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Improvement of indoor air quality in four problem homes

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Abstract

The occupants of six houses suffered from symptoms which improved upon leaving their houses. In a previous study, tests were conducted in these six houses to measure various physical parameters related to their indoor environments. Four of these houses were subsequently renovated to improve indoor air quality. Tests were repeated on the four houses to assess the effectiveness of the applied remedial measures. The post-renovation tests which were identical to the pre-renovation tests, included measurements of air temperature, relative humidity, ventilation rates, air distribution patterns, levels of carbon dioxide, concentrations of formaldehyde, and concentrations of volatile organic compounds.

This paper describes the remedial measures applied to these houses. Also presented is a comparison of the ventilation conditions, and concentrations of chemical contaminants in the houses before and after the renovation. Crown Copyright © 1998 Published by Elsevier Science Ltd. All rights reserved.

Keywords: Indoor Air Quality; Ventilation; Volatile Organic Compounds; Measurement; House; Indoor Contaminants; Renovation

1. Introduction

In recent years, there has been an increased number of homeowners seeking assistance in identifying indoor air quality problems in their homes. They suspect that their houses are causing or aggravating their health problems. Usually, one member of the family is affected, while other members appear to be unaffected. They report feeling better outside their houses, and when they leave the house for an extended period, their symptoms diminish.

Six such houses, identified as Houses I through VI, were tested to assess their indoor air quality conditions [1, 2]. After the test, four of these houses, i.e. Houses I, II, III, and VI, were renovated to improve air quality. Tests were repeated on these four houses to assess the effectiveness of applied renovation measures.

The results of the indoor air quality measurements conducted in these houses before renovation are presented in a companion paper [3]. This paper describes the renovation measures applied in these houses and presents the after-renovation measurement results. A comparison between the pre- and post-renovation results was made to assess the applied renovation measures. The results were also compared with that measured from a reference house, House R2, which was specially designed and constructed to provide an acceptable indoor environment for a family with several members who suffer from asthma and environmental hypersensitivity. The comparison will provide some indication of the adequacy of the applied renovation measures. A summary of key characteristics of each of the four test houses and the reference house is given in Table 1.

2. Methods

Similar to the pre-renovation test, the measurements included air temperature, relative humidity, ventilation rate, air distribution, and concentrations of chemical contaminants. Measurements were conducted on all houses to determine their ventilation performance and the levels and sources of chemical contaminants. The measurement methods and procedures used in this study were identical to those used in a previous study which was conducted to assess the indoor air quality conditions of these houses before they were renovated [2, 3]. The following is a brief description of the methods.

2.1. Performance of heating and ventilating systems

For each house, the performance of the heating and ventilating system was assessed on the basis of air change

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Table 1
Test house details, pre-renovation

House ID no.	House location	Number of occupants	Test date (pre-renov)	Construction details: House style	Age, yrs	~Sq ft (m^2)	Exterior	Basement	Garage	Heating type	HRV
I	Ottawa, Ontario	1	Mar–May, 94 (Apr, 93)	2-Storey	50	1400 (130)	Brick and wood siding	Half + crawlspace	No	Electric furnace	No
II	Fredericton, New Brunswick	0	Nov, 93 (Apr, 93)	2-Storey	2	3000 (280)	Wood siding	Full	Double, attached	Electric furnace	Yes
III	Kanata, Ontario	0	Jun, 93 (May, 93)	2-Storey townhouse	3	1100 (100)	Vinyl siding/brick	Crawlspace	No	Gas	No
VI	Ottawa, Ontario	1–4	Oct, 94 (Mar, 94)	Split	25	3000 (280)	Stone/brick/wood siding	Full	Double, attached	Radiant hot water	No
R2	Carp, Ontario	3–5	Oct, 93	Bungalow	8	1800 (165)	Stucco	No	No	Electric furnace	Yes

rates, air distribution patterns, air temperature, and re tive humidity in the occupied areas [4]. Except for Hou VI which was heated with a hot-water heating system, houses had a forced-air heating system.

2.1.1. Air change rate.

Air change rates were measured using the tracer g decay method. During the test, all windows and exteri doors were tightly closed, and all exhaust fans turned o Interior doors were opened prior to injection of sufficie SF_6 into the return air duct. After allowing 30 min f mixing, air samples were taken from the return air du for 1 to 2 h, at approximately 10 min intervals. For Hou VI, the tracer gas was injected into four locations with the house (e.g. living room, family room, upstairs ha and recreation room). The air from the four injectic locations was pumped continuously to a manifold whe the samples were taken. Mixing fans were used to assi with the mixing of the tracer gas with the room ai Weather data at the time of each air change test we obtained from the local weather office.

2.1.2. Air distribution.

The tracer gas technique was used to measure the a distribution patterns. The test involved the injection of small amount of SF_6 into the main return air duct an the measurement of the tracer gas concentrations, at five min intervals, at several locations in the house. The mea sured tracer gas concentrations of each sampling locatio were then plotted against time. The length of time afte the tracer gas injection required for the concentrations a all sampling locations to reach approximately a sing level was used to estimate the mixing time of the ver tilation air with the room air. A mixing time of 60 min considered to be acceptable for houses with a forced-a heating system [4]. Figure 1 shows a typical example o such a plot. During the test, the furnace fan was set t run continuously but all kitchen and bathroom exhau fans were turned off. The interior doors in the house wer closed, and all windows and exterior doors were close and locked. As House VI did not have a forced-air hea ing system, two special tests were conducted instead o the above test. The tracer gas was injected either in th garage or the furnace room and the tracer gas co centrations at several locations in the house wer measured. The detection of the tracer gas within th house indicated that the air from the injection locatio had reached the sampling location within the house.

2.1.3. Air temperature/relative humidity.

Air temperatures and relative humidities at sever locations in each house were monitored continuousl The instruments were calibrated in the laboratory again reference temperature and humidity apparatus. Th specified accuracy is ± 1.0°C and ± 3% for temperatur and RH, respectively. The calibration was checked an

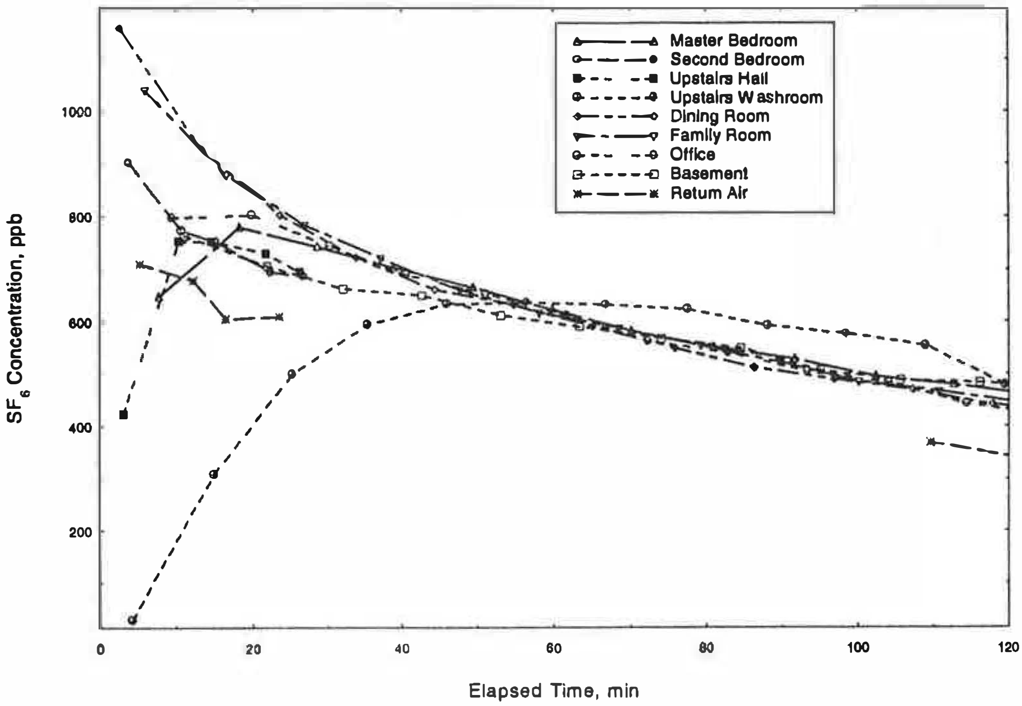

Fig. 1. Air distribution test: House II, POST-renovation.

adjusted daily at the test house, during the measurement period.

2.2. *Chemical contaminants*

Measurements of chemical contaminants included carbon dioxide (CO_2), formaldehyde (HCHO), and volatile organic compounds (VOCs).

2.2.1. *Carbon dioxide.*

CO_2 concentrations were monitored continuously at several locations. Samples were pumped from the sampling locations to the CO_2 analyzer. The analyzer's calibration was checked daily using certified high purity air and CO_2/air mixtures. The specified repeatability and noise of the analyzer were both 1% of full scale. Zero and span drifts were also $\pm 1\%$ of full scale per day.

2.2.2. *Formaldehyde.*

Spot checks of formaldehyde concentrations at locations throughout the test houses were conducted using a portable analyzer with an electrochemical voltammetric sensor. This unit has a full scale range of 1 ppm formaldehyde. Its specified minimum detectability and accuracy are 0.01 ppm, and ± 0.02 ppm, respectively.

2.2.3. *Volatile organic compounds (VOC).*

For measuring the VOCs, air samples at the houses were collected at various locations in the house, using three-layer glass sorption tubes packed with silanized glass beads, Tenax and synthetic charcoal and analyzed later at the laboratory. The sampling flow rate and sampling time were 250 ml/min and 20 min, respectively. VOC sampling was conducted concurrently with air change measurements so that the house air change rate at the time of the VOC sampling was known.

The air samples were thermally desorbed using a commercially available thermal desorption unit which has two sequentially packed three-layer traps to pre-concentrate the analyte. A small portion (3%) of the desorbed stream was analyzed by a flame ionization detector (FID) calibrated against a cyclohexane standard prepared in nitrogen for total VOC (TVOC) content. The remaining stream was directed into a GC equipped with DB-5 capillary column (a 60 m long, 0.32 mm I.D. and 25 μm film thickness) and a quadruple mass spectrometer (MS) for analysis. Individual VOCs were identified by comparing corresponding mass spectrum of peaks with the standard spectra in the National Bureau of Standards library that were installed in the instrument. The identification was supported by comparing the normalized retention time (RT) to the intra-laboratory set of well established RT values. Single ion extraction was performed when needed in search of specific compounds [5].

3. Results

A summary of the identification codes, test dates, locations, occupancy, construction details, and heating/ventilating systems for the test houses is given in Table 1. Table 2 describes the occupants affected, possible sour-

Table 2
Summary of suspected problem(s)

House	Occupant(s) affected	Suspected problem(s)	Remediation measures taken
I	Single occupant, very sensitive	(a) mold problems in basement and crawlspace (b) possible offgassing from basement dirt floor	(a) dirt floor in basement covered (poured concrete, polyethylene sheet crushed stone in crawlspace) (b) HRV unit installed (c) carpets replaced with hardwood flooring (d) Main supply and return ducts modified by turning the furnace to horizontal position
II	Both husband and wife became ill in house, no previous history of illness	(a) off gassing from carpet and flexible plastic ducting (b) major leaks in ducts (c) possible moisture problems (d) some pesticide residues	(a) flexible plastic ductwork replaced with metal ducts (b) Leaking ductworking replaced (c) carpeting replaced with ceramic or hardwood flooring (d) kitchen cabinets sealed (e) basement ceiling replaced (f) central vac unit moved to garage
III	Family of four affected; young child diagnosed with kidney cancer	(a) mold in crawlspace due to flooding each spring	(a) complete cleaning of house interior (b) ducts in crawlspace sealed (c) wet insulation in crawlspace replaced (c) access to crawlspace sealed (d) exhaust fan in crawlspace set to run continuously
VI	Middle-aged female, symptoms triggered by renovation of kitchen in 1992	(a) air leakage from furnace room and garage into occupied area (b) offgassing of particleboard kitchen cabinets (c) mold in basement	(a) sealing/caulking at garage door, front entrance and dryer exhaust (b) family room carpeting replaced with hardwood flooring (c) new countertop in kitchen (d) boiler and gas water heater replaced with sealed combustion unit

ce(s) of the problems, and applied remedial measures in each test house. Table 3 gives a summary of the results, excluding the VOCs which are presented in Table 4. For comparison, the pre-renovation test results were also included in Tables 3 and 4 [2]. A brief discussion on the results, as presented in Tables 1 through 4 is given below.

3.1. House I

House I is a 50 year-old, 130 m^2 two-storey detached house with a rubble stone foundation basement, located in a residential district. The basement is divided into two parts: a 1.5 m-height portion with an uncovered dirt

Table 3
Summary of measured data

House	Outdoor temp. °C	Indoor temp. °C	RH %	Wind km/h	Ventilation rate ach	Mixing time min	Formaldehyde ppm	CO_2 ppm
I-Pre	9.9–17	19–25	40–73	20–24	0.52–0.72	60	0.01–0.02	460–1350
I-Post	3.7–14.5	20–25	20–30	6–26	0.66–0.99	45	0.01–0.02	440–660
II-Pre	5–6	21–23	32–40	22–45	0.34–0.37	30	0.04–0.05	340–600
II-Post	8.8–10	19–21	35–40	11–15	0.28–0.30	30	0.03–0.04	410–660
III-Pre	18–25	20–27	40–50	9–28	0.38–0.65	45	0.04–0.07	375–600
III-Post	16–17	20–24	40–50	17–20	0.57–0.66	30	0.03–0.04	375–650
VI-Pre	−0.6–−5.2	20–25	20–29	6–13	0.73–0.81	—	0.02–0.05	360–1150
VI-Post	8–10	20–22	54	15–30	0.3–0.33	—	0.04–0.05	400–1350
R2	7–15	21–22	35–50	4–41	0.52–0.67	30	0.01–0.01	140–1700

Table 4-1
Volatile organic compounds detected in house I. Concentration in $\mu g\ m^{3}$

Compound or Group of Cmpds.	Before enovation							
	Indoor air			Head space analysis of carpet samples				
	BPM02 Living rm.	BPM04 2nd Bdrm	BPM03 basement	BPM13 Bathroom	BPM14 Upper hall	BPM15* BR's carpet	BPM17† 2nd Bdrm	BPM16 Makeup air
C3 and C4	44	11	68	13	4	25	26	41
Cl and F	181	6	22	0	0		0	0
Ethanol	16	12	16	9	0	16	7	0
Acetone	47	30	39	16	23	98	38	0
Other Ox.	0	0	0	0	0	0	0	0
Aromatic	93	38	100	12	9		38	0
C5 and C6	186	126	223	3	169		29	74
C7 and C8	212	44	279	0	13	5	19	0
C9 and C10	51	6	49	0	0		44	23
Terpenoids	0	0	0	0	0	0	0	0
C11 and C12	0	0	0	33	17	29	143	45
>C12	0	0	0	0	0	7	30	0
Other	31	17	13	24	25	0	25	0
Total	860	290	810	110	260	180	400	200

Compound or Group of Cmpds.	After Renovation							
	Indoor Air. 1st Sampling				Indoor Air. 2nd Sampling			
	BPM63 Living Rm	BPM65 2nd Bdrm	BPM62 Basement	BPM64 Outdoor Air	BPM69 Living Rm	BPM71 2nd Bdrm	BPM68 Basement	BPM70 Outdoor air
C3 and C4	3	39	3		16	0	16	0
Cl and F	28	20	116	44	0	0	0	0
Ethanol	0	0	1	0	0	0	0	0
Acetone	7	44	7	6	41	49	68	0
Other Ox.	0	0	0	0	0	0	0	0
Aromatic	3	5	4	12	24	36	10	5
C5 and C6	0	0	3	0	0	14	8	0
C7 and C8	3	18	6	4	27	0	13	27
C9 and C10	4	12	0	2	28	10	0	58
Terpenoids	0	0	0	0	0	0	0	0
C11 and C12	4	0	7	0	11	23	0	0
>C12	0	0	0	0	0	0	0	0
Other	7	1	13	13	2	19	5	30
Total	60	140	160	80	150	150	120	120

* 24 h in the chamber.
† 72 h in the chamber.

floor where the electric furnace for the forced-air heating system is located and a narrow crawl space where the dirt floor was covered with polyethylene sheeting. The single occupant of the house is a middle-aged woman whose health problems were apparently triggered by a workplace exposure to elevated concentrations of chemicals used to clean and disinfect carpets. She reported the basement of her house to be particularly irritating. Air sampling of the house before this study had showed abundant molds.

Before renovation, wood and ceramic flooring were used throughout the main level of the house. The master bedroom had wood flooring. The remainder of the second storey, including the bathroom and the stairway, was carpeted. The occupant stayed mainly in the master bedroom with the door closed and the supply air floor vents in this room sealed during the measurement period. An air cleaning device was in continuous operation in the master bedroom. At her request, no samples were taken in the master bedroom.

Major renovation measures included the modification of the main supply and return ducts in the basement by turning the existing electric furnace from its original upright position to a horizontal position. Joints in the ductwork in the basement were also sealed. A heat recovery ventilator (HRV) was installed with exhaust pick-ups located in the dining room, main floor washroom, master bedroom closet, and upstairs washroom. The plastic core of the HRV appeared to be a major source of irritation to the occupant and was subsequently replaced with a stainless steel core. The outdoor air intake for the HRV was located at the front of the house, beside the main entrance. Carpeting was removed throughout the second floor and from the stairs. Hardwood flooring was installed in the upper hallway and second bedroom. Ceramic flooring was installed in the bathroom. A cement floor was laid in the main part of the basement.

As shown in Table 3, before renovation, the measured air temperatures in the occupied area varied between 19 and 25°C. Relative humidities ranged between 40% and 73%. The measured air change rates were 0.52 and 0.72 ach. The ventilation air in the house was well mixed with the indoor air with a mixing time of approximately 60 min. After renovation, the air temperatures were between 20 and 25°C but the relative humidity had decreased to levels typically observed in other houses (i.e. between 20 and 30%). With the installation of a HRV after the renovation, the air change rates (ventilation rates) were between 0.66 and 0.79 air changes per hour (ach) with the HRV in operation at low fan speed. The air change rate increased to 0.99 ach with the HRV running at medium speed. The mixing time was improved to 45 min. The results indicate that the new HRV and the modification of the main supply and return ductwork improved the air change rate and the air distribution of the house. The lower relative humidity levels observed after renovation would probably be a result of the new cement floor installed in the basement.

Before renovation, the formaldehyde levels in the house ranged between 0.01 and 0.02 ppm and the CO_2 concentrations were between 460 and 1350 ppm. After renovation, the formaldehyde levels were not changed but the CO_2 concentrations were between 440 and 660 ppm. Figure 2 shows, as an example, the CO_2 profiles measured in this house before and after renovation.

The pre-renovation TVOC levels were 0.29 mg/m^3, 0.86 mg/m^3, and 0.81 mg/m^3 for the bedroom, living room, and basement, respectively. The post-renovation TVOC concentrations dropped significantly to 0.14 mg/m^3, 0.06 mg/m^3, and 0.16 mg/m^3 for the bedroom, living room and basement, respectively (1st sample). Table 4-I shows that the concentrations of all identified VOCs also decreased significantly to the extent that no identified VOCs had a concentration greater than 0.12 mg/m^3. To ensure that the post-renovation results were correct, the sampling was repeated (2nd sample). There were some differences in the concentrations of some VOCs, but the average TVOC levels in the house for the two sets of samples were similar.

A comparison between the before and after renovation results indicate a significant reduction in some VOCs such as aromatic (benzene, toluene and xylene) compounds and C5 through C8 hydrocarbons (pentane to octane). As this house had an oil furnace and an oil tank in the basement, some of the contaminants originated from heating oil might have been absorbed in the dirt floor of the basement. The new cement floor would be very effective in preventing these contaminants from re-emitting into the basement. The removal of the carpet would also help to reduce the levels of some compounds.

Also, a comparison of the post-renovation individual VOC concentrations between this house and House R2 (Table 4-R2) indicates that even though there were several VOCs in this house that were not detected in House R2, the concentrations were lower than 0.012 mg/m^3.

3.2. House II

This is a 279 m^2 two-storey detached house with a basement located in a new subdivision. An attached two-car garage has a door providing direct access to the house. It is heated by a forced air electric furnace fitted with an electrostatic air cleaner. It also has a HRV whose supply air is ducted to the return air of the furnace, but a short section of this duct was removed so that a portion of the HRV supply air spilled into the furnace room. A flexible plastic duct was used to connect the outdoor air intake to the HRV. Exhaust pick-ups for the HRV are located in each bathroom and in the basement kitchen.

In addition to storage and furnace rooms, the basement also contains an apartment area with a full kitchen, bedroom, living area and large bathroom. The supply air duct behind the finished ceiling in the basement bedroom had numerous holes cut along its length. As a result, air leaked continuously into the ceiling cavity. Gypsum wallboard in the ceiling of this room was found to have a pink discolouration possibly due to yeast growth. The space between floor/ceiling joists in the furnace room were filled with exposed fiberglass pink insulation. A carbamate pesticide had been applied in the basement.

The original owners were a retired couple who experienced no signs of problems with their previous home. About two years after they moved in, they had to move out of the house. The husband was the first to develop signs of hypersensitivity and eventually could only tolerate brief visits to the house. He reported that the master bedroom, family room and office were particularly irritating. His wife eventually developed a less severe sensitivity to the house. The house was unoccupied during the test periods.

Major renovation measures included the replacement of carpeting in the family room, office, and basement with ceramic tiles. Carpeting was removed and hardwood flooring installed in the upstairs bedrooms. The flexible plastic ducting of the HRV was replaced with metal ducting. The fiberglass insulation was removed from the furnace room ceiling. The central vacuum unit originally installed in the furnace room was moved to the garage.

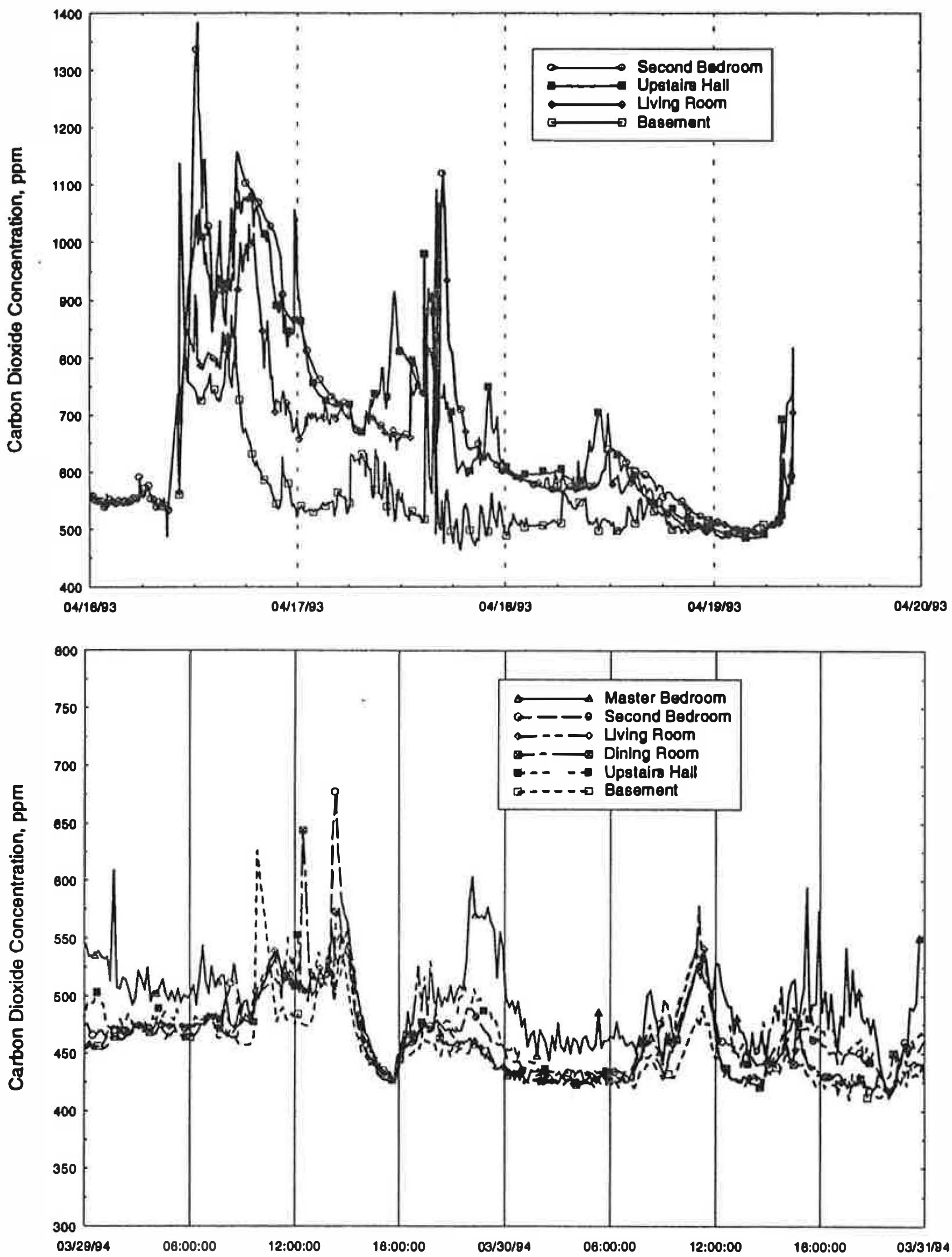

Fig. 2. (a) Carbon dioxide observations, Hose I, PRE-renovation. (b) Carbon dioxide observations, Hose I, POST-renovation.

The supply duct and gypsum wallboard in the basement ceiling was replaced.

The air temperatures in the occupied area before renovation, were between 21°C and 23°C, and the relative humidity ranged from 32% to 40%. After renovation, the air temperatures decreased slightly to between 19 and 21 C and the relative humidity ranged from 35 to 40%. The measured air change rates (ventilation rates) were between 0.34 and 0.37 ach, and between 0.28 and 0.3 ach, before and after renovation, respectively. The ventilation air was well mixed with the indoor air. The mixing time for both the pre- and post-renovation periods was about 30 minutes. The results were expected because no special effort was made to increase the air change rate.

For the pre-renovation period, the CO_2 concentrations varied from 375 ppm to 600 ppm and the formaldehyde levels were between 0.04 and 0.05 ppm. For the post-renovation tests, the CO_2 concentrations varied from 475 ppm to 660 ppm and the formaldehyde levels were between 0.03 and 0.04 ppm after renovation.

The measured TVOC levels before renovation were 0.66 mg/m^3, 0.62 mg/m^3, 0.85 mg/m^3, and 0.7 mg/m^3 for the family room, bedroom, basement, and office, respectively. The corresponding values for the post-renovation period were 0.49 mg/m^3, 0.5 mg/m^3, 0.5 mg/m^3, and 0.41 mg/m^3. Table 4-II show the concentrations of various VOCs in the indoor air. The results indicate that the renovation was very successful in eliminating all identified VOCs, except for acetone, C9 and C10, and C11 and C12 compounds. The renovation measures included the removal of carpeting and flexible plastic ducts. As indicated in Table 4-II, before renovation, almost all VOC compounds identified from the carpet and the plastic duct samples were detected in the indoor air of this house. The concentrations of these three VOCs were lower than 0.2 mg/m^3. A comparison of the individual VOCs between this house and House R2 (Table 4-R2) indicates that all identified VOCs that existed in this house after renovation were also detected in House R2.

3.3. House III

This two-storey townhouse is one of 74 units built on a flood plain near a river in 1991 by a housing co-oper-

Table 4-II
Volatile organic compounds detected in house II. Concentration in μg/m^3

Compound or group of cmpds.	Before renovation							
	Indoor air				Headspace analysis			
	BPM05 Family rm	BPM06 Office	BPM07 Basement	BPM08 Master BR	NFL15 Carpet	NFL16 Air Duct	NFL17 Carpet 2	NFL18 Air Duct 2
C3 and C4	15	48	70	32	0	67	166	140
Cl and F	10	10	12		0	159	0	457
Ethanol	22	25	30	28	0	33	131	100
Acetone	68	68	69	59	0	7	0	27
Other Ox.	16	11	41	12	155	24	324	80
Aromatic	173	214	231	203	393	107	228	200
C5 and C6	9	10	17	10	82	9	50	0
C7 and C8	31	21	21	10	0	0	0	0
C9 and C10	31	33	8	37	0	0	0	0
Terpenoids	59	59	120	65	150	0	89	89
DiClBenz.	0	0	0	0	0	22	0	31
C1 and C12	63	75	162	113	57	24	81	0
>C12	48	66	22	37	0	29	0	65
Other	115	62	47	14	133	497	32	1000
Total	660	700	850	620	970	970	1100	2190

Compound or Group of Cmpds.	After Renovation			
	Indoor Air			
	BPM48 Family Rm	BPM49 Office	BPM50 Master BR	BPM51 Basement
C3 and C4	0	0	0	0
Cl and F	0	0	0	0
Ethanol	0	0	0	0
Acetone	135	117	157	195
Other Ox.	0	0	0	0
Aromatic	0	0	0	0
C5 and C6	0	0	0	0
C7 and C8	0	0	0	0
C9 and C10	38	19	55	
Terpenoids	0	0	0	0
DiClBenz.	0	0	0	0
C11 and C12	44	0	0	0
>C12	0	0	0	0
Other	274	274	288	305
Total	490	410	500	500

ative. It is a central unit in a row of eight similar homes. It had a full crawlspace which could be accessed through a hatch. The foundation walls and crawlspace floor were poured concrete. Fiberglass insulation with a polyethylene sheet vapour barrier had been installed floor to ceiling on the inside surface of the exterior walls of the crawlspace. A shallow pool of water approximately two meters in diameter remained at one end of the crawlspace. The forced-air gas furnace is located on the main floor with some of the duckwork located in the crawlspace.

From the outset, moisture and flooding problems were experienced at the site. The house and several other units in the development were inspected by another research team in April, 1993 following continuing complaints by the occupants of this particular unit [1]. The inspection and subsequent measurements confirmed that a serious mold contamination problem existed, particularly, in the crawlspace. The family moved out of the home shortly after the inspection. The house was unoccupied during both the pre- and post-renovation test periods.

For renovation, the Co-Op hired a private company to thoroughly clean the interior of the house. All furnishings and surfaces were vacuumed, and all walls and ceilings were washed with a bleach solution. The ductwork of the forced-air heating system in the crawlspace was sealed and the crawlspace ceiling was insulated with polyurethane foam. The fiberglass insulation on the foundation walls was removed. Water pipes were replaced. The existing exhaust fan in the crawlspace was set to operate continuously at a flow rate of approximately 100 l/s. The hatch to the crawlspace was sealed with duct tape.

Before renovation, the air temperatures in the occupied area were between 20°C and 27°C, and the relative humidity ranged from 40% to 50%. The relative humidity in the crawlspace ranged between 80% and 90%. Little change in air temperatures and relative humidities in the occupied area was observed after renovation. No measurements were taken in the crawlspace after renovation, because it was no longer accessible. The measured air change rates (ventilation rates) were between 0.38 and 0.65 ach, and between 0. 57 and 0. 66 ach, before and after renovation, respectively. The ventilation air was well mixed with the indoor air. The mixing times were about 45 and 30 min for the pre- and post-renovation periods, respectively. The increase in air change rates would likely be caused by the sealing of the ductwork in the crawlspace.

For the pre-renovation period, the measured CO_2 concentrations varied between 375 ppm and 600 ppm. The CO_2 concentrations measured during the post-renovation period were between 375 and 650 ppm. The measured formaldehyde levels prior to renovation were between 0.04 and 0.07 ppm. The formaldehyde levels following renovation were 0.03 and 0.04 ppm.

The measured TVOC levels before renovation were 0.65 mg/m^3, 0.66 mg/m^3, 0.7 mg/m^3, and 0.66 mg/m^3 for the master bedroom, the upstairs hall, the living room and the basement, respectively. The corresponding values for the post-renovation period were 0.2 mg/m^3, 0.28 mg/m^3, and 0.42 mg/m^3 for the master bedroom, the upstairs hall and the living room, respectively.

Table 4-III shows the concentrations of various VOCs in the indoor air. A comparison of the individual VOCs between the pre-and post-renovation periods indicates a general reduction of the concentrations of the identified

Table 4-III
Volatile organic compounds detected in house III. Concentration in $\mu g\ m^3$

	Before Renovation			
	Indoor Air			
Compound or group of cmpds.	BPM09 Master BR	BPM10 Upper hall	BPM11 Living room	BPM12 Basement
C3 and C4	6	15	6	0
Cl and F	0	7	0	0
Ethanol	104	109	129	0
Acetone	39	42	40	0
Other Ox.	55	11	76	14
Aromatic	63	61	86	96
C5 and C6	9	35	21	0
C7 and C8	0	32	0	28
C9 and C1	0	40	40	0
Terpenoids	201	225	214	202
C11 and C12	52	58	42	7
>C12	7	12	34	0
Other	113	12	13	313
Total	650	660	700	660

	After Renovation			
	Indoor Air			
Compound or group of cmpds.	BPM1 Master BR	8BPM19 Upper Hall	BPM20 Living Rm	Basement
C3SC4	0	30	39	
Cl and F	0	0	0	
Ethanol	0	0	0	
Acetone	31	22	42	
Other Ox.	0	0	0	
Aromatic	31	47	37	
C5 and C6	0	17	0	
C7 and C8	0	0	43	
C9 and C10	0	0	0	
Terpenoids	70	57	11	
C11 and C12	0	41	37	
>C12	0	0	0	
Other	68	65	211	
Total	200	280	420	

VOCs. The decrease in VOC concentrations would likely be due to the fact that this house was unoccupied and the ventilation system was in operation continuously. Even though several identified VOCs that existed in this house after renovation were not detected in House R2, their concentrations were all less than 0.06 mg/m^3.

3.4. House VI

This 279 m^2 split level home is located in a mature residential neighborhood. There are wood-burning fireplaces in both the living room and the family room. The house is heated by a hot water system, with the gas-fired

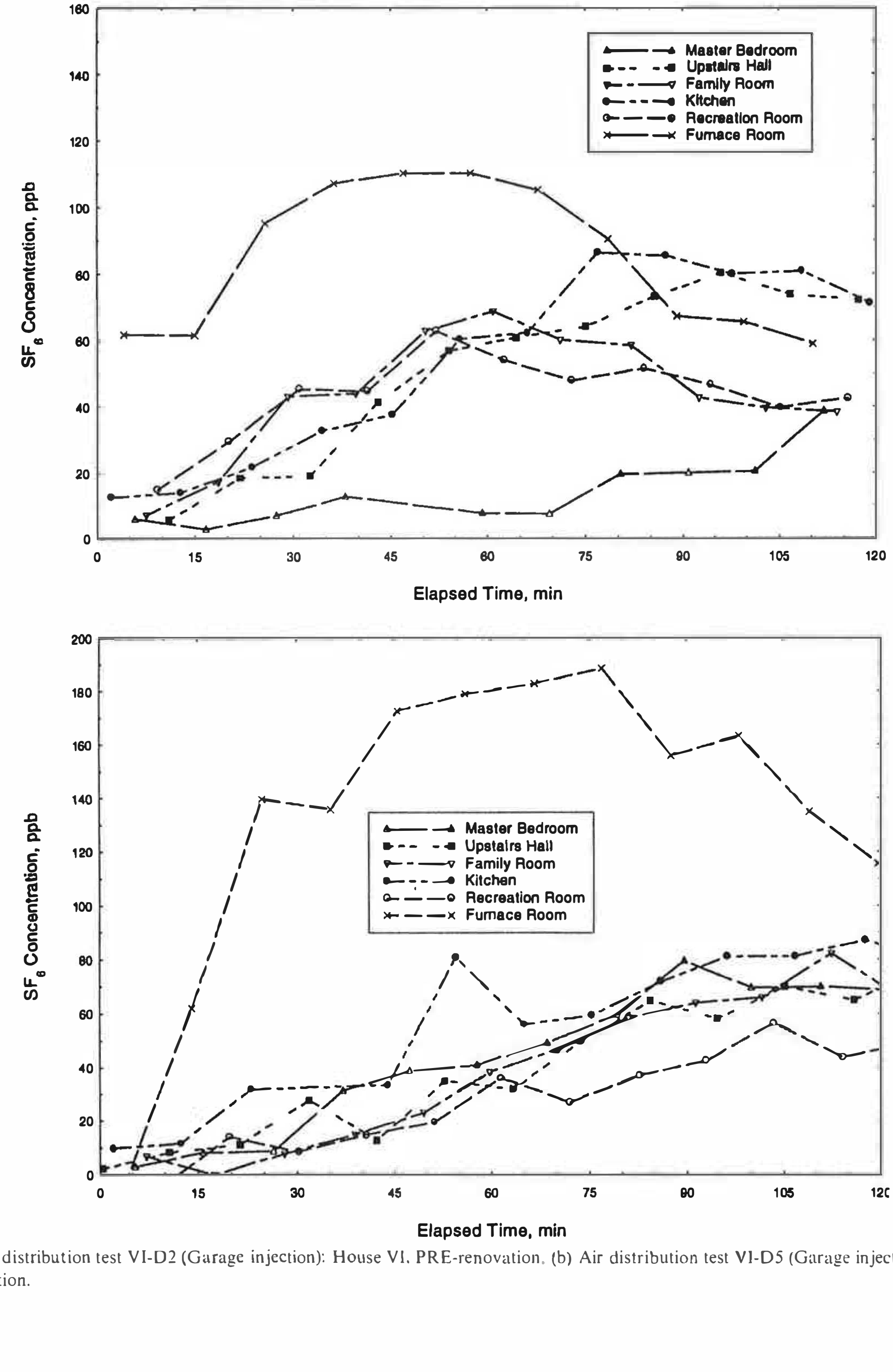

Fig. 3. (a) Air distribution test VI-D2 (Garage injection): House VI, PRE-renovation. (b) Air distribution test VI-D5 (Garage injection): House VI, POST-renovation.

boiler located in the basement furnace room. A hole through the foundation wall in the furnace room provides combustion air for the boiler. No air circulation system exists. The house is occupied by a family of four. The wife has asthma. She apparently became environmentally hypersensitive in 1992 when the owner renovated the kitchen area. Particle-board kitchen cabinets were added to the kitchen during the renovation. There is significant bus traffic on the street on which the house is located. This appeared to be an additional irritant to the woman. A previous investigation by another research team revealed that spillage of combustion gas from the boiler unit was occurring [1]. No molds of concern were detected in the house at that time.

Major renovation measures included the replacement of the boiler and gas water heater with a single high efficiency sealed-combustion unit. Carpeting in the family room was replaced with hardwood flooring. A new countertop was installed in the kitchen. The exterior cedar siding on the kitchen addition was sealed with acrylic urethane in an attempt to prevent off-gassing from the previously applied wood preservatives. Attempts had been made to seal the electrical outlets located in the kitchen exterior wall to prevent infiltration of VOCs from the exterior siding. At the front of the house, a new step was added to the mud/laundry room entrance to cover a hole in the foundation that had been allowing infiltration of outside air. The clothes dryer hose was repaired and a

Table 4-VI
Volatile organic compounds detected in house VI. Concentration in $\mu g/m^3$

Compound or Group of Cmpds.	Before renovation				
	Indoor air				
	BPM56 Office	BPM57 Master BR	BPM58 Family Rm	BPM59 Kitchen	BPM60 Basement
C3 and C4	0	0	0	0	0
Cl and F	0	0	0	0	0
Ethanol	0	0	0	0	0
Acetone	0	0	0	0	0
Other Ox.	0	0	0	0	0
Aromatic	0	0	0	0	0
C5 and C6	11.2	20	0	0	0
C7 and C8	0	0	0	0	0
C9 and C10	31.6	22	0	31	14
Terpenoids	50.3	78	33	49	0
C11 and C12	135.3	218	780	337	0
>C12	16.5	66	63	0	0
Other	65.1	86	64	83	106
Total	310	490	940	500	120

Compound or Group of Cmpds.	After Renovation			
	Indoor Air			
	BPM72 Master BR	BPM73 Family Rm	BPM74 Kitchen	BPM75 Basement
C3 and C4	911	88	20	19
Cl and F	39	922	48	0
Ethanol	24	57	0	46
Acetone	68	67	81	33
Other Ox.	48	0	0	0
Aromatic	40	50	93	69
C5 and C6	32	38	12	27
C7 and C8	0	0	0	0
C9 and C10	66	26	42	126
Terpenoids	78	0	42	0
C11 and C12	44	126	156	67
>C12	10	0	12	49
Other	232	265	155	65
Total	690	740	660	500

Table 4-R2
Volatile organic compounds detected in reference house R2. Concentration in [$\mu g/m^3$]

Compound or group of compounds	Indoor air					
	BPM44 Living Rm	BPM45 Master BR	BPM46 2nd BR	BPM47B Closet	PM67BPM66 Exhaust air	Outdoor air
C3 and C4	152	140	117	11	13.3	0
Cl and F	204	132	259	609	60.2	0
Ethanol	423	330	162	72	53.2	0
Acetone	31	9	51	65	32.6	0
Other Ox.	0	0	0	0	0	0
Aromatic	0	0	0	0	0	0
C5 and C6	0	0	0	0	0	0
C7 and C8	0	0	0	0	0	0
C9 and C10	0	0	49	19	0	0
Terpenoids	0	0	12	34	62.3	0
C11 and C12	0	0	0	0	10	0
>C12	0	0	0	8	11.6	0
Other	0	9	1	71	86.8	40
Total	810	620	650	890	330	40

properly dampered exhaust vent installed. Caulking was added to the garage door.

The air temperatures in the occupied area before renovation, were between 20°C and 25°C, and the relative humidity ranged from 20% to 29%. After renovation air temperatures were between 20 C and 22°C, and the relative humidity increased to approximately 54%. The measured air change rates (ventilation rates) were between 0.73 and 0.81 ach, and between 0.3 and 0.33 ach, before and after renovation, respectively. As the house did not have a HRV, the reduction in the air change rates after renovation was mainly caused by increased outdoor air temperatures. Air distribution tests conducted during the pre-renovation period revealed a noticeable air movement from the furnace room to the living area. Also, a significant amount of air movement from the garage to the house. The air inflows from the furnace room and particularly, from the garage to the house were not stopped after significant efforts were made to seal the air leakage openings. Figure 3 shows the tracer gas test results, before and after renovation, which indicate that as soon as the tracer gas was injected in the garage, the tracer gas, and hence, the garage air, reached all the sampling locations in the house.

The CO_2 concentrations before renovation varied from 360 ppm to 1150 ppm and they were between 400 ppm to 1350 ppm after renovation. The formaldehyde levels in the house were between 0.02 and 0.05 ppm, and between 0.04 and 0.05 ppm before and after renovation, respectively.

Before renovation, the measured TVOC concentrations were 0.94 mg/m^3, 0.49 mg/m^3, 0.12 mg/m^3, 0.5 mg/m^3, and 0.31 mg/m^3 for the family room, the master bedroom, and the furnace room, the kitchen and the office, respectively. After renovation, the TVOC levels increased slightly to 0.74 mg/m^3, 0.69 mg/m^3, 0.5 mg/m^3, and 0.66 mg/m^3 for the family room. the master bedroom, the furnace room and the kitchen, respectively.

Table 4-VI shows the concentrations of various VOCs. A comparison of the identified VOCs before and after the renovation indicated that several VOCs that were not detected in this house before renovation were detected after renovation. Some of these VOCs could have been generated from the materials used to seal the leakage openings. It is expected that the concentrations of these VOCs would reduce to the pre-renovation levels eventually. A comparison of the identified VOC concentrations between this house and House R2 (Table 4-R2) indicates several VOCs existed in this house that were not detected in House R2. Except for the C11 and C12 compounds, none of these compounds, before and after renovation, had a concentration greater than 0.78 mg/m^3.

4. Summary

Four houses were tested before and after they had been renovated to improve their indoor air quality. The pre-renovation test results have been presented in a companion paper. This paper presents the post-renovation test results and an assessment of the effectiveness of the applied renovation measures. The VOC detected in the four test houses were not the same as those in the reference house. Their concentrations of all identified VOCs were lower than 0.27 mg/m^3. The results are summarized below.

House I—The installation of a HRV and the modification of the main supply and return ductwork resulted in some improvement in the air distribution and the air change rate of the house. The VOC concentrations were significantly decreased after the renovation. This was mainly caused by the new cement floor in the main part of the basement and the removal of the carpet.

House II—The removal of carpeting and flexible heating ducts were very effective in reducing or eliminating most of the VOCs in the house.

House III—The thorough cleaning of the interior of the house, the wash of the ceiling and wall, and the repair of the flooded crawelspace were necessary. The decrease in the VOC concentrations would likely be due to the fact that the house was unoccupied between the pre- and post-renovation tests and the forced-air heating system was operating continuously during this period.

House VI—The applied renovation measures did not seem to produce the expected results. The leakage of the furnace room air and the garage air into the house was not stopped. Nor the removal of the carpet resulted in a reduction of the VOC levels in the house.

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