well below 0C, indoor humidities were low, and the controls did not permit the fans to operate. Only in early April did the temperature rise above the cut-in point, allowing operation of the exhaust fans for more than a few hours. Around this time of the year the combination of indoor humidity and outdoor temperatures was such that condensation was not a problem. It is evident from the humidity records that it is not necessary to ventilate houses # 3 and # 6 at this time of the year for the purpose of controlling humidity. Please refer to Figure 2.6.2.A. There may be other air quality problems that would require ventilation, such as elevated formaldehyde levels. It is expected that the operation of exhaust fans in the fall will have a more significant impact on indoor humidity than in the spring due to the higher starting level of humidity in the house in the fall. The operation of the exhaust fan in house #3 in April and May appears to have reduced the average daily indoor CO_2 level below 800 ppm (average operation during both April and May was 17 hours per day). Please see Figure 2.6.2.B.

2.6.3 Through-the-Floor Fan Mixing System, System B

Two fans were installed in house #4, one through the floor of the living room, pushing air up from the recreation room, where a wood-stove is normally in use, and one through a staircase wall connecting to the basement, pushing air into the basement. The door to the basement is normally kept closed. The second fan is sized for about 14L/s higher flow than the first, in order to cause an intentional flow imbalance between floors. The rationale is that this flow pattern will produce more mixing of household air, and the flow imbalance may contribute towards maintaining a somewhat higher pressure in the basement relative to the upper level, thus tending to lower the neutral pressure zone. The actual change in absolute pressures will be a function of the flow differential as well as the location and size of the structural leakage.

The extensive use of wood in this house tends to maintain low humidity and carbon dioxide levels most of the time. Bedroom door closings occasionally lead to elevated carbon dioxide levels. The most notable changes in the humidity and carbon dioxide levels in house after the fans were started early in January, was that the amplitude of the swings in humidity and carbon dioxide were reduced markedly. This smaller amplitude is accompanied by a reduction in peak levels which would tend to reduce condensation as well as local CO_2 peak levels. Please see Figures 2.6.3.A and 2.6.3.B.

Figure 2.6.2.A Daily Average Indoor Absolute Humidity, Houses #3 and #6

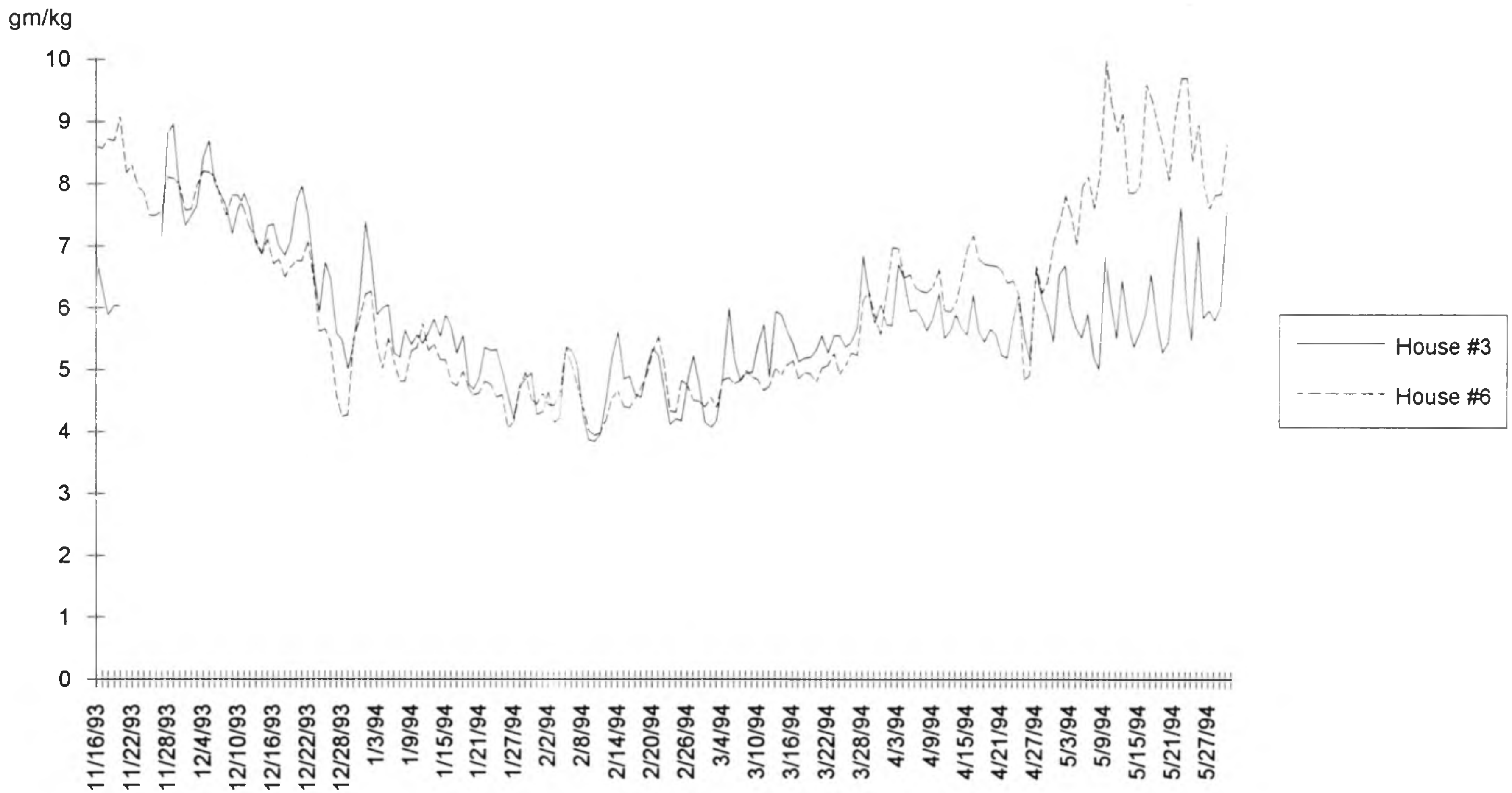


Figure 2.6.2.B Daily Average CO_2 Levels, Houses #3 and #6

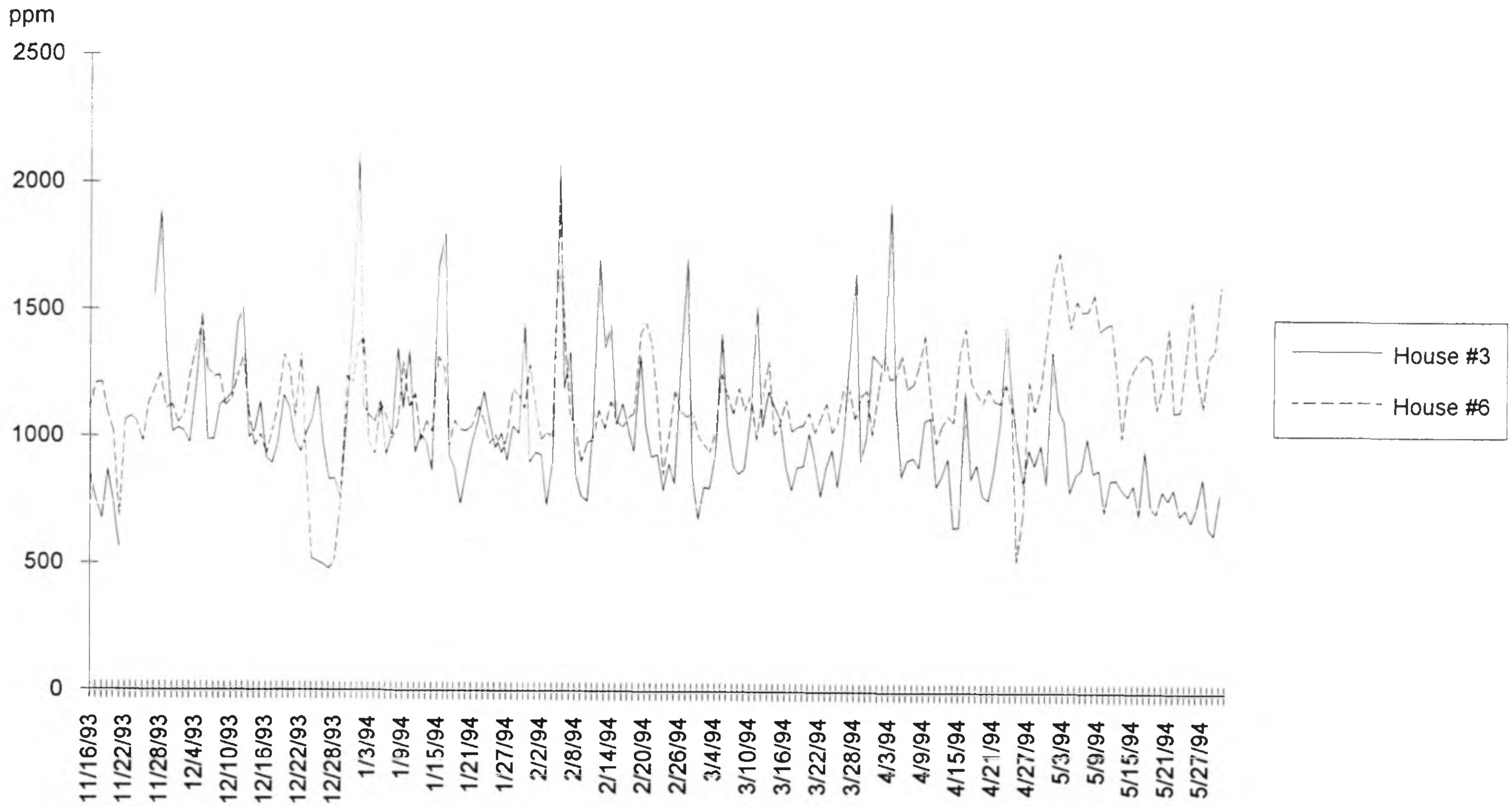


Figure 2.6.3.A Daily Swing in Absolute Humidity, House #4

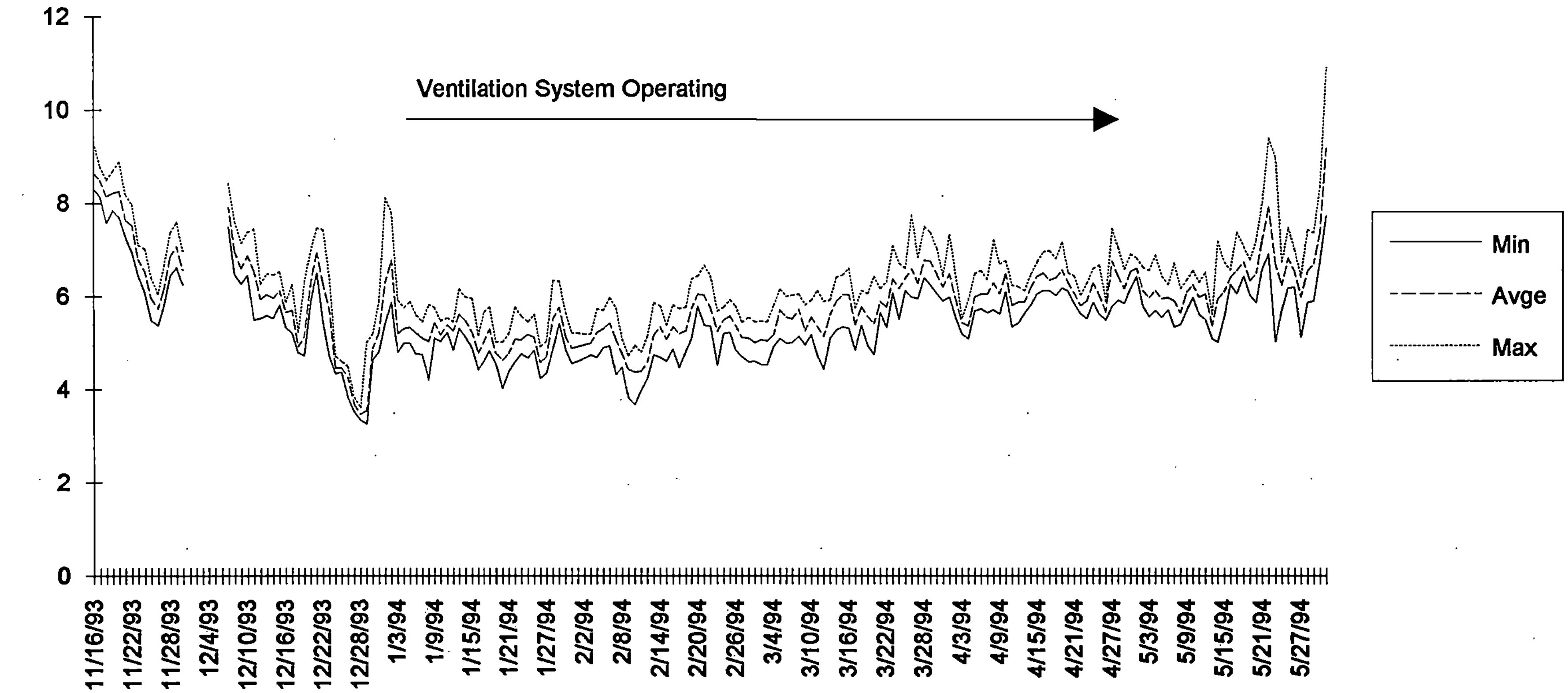
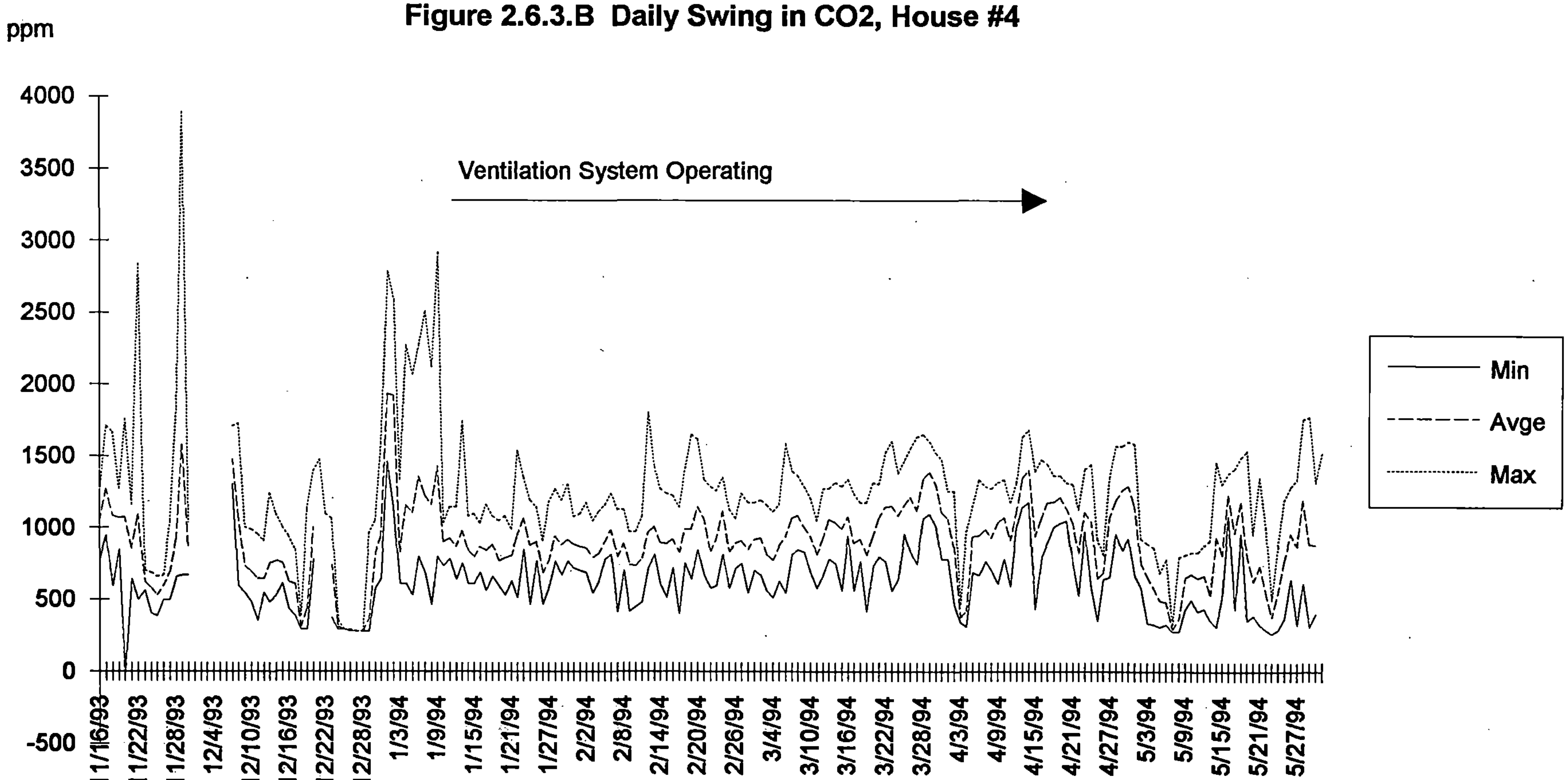


Figure 2.6.3.B Daily Swing in CO2, House #4



The occupants found the operation of the system to help in the distribution of the heat from the wood stove to other parts of the house and to reduce overheating the family room in the basement where the stove is located.

2.6.4 Fresh Air Tempering System Plus Exhaust, System C

The system installed in House #5 consisted of a fresh air supply (9L/s) and a mixing system taking 19 L/s from each of three bedrooms, and discharging the mixed air into the hallway. In addition, a bathroom exhaust fan was replaced with a quiet model with a new control. The control was set to run the exhaust fan during periods when the outdoor temperatures are between 2C and 18C.

The occupants of this house normally sleep with the bedroom door closed. The effects on indoor humidity and CO_2 of the new bedroom ventilation system, which was turned on in the middle of December, are clearly visible on Figure 2.6.4.A. The carbon dioxide levels dropped immediately. Peak levels dropped from 4000 ppm to 1500 ppm, and mean levels dropped from about 2000 to 1100. Shutting off the system for one week on January 3 caused the carbon dioxide to rise to the earlier levels for the week. During the period of April 9 onwards, the exhaust fan started operating over long periods of time, and the level of carbon dioxide can be seen to drop moderately. At this stage, the additional ventilation supplied by the exhaust fan appears to be unnecessary to control carbon dioxide. The same may not be true for formaldehyde or other pollutants.

2.6.5 Air Distribution System with Balanced Intake and Exhaust, System D

House #8 was originally equipped with an air distribution with air exchange system taking air from the upper level hallway and exhausting (at "high speed") 20.5 L/s outdoors, and taking 20.5 L/s fresh air from outside, mixing it with air from upstairs, and discharging the mixture into the basement. The system was operated at "high speed" only. The stratification of carbon dioxide in this house was described earlier in Section 2.4.1

Both the humidity and carbon dioxide levels in this house were very low compared to the other seven houses. The operation of the fresh air intake and exhaust are credited for the low levels. Please see figures 2.6.5.A and 2.6.5.B, which present the daily swing in absolute humidity and carbon dioxide respectively.

2.7 The Cost of Additional Ventilation

2.7.1 Tight Houses

Knowing the source strength of each air contaminant in each of the houses in the study, one can specify the minimum ventilation required to maintain the most critical pollutant at an acceptable level. However, the natural ventilation of houses varies with the weather as

Figure 2.6.4.A Daily Swing in Absolute Humidity, House #5

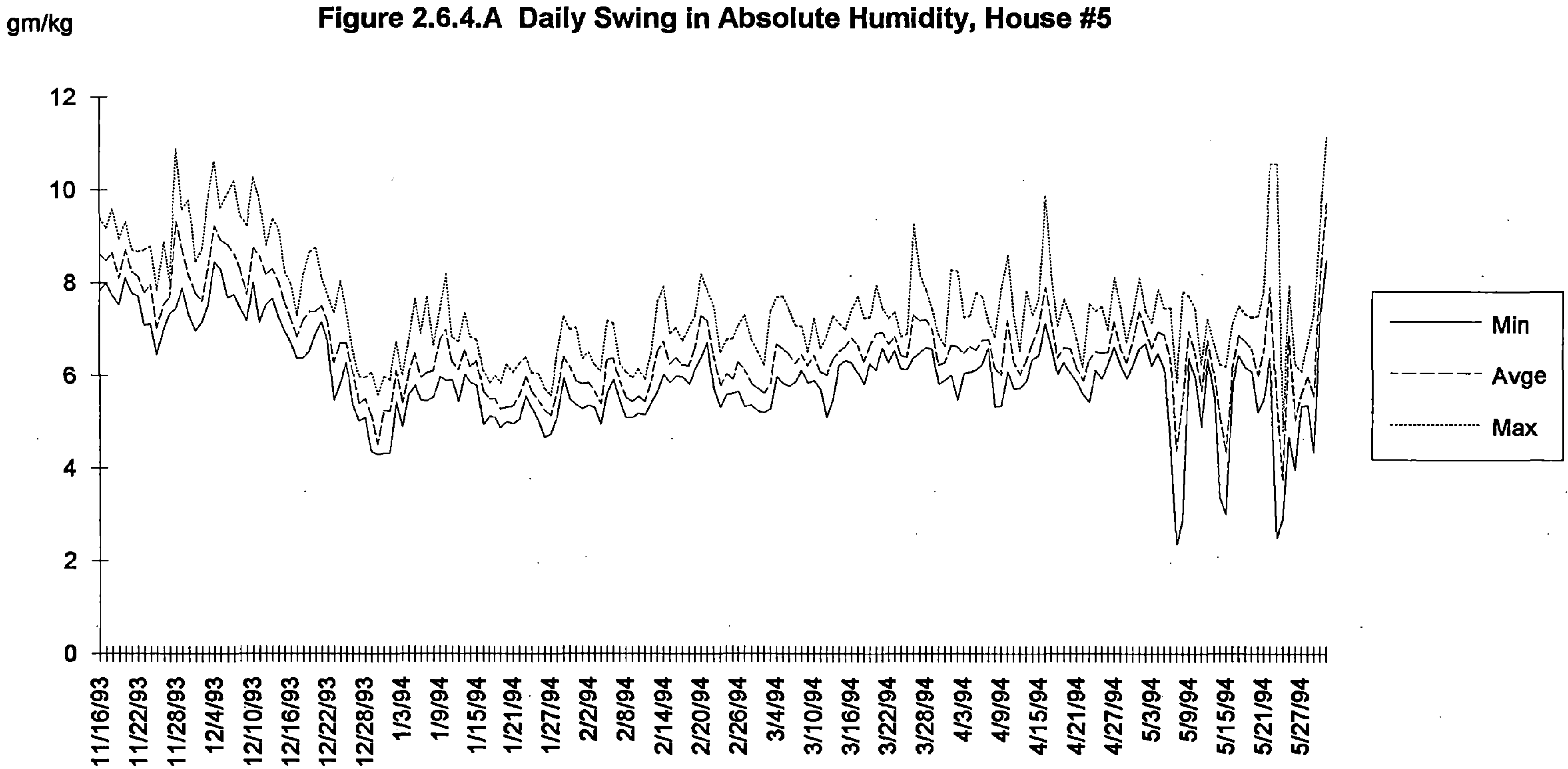


Figure 2.6.5.A Daily Swing in Absolute Humidity, House #8

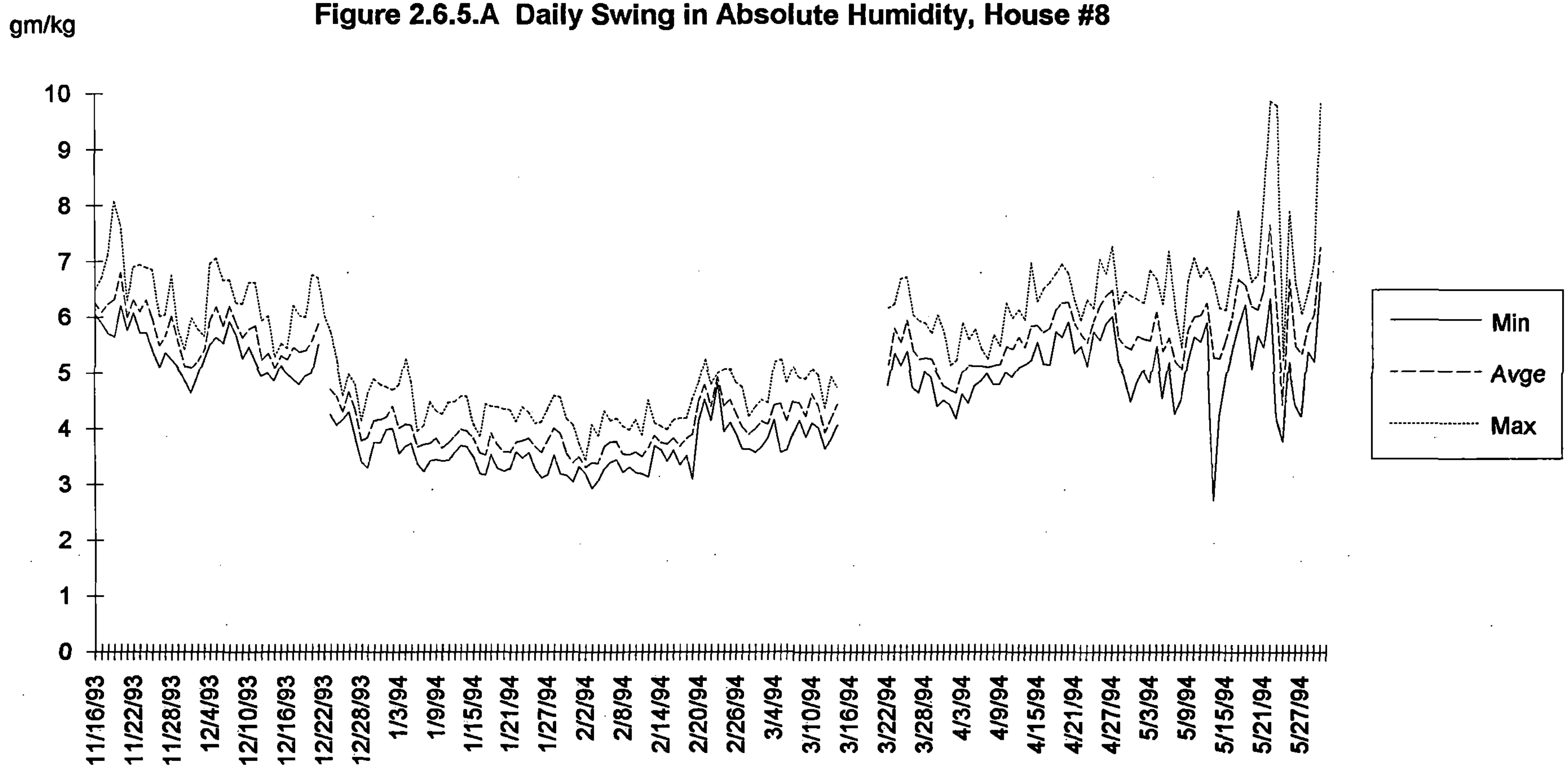
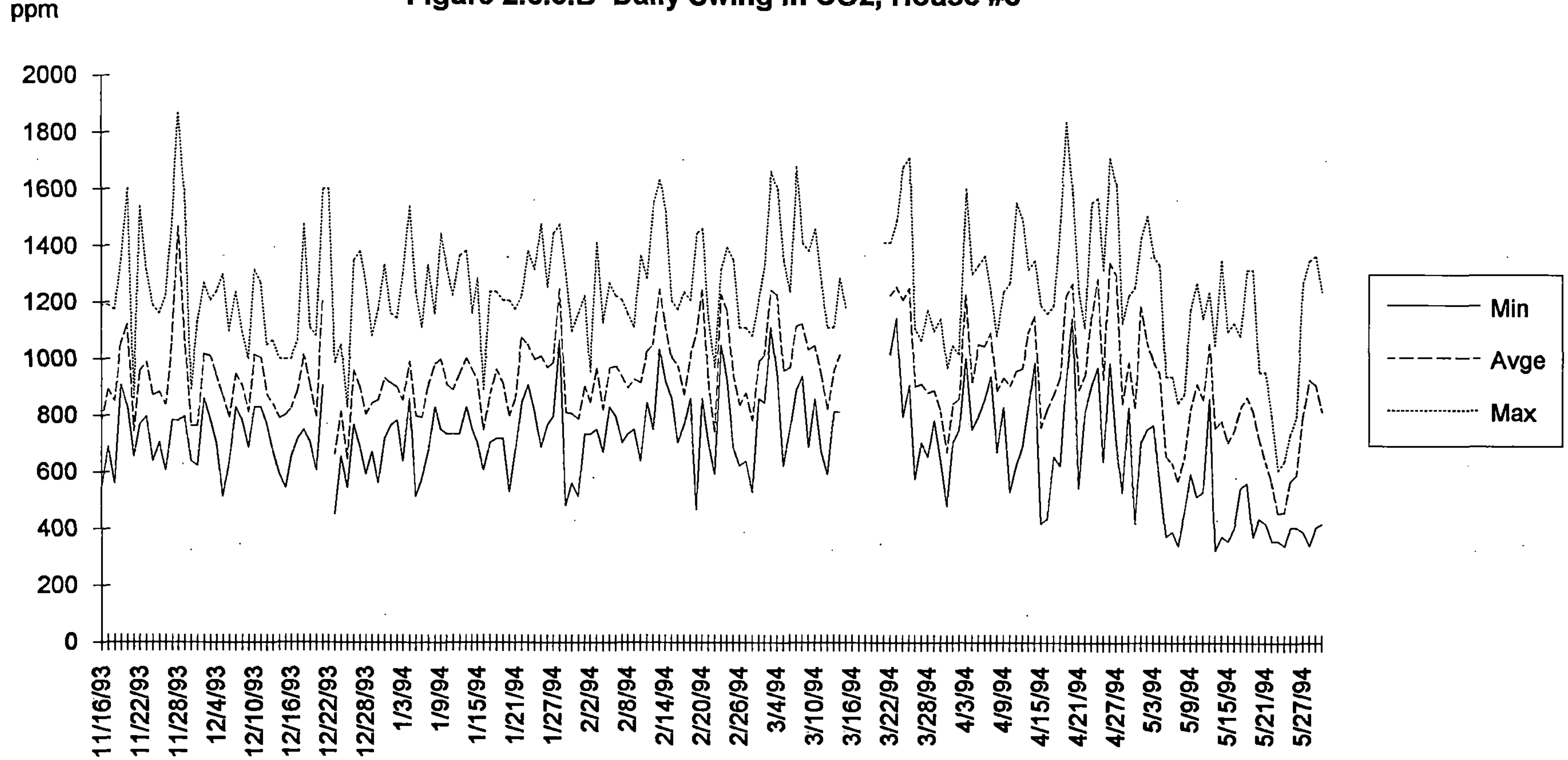


Figure 2.6.5.B Daily Swing in CO2, House #8



well as with occupant activities. The challenge is to determine ***how much*** additional ventilation is required, and ***when.***

For houses that are experiencing fall condensation problems (such as House #3 and #6), it may be possible to control the problem by increasing ventilation. It was noted that four of the eight test houses which operate a wood stove or fireplace in the fall and winter appear to have no condensation problems. Airtight wood stoves add 9 - 14 L/s of additional ventilation. Fireplaces can add considerably more ventilation.

For houses which experience chronic low ventilation as well as a high humidity problem in the fall, such as House #5, it was observed that an additional 9 L/s continuously maintained the average CO_2 level between 1000 and 1500 ppm in the master bedroom. We will be watching its performance with respect to condensation in the fall with the additional ventilation. More than 9 L/s additional ventilation may be required in this house due to the fact that there are five occupants.

The amount of energy required to provide 9.4 L/s until mid-December and of providing 9.4 L/s continuously through most of the heating season can be estimated from the indoor-outdoor temperature difference and the specific heat of air. This calculation has been done for 9.4 L/s of exhaust assuming an indoor temperature of 20C and the outdoor temperatures experienced in Trois Rivières during the past heating season. The results have been plotted as the daily losses and the integrated losses on Figures 2.7.1.A and 2.7.1.B. respectively For higher or lower ventilation rates, the answer can be adjusted proportionately. As can be seen, the amount of energy associated with an additional ventilation of 9.4 L/s during the fall is about 200 kWh, and for the entire heating season, about 1200 kWh. It must be remembered that this is for tight houses which have inadequate ventilation. Leakier houses are dealt with in the following section.

2.7.2. Leaky Houses

"Leaky" houses, or those with measured equivalent leakage areas in the higher ranges, may have more natural ventilation than is necessary in order to maintaining acceptable indoor air quality and indoor humidity levels. For example, Houses # 20, 21 and 27 are the leakiest, since they have a measured ACH_{50} of 9.96, 10.06 and 11.35 respectively according to the blower door test (please refer to Tables 2.1.A and 2.2.A). The observed ***natural ventilation rate*** of each of these houses over a 1-week test period in winter was 114, 54 and 88 cu.m/hr (or 32, 15 and 24.5 L/s) respectively. All the other houses have lower AC/H_{50}, but many experienced higher natural ventilation rates during the test week, ranging up to 292 cu. m/hr (81 L/s).

There may be times when the natural ventilation forces in leaky houses are too low to provide the necessary ventilation. There may be significant energy savings possible by tightening these houses and reducing air leakage, but the number of times that natural ventilation will be inadequate to meet the fresh air requirements will rise if the building is tightened. Due to the strong dependence of natural ventilation on wind, it is expected that

Figure 2.7.1.A Daily Energy Losses @ 20 cfm

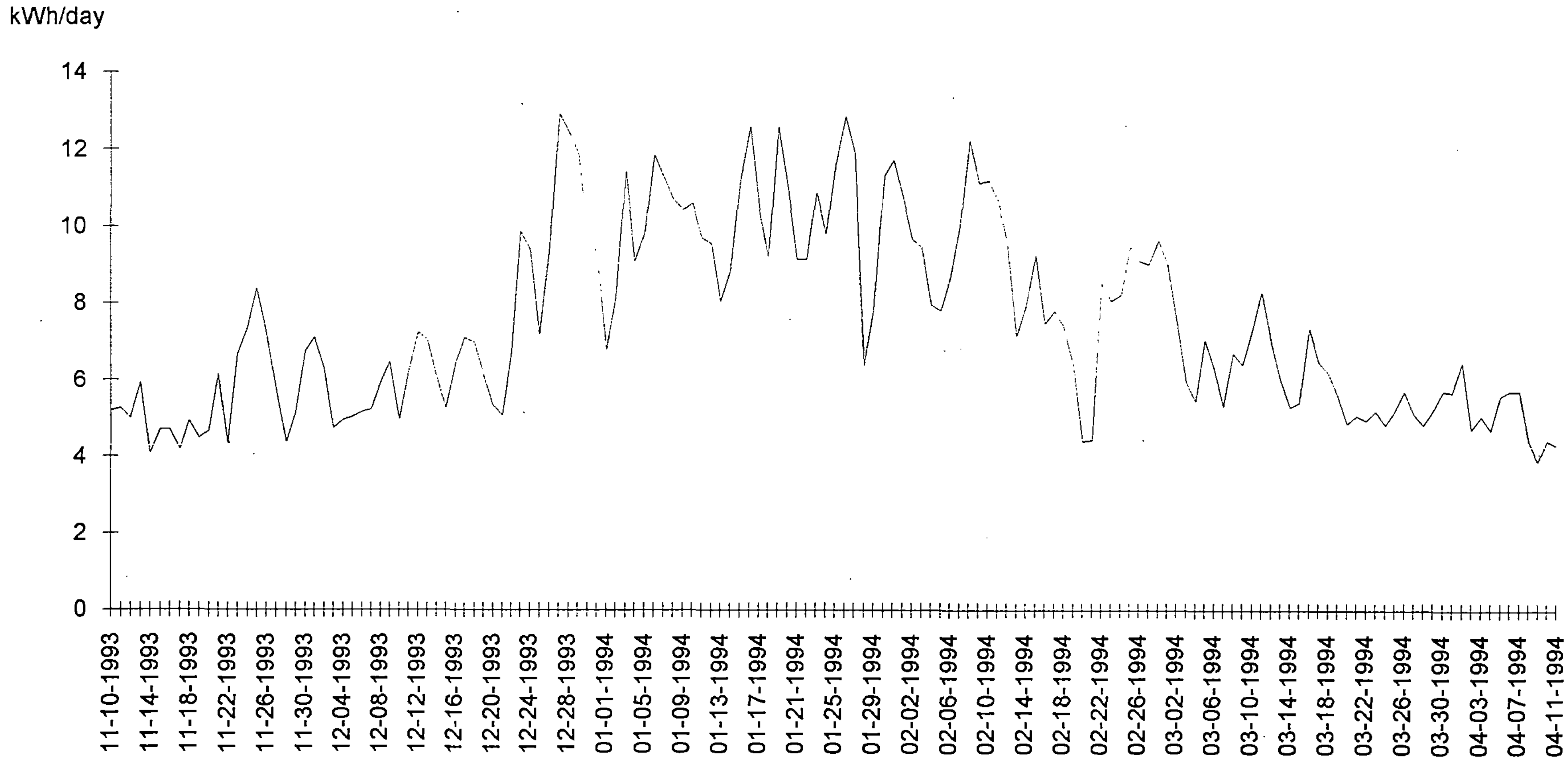
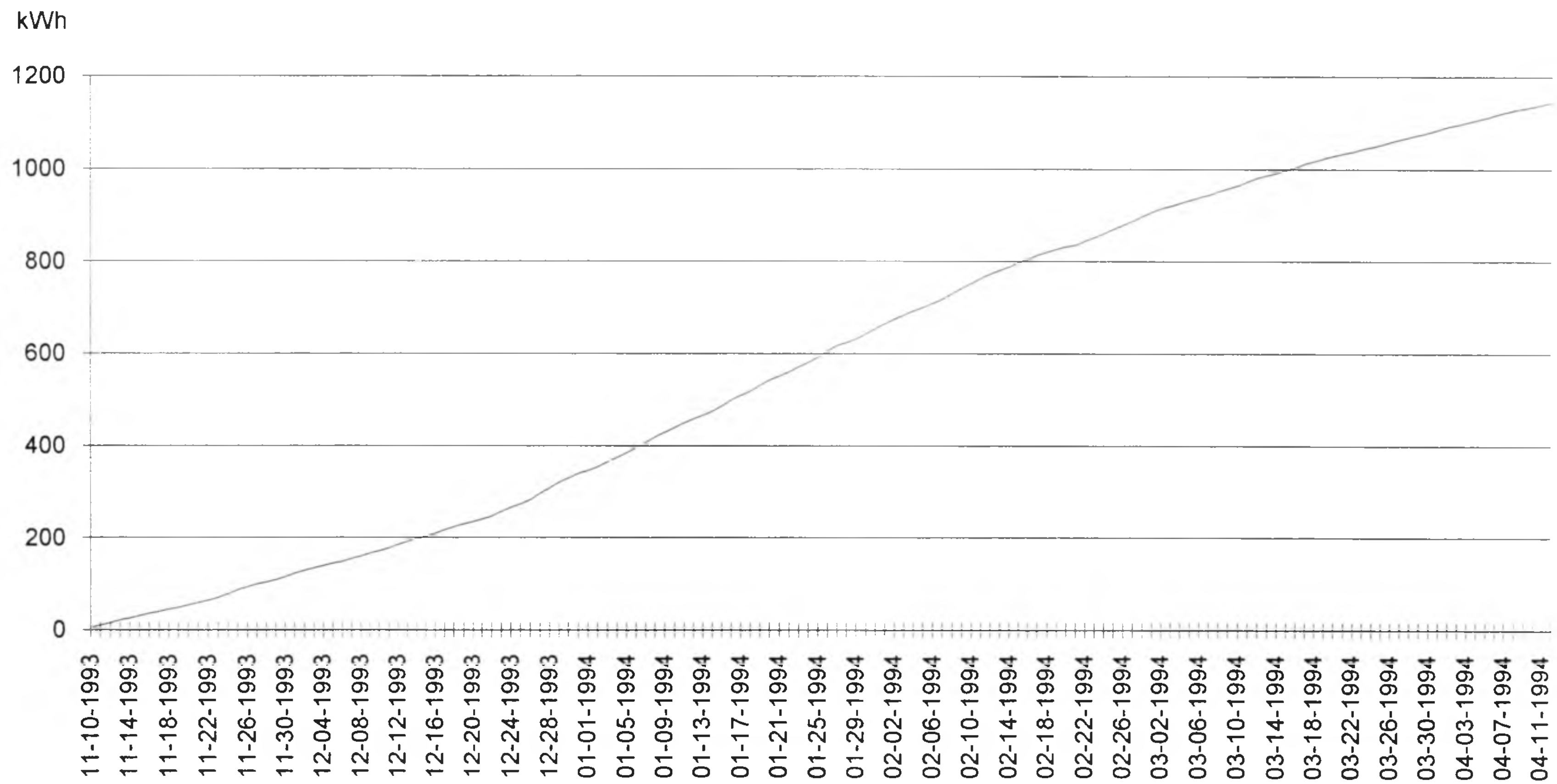


Figure 2.7.1.B Total Energy Exhausted @ 20 cfm



air-tightening of very leaky buildings can save a significant amount of energy. Adding the relatively small of ventilation that may be required to maintain acceptable indoor air quality during calm periods will offset some of the savings that can be achieved through air-tightening. The right balance must be found between tightening and adding the required amount of ventilation in order to achieve a net saving in energy.

2.8 Basement Pressure Difference

The pressure difference between indoors and outdoors was recorded by means of converting an analog signal to a pulse-rate, in order to take advantage of a spare recorder channel. Unfortunately, there was a compatibility problem between the converter and the recorder, that was not caught until the end of the winter, and most of the data recorded during the higher wind speed periods is unreliable. The problem has been resolved and data will be collected during the fall season.

3. Ventilation Model

A ventilation model which was developed by Canada Mortgage and Housing Corporation, called AQ1, was used to estimate the natural ventilation during a one-week period in order to compare the results with the ventilation rates actually measured in eighteen of the houses during the 1993-4 winter field test. Once "calibrated" to a house, the ventilation model is capable of predicting the ventilation rate and pollutant levels on an hourly basis or on a monthly average basis from given house leakage characteristics, source strength information and weather data. The model has the capability of taking into account the use of ventilation equipment and wood-burning appliances by keeping track of schedules of equipment use.

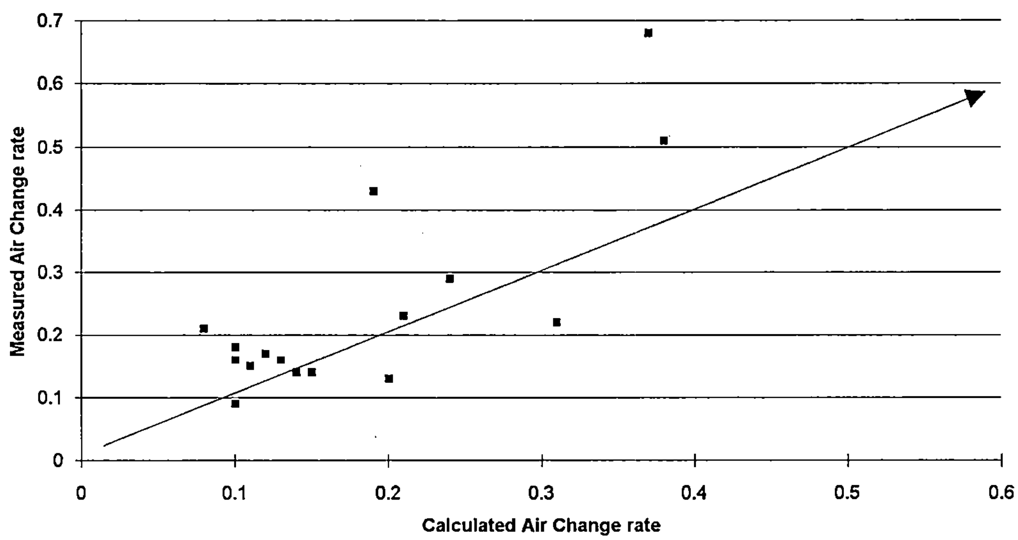
The reliability of the model was tested by comparing simulation results against measured air change rates in the test houses measured during the one-week test employing the PFT tracer method. The results of these tests on the model are summarized in Table 3.A below. Please refer to Appendix 5 for the detailed results.

Table 3.A Measured and Calculated Natural Ventilation

House Number	Natural Air Change Rate Measured (AC/H)	Calculated Air Change Rate using AQ1 Model (AC/H)
1	0.12	.17
2	0.31	.22
3	0.11	.15
4	0.14	.14
5	0.10	.09
6	0.10	.16
7	0.10	.18
8	0.13	.16
9	0.21	.23
10	0.08	.21
11	0.24	.29
12	0.20	.13
13	0.58	.58
14	0.15	.14
15	0.19	.43
16	0.20	.13
17	0.37	.68
18	0.38	.51

These results are presented graphically on Figure 3.A. The R-squared for the relationship between measured and calculated air change rates was 0.65, and the standard error of estimate was 0.1 air changes per hour.

Figure 3.A Measured vs. Calculated Air Change Rates



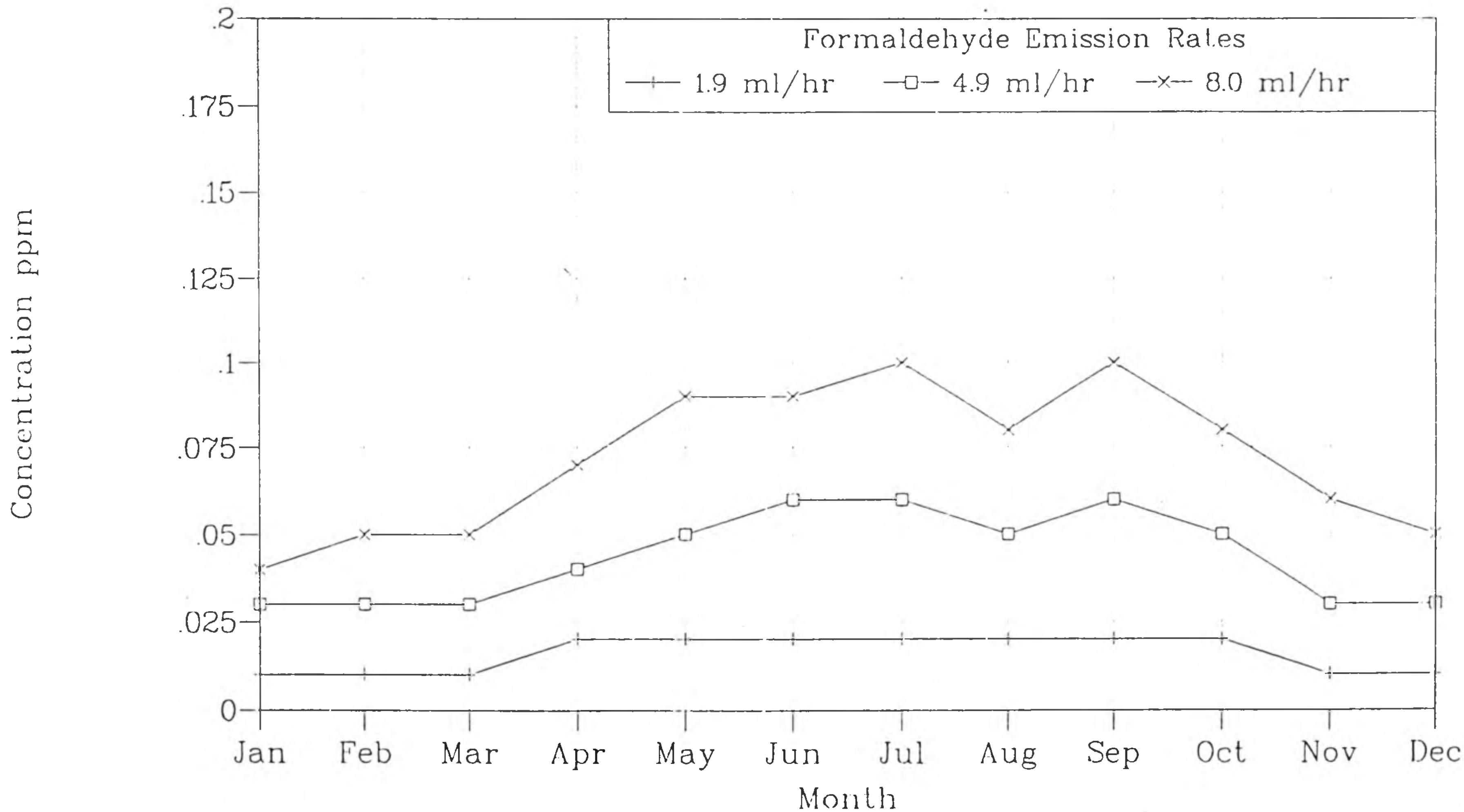
Using three different emission rates for formaldehyde covering the range found in the test houses, and weather data for Montreal, the AQ1 model was used to predict the average level of formaldehyde over an entire year in several houses. For example, using the air change rate of House #9, we show the effect of different levels of source strengths. Please refer to Figure 3.A. At the lowest formaldehyde source strength of 1.9 ml/hr, the formaldehyde level remained below 0.02 ppm, well below the Health Canada limit of 0.1 ppm. Only during the lowest ventilation periods (during July and September) and at the highest source strength encountered in the 30 houses (8 ml/hr), does the predicted level of formaldehyde reach the 0.1 ppm level in this house. Taking a tighter house such as #14 and the highest source strength, the model predicted levels well above 0.1 ppm during the period April to November. Assuming the medium source strength of 4.9 ml/hr in the same house, the model predicts a level of 0.1 ppm between the months of June to September, and lower levels during the colder seasons.

The model is useful in predicting periods of maximum pollutant concentration and the number of houses that will exceed pollutant guidelines if tightened to a specific level.

4. Summary

The relationship between the measured airtightness of a house (AC/H_{50}) and natural ventilation is complicated by the effects of weather and "living habits" of the occupants on air leakage. It has been observed that under certain conditions, all buildings (without

Figure 3.A – Projections of Formaldehyde Concentrations (ppm) for House #9 – Montreal



forced ventilation) have periods of very low ventilation. During these periods, the volume of air contained within the building becomes very important as diffusion and air movement between zones are the only mechanisms which can effectively dilute pollutants during these low natural ventilation periods.

The Ventilation Rate (in L/s) is a more meaningful quantity than the Air Change Rate (in air changes per hour) to determine the indoor air quality. This is especially true when ventilation in a room or a zone is discussed. For example, 14 L/s in a normal bedroom of 27 cu.m. represents about 1.9 AC/H, but in a 453 cu.m house represents only 0.11 AC/H.

Each house experiences a range of natural ventilation which varies from practically zero during calm, warm days, to a maximum during cold, windy days when appliances such as fireplaces and other exhaust equipment may be operating. Opening windows on a regular basis, operating a fireplace or wood stove regularly, or operating venting appliances such as exhaust fans and dryers add considerably to the natural ventilation which normally takes place though crackage and structural leaks.

Effective air sealing tends to reduce natural ventilation during both windy, cold periods, and during calm, milder periods. For health and comfort, additional ventilation may be required during the calm, milder periods. Net savings in energy will be achieved after air sealing only when the savings achieved due to reduced air leakage (especially during windy, cold periods) exceed the additional energy required to ventilate properly during the calm, milder periods.

Since indoor pollution levels are determined by both the source strength *and* the natural ventilation rate, we can now put all the factors together necessary to specify what needs to be done in each house as a corrective measure or as a preventative measure in case the house is air-tightened.

Important Sources of Pollutants:

CO_2: human and pet occupancy (person-hours per day)
cigarette smoking
brewing of beer and wine
candle use

Particulates: cigarette smoking
fireplaces

Formaldehyde: new construction
carpeting
cigarette smoking

Important factors that determine the amount of ventilation that takes place:

Natural:
- house airtightness
- building exposure to the wind
- window openings
- bedroom door closing
- use of wood burning stove and fireplace
- use of ventilation turbine

Mechanical:
- use of air exchangers
- extensive use of exhaust fans
- use of vented clothes dryer

Other factors that impact on the amount of ventilation required:

- fall condensation problem
- damp or wet basement
- open sump in basement (potential radon problem)
- number of occupants
- activities (use of solvents, hobbies, etc.)

Complicating Factors

Ventilation and living habits may differ from family to family.
The number of occupants in a house may change over time.
Families grow up, and bedroom door closings may become more common as children grow up and want more privacy.

Average Level of Indoor Pollution in Québec houses

Although the houses selected for this field study have a similar distribution of ACH_{50} leakage characteristic as observed in the Éval-Iso field test, it does not follow that the distribution of source strengths of the various indoor pollutants will also be representative of Québec houses. Comparison between Québec and Ontario pollutant source strength data indicates that Ontario houses experience higher source strengths than our sample.

5. Conclusions

1. The correlation between the measured airtightness of houses (ACH_{50}) and natural ventilation in houses is very loose, and is influenced by many different factors, some related to the building itself (leak location, amount of shelter, building height, etc.) and others related to the occupants (fireplace use, window openings, use of ventilation equipment, etc.)

2. Natural ventilation in houses is affected by several factors including the use of wood-burning fireplaces and stoves, window opening practices, and ventilation equipment such as turbines, air exchange systems and exhaust fans. The average daily ventilation of houses varies considerably depending on external as well as internal factors. The estimated distributions indicate that all houses have periods of very low natural ventilation during which the pollutant levels may approach or exceed the Health Canada guidelines for RSP's, formaldehyde, and occasionally for CO_2.

3. The ventilation requirements of houses in Québec are dependent on both the source strength of pollutants found in each house including RSP's, formaldehyde and carbon dioxide, and on the minimum amount of natural ventilation. Some of the pollutants are generated by the occupants and their activities, others are released by materials in the house.

4. Carbon dioxide levels are directly dependent on the person-hours of occupancy, as well as on the use of candles. The local levels of CO_2 and humidity become elevated when the door of an occupied room is closed.

5. During the heating season, natural ventilation is inadequate to maintain indoor pollutant levels below the recommended limits during mild weather in the majority of houses tested. During the coldest part of the season, natural ventilation is adequate in about half of the houses. The main determining factors are pollutant source strength, building leakage characteristics, and operation of fire-places, exhaust equipment and window openings.

6. From field measurement of source strength of pollutants, the amount of ventilation required in the sample of houses so as to remain within the Health Canada levels are in the following ranges:

Pollutant	Range of Ventilation (L/s)
RSP's	3 - 53
Formaldehyde	9 - 50
Moisture	12 - and up (assuming dry air)
Carbon Dioxide (1000 ppm)	6 - 47
Carbon Dioxide (3500 ppm)	1 - 10

Other pollutants such as radon and VOC's require smaller amounts of ventilation, unless there is an unusually high local source of the pollutant.

7. While the use of wood stoves and fireplaces increase the amount of ventilation in the house, in some cases these appliances can cause an increase in indoor air particulate levels. Combustion products which escape into the living space due to back drafts (loading firewood into the stove, low chimney temperature, operation of powerful exhaust fans, etc.) add to other RSP sources such as cigarette smoke. The net effect is elevated RSP levels in some houses with operating wood fired appliances.