RESEARCH REPORT

Study of Displacement Ventilation Systems for Residential Houses with Radiant Floor Heating Systems

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Client Report

A3558.1

Study of Displacement Ventilation Systems for Residential Houses with Radiant Floor Heating Systems

for

Canada Mortgage and Housing Corporation
700 Montreal Road
Ottawa, Ontario
K1A 0P7

22 December 1998

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Study of displacement ventilation systems for houses with radiant floor heating systems

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Study of Displacement Ventilation Systems for Houses With Radiant Floor Heating Systems

Executive Summary

Hypersensitive persons make up about 1 % of the Canadian population. In the presence of air-born contaminants, these people suffer partial to total infirmity. Some of them require a home environment that is as free as possible from contaminants.

A prototype house designed specifically for the needs of hypersensitive persons was built by Canada Mortgage and Housing Corporation (CMHC). This house combines materials and mechanical systems that disperse little or no contaminants and includes unique features such as a clothes drying closet. It was constructed in two modules by a housing prefabricator and erected at the test site in Ottawa in 1994. It has only one storey and no basement.

A joint project was established between CMHC and the Institute for Research in Construction to assess the performance of the displacement ventilation system installed in this prototype house. The results will help to develop guidelines for designing and constructing suitable and affordable housing for environmentally hypersensitive individuals. Some of the measures used in this prototype house may also be adopted in new and existing houses to improve indoor air quality.

The house is heated by a radiant floor hydronic heating system and cooled by a small air-conditioning system. An antifreeze mixture is heated or cooled and circulated through pipes in the floor and a heating/cooling coil in the displacement ventilation system.

The displacement ventilation system consists of a specially designed air intake and exhaust module mounted on the outside of the utility room, a ventilation unit and the ductwork. Air circulates through the house in such a way that

- cross contamination is minimized;
- the need for individual exhaust air ducts is minimized;
- no contaminated air from other living areas enter the bedroom; and

- exhaust of the drying closet is facilitated.

The performance of the displacement ventilation system was evaluated by a series of tests developed to measure:

- air distribution;
- contaminant removal performance;
- vertical temperature and air speed profiles;
- performance of air intake and exhaust module; and
- performance of drying closet.

The tests were successful in assessing the displacement ventilation system designed for the prototype house. Outdoor air is distributed and indoor generated contaminants are removed by the test ventilation system as well as with a conventional forced-air heating systems. Also like the forced-air heating system, the ventilation air was well mixed with the room air in the test room. The displacement ventilation system tested was not able to establish a stable vertical temperature gradient in the room as expected from the theory of displacement ventilation due to the large fluctuations in the outdoor air temperature. As designed, cross contamination between the intake and exhaust was prevented successfully by the integrated outdoor air intake and exhaust module. And lastly, the drying closet was capable of drying a typical load of wet clothes overnight.

Étude des systèmes de ventilation par déplacement d'air dans les maisons munies d'installations de chauffage à eau chaude par rayonnement par le sol

Résumé

En présence de contaminants aériens, les personnes hypersensibles, qui composent environ 1 % de la population canadienne, sont atteints d'une incapacité totale ou partielle. Certaines d'entre elles requièrent un milieu intérieur résidentiel quasiment exempt de tout contaminant.

La Société canadienne d'hypothèques et de logement (SCHL) a construit un prototype de maison qui répond aux besoins spécifiques des personnes hypersensibles. Le prototype comporte des matériaux et des installations mécaniques qui dispersent peu de contaminants, voire aucun, et offre des caractéristiques uniques comme une penderie de séchage pour la lessive. Cette maison de recherche d'un étage dépourvue de sous-sol a été réalisée en deux modules par un constructeur de maisons préfabriquées et érigée en 1994 sur le lieu d'essai à Ottawa.

La SCHL et l'Institut de recherche en construction ont monté ce projet ensemble afin d'évaluer le rendement du système de ventilation par déplacement d'air installé dans la maison d'essai. Les résultats serviront à élaborer des lignes de conduites pour la conception et la construction de maisons abordables pour les personnes hypersensibles aux polluants environnementaux. Certaines des mesures utilisées dans cette maison pourraient être mises en œuvre dans des maisons neuves et existantes pour améliorer la qualité de l'air intérieur.

Le chauffage est assuré par une installation à eau chaude par rayonnement par le sol, et l'air est climatisé grâce à un petit climatiseur. Un mélange à antigel, chauffé ou refroidi selon le cas, circule dans la tuyauterie du plancher ainsi que dans le serpentin de chauffage-climatisation du système de ventilation par déplacement d'air.

Le système de ventilation par déplacement d'air est composé d'un bloc de ventilation, de conduits et de modules d'alimentation et d'extraction de conception particulière montés sur l'extérieur du local technique. L'air se déplace dans la maison de telle sorte que :

- la contamination croisée est réduite au minimum,
- le nombre de sorties individuelles d'extraction d'air vicié est réduit au minimum,
- l'air de la chambre n'est pas contaminé par l'air provenant des autres pièces et que
- l'extraction de l'air de la penderie de séchage s'en trouve facilitée.

La performance du système de ventilation par déplacement d'air a été évaluée à l'aide d'une série d'essais mis au point pour mesurer :

- la répartition de l'air,
- le taux de rétention des contaminants,
- la stratification verticale des températures et le profil de la vélocité de l'air,
- la performance des modules d'admission et d'extraction d'air et
- le rendement de la penderie de séchage.

À l'aide de ces essais, on a réussi à évaluer la performance du système de ventilation par déplacement d'air élaboré pour la maison de recherche. La diffusion de l'air frais et la rétention des contaminants produits dans le milieu intérieur ont été aussi efficaces que dans une installation classique de chauffage à air pulsé. Tout comme cette dernière, l'air frais est bien mélangé avec l'air de la pièce d'essai. Le système de ventilation par déplacement d'air mis à l'essai n'a pu maintenir un gradient vertical de température stable comme on s'y attendait suivant la théorie de la ventilation par déplacement d'air, en raison des fluctuations importantes de la température extérieure. Les modules intégrés d'admission et d'extraction d'air ont empêché la contamination croisée entre la prise d'admission d'air frais et la sortie d'extraction d'air vicié. Enfin, la penderie de séchage a réussi à sécher, en une seule nuit, une brassée normale de lessive.

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Study of Displacement Ventilation Systems for Houses With Radiant Floor Heating Systems

by

J.S. Zhang, R.J. Magee and C.Y. Shaw

Introduction

It is estimated that about 1% of Canadian are environmentally hypersensitive. These people suffer partial to total debilitation. Some of them require a home environment that is as free as possible from air-borne contaminants. Designing and constructing such houses are hampered by the lack of practical guidelines both for selecting suitable building materials and furnishings, and for designing and installing effective ventilation systems. The Canada Mortgage and Housing Corporation has recently designed and constructed a prototype house for environmentally hypersensitive individuals. It includes a range of features to help to achieve an acceptable indoor environment for these people at a minimal cost. These features include the use of commercially available low emission building materials and easily cleanable interior finishing, and a specially designed displacement ventilation system.

A joint project was established between the Canada Mortgage and Housing Corporation and the Institute for Research in Construction to assess the performance of the displacement ventilation system installed in this prototype house. This report presents the results of this evaluation.

The results will help to develop guidelines for designing and constructing suitable and affordable housing for environmentally hypersensitive individuals. Some of the measures used in this prototype house may also be adopted in new and existing houses to improve indoor air quality.

Test House

The single storey prototype house was constructed in two modules by a housing prefabricator and erected at the test site in Ottawa (CMHC 1994). It has no basement. As shown in Figure 1a, the dimensions of the house are approximately 3.85m by 3.43m by 2.40m (12.6ft by 11.3ft by 7.79ft). It has one bedroom, a living room, a kitchen, a bath room, and a utility room. The roof and floor are of conventional wood-frame construction. As shown in Figure 2, the exterior wall, floor and ceiling are comprised of the following:

Exterior Wall - prefinished tempered hardboard siding, 38 mm by 38 mm horizontal strapping, TYVEK air barrier, 38 mm by 300 mm stand-off studs, RSI 5.6 rockwood insulation, 12.5 exterior grade spruce plywood, 38 mm by 89 mm spruce wall studs, 12.5 mm gypsum board, and 2 mm veneer plaster.

Floor - continuous air barrier, 38 mm by 235 mm wood joists, RSI 7 glass fibre batt insulation, 16 mm plywood subfloor, 6 mm cement-bonded particle board, ceramic tile.

Ceiling - 12.5 mm gypsum board and 2 mm veneer plaster.

The windows are all triple-pane, argon-filled insulated glazing units with insulation-filled fiberglass frames that have a baked enamel finish. The exterior doors are standard steel-clad insulated doors with double-glazed window inserts.

All building materials and interior furnishing were selected to minimize the contamination of the indoor air. Special efforts were made to minimize the migration of odours from building materials and furnishing into the house. For example, Interior doors are of birch veneer on basswood frames coated with four coats of acrylic sealant. The sealant serves to encapsulate odours from the veneer and core materials.

Heating, Cooling and Ventilating Systems

Heating System: the heating is provided by a radiant floor hydraulic heating system and the ventilation system. As shown in Figures 3 and 4, an antifreeze mixture is heated by hot water in an liquid to liquid heat exchanger. An electrically-heated domestic hot water tank with a maximum hot water temperature of 55°C is used to supply heat to the heat exchanger. The heated antifreeze mixture is circulated through the pipes in the floor and the heating/cooling coil in the ventilation system.

Cooling System: Figure 4 shows that a small air-conditioning system is used to cool the antifreeze mixture circulated through the heating/cooling coil in the ventilation system and the pipes in the floor to provide some cooling and dehumidification for the occupied area.

Ventilation System: the house has a displacement ventilation system (Figure 5), consisting of a specially designed air intake and exhaust module to minimize cross contamination between intake and exhaust, a ventilation unit and the ductwork. The air intake and exhaust module (see Figure 6 for detail), is mounted on the outside of the utility room. It contains a washable air pre-filter. The ventilation unit, Figure 7, consists of an air intake fan, an exhaust fan and a heat recovery unit for recovering heat from the exhaust air, a pleated paper air filter, and a charcoal filter. Under normal conditions, only the paper filter is used. When odour removal is needed, an auxiliary fan is used to draw the supply air through the charcoal filter. As shown in Figure 5, the ventilation air at 18°C is supplied to the living room and bedroom only through the supplier air registers located near the floor level. From these two rooms air moves to the bathroom and kitchen and into closets and cabinets, from which it is exhausted. A ceiling exhaust plenum is used to minimize the need of individual exhaust air ducts. The bedroom is pressurized to ensure that no contaminated air from other area would enter this room. An exhaust grille is located in the interior wall between the bedroom and the living room to allow the bedroom air to discharge into the living room. Also, an exhaust opening is located inside the closet to facilitate the exhaust of the closet air to the exhaust air plenum in the ceiling.

In addition, Figure 8 indicates that moist air generated in the drying closet due to cloth drying is removed by the ventilation system. The exhaust removed from the drying closet is also circulated through the heat recovery unit.

Test Methods

Prior to the planned tests, the supply airflow rates to the living room and bedroom provided by the existing displacement ventilation system were measured using a flow hood. Based on these measurements, the volume control dampers in the supply ducts were adjusted to match the designed airflow rates to these two rooms. An attempt was made to measure the static pressures in the ceiling plenum, each room, kitchen cabinets, and closets using micro-manometers to determine the directions of interzonal airflows. No measurable pressure readings were obtained because of leaky interior partitions. However, a visual inspection did confirm that the for the bed room, the airflow direction was from the bedroom to the living room when the bedroom door was closed.

Tests were conducted in the bedroom to assess the performance of the displacement ventilation system in terms of air distribution, contaminant removal, indoor air quality and thermal comfort conditions under winter conditions. For these tests, the supply air flow rate to the bedroom (100% outdoor air) was kept constant at 21.5 L/s.

The results were compared with that provided by a conventional forced-air heating system which was installed in the bedroom for this study. To create such a system, the existing outdoor air supply outlet to the bedroom was connected to a rectangular box. The outdoor air supply rate was maintained at about 21.5 L/s. A new return air system including a retrun air fan was installed by connecting an air duct between the bedroom closet and the box. The return air fan was operating to maintain a constant return air flow rate of approximately 21.5 L/s. A supply air register was located on the top of the box. In addition, a portable electric heater-fan unit which was controlled by the room thermostat was placed inside the box. When heat was not required, the outdoor and return air would mix with each other and discharge into the room through the supply air register. When heat was required, the thermostat would turned on the heater-fan unit. The heater fan would circulate the air through heater. No modifications were made for the main exhaust outlet for the bedroom. The existing radiant floor heating system was shut down when the conventional forced-air heating system was in operation.

In addition, the performance of the air intake and exhaust module and the drying closet were also evaluated.

The test procedures are described as follows:

Air Distribution: To assess the air distribution performance, approximately 65 ml tracer gas (SF_6) was injected into the outdoor air supply duct to mark the ventilation air. Immediately following injection, concentrations of SF_6 were measured using a B&K gas monitor/analyser at two locations in the occupied region of the bedroom, the outdoor air supply duct, two exhaust openings including the main exhaust opening and an exhaust opening inside the bedroom closet, and at the intake of the air intake unit of exhaust module. The sampling locations are shown in Figure 1b. The measured concentrations of each sampling location were plotted against time to determine how fast the ventilation air reached the measuring locations.

Contaminant Removal Performance: To measure the contaminant removal performance, CH_4 was injected continuously at the center of the bedroom on the floor level to simulate a contaminant source. The injection rate was controlled by a mass flow controller. Immediately after the injection, concentrations of CH_4 were measured at the supply outlet, one location at the occupied region and at several exhaust openings. The measured concentrations were plotted against time for each measuring location to determine the contaminant removal efficiency at that location. The locations where the measurements were conducted are shown in Figure 1b.

Vertical Temperature and Air Speed Profiles: Three measurement trees were installed to measure the vertical temperature and air speed profiles in the occupied region of the bedroom. Each measurement tree had 8 air temperature & speed sensors. The three measurement trees were located at the center of the room to form an equal triangle (see Figure1b). The degree of thermal stratification existed in the room with the displacement ventilation system in operation was determined from the measured vertical temperature profiles. During the tests, the bedroom door was closed and the temperature in the room was controlled by the room thermostat.

Performance of Air Intake and Exhaust Module: To determine how successfully this specially designed air intake and exhaust module prevents the exhaust air from re-entering into the house, air samples were taken at regular intervals from the outdoor air intake during each tracer gas test. Any detection of SF_6 or CH_4 at the outdoor air intake would indicate some contamination of the ventilation air by the exhaust air. The results were correlated to the wind speed and direction data from a nearby weather station.

Performance of Drying Closet: 6 kg lbs of wet clothes were placed inside the drying closet on clotheslines to dry. The air temperatures and relative humidities at the air intake (supply) and exhaust (return) of the drying closet were measured. The time required for the relative humidity at the exhaust reaches approximately a constant value was assumed to be the required drying time for drying such a load of clothes. The dried clothes were also weighed to determine how much water had been removed during the drying period. The results will be used to determine how much wet clothes can be dried overnight.

Results and Discussion

Seven tests were conducted: five with the displacement ventilation system in operation and two with a temporarily installed conventional forced-air heating system in operation. The test conditions are listed in Table 1. Of the seven tests, Tests 1,2 and 3, all with the displacement ventilation system in operation, were conducted under similar conditions to check the repeatability of the measurement results. Tests 4 (displacement) and 5 (conventional forced-air) were conducted under conditions with similar return and supply air temperatures to enable the results be compared with each other. So too, were Tests 6 (conventional forced-air) and 7 (displacement). For the displacement ventilation system, a constant supply airflow rate of approximately 21.5 L/s which was equal to the outdoor airflow rate was used for all the tests (i.e., no recirculating air). For the forced-air heating system, the outdoor airflow rate was the same as that for the displacement ventilation system; the total supply airflow rate varied according to the internal heating or cooling loads and supply air temperature (values that are typical to conventional forced air systems were used). Table 1 shows the test conditions. The results are discussed below.

Air Distribution: Figures 9 through 15 show the air distribution patterns in terms of the measured SF_6 concentrations as a function of time at each sampling location for both the displacement and conventional forced-air heating systems. There were four sampling locations including two locations in the bedroom and two inside the exhaust openings (only one for the conventional forced-air heating system, i.e., no measurements were taken inside the exhaust opening inside the closet). For the displacement system (Tests 1,2,3,4 and 7), Figures 9,10,11,12 and 15 indicate that about 10 minutes after the injection, the tracer gas concentrations in the occupied region (sampling locations 1 and 2) and inside the main exhaust grille (sampling location 3) were almost identical. The results also indicate that it required about 10 minutes longer for the concentration in the closet exhaust (sampling location 4) to reach the level similar to the other three locations.

As the test conditions for these five tests differed only in the temperature differences between the floor surface and the room air, the results suggest that the effect of temperature stratification, caused by the floor-room temperature differences, on the mixing between the ventilation air and the room air was negligible.

Figures 13 and 14 indicate that similar to the displacement system, the ventilation air and the room air with the conventional forced-air heating system was well mixed within 10 minutes after the injection.

A comparison between the two systems is shown in Figures 16 (Test 4 vs. Test 5) and 17 (Test 6 vs. Test 7). The results indicate that (a) the tracer gas concentrations at all sampling locations for the conventional forced-air heating system were lower than those for the displacement system in the first 45 minutes following injection, and (b) the decay rate for the conventional system was also lower. The lower tracer gas concentrations were mainly caused by the fact that the conventional system had return airflow rate. In addition to the 21.5 L/s outdoor air, the supply air of the conventional forced-air heating system also included 21.5 L/s return air from the room via the closet and from the rest of the house through the "exhaust" opening in the closet. The air in the closet contained much less tracer gas than the room air during the initial mixing period. So too was the air from the rest of the house. The low decay rates for the conventional forced-air heating was also due to the return airflow. The airflow from the rest of the house via the "exhaust" opening in the closet was an additional source of SF_6 for the bedroom, which decreased the decay of the SF_6 in the bedroom.

Contaminant-Removal Efficiency: Figures 18 through 24 show the measured CH_4 concentration profiles for the seven tests. As shown, the CH_4 concentrations at the two sampling locations in the room and that at the main exhaust outlet (Figure 1b) were almost identical for all seven tests. These profiles were used to calculate the contaminant-removal efficiency from the equation

$$\varepsilon_v = \frac{C_e(\infty)}{C_i(\infty)} \qquad (1)$$

where

ε_v = contaminant-removal efficiency,
$C(\infty)$ = steady-state concentration (ppm),
Subscripts:
e = main exhaust opening
i = measurement location, I = 1, 2.

Table 2 lists the calculated contaminant-removal efficiencies for the seven tests. For the displacement system (Tests 1,2,3,4 and 7), the measured values varied from 0.93 to 0.99 for the head level (sampling location 1) and they varied from 0.89 to 1.01 for the foot level (sampling location 2). For the conventional system (Tests 5 and 6), they varied from 0.94 to 1.00 for the head level and 0.97 to 1.02 for foot level. The difference between the two systems was too small to indicate that one system would perform better than the other.

Vertical Temperature Profile: Figure 25 shows the vertical temperature profiles for the 5 tests conducted for the displacement ventilation system. The measurements were conducted under different return-supply air temperature differences (1.4 to 2.5 °C for Tests 1 2 and 3, 6 °C for Test 4, and 3.5 °C for Test 7). The return air temperature was measured at the main exhaust (Sampling Location 3, Figure 1b). As shown in Figure 25, the maximum vertical temperature differences for different return-supply air temperature difference (Test 4) were less than 2 C. This suggests that the air was well mixed with the displacement ventilation system in operation. This agreed with the tracer gas results discussed above, which also showed that the room air was well mixed.

Figure 26 shows the vertical temperature profiles for Tests 5 and 6 (conventional system). Also shown for comparison are the temperature profiles for Tests 4 and 7 (displacement system). The results indicate that the conventional system also had relative small vertical temperature differences at elevations greater than 0.5 m above the floor. The temperature gradients between 0.25 and 0.5 m above the floor were slightly larger for the conventional ventilation system than for the displacement ventilation system. This was because that floor was not heated when the conventional forced-air heating system was in operation.

Vertical Air Speed Distribution

Figures 27a and 27b show the vertical air speed distributions for the displacement system (Tests 4 and 7) and the conventional forced-air heating system (Tests 5 and 6), respectively. The results indicate that the measured air speeds for all four tests were less than 0.1 m/s. These air speeds would not cause any discomfort (draft) to the occupant.

Variations of Room Air Temperatures with Time

The results discussed above indicate that the test displacement ventilation system did not produce the typical airflow pattern which characterized such a system, i.e., the supply air is spread over the floor and then rises when heated by heated sources (e.g., a person) to the ceiling level, carrying with it the contaminants. Instead, the test displacement ventilation system performed like a conventional forced-air heating system in that the ventilation air was well mixed with the room air in the test room. This may have been due to the room temperatures fluctuating during the test period caused by the changes in the outdoor air temperature and the on/off control for the radiant floor heater. To confirm this assumption, additional tests were conducted to monitor the outdoor air temperature, the floor surface temperature, the supply and exhaust air temperatures, and the room air temperatures at four different heights (0.1 m, 1.0 m, 1.58 m and 2.3 m above the floor) at location 2 (see Figure 1b) for several days. The results are shown in Figure 28a and 28b.

The results indicate that both the supply air and the room temperatures varied rapidly with the outdoor air temperature. When the room temperature decreased to the room thermostat set point (i.e., 23±1 °C), the thermostat turned on the floor heating system which resulted in a rapid increase in the floor surface temperature. This caused an increase in the room air temperature. The rate of increase in the room air temperature was very low, unless the outdoor air temperature happened to increase as well. When the room air temperature reached above 26±1 °C, the floor heating system was turned off, and the floor surface temperature started to decrease, followed by the room air temperature. At the onset of the next outdoor air temperature increase, the cycle repeated. As a displacement ventilation system relies on the rise of warm air to carry the pollutants to the exhaust air grille near the ceiling level, it would not work properly if a stable thermal stratification condition cannot be maintained. As shown in Figure 28a, for a period of 5 days, only two short periods (approximately, between 8 am and 12 am on April 17, and between 1 am and 7 am on April 18) displayed a relatively stable thermal stratification condition in the test room.

It appears that the test ventilation system performed as well as a conventional forced-air heating system. However, if the objective was to design and construct a ventilation system that would produce a displacement ventilation-type airflow pattern, a few modifications would be required. One of such modifications would be to replace the existing on-off controller to a proportional control system for the floor heating system. A more detailed study would be necessary to determine what is the maximum acceptable temperature fluctuation for the system to achieve the the displacement ventilation-type airflow pattern. It would also be helpful if additional supply air registers were added to the existing system to distribute the airflow. In addition, a high capacity heating system would be needed to maintain a constant outdoor supply air temperature to reduce the influence of the outdoor air temperature on the indoor air temperature.

Performance of the Air Intake and Exhaust Module

During the periods when the tracer gas tests were conducted (see Figures 9 through 15 and Figures 18 through 24), no cross contamination was detected. The weather conditions encountered during these periods are listed in Table 3. Since the weather conditions during the test periods covered a wide range of wind speeds and directions, it may be concluded that the air intake and exhaust module was effective in preventing the exhaust air from re-entering into the house through the air intake.

Performance of Drying Closet

Figure 29 shows the temperatures and relative humidities measured at the supply and exhaust air ducts of the drying closet during a drying test. It shows that the relative humidity of the exhaust air became stable at about 8 hours after the wet clothes were put into the drying closet. The clothes were 6 kg when they were wet and the weight reduce to 3.7 kg when the clothes were dry. Therefore, a total of 2.3 kg of water was removed. The result suggests that the drying closet has the capacity to dry clothes up to 6 kg of wet clothes overnight, as designed.

Conclusions

The following conclusions can be reached from the results of this study:

1. The test ventilation system performed as well as a conventional forced-air heating system to distribute the outdoor air properly to the room and to remove indoor generated contaminants.
2. The test displacement ventilation system did not produce the typical airflow pattern which characterized such a system, i.e., the supply air is spread over the floor and then rises when heated by heated sources (e.g., a person) to the ceiling level, carrying with it the contaminants. Instead, the test displacement ventilation system performed like a conventional forced-air heating system in that the ventilation air was well mixed with the room air in the test room.
3. The displacement ventilation system tested was not able to establish a stable vertical temperature gradient in the room as expected from on the theory of displacement ventilation due to the large fluctuations in the outdoor air temperature.
4. The integrated outdoor air intake and exhaust module was successful in preventing any cross contamination between the intake and exhaust, as designed.
5. The drying closet was capable of drying a typical load of wet clothes overnight, as designed.

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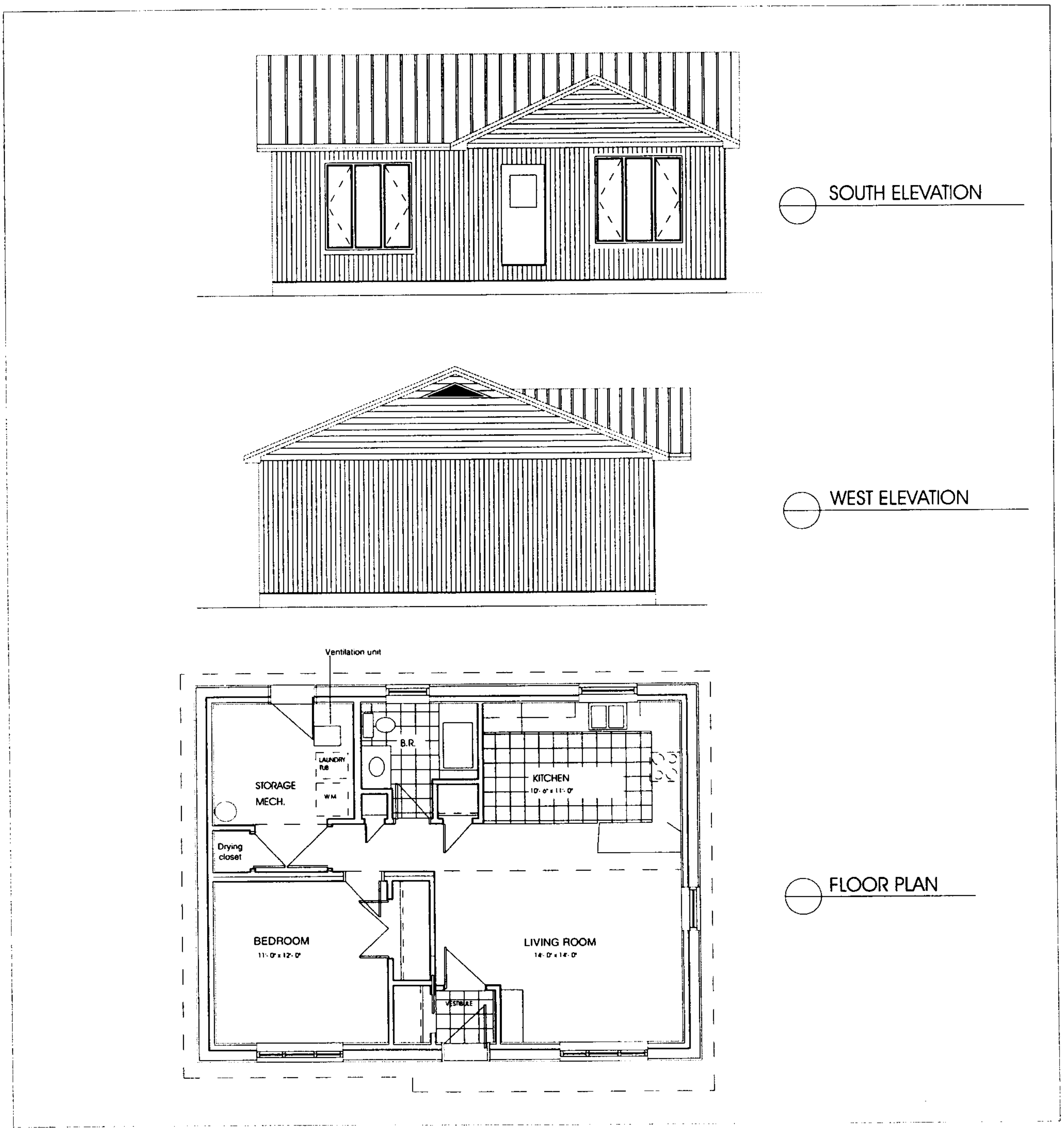
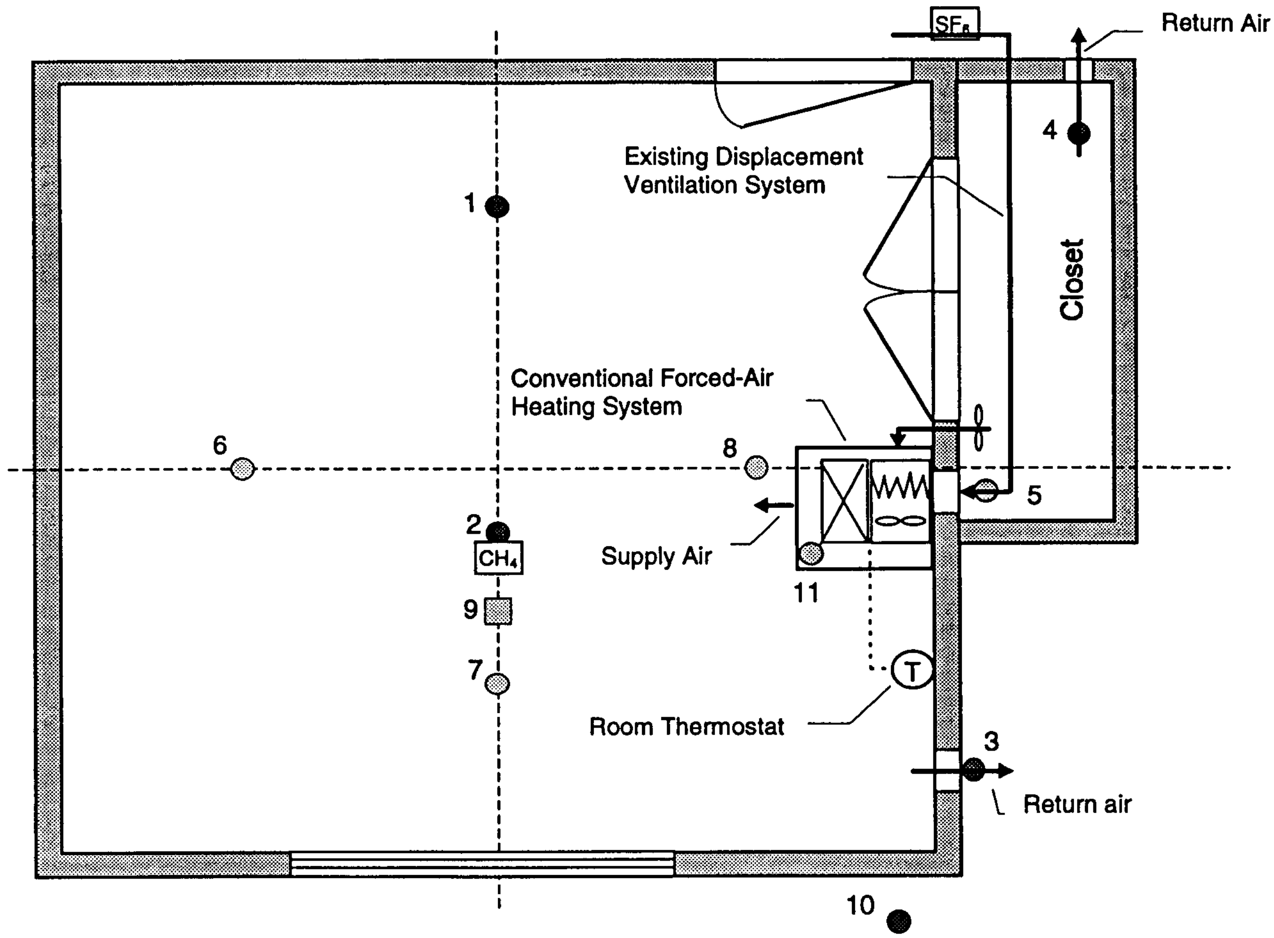


Figure 1.a. Elevations and plan of the house



No.	Symbol	Parameter Measured	Location
1, 2	●	SF_6, CH_4, Temperature	Bedroom (1.0 m above floor)
3	●	SF_6, CH_4, Temperature	Main Exhaust (2.3 m above floor)
4	●	SF_6, CH_4, Temperature	Exhaust in the Closet
5	◎	Temperature	Supply Air Duct
6, 7, 8	○	Temperature, Velocity	Bedroom
9	□	B&K	Bedroom
10	●	SF_6, CH_4, Temperature	Outdoor Air
11	◎	Temperature	Heat box
	CH_4	CH_4 Injection	Bedroom (on the floor)
	SF_6	SF_6 Injection	Supply Air Duct

Figure 1.b. Sampling locations

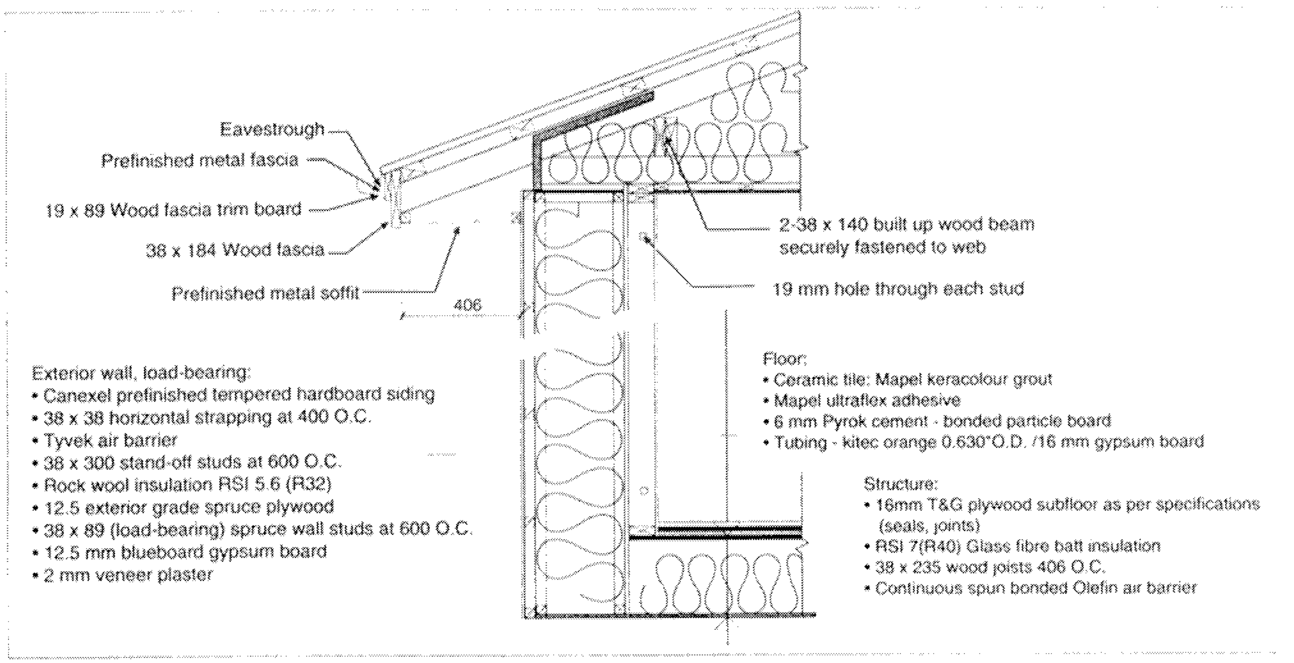


Figure 2. Wall, roof and floor section

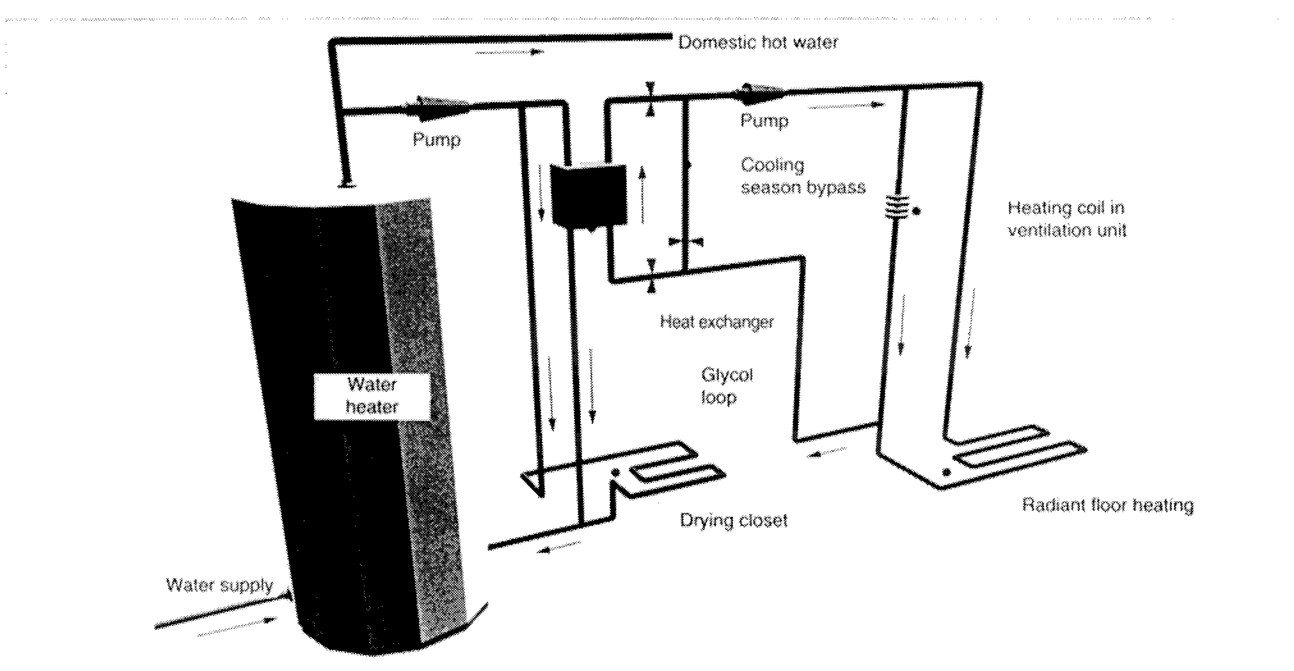


Figure 3. Heating system

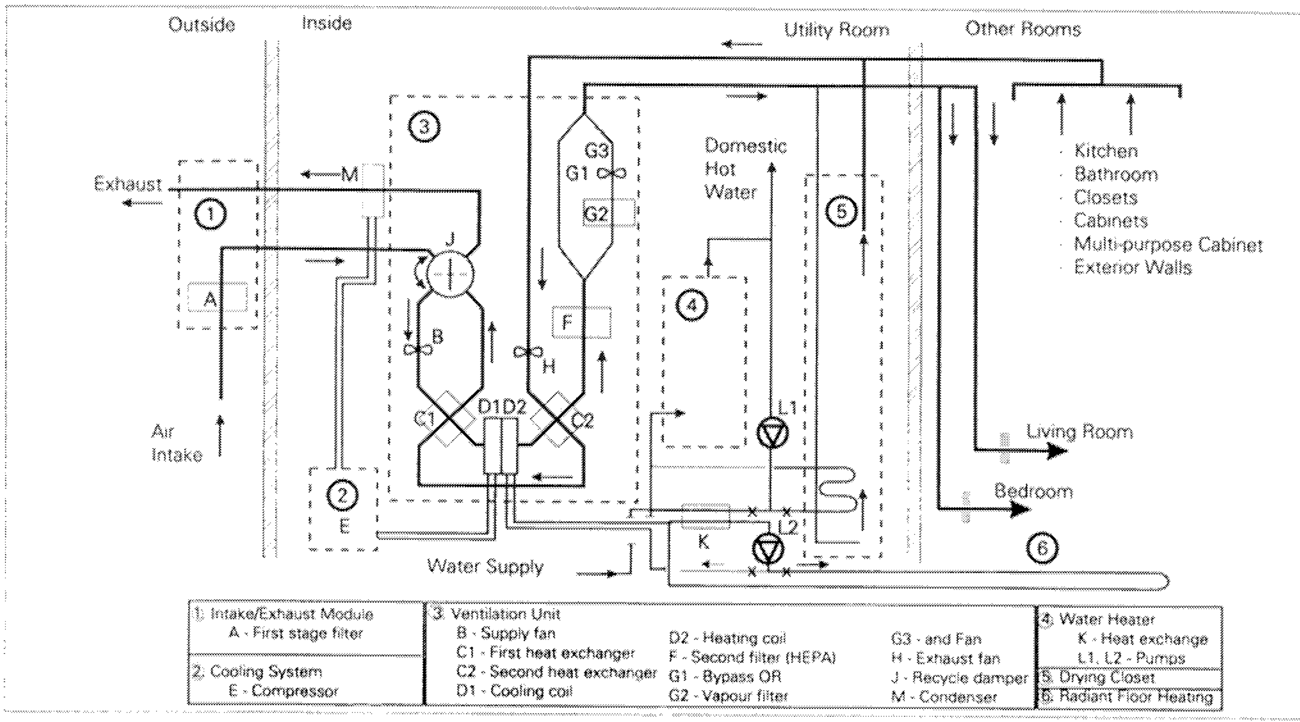


Figure 4. **Ventilation system schematic**

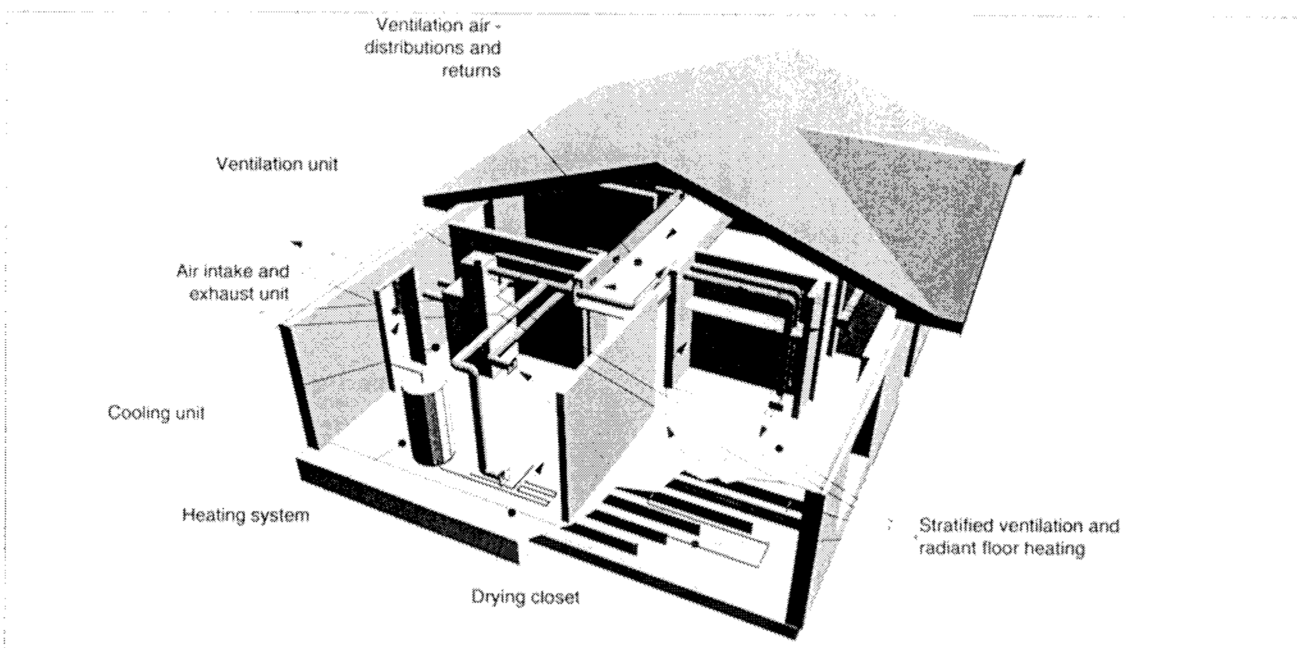


Figure 5. **Ventilation system layout**

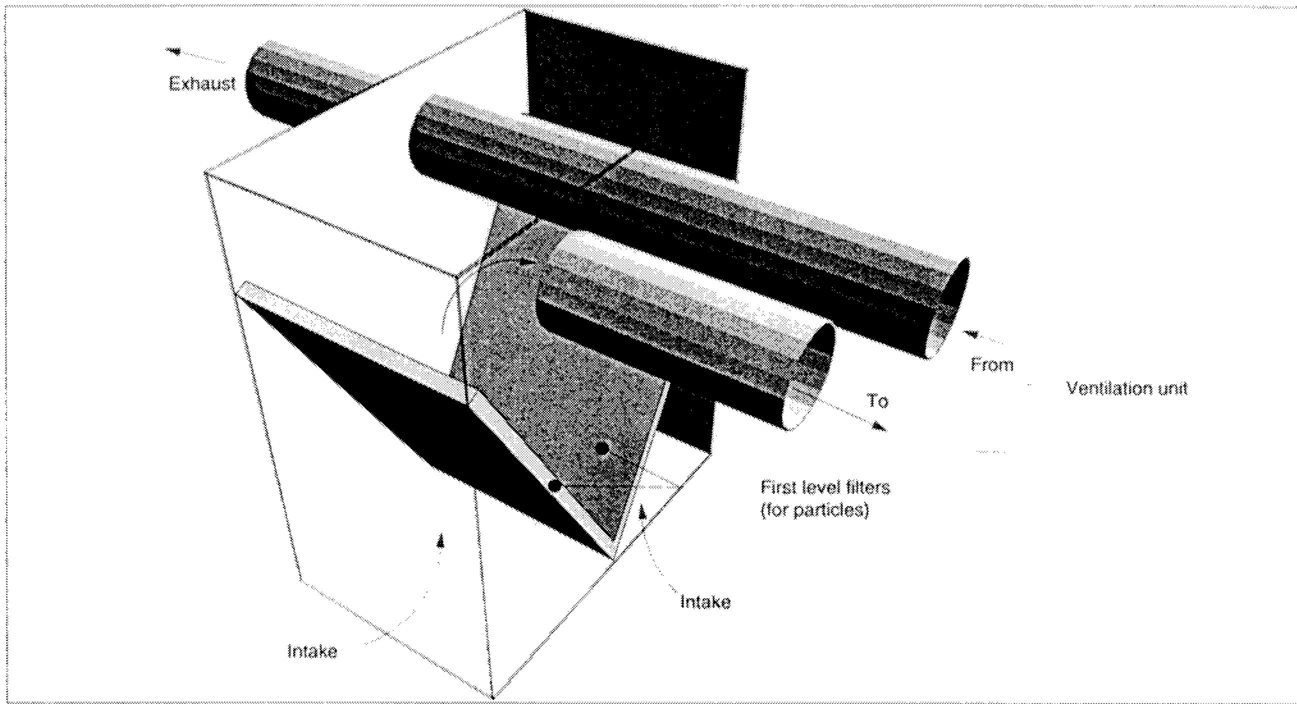


Figure 6. Air Intake and exhaust unit (located outside)

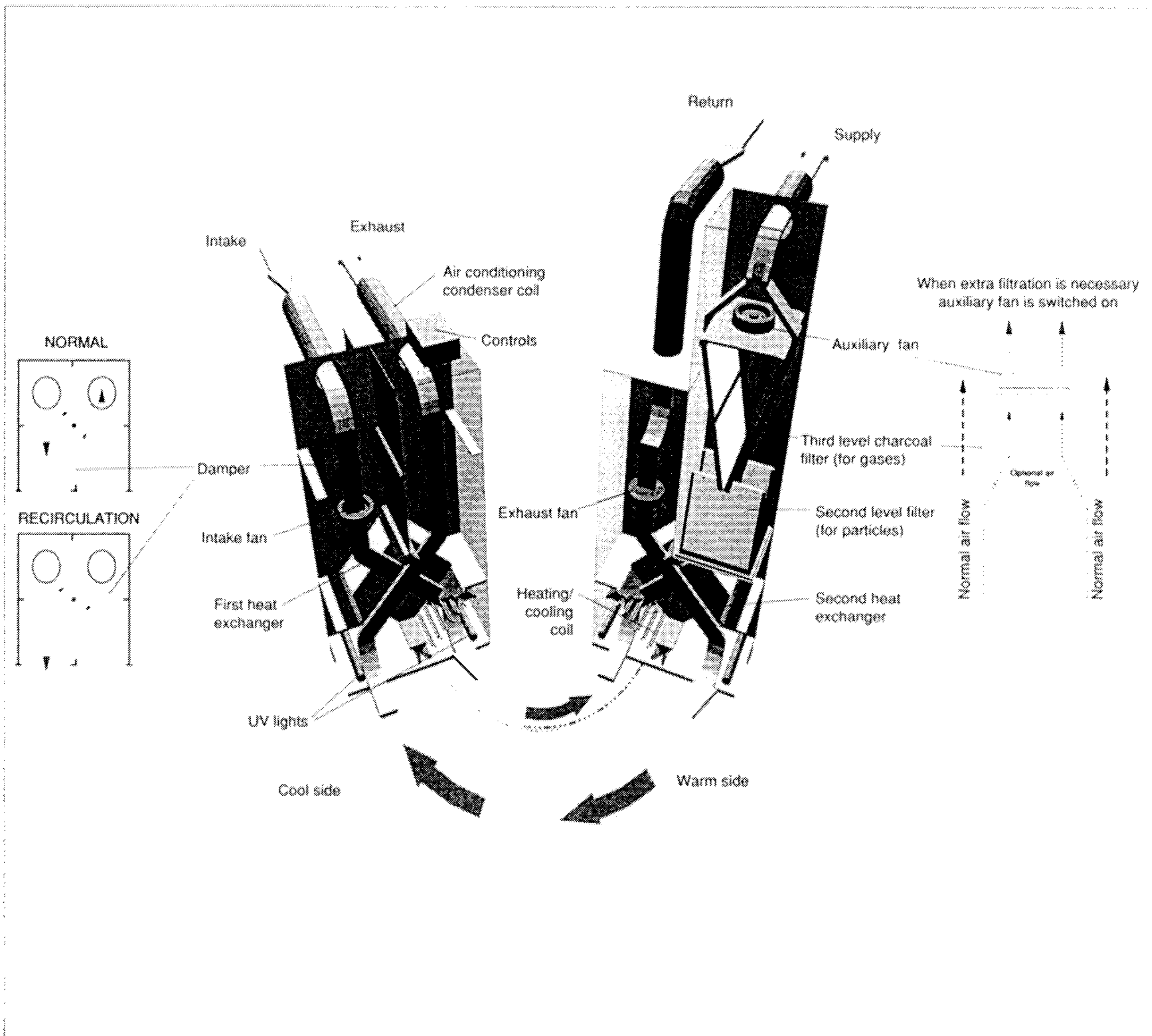


Figure 7. Ventilation unit

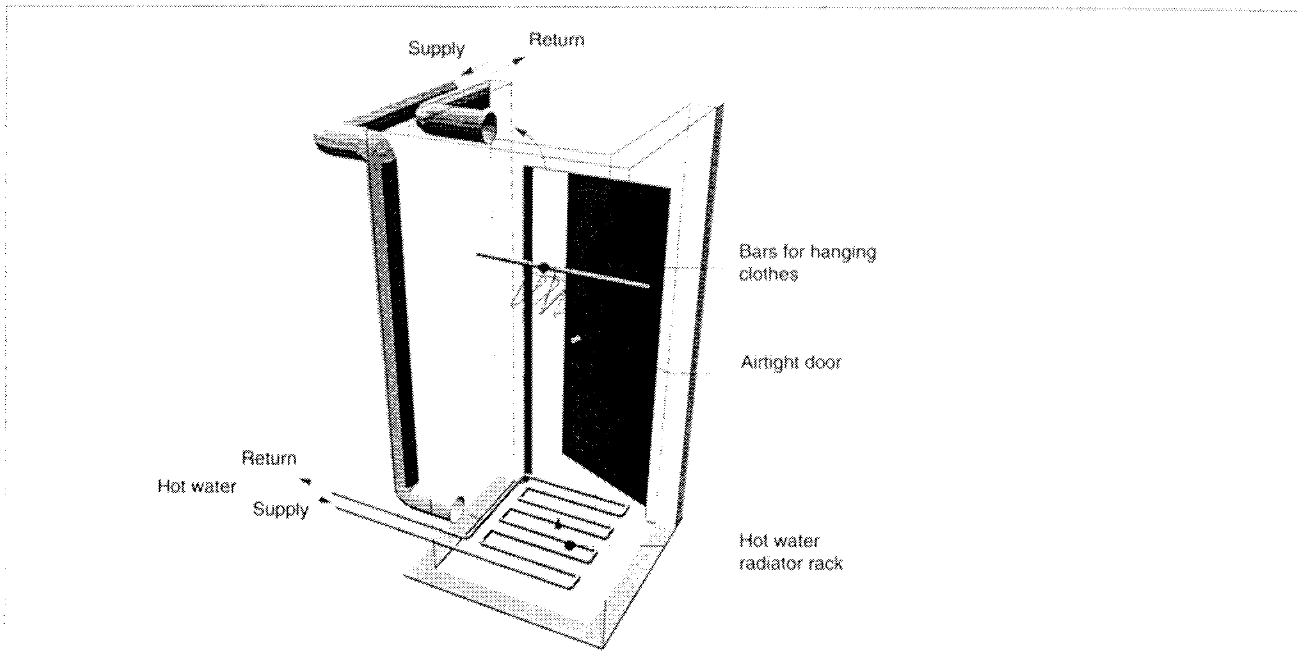


Figure 8. Clothes drying closet

TABLE 1

Experimental Conditions

Test No.	Ventilation Mode	Heated by	T_{sa} (°C)	T_f (°C)	T_r (°C)	$T_r - T_{sa}$ (°C)	Q_{sa} (L/s)	Test Purpose
1	Displacement	Radiant Floor	30.2	34.8	32.1	1.9	19.8	Repeatability
2			29.2	34.1	30.6	1.4	19.8	
3			28.1	31.1	30.6	2.5	19.8	
4	Displacement	Radiant Floor	27.0	38.6	33.0	6.0	19.8	Comparison
5	Conventional	Heater Box	25.6	30.2	32.5	5.3	19.8	
6	Conventional	Heater Box	25.6	*	29.1	3.5	19.8	Comparison
7	Displacement	Radiant Floor	25.8	33.1	29.8	4.0	19.8	

T_{sa} = supply air temperature; T_f = floor temperature; T_r = return air temperature;
Q_{sa} = supply air flow rate; * same conditions as the test 5.

TABLE 2

Measured Contaminant-Removal Efficiencies in the Occupied Regions

Test No.	1	2	3	4	5	6	7
Ventilation Mode	displ.*	displ.	displ.	displ.	conven.*	conven.	displ.
1**, Bedroom	0.94	0.99	0.95	0.99	1.00	0.95	0.94
2**, Bedroom	0.90	0.99	0.90	1.01	1.02	0.98	0.99
Avg.: 1, 2	0.92	0.99	0.93	1.00	1.01	0.97	0.97

* displ.= displacement ventilation; conven.= conventional ventilation.
** Sampling location No. (see Figure 1b)

TABLE 3

Weather Conditions during the Tracer Gas Tests

Test	Outdoor Temperature (°C)	Wind Speed (km/h)	Wind Direction
1	13.5 to 15.7	35 to 39	SW, WSW
2	8.5 to 9.4	19 to 22	E
3	8.8 to 12.3	19 to 31	W, WNW
4	15.7 to 16.9	15 to 22	WNW
5	8.9 to 9.5	19 to 28	SSW, SW
6	2.4 to 6.8	6 to 9	SW, W, N
7	14.2 to 16.1	0 to 4	C*, SE

* C = Calm

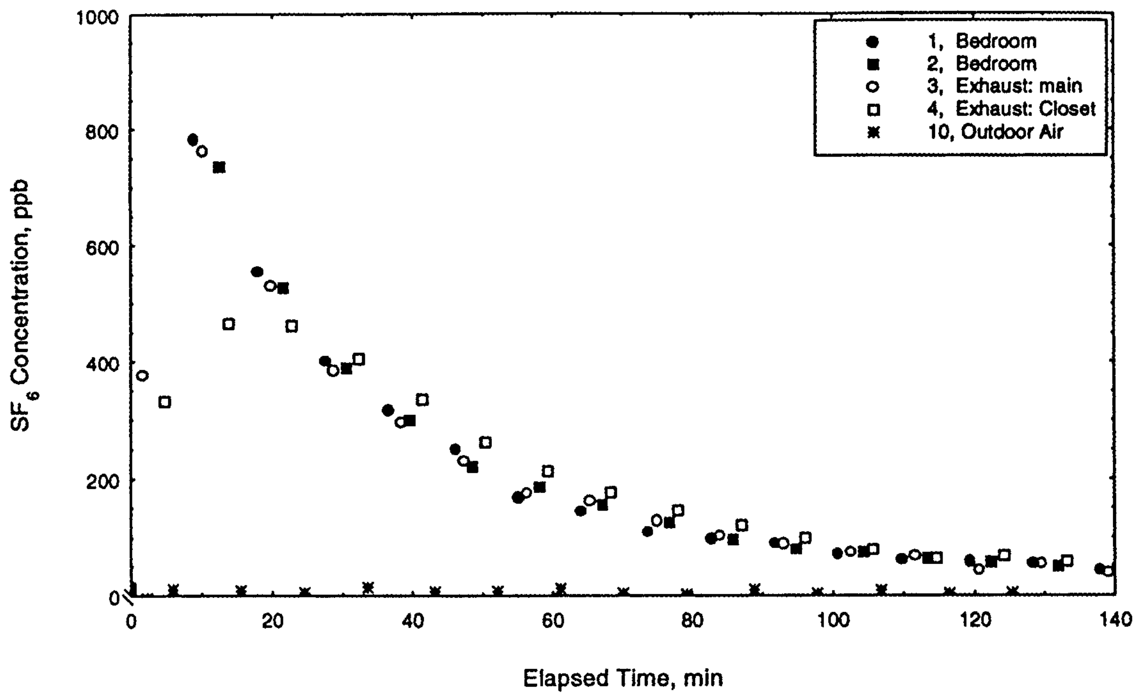


Figure 9. Measured SF_6 concentrations for test 1 (Displacement ventilation; $T_r - T_{sa} = 1.9$ °C, $Q_{sa} = 19.8$ L/s)

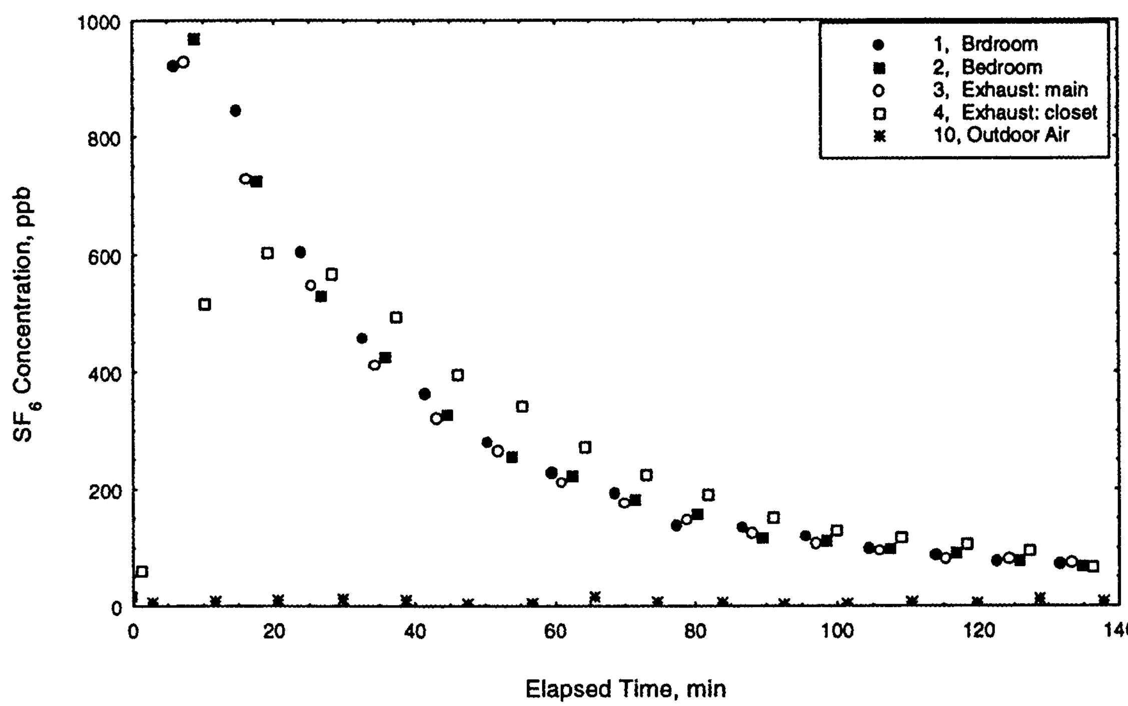


Figure 10. Measured SF_6 concentrations for test 2 (Displacement ventilation; $T_r - T_{sa} = 1.4$ °C , $Q_{sa} = 19.8$ L/s)

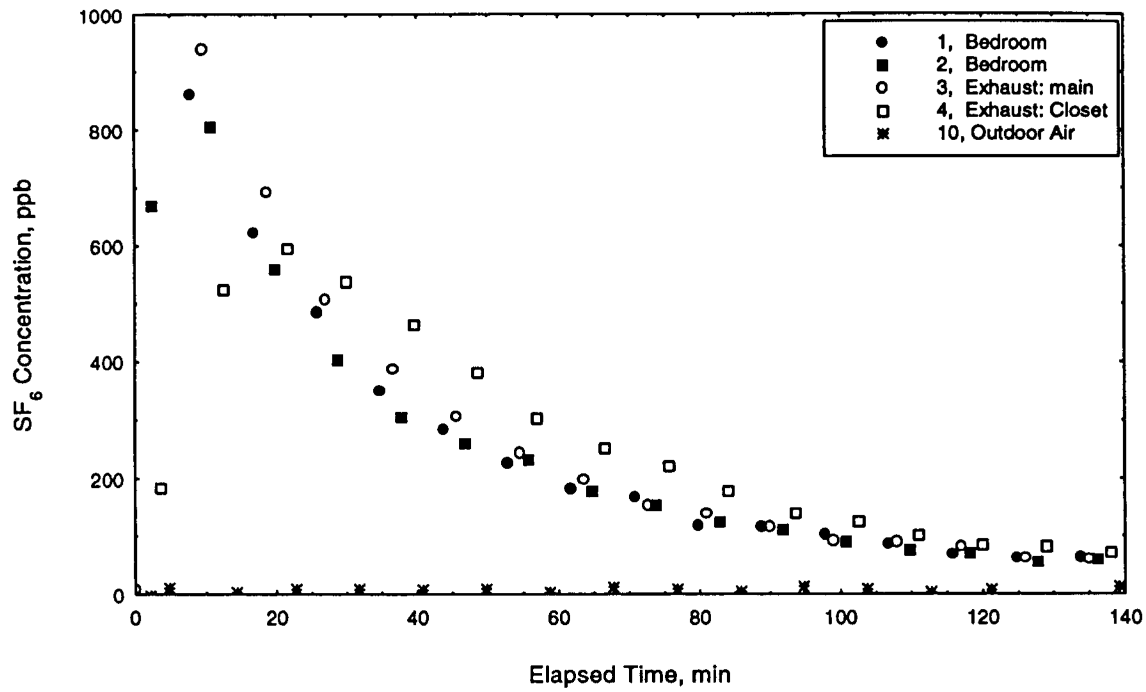


Figure 11. Measured SF_6 concentrations for test 3 (Displacement ventilation; $T_r - T_{sa} = 2.5$ °C, $Q_{sa} = 19.8$ L/s)

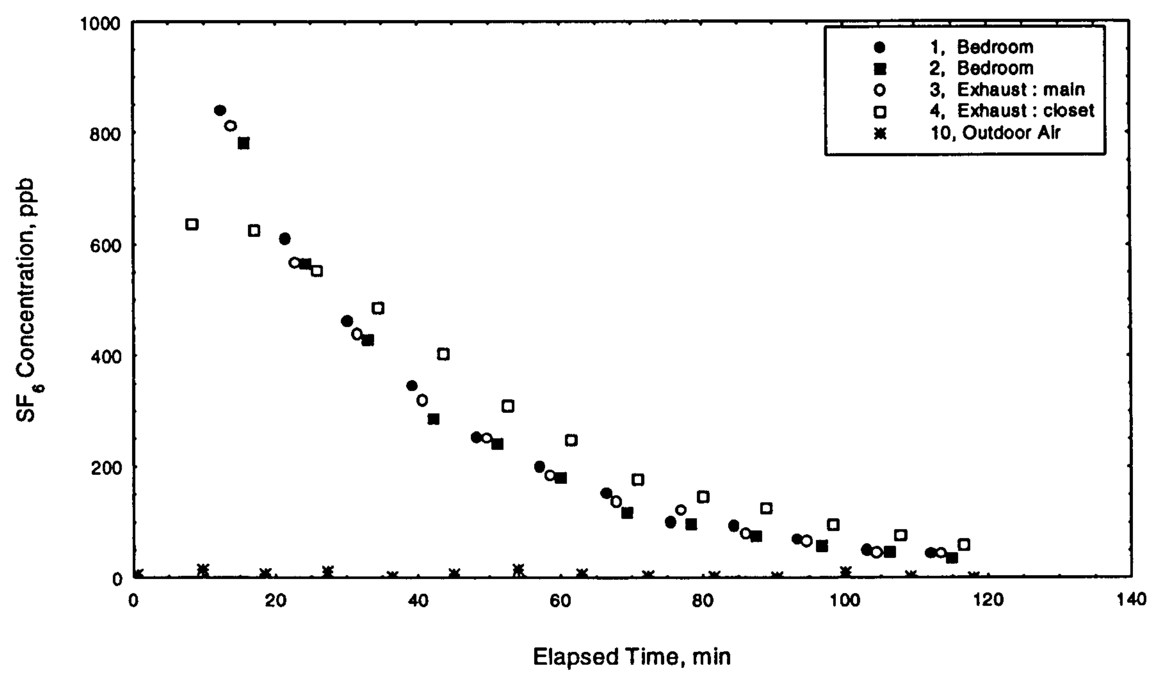


Figure 12. Measured SF_6 concentrations for test 4 (Displacement ventilation; $T_r - T_{sa} = 6.0$ °C, $Q_{sa} = 19.8$ L/s)

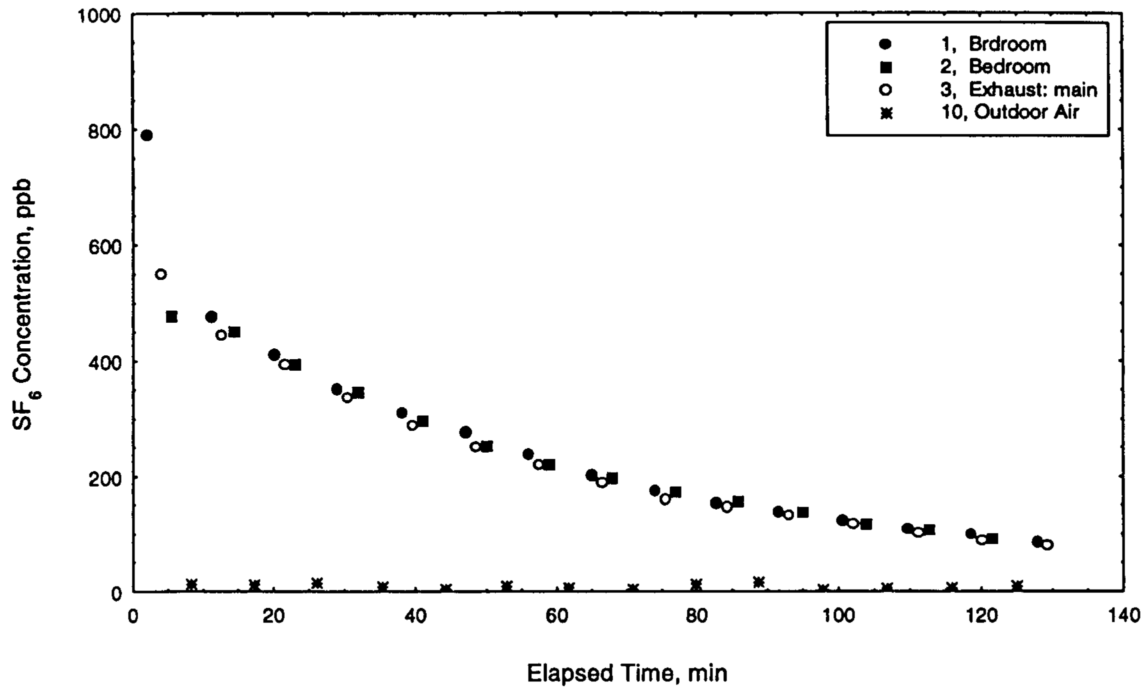


Figure 13. Measured SF_6 concentrations for test 5 (Conventional ventilation; $T_r - T_{sa}$ = 5.3 °C, Q_{sa} = 19.8 L/s)

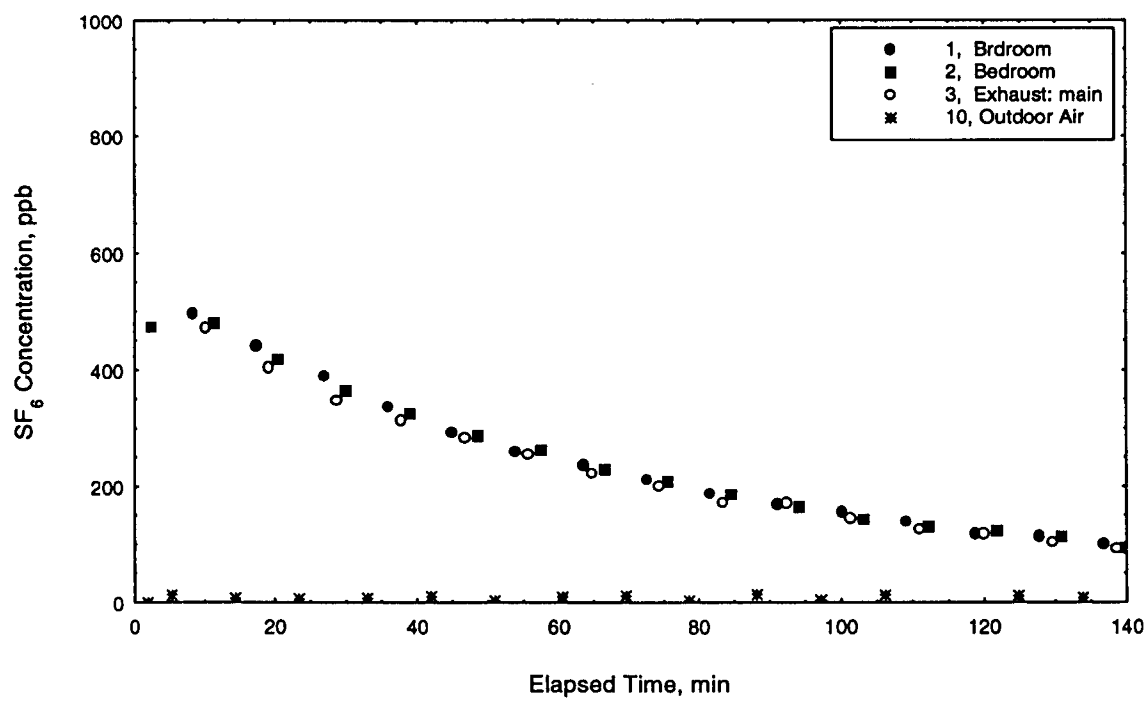


Figure 14. Measured SF_6 concentrations for test 6 (Conventional ventilation; $T_r - T_{sa}$ = 3.5 °C, Q_{sa} = 19.8 L/s)

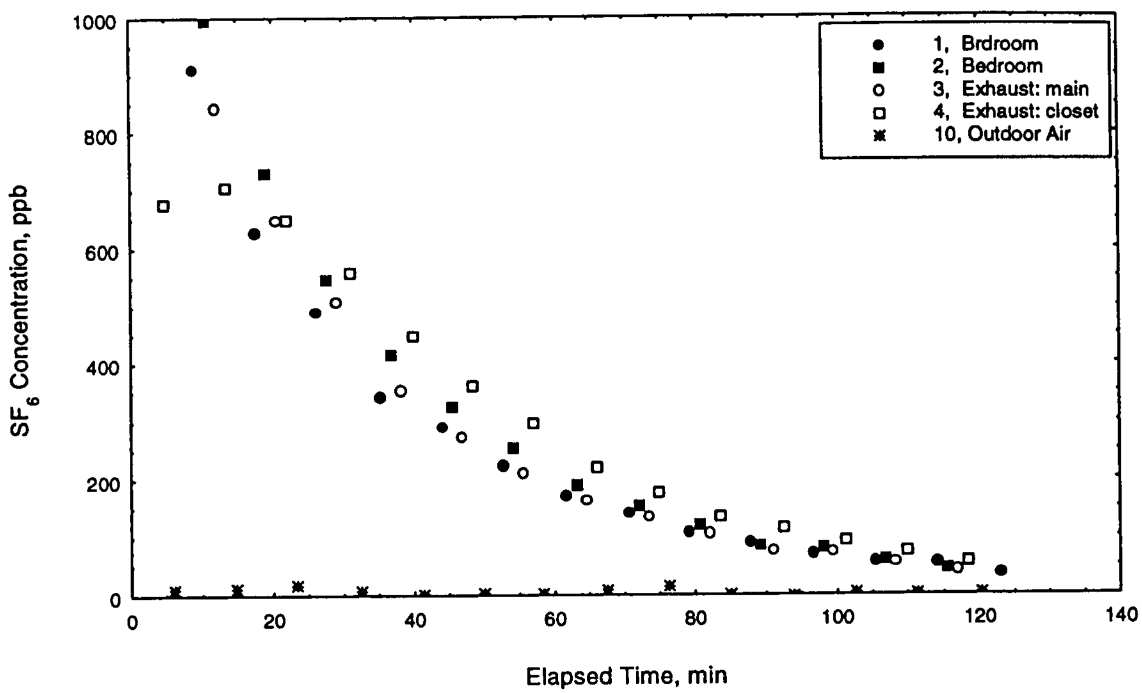


Figure 15. Measured SF_6 concentrations for test 7 (Displacement ventilation; $T_r - T_{sa} = 4.0$ °C, $Q_{sa} = 19.8$ L/s)

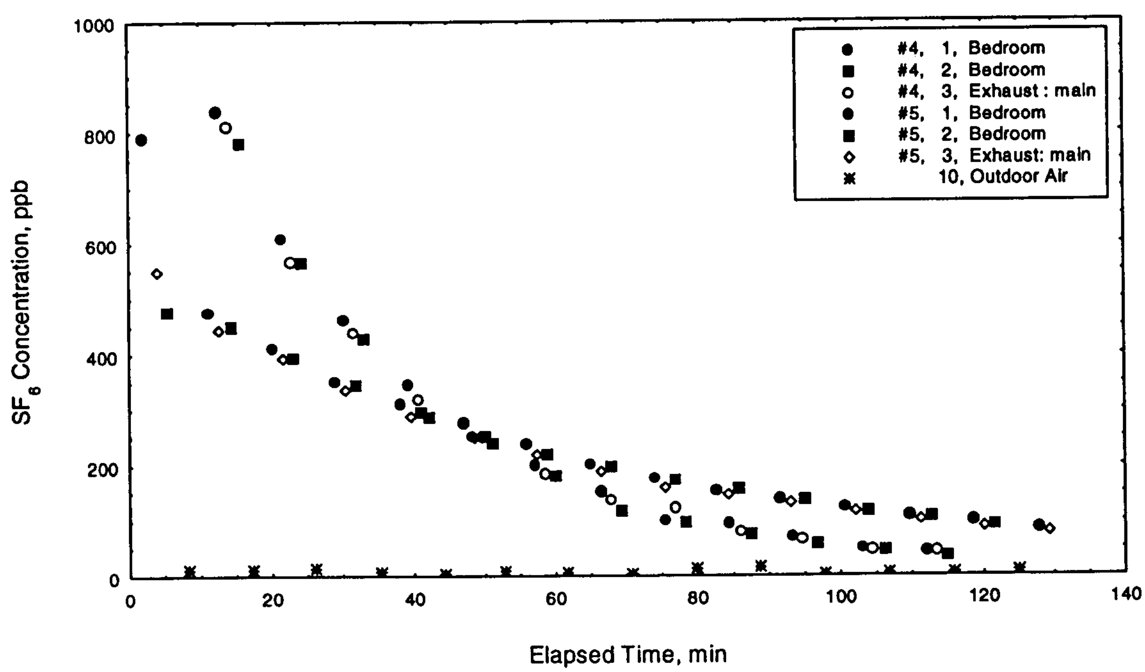


Figure 16. A comparison of measured SF_6 concentrations between Test 4 (displacement ventilation) and Test 5 (conventional ventilation)

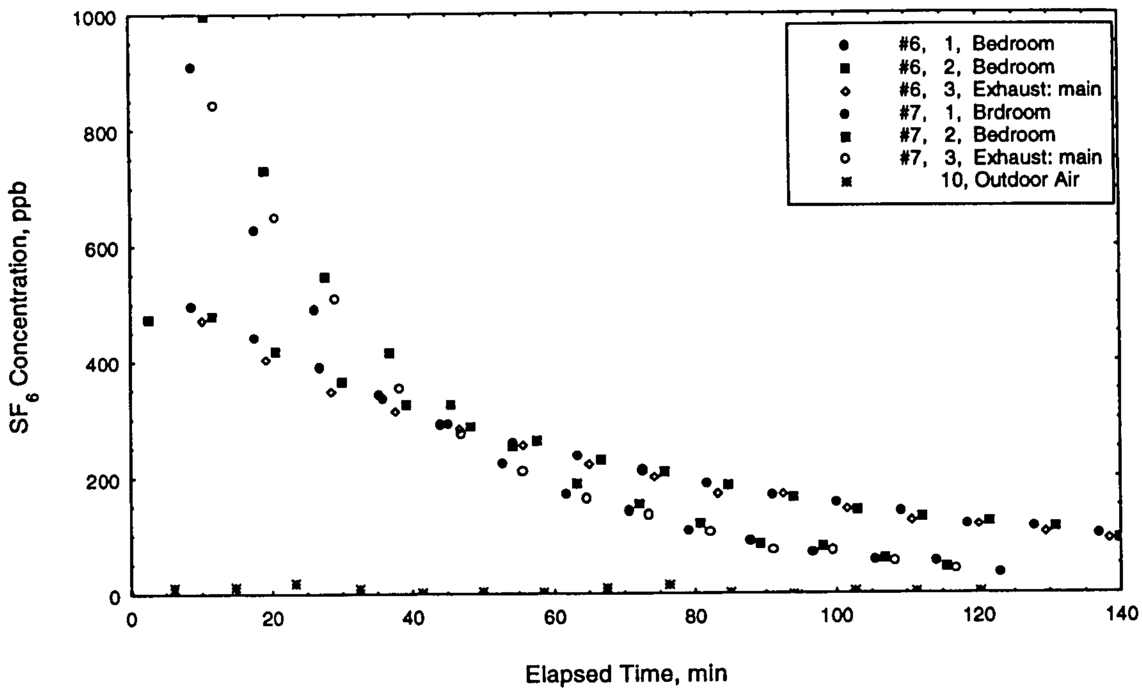


Figure 17. A comparison of measured SF_6 concentrations between Test 7 (displacement ventilation) and Test 6 (conventional ventilation)

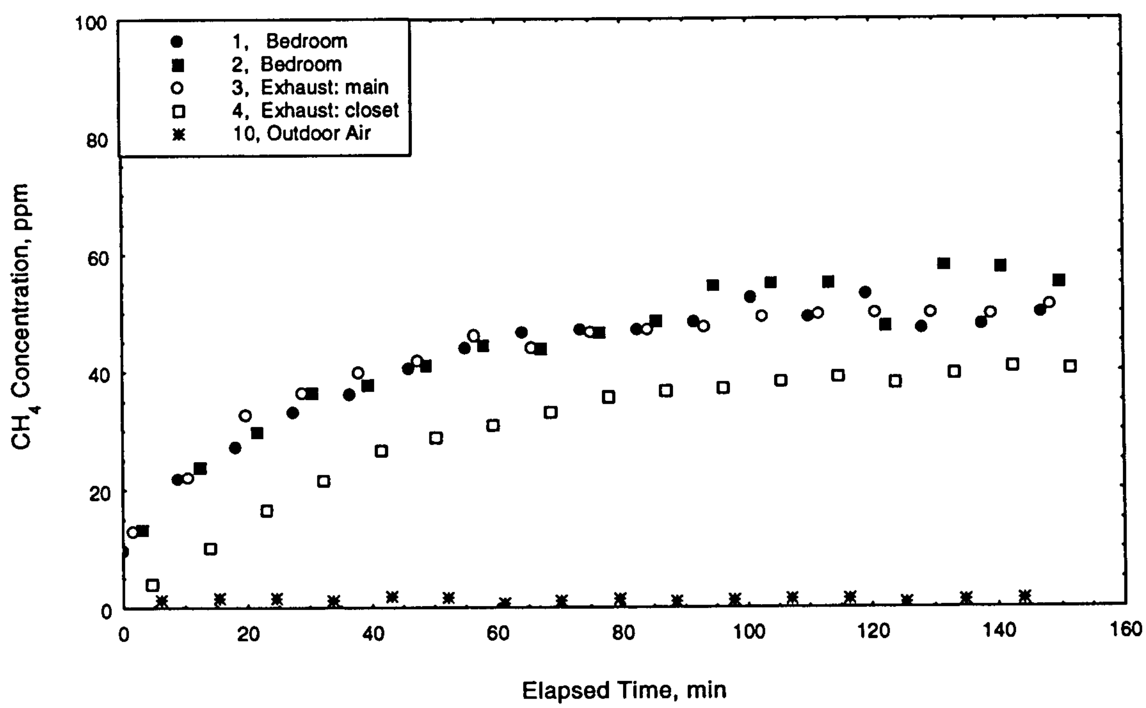


Figure 18. Measured CH_4 concentrations for test 1 (Displacement ventilation; $T_r - T_{sa} = 1.9$ °C, $Q_{sa} = 19.8$ L/s)

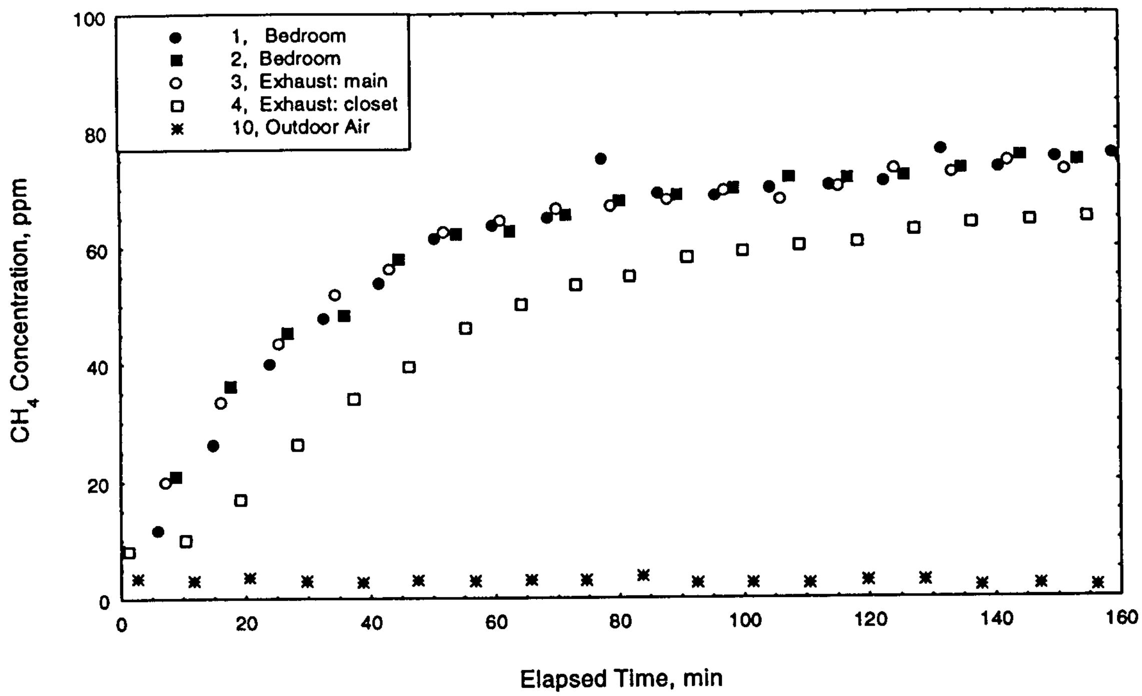


Figure 19. Measured CH_4 concentrations for test 2 (Displacement ventilation; $T_r - T_{sa} = 1.4$ °C, $Q_{sa} = 19.8$ L/s)

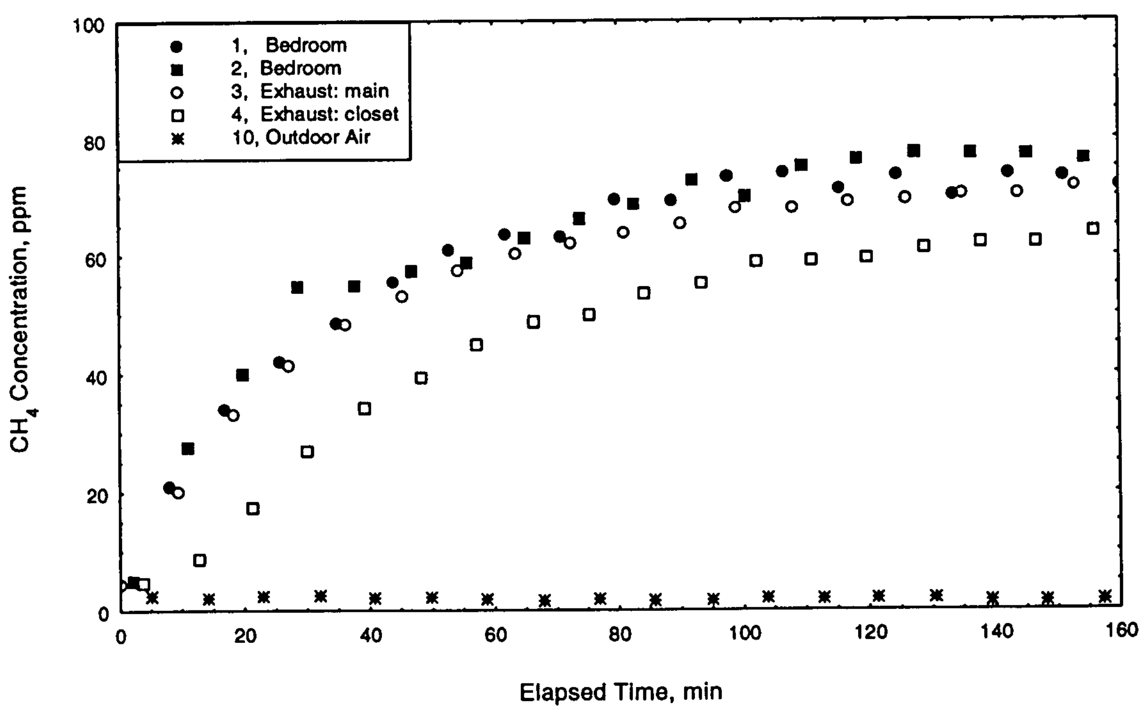


Figure 20. Measured CH_4 concentrations for test 3 (Displacement ventilation; $T_r - T_{sa} = 2.5$ °C, $Q_{sa} = 19.8$ L/s)

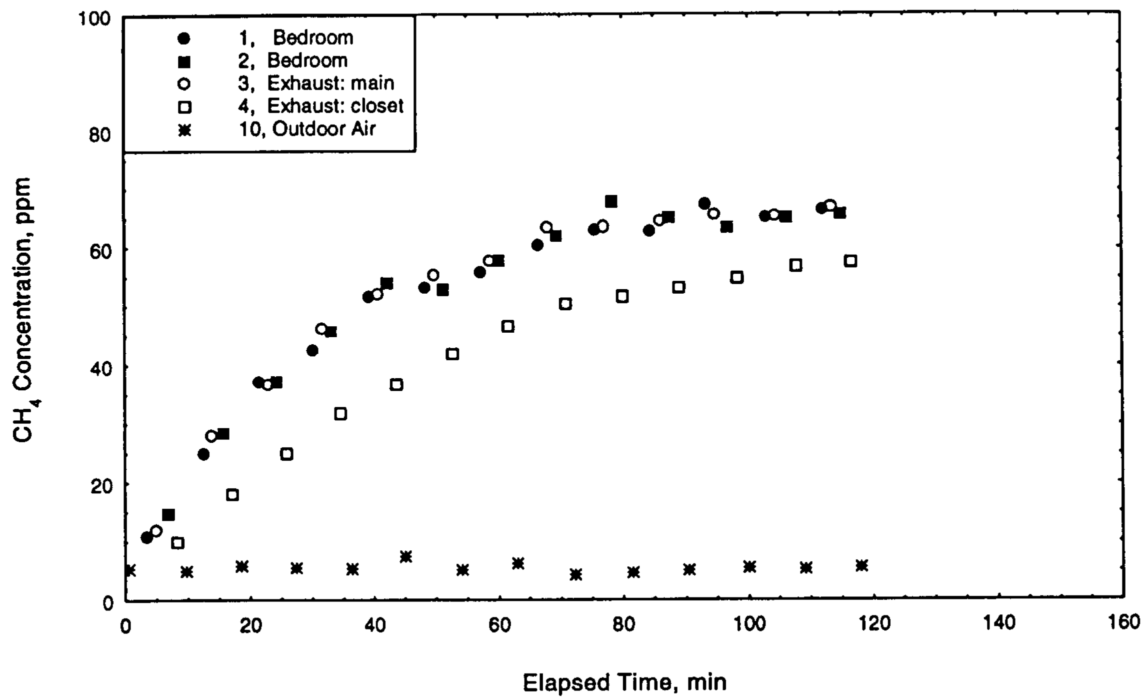


Figure 21. Measured CH_4 concentrations for test 4 (Displacement ventilation; T_r - T_{sa} = 6.0 °C, Q_{sa} = 19.8 L/s)

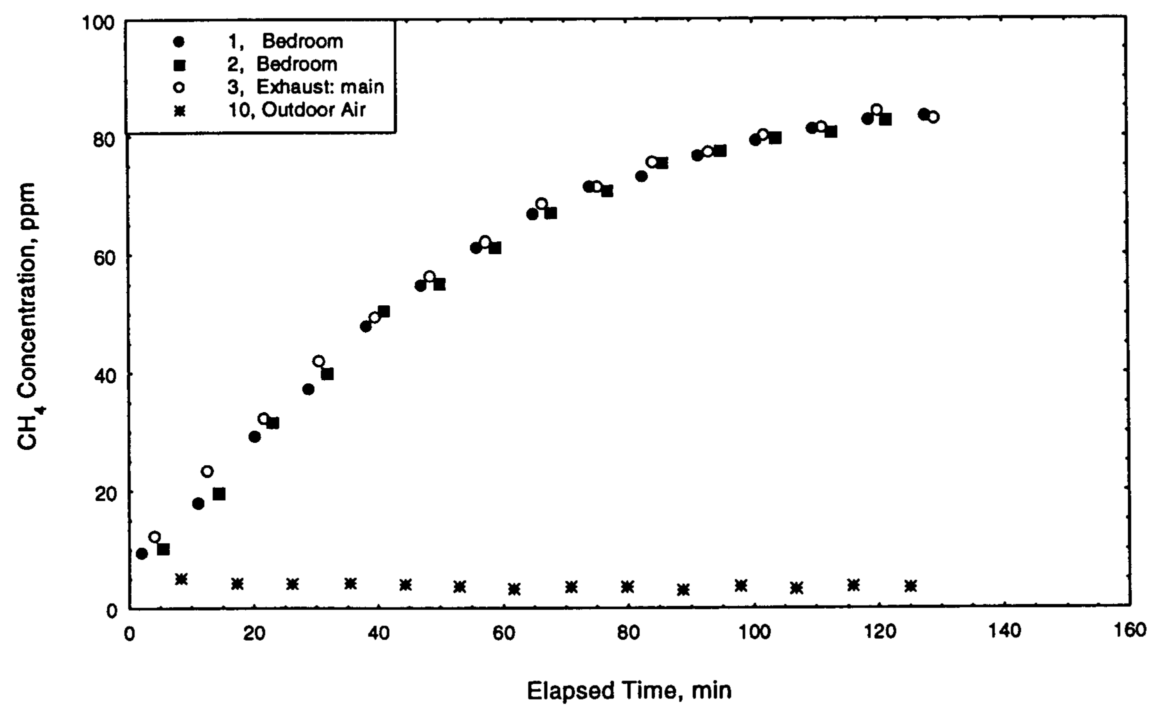


Figure 22. Measured CH_4 concentrations for test 5 (Conventional ventilation; T_r - T_{sa} = 5.3 °C, Q_{sa} = 19.8 L/s)

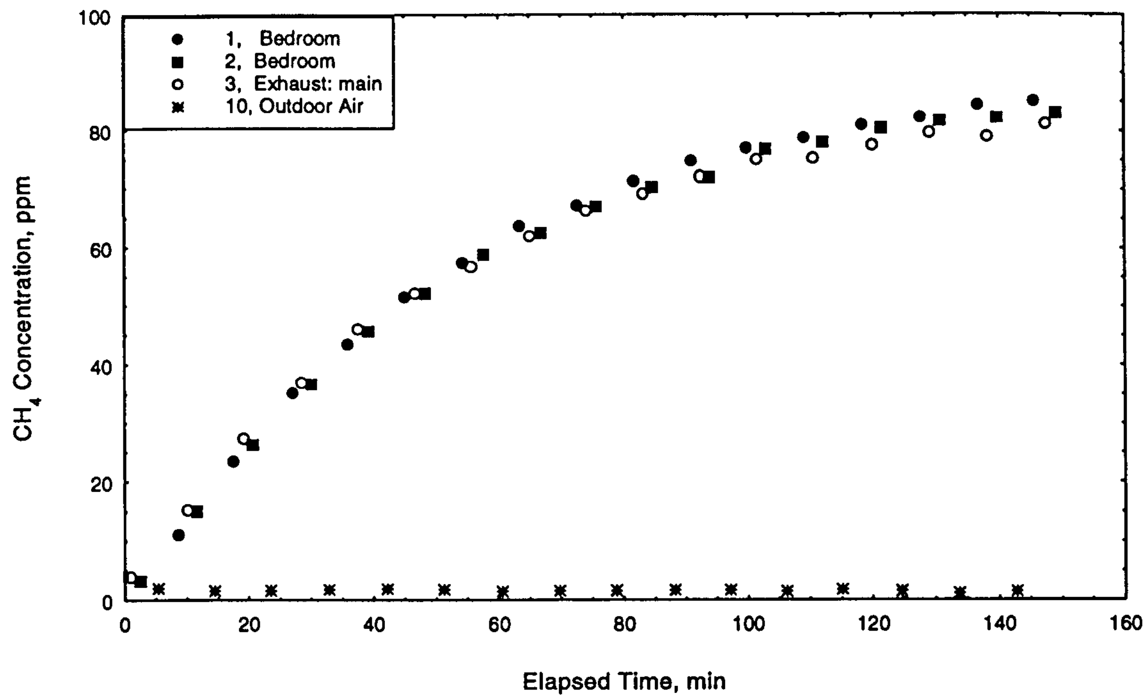


Figure 23. Measured CH_4 concentrations for test 6 (Conventional ventilation; $T_r - T_{sa} = 3.5$ °C, $Q_{sa} = 19.8$ L/s)

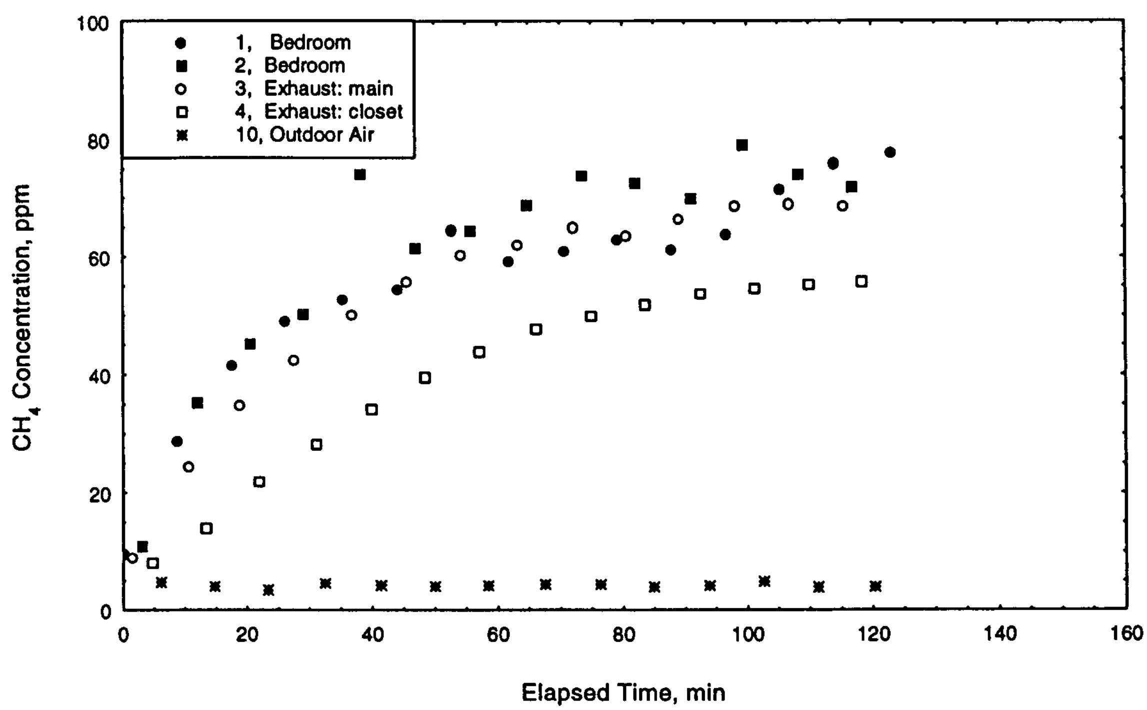


Figure 24. Measured CH_4 concentrations for test 7 (Displacement ventilation; $T_r - T_{sa} = 4.0$ °C, $Q_{sa} = 19.8$ L/s)

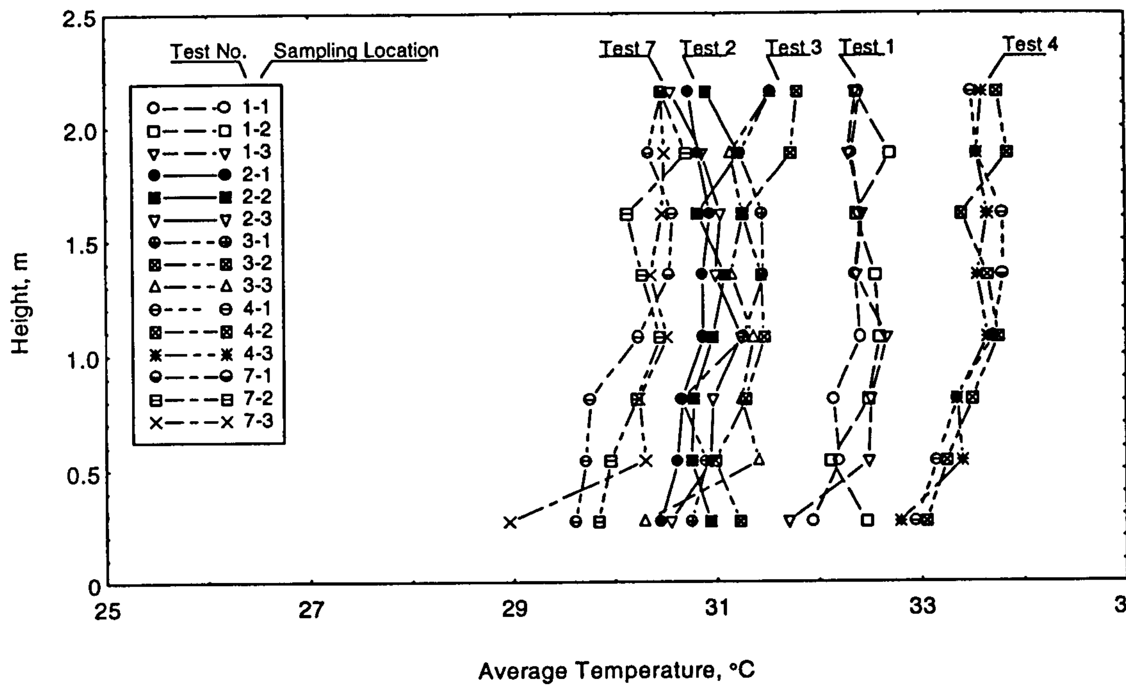


Figure 25. Measured vertical temperature profits for the displacement ventilation system

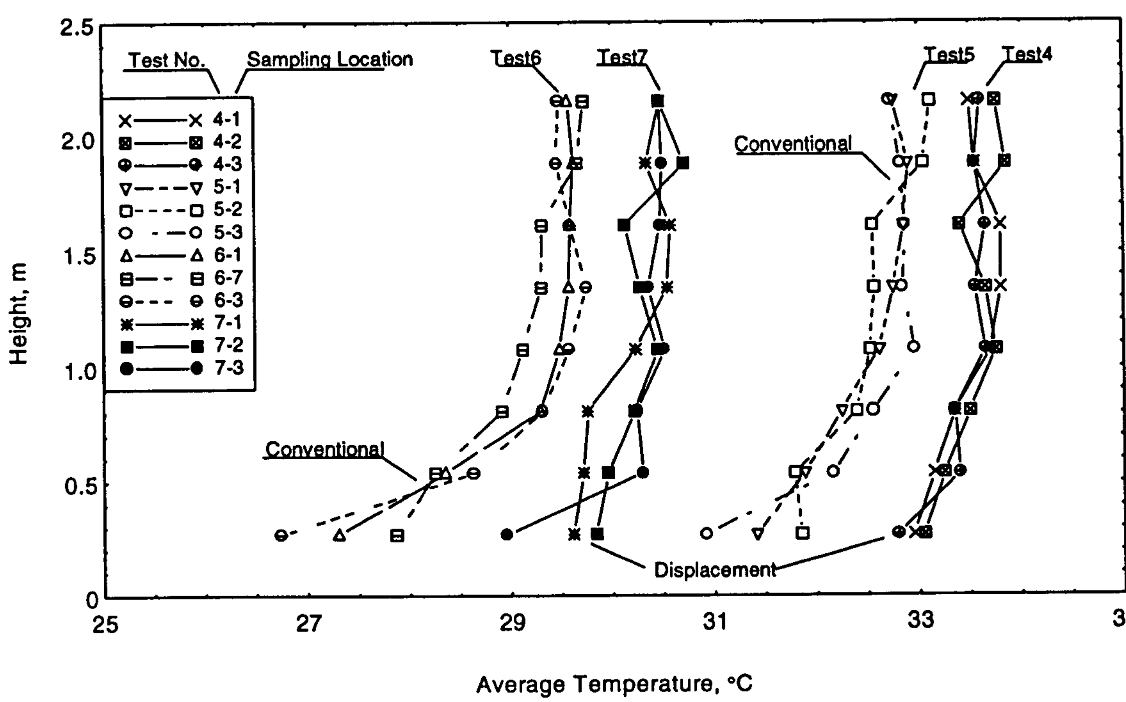


Figure 26. Measured vertical temperature profits for the displacement (Test 4, 7) and conventional (Test 5, 6) ventilation system

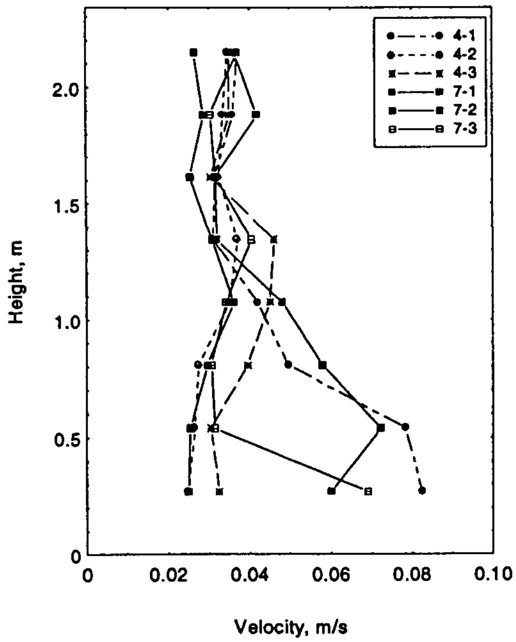


Figure 27.a. Velocity distribution in the displacement ventilation system (test 4, 7)

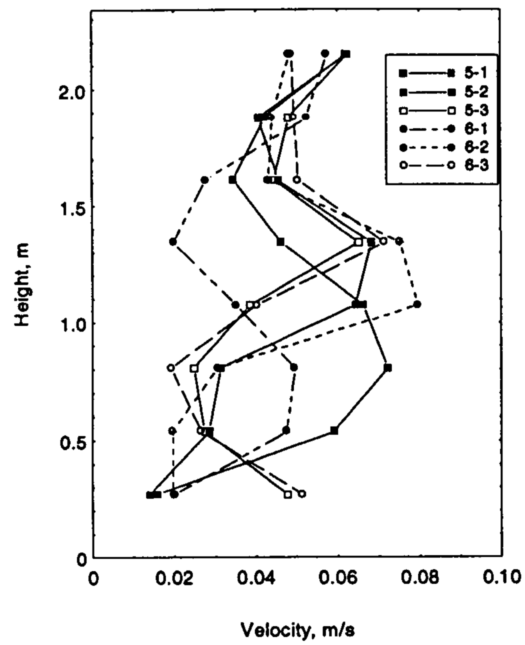


Figure 27.b. Velocity distribution in the conventional ventilation system (test 5, 6)

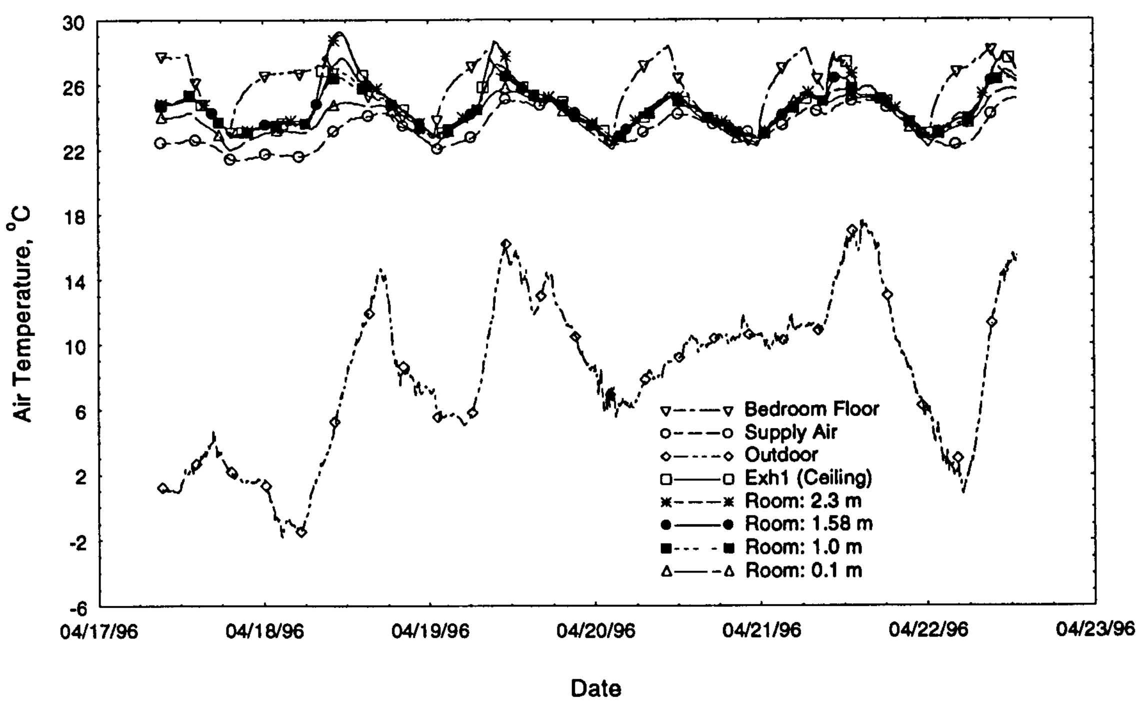


Figure 28.a. Measured temperature variations with time

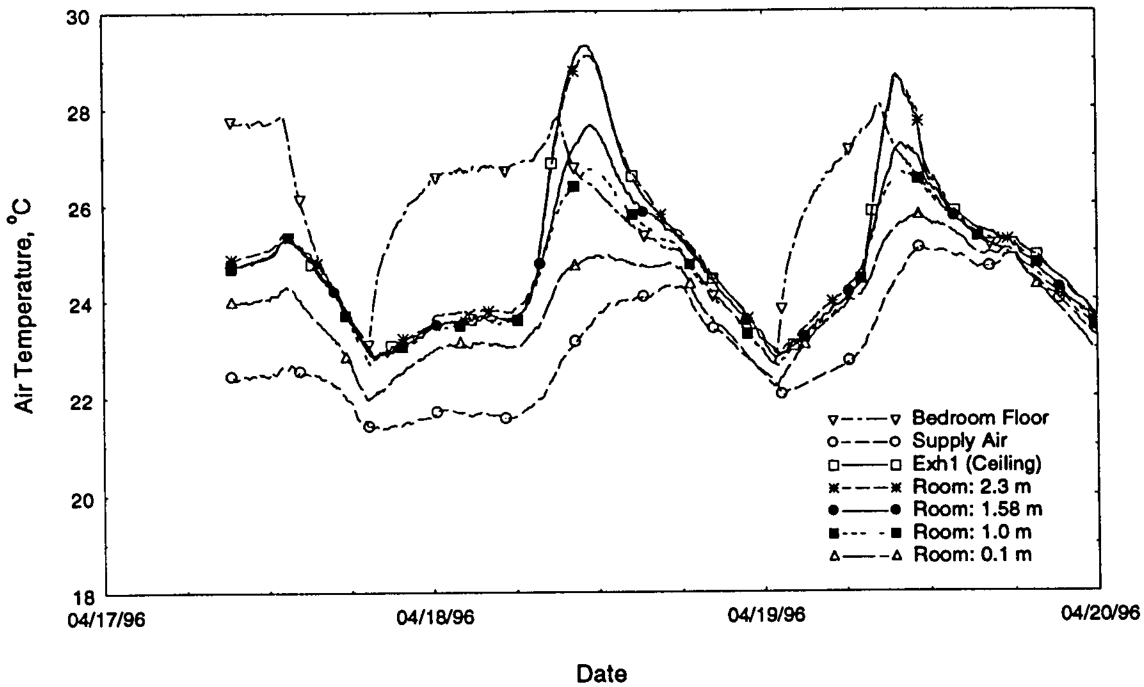


Figure 28.b. Measured temperature variations with time — a close up

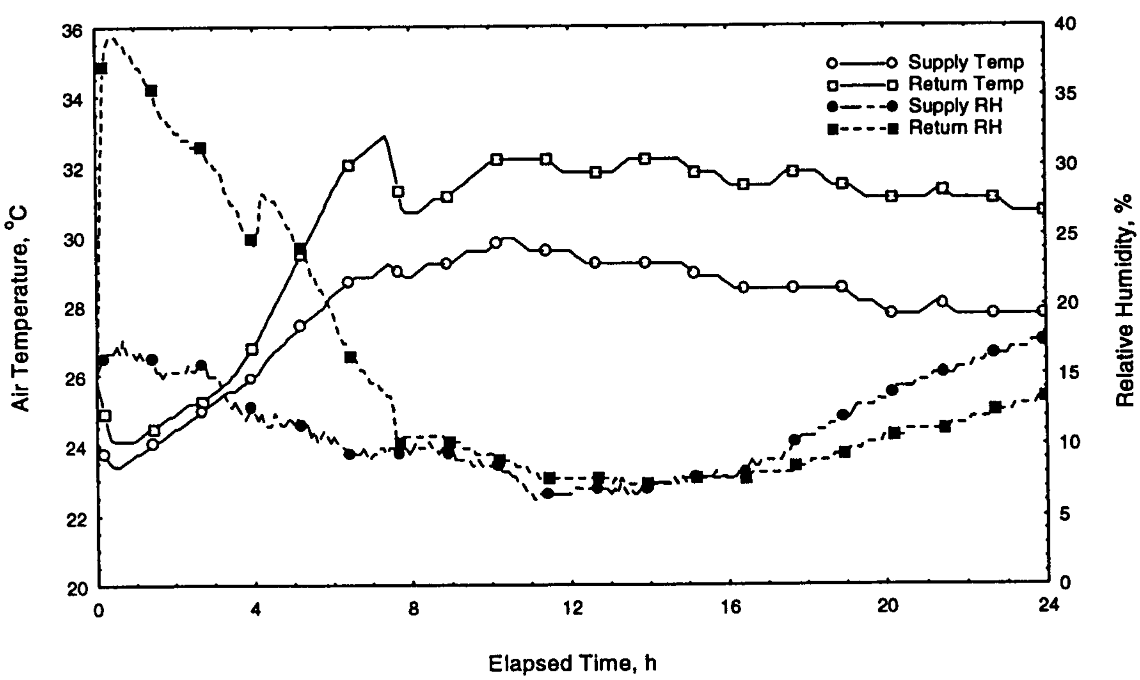


Figure 29. Measured temperatures and relative humidities during the drying closet test