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INDOOR FORMALDEHYDE LEVELS IN HOUSES WITH DIFFERENT VENTILATION STRATEGIES

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1. Synopsis

This paper discusses the indoor formaldehyde levels in two groups of houses. With the exception of the heating and ventilation systems, the house construction, formaldehyde sources and occupancy were similar for the two groups. One group (A) used electric baseboard convective heaters for space heating and semi-ducted heat recovery ventilators (HRV) for supplying outdoor air and exhausting indoor air. The second group (B) had electric forced-air furnaces with a ducted air supply to every room. Outdoor air was drawn in via a connection to the return air ductwork.

During the winter, 77% of the Group A houses had bedroom formaldehyde levels higher than the living room levels. In the Group B houses, only 20% had a bedroom level higher than the living room level. These data suggest that the semi-ducted HRV systems provide limited air circulation within the houses compared to the fully ducted forced-air furnaces.

The average winter HCOH levels were similar for both house groups; however, the Group A houses had ventilation rates twice as high as the Group B houses. Since the HCOH source strengths within the house groups should be equal, superior mixing efficiency in the Group B houses may be responsible.

The results also show that a continuous supply of ventilation air is necessary to prevent the build-up of indoor pollutants. Ventilation systems that are coupled to the air circulation/heating system (Group B) are not reliable during low/no heat periods. In energy-efficient houses with low auxiliary heating requirements, indoor air quality problems may develop.

2. Introduction

Concerns over the build-up of pollutant levels in new "low-energy" houses have arisen recently. Typically, low-energy houses have well sealed air-vapour barriers to minimize air leakage and use mechanical systems to supply ventilation air.

This study was initiated to provide field data on the indoor formaldehyde (HCOH) concentrations in a group of 33 relatively new (1-2 years old) "low-energy" houses located in Winnipeg and Pinawa, Manitoba. Using passive dosimeters, concentrations were measured in December 1983 (ventilation via infiltration and mechanical system only) and again in September 1984 (occupant-controlled window openings to supplement ventilation).

The December 1983 HCOH data for a sub-group of 16 houses have already been analyzed in detail[1] and the results indicated that for a given type of occupancy, indoor HCOH levels could be related to the ventilation rate by the simple expression (Fig. 1):

$$C_i = C_o + \frac{\hat{N} A_f}{K \hat{V}} \quad (1)$$

where C_i = indoor HCOH concentration ($\mu g/m^3$)
C_o = outdoor HCOH concentration ($\mu g/m^3$)
$\hat{N}$ = net apparent HCOH source strength ($\mu g/s \cdot m^2$)
$\hat{V}$ = net ventilation rate (m^3/s)
K = mixing factor (K = 1 perfect mixing)
A_f = main floor area (m^2).

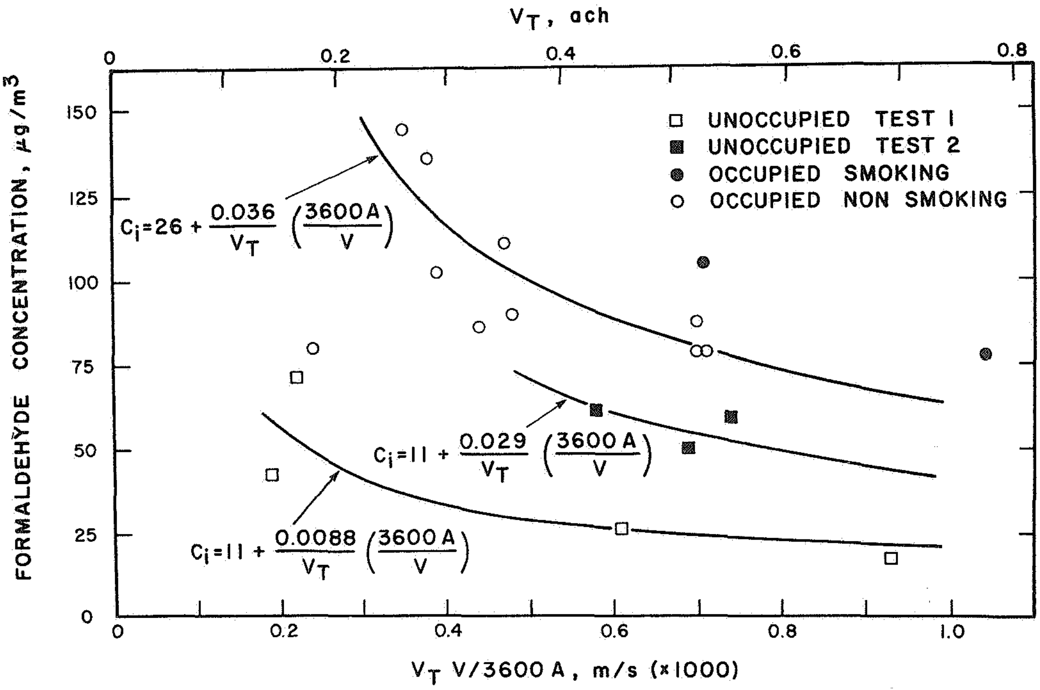

Fig. 1. Indoor formaldehyde concentration vs air flow rate for four test cases (Ref. 1)

Conversely, the study demonstrated that pollutant concentration measurements in the absence of ventilation rate data are difficult to analyze since variations in concentration levels could be caused by variations in pollutant source strengths and/or ventilation rates.

This paper is intended to outline the methodology of the indoor pollutant measurement program and discuss the implications of the data on the design of heating and ventilating systems for housing. This data base may also be of use to health professionals and policymakers who must assess the potential health risks of exposures to indoor pollutants.

For the purposes of the paper, ventilation air will refer to outdoor air introduced into the building via infiltration or mechanical means. Circulation air will refer to air moving within the building enclosure due to the action of a central forced-air distribution system.

3. Description of the Houses

All of the houses examined in this study were new, wood-frame single-family residences containing glass fibre insulation. The cast-in-place concrete basements were insulated on the interior using wood studs and glass fibre batts.

The houses in Group A were located in Pinawa, Manitoba and Winnipeg, Manitoba and were built by one contractor using similar construction materials and techniques. The above-grade walls were constructed using the double-stud technique.[2] Heat recovery ventilators (HRV) were used to supply outside air and circulate air within the houses. The units had interlocked supply and exhaust fans with the ON/OFF operation controlled by a humidistat. The exhaust air was removed (via ductwork) from the kitchen and bathroom. The outside air was supplied into the centre of the basement and allowed to migrate through the house. Floor registers were cut through the main floor to facilitate air movement between the main floor and basement. Electric baseboard heaters (convective) were used for space heating.

The houses in Group B were located in Pinawa, Manitoba but were built by a different contractor than those in Group A. The above-grade walls were conventional single-stud. All other construction materials and techniques were similar to those used in the Group A houses. Group B had electric forced-air heating systems (20-kW input) with ducted supply air into every room and two centralized main floor return air grilles. Outdoor air was supplied via a 125-mm diameter duct connected to the return air plenum. The single-speed furnace fan (≈400 L/s) operation was controlled by heating demand.

Details on the houses are given in Table 1.

4. Experimental Procedure

Airtightness measurements[3] were taken for all of the house envelopes. This involved depressurizing the house using an exhaust fan and measuring the air flow, Q(L/s), and corresponding values of the differential pressure across the building envelope, ΔP(Pa). Values for the flow coefficient, $C(L/s \cdot m^2 (Pa)^n)$, and flow exponent, n (dimensionless), can then be calculated using the expression:

$$Q = CA\ (\Delta P)^n \tag{2}$$

where A = area of the building envelope (m^2).

The Group A houses were extremely airtight, having a group average induced air leakage of 0.25 air change per hour (ach) @50 Pa with

Table 1. Basic House Data

	House Code	Year of Construction	Construction Style	Volume (m^3)	Total Floor Area Excluding Basement (m^2)	Pressure Test Result Q/V(ach @ 50 Pa)	Age of Furniture
Group A	2	82	Bungalow	465	91.7	0.18	none
	3	82	Bungalow	465	91.7	0.14	none
	4	82	Bungalow	465	91.7	0.26	none
	5	82	Bungalow	465	91.7	0.16	2-5 yr
	6	N/A	Bungalow	465	91.7	0.17	none
	7	82	Bungalow	465	91.7	0.15	N/A
	8	82	Bungalow	465	91.7	0.19	none
	17	81	1½ Storey	513	92.6	0.25	new
	18	81	Bungalow	465	91.7	0.22	3 yr
	19	82	Bungalow	455	91.0	0.67	2 yr
	20	83	Split Level	374	76.9	N/A	2-5 yr
	21	81	Bungalow	465	91.7	0.20	3 yr
	22	82	Split Level	373	75.1	0.19	2 yr
	23	82	Bungalow	465	91.7	0.21	2 yr
	24	81	1½ Storey	513	92.6	0.27	3 yr
	25	N/A	Bungalow	465	91.7	0.25	2 yr
	26	82	Bungalow	465	91.7	0.32	2-5 yr
	27	83	Split Level	304	59.3	0.39	new
	28	N/A	Bungalow	465	91.7	0.23	2-5 yr
	29	81	Bungalow	465	91.7	0.15	new
	30	81	Bungalow	465	91.7	0.35	2 yr
	31	N/A	Bungalow	465	91.7	0.27	N/A
	32	N/A	Bungalow	465	91.7	0.28	2 yr
	33	N/A	Bungalow	465	91.7	0.24	N/A
	34	81	1½ Storey	513	92.7	0.49	3 yr
	35	81	Bungalow	465	91.7	0.16	new
Group B	9	82	Bungalow	477	95.6	N/A	N/A
	10	82	1½ Storey	452	102.8	1.61	N/A
	11	N/A	Bungalow	507	102.1	1.23	N/A
	2	82	Bungalow	545	110.2	1.54	N/A
	13	82	Bungalow	477	95.6	1.54	2 yr
	14	82	Bungalow	545	110.2	1.95	N/A
	15	82	1½ Storey	452	102.8	2.12	none

a standard deviation of 0.12. For Group B, the average air leakage test value was 1.67 ach @50 Pa with a standard deviation of 0.32. Data for the individual houses are given in Table 1. The tests were conducted with all intentional envelope openings (doors, windows, air intake and exhaust ducts) blocked.

Two separate sets of HCOH and ventilation measurements were taken. One set (Test 1) was taken in December 1983 and the second (Test 2) in September 1984. The data for Test 1 and 2 are presented in Tables 2 and 3, respectively.

Formaldehyde levels were measured in the living room and master bedroom using Dupont C-60 dosimeters exposed for approximately seven days. During Test 2, outdoor HCOH levels were measured at five representative locations.

Elapsed time meters were installed to monitor the ON time of the interlocked HRV fans. The HRV air flow rates (supply and exhaust) and the outside air flows to the electric furnaces were measured using a heated probe anemometer traverse. At the beginning and end of the HCOH testing, the indoor air temperature and relative humidity were estimated using an aspirating psychrometer. Interviews were conducted with the household occupants to determine occupancy, smoking habits and non-building-related pollutant sources.

Outdoor air temperature and wind speed data were taken from Environment Canada[4] summaries.

5. Analysis of Data

The total ventilation rate (V_T) for the Group A houses was calculated as:

$$V_T = V_M + V_I \qquad (3)$$

where V_M = time-averaged mechanical ventilation flow rate (ach)
V_I = infiltration flow rate (ach).

For the Group A houses, V_M was calculated by dividing the total volumetric air flow rate through the HRV during the test (total running time X average duct air velocity) by the total test time. In most cases, the supply and exhaust air flows through the HRV were not balanced, so the larger of the two values was used. This would normally result in a mechanically induced pressure difference which would upset the infiltration. However, since the initial calculated values of V_I were relatively small, no attempt was made to correct them. The value of V_M for the Group B houses was calculated by multiplying the furnace ON time by the outdoor air flow rate with the furnace fan ON (35 L/s) and dividing by the total test time. The furnace ON time was approximated as the total measured furnace electrical energy consumption (kWh) divided by the rated heat output (20 kW).

Shaw's[5] method was used to calculate the infiltration rate (V_I) using the value from the fan depressurization test.

The winter values were calculated for Type 1 infiltration (temperature-driven) data using the expression:

$$V_I = 0.32CA\,(\Delta T^n)/V \qquad (4)$$

where V = house volume (m^3)
ΔT = average indoor/outdoor temperature difference (°C).

The summer values assume Type 2 infiltration (wind-driven) and were calculated as:

$$V_I = \frac{0.76\ CA\ v^n}{V} \qquad (5)$$

where v = wind speed (m/s).

The values for V_T are given in Tables 2 and 3. The summer values of V_T will not represent the total ventilation rate since windows were frequently opened.

The average of the living room and bedroom indoor air HCOH levels for the Group A houses are shown in Figs. 2a and 2c. Figs. 2b and 2d show the distribution of the average indoor HCOH concentration for the Group B houses.

Table 2. Test 1 (Winter) Data

	HOUSE CODE	TEMP (°C)	RH (%)	V_T (ach)	LR HCOH (ppm)	BR HCOH (ppm)	AV HCOH (ppm)	(BR-LR)/LR (% diff.)	OCCUPANCY (Adults/ Children)	RADON (pCi/L)
Group A	2	22	29	0.51	0.035	0.046	0.041	31.4	0	6.71
	3	14	57	0.16	0.057	0.058	0.058	1.8	0	22.74
	4	20	34	0.55	0.039	0.058	0.049	48.7	0	7.20
	5	20	34	0.18	0.061	0.066	0.064	8.2	2/0	6.66
	6	21	31	0.42	0.051	0.049	0.051	-3.9	0	6.92
	7	17	55	0.77	0.056	0.067	0.062	19.6	0	5.58
	8	19	49	0.01	0.109	0.131	0.120	20.2	0	25.02
	17	21	48	0.29	0.074	0.089	0.082	20.3	3/1	2.83
	18	N/A	N/A	N/A	N/A	N/A	N/A	N/A	2/2	3.53
	19	23	38	N/A	0.093	0.078	0.086	-16.1	2/0	2.20
	20	20	32	0.40	0.042	0.044	0.043	4.8	2/4	1.71
	21	21	33	0.35	0.063	0.115	0.089	82.5	2/3	8.75
	22	23	46	0.33	0.069	0.069	0.069	0	2/0	2.61
	23	19	45	0.28	0.103	0.114	0.109	10.7	2/0	3.67
	24	N/A	N/A	0.20	N/A	N/A	N/A	N/A	2/0	3.33
	25	N/A	N/A	0.26	N/A	N/A	N/A	N/A	2/2	3.04
	26	22	48	0.61	0.123	0.124	0.124	0.8	2/0	1.69
	27	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1/0	2.63
	28	20	46	0.53	0.089	0.079	0.084	-11.2	2/2	3.37
	29	23	42	0.52	0.066	0.074	0.070	12.1	2/1	0.91
	30	22	41	0.52	0.054	0.071	0.063	31.5	2/1	6.91
	31	20	52	0.36	0.067	0.076	0.072	13.4	2/2	2.73
	32	21	46	0.53	0.051	0.075	0.063	47.1	2/1	4.15
	33	22	38	N/A	0.060	0.074	0.067	23.3	2/2	3.14
	34	22	48	0.26	0.112	0.119	0.116	6.3	4/0	0.95
	35	19	48	0.01	0.048	0.039	0.044	-18.8	2/0	2.17
Group B	9	21	55	N/A	0.061	0.065	0.063	6.6	2/0	3.31
	10	18	52	0.16	0.079	0.077	0.078	-2.5	4/1	3.59
	11	N/A	N/A	0.14	N/A	N/A	N/A	N/A	2/1	6.22
	12	21	50	0.17	0.111	0.084	0.098	-24.3	2/2	6.22
	13	20	63	0.17	0.069	0.059	0.064	-14.5	2/3	4.24
	14	23	40	0.20	0.059	0.057	0.058	-3.4	2/2	2.77
	15	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0	4.37

Table 3. Test 2 (Summer) Data

	HOUSE CODE	TEMP (°C)	RH (%)	V_T (ach)	LR HCOH (ppm)	BR HCOH (ppm)	AV HCOH (ppm)	(BR-LR)/LR (% diff.)	OCCUPANCY (Adults/ Children)	RADON (pCi/L)
Group A	2	20.6	47	0.52	0.041	0.056	0.049	36.6	0	3.08
	3	21.1	50	0.52	0.055	0.076	0.066	38.2	0	6.27
	4	20.0	52	0.26	0.034	0.032	0.033	-5.9	2/1	6.94
	5	19.7	48	0.37	0.029	0.047	0.038	62.1	2/1	3.16
	6	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0	N/A
	7	18.9	52	0.77	0.033	0.028	0.031	-15.2	2/1	1.91
	8	18.9	48	0.01	0.047	0.051	0.049	8.5	2/2	5.93
	17	20.6	51	0.39	0.048	0.067	0.058	39.6	4/0	2.02
	18	22.2	56	0.12	0.068	0.057	0.063	-16.2	2/2	2.97
	19	22.8	53	N/A	0.101	0.100	0.101	-1.0	2/0	1.07
	20	20.6	52	0.33	N/A	0.030	0.030	N/A	2/4	2.43
	21	21.1	52	0.36	0.039	0.046	0.043	17.9	2/3	4.19
	22	22.8	69	0.38	0.132	0.087	0.110	-34.1	2/0	8.57
	23	18.9	61	0.29	0.082	0.079	0.081	-3.7	2/0	2.30
	24	21.7	60	0.07	0.101	0.090	0.096	-10.9	2/0	N/A
	25	22.8	49	0.01	0.049	0.043	0.046	-12.2	2/2	6.27
	26	22.2	48	0.64	0.055	0.069	0.062	25.5	2/0	2.20
	27	19.4	38	0.33	0.045	0.068	0.057	51.1	1/0	N/A
	28	20.0	54	0.54	0.058	0.054	0.056	-6.9	2/2	4.75
	29	21.1	51	0.22	0.048	0.046	0.047	-4.2	2/1	1.42
	30	21.1	44	0.53	0.029	0.037	0.033	27.6	2/2	5.05
	31	22.2	45	0.06	0.059	0.037	0.048	-37.3	2/2	1.34
	32	22.2	42	0.01	0.038	0.047	0.043	23.7	2/1	1.27
	33	22.2	64	0.33	0.088	0.100	0.094	13.6	2/2	1.11
	34	22.2	56	0.31	0.097	0.072	0.085	-25.8	4/0	2.10
	35	20.0	60	0.01	0.066	0.062	0.064	-6.1	2/0	2.10
Group B	9	16.1	77	N/A	0.178	0.182	0.180	2.2	0	N/A
	10	19.4	53	0.08	0.054	0.048	0.051	-11.1	4/0	5.60
	11	20.0	71	0.05	0.106	0.093	0.100	-12.3	2/1	6.27
	12	19.4	53	0.06	0.115	0.038	0.077	-67.0	2/1	7.95
	13	19.4	57	0.06	0.037	0.036	0.037	1.4	2/2	2.41
	14	20.0	50	0.10	0.086	0.130	0.108	51.2	2/1	2.07
	15	18.6	59	0.10	0.185	0.235	0.210	27.0	0	9.96

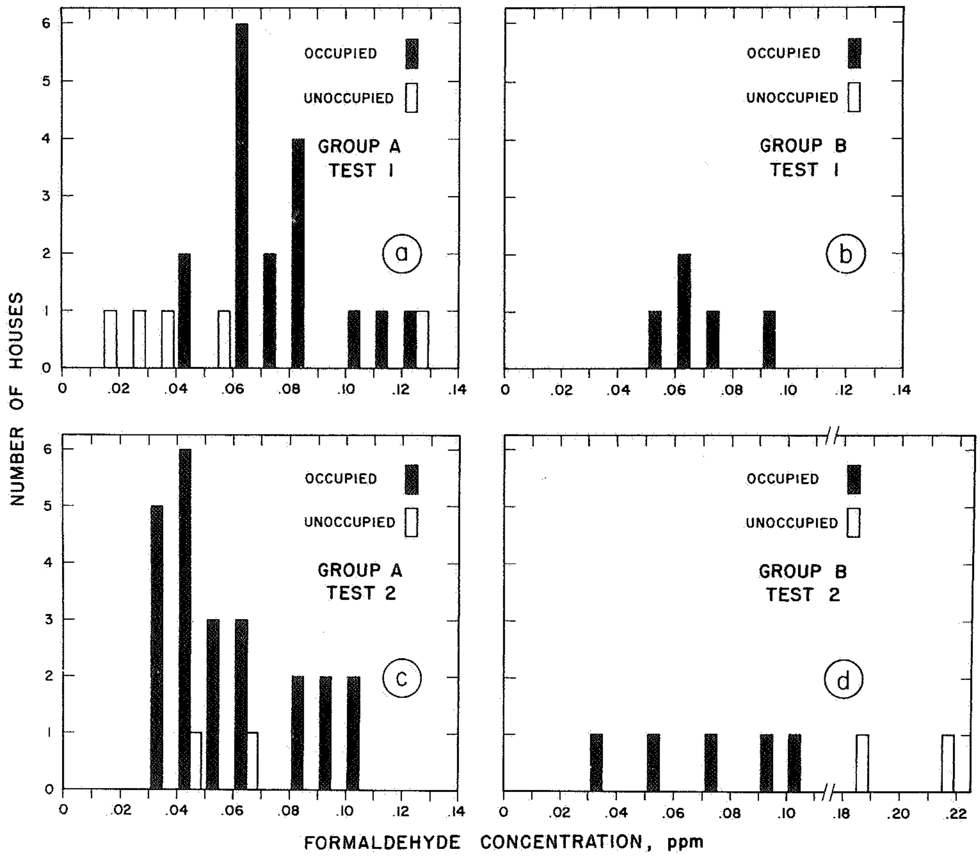

Fig. 2. Distribution of the average indoor formaldehyde levels

The distribution of pollutant levels in the houses was also examined by comparing the percentage difference between the bedroom and living room HCOH concentrations. The results are shown in Figs. 3a (Group A) and 3b (Group B) for Test 1, and Figs. 3c and 3d respectively for Test 2.

6. Discussion

To date, Canada does not have an accepted standard that defines the maximum allowable HCOH concentration in residences. For the purposes of this discussion, 0.1 ppm[6] will be used as an arbitrary standard.

The HCOH sources in the houses can be divided into two major areas: building sources and occupant sources. The major building sources are assumed to be urea formaldehyde resin bonded particle board construction materials including:

1) 9.5-mm subfloor
2) formica-covered counter tops
3) kitchen cupboards and vanities
4) closet shelving.

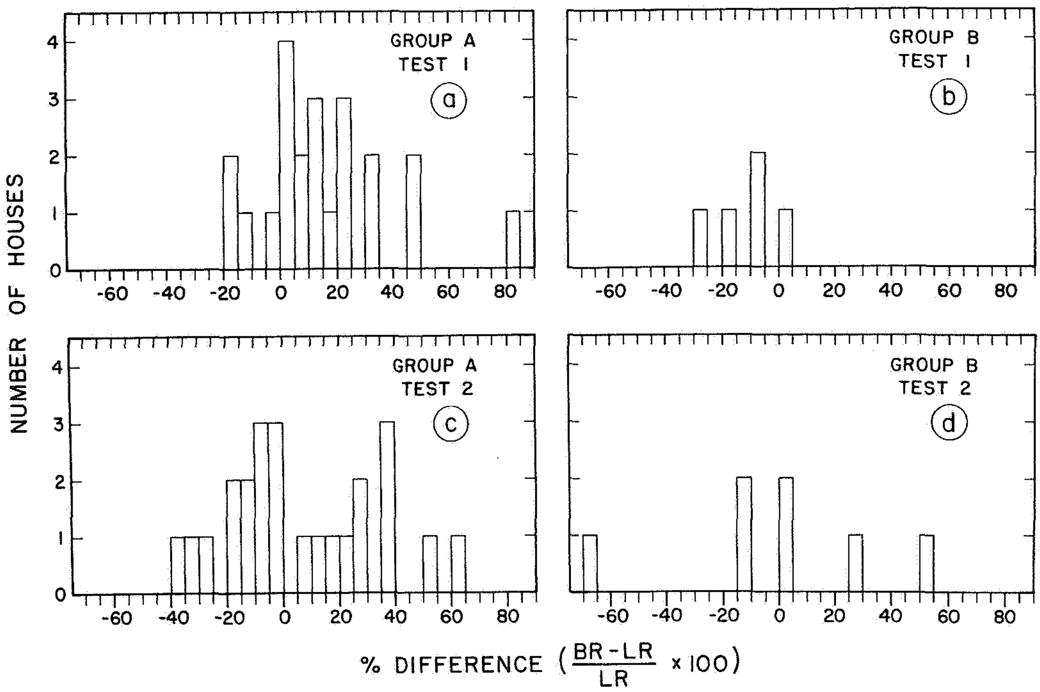

Fig. 3. Distribution of the percentage difference of formaldehyde levels between bedrooms and living rooms

All of the houses used similar quantities of these materials. The occupant-related sources included:

1) furnishings constructed with particle board
2) smoking
3) miscellaneous materials such as paper, textiles and cleaning products.

To establish a relationship between the HCOH level and the ventilation rate for a single house, a series of measurements of the HCOH concentration and ventilation rate would be required. An alternate analysis of these winter data[1] (Fig. 1) showed that the single individual house measurements could be grouped as having been taken from one "average house". The high correlations (correlation coefficient ≥ 0.8) obtained when an equation of the form of Equation 1 was fitted to the data suggested that (for a given occupancy load) the net apparent HCOH source strengths within the houses were similar. The major HCOH sources were the building materials ($\dot{N}$ = 0.029 μg/s·m^2). The study showed that normal occupancy (non-smokers) increased the net apparent HCOH source strength by approximately 20% to $\dot{N}$ = 0.036 μg/s·m^2. Hence, for this pollutant, developing ventilation^{m}criteria based on predicted source strengths seems to be a valid approach.

The average ventilation rates and HCOH levels for each of the groups (occupied and unoccupied) are given in Table 4.

Table 4. Average Ventilation Rates and Indoor HCOH Levels For Tests 1 and 2

	Winter (Test 1)		Summer (Test 2)	
House Group	V_T	HCOH (ppm)	V_T	HCOH (ppm)
A (unoccupied)	0.40	0.064	0.48	0.058
A (occupied)	0.35	0.078	0.29	0.060
B (unoccupied)	N/A	N/A	0.10	0.210
B (occupied)	0.18	0.075	0.07	0.075

The distribution of the average HCOH concentration in the Group A houses for December 1983 (Fig. 2a) shows that only three occupied and one unoccupied house exceeded the 0.1-ppm level. The 17 occupied houses had an average ventilation rate of 0.4 ach and a mean indoor HCOH level ($\bar{x}$) of 0.078 ppm. For two of the three occupied houses with HCOH levels above 0.1 ppm (houses 23 and 34), increased operation of the HRV fans (see Fig. 1) could reduce the levels to below 0.1 ppm. Both houses had average HCOH levels only slightly greater than 0.1 ppm with V_T values below 0.3 ach. The other occupied house (house 26) had a level of 0.12 ppm with the HRV operating continuously at maximum flow (0.6 ach). For this house, the mechanical ventilation system was inadequate to control the indoor level below 0.1 ppm. In the case of the unoccupied house (house 8), the HRV fans were shut off.

The Group B houses (Fig. 2b) maintained relatively low HCOH levels during the December 1983 test period ($\bar{x}$ = 0.075 ppm). All of the houses were occupied and none of the indoor levels exceeded 0.1 ppm.

For the winter test, the average HCOH concentration in the occupied Group B houses was comparable with that of the occupied Group A houses. However, the calculated ventilation rate was less than one-half. Since the net HCOH source strength should be similar for both groups, the initial comparison would indicate an inconsistency with Equation 1. The most likely explanation lies with the value of the mixing factor K. The forced circulation Group B houses would have a larger mixing factor than the Group A houses.

The summer (September 1984) values for the occupied, Group A houses showed a general reduction in the indoor levels ($\bar{x}$ = 0.060 ppm) when compared to the previous December 1983 data. The average mechanical ventilation rate was also lower, suggesting that additional ventilation must have been supplied via undocumented window and door openings. In this group, two occupied houses had average indoor HCOH levels marginally above 0.1 ppm, although increased operation of the HRV could have reduced the levels. The relationship between the indoor HCOH level and the ventilation rate did not change for the unoccupied Group A houses (this assumes no occupants, hence no window or door openings), indicating that the net apparent source strength of the building had not changed appreciably.

In contrast, the September 1984 test showed acceptable levels in the occupied houses ($\bar{x}$ = 0.075 ppm) but high levels (average HCOH = 0.18 and 0.21 ppm) in the two unoccupied houses where windows were not opened. These data are consistent with the intuitive observation that during the cold weather monitoring period the furnace was running frequently and drawing in fresh air. In the summer, the furnace fans would not be operating; hence the primary source of ventilation would be window openings. In addition, the stack effect is reduced in the summer.

These data suggest that while both systems (passive or mechanical) can provide adequate ventilation for the control of indoor HCOH levels, properly maintained mechanical systems do not require deliberate occupant input and may, therefore, be more reliable. In cases where occupants of houses without mechanical ventilation systems do not use window openings to introduce passive ventilation (such as air-conditioned houses), indoor HCOH levels could become excessive.

During the winter (Test 1) the Group A houses had air circulation rates controlled by the air flow of the HRV. When ON, typical HRV flow rates were ≈0.7 ach; however, ON/OFF control reduced the time-averaged rates (see Tables 2 and 3). The absence of a supply air ductwork system further reduced the complete circulation of the available ventilation air. The furnace fans in the Group B houses had circulation capacities of between 2.6 and 3.0 ach when ON.

In the Group A houses (Test 1), 17 out of 22 had bedroom levels higher than living room levels (Fig. 3a). In contrast, only one of the five Group B houses (Fig. 3b) had a bedroom level higher than the living room level.

During the summer (Test 2) when window openings were extensively used by all of the house groups, the Group A houses had 11 out of 24 cases where the bedroom level was higher than that of the living room (Fig. 3c). Similarly, four out of seven of the Group 2 houses had elevated bedroom levels (Fig. 3d).

Although the pollutant level in a space is a function of the source strength and the air exchange rate, similarities in construction materials and occupancy loadings suggest that during the winter, poor air circulation in the Group A houses may be responsible for the elevated bedroom levels. During the summer, window openings increased the distribution of the ventilation in the Group A houses and the winter pattern of consistently high levels in the bedrooms was eliminated.

It is obvious from these data that difficulties in analysis arise when a one-compartment model is used for ventilation and a two-compartment model is used for measurements. In general, however, uniform pollutant levels throughout a house would be expected if the air circulation rate were relatively high, as in the case of window openings or furnace fan operation. Conversely, in areas with uneven ventilation rates, stratified levels of pollutants should exist.

7. Conclusions

Although firm conclusions cannot be drawn from this small data set, a number of observations can be made:

- the only average HCOH levels substantially above 0.1 ppm were observed in unoccupied passively ventilated houses (Group B). This suggests that the mechanical ventilation systems used in the Group A houses were providing reliable indoor HCOH control. Further, since natural infiltration forces are minimal in summer, deliberate window openings are required to provide adequate ventilation in passively ventilated houses.

- houses with low air circulation rates can have significant interior variations in pollutant concentrations. For the group A houses, 77% of the houses had bedroom HCOH levels higher than those in the living room.

8. References

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