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PASSIVE VENTILATION TO MAINTAIN INDOOR AIR QUALITY

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EXTENDED SUMMARY

Objectives and Background

This report describes the results of a three year project that made direct measurements of the effectiveness of passive ventilation from strategically placed air inlets and exhaust outlets on houses. The feasibility of using passive ventilation was studied to provide a simple maintenance-free alternative to the mechanical ventilation systems that are required by CSA and ASHRAE standards to maintain acceptable indoor air quality for occupants.

Before ventilation standards for indoor air quality were introduced by ASHRAE and CSA in 1989, the only ventilation requirements were to provide sufficient combustion make-up air for gas and oil fired furnaces and water heaters, and to have a furnace flue to exhaust combustion products. Fortunately, the combination of a combustion air intake and a furnace flue exhaust was usually enough to provide adequate ventilation for indoor air quality. However, during spring and fall when outdoor air is cold enough for occupants to keep windows closed, there is often insufficient natural ventilation and combustion air make-up to provide adequate ventilation. In these spring and fall shoulder seasons the conventional wisdom has been that occupants are intelligent enough to open windows when indoor air becomes "stuffy". Unfortunately, the regulators who developed the Canadian standard make no allowance for occupant intelligence (or passive ventilation) and require all fresh air to be provided by mechanical supply and exhaust fans.

The current ASHRAE standard for residential ventilation requires an overall exchange rate of 7.5 liters per second for each occupant, or a total building rate of 0.35 air changes per hour (ACH). The fresh air may be provided by a combination of natural ventilation through the building envelope, and mechanical ventilation from exhaust and supply fans. For houses with ventilated basements the ASHRAE requirement of 7.5 liters per second per person can be met by 0.2 to 0.3 ACH when the basement is included in the active air exchange volume.

The CSA standard is much more restrictive, and requires an air exchange rate of 0.3 ACH **provided by mechanical ventilation alone,** with no credit given for natural ventilation through passive inlets, and air infiltration through building envelope leaks. The present study was undertaken to determine if passive ventilation is a viable alternative to the mechanical ventilation system required by the CSA standard.

Passive Ventilation Measurements

The original experimental design was the essence of simplicity. A few intelligently placed holes were to be located on four of five test houses of the Alberta Home Heating Research Facility. Tracer gas measurements would then be used to monitor the total house ventilation rate, and dampers would control the flow area of the passive inlets. Measurements taken over a three

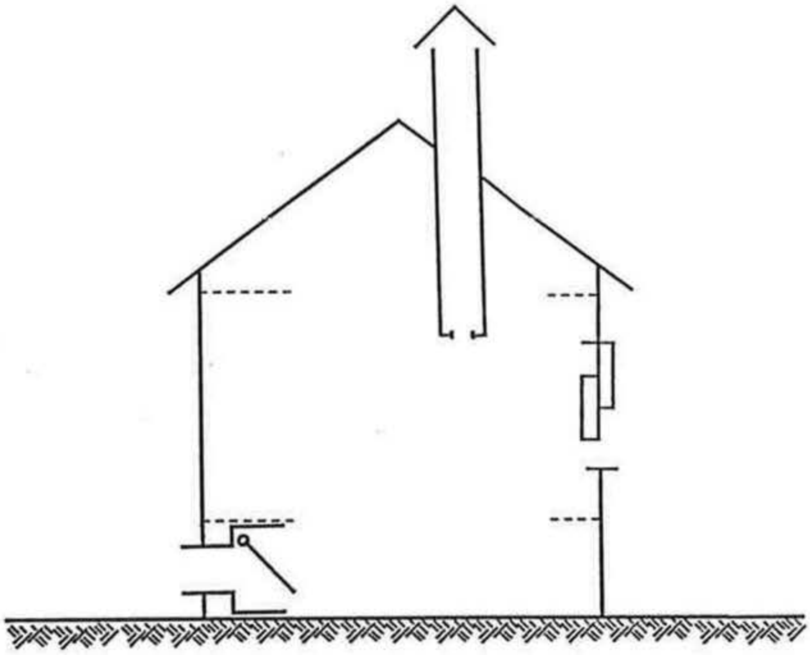
year period would be used to suggest the best locations for passive ventilation inlets and exhausts. The measurements could also be used to develop control strategies to vary passive ventilator flow areas to prevent excessive air flow and energy use during the winter heating season when the stack effect of the warm air in the house increases passive ventilation and infiltration rates.

One of the key variables in determining passive ventilation effectiveness is the shelter provided by nearby houses on the passive ventilation openings. The test houses of the Alberta Home Heating Research Facility are arranged in a closely spaced east-west row with exposed north and south walls, and sheltered east and west walls. To investigate various passive ventilation alternatives the following five house configurations were tested:

- **House 1**: with a passive vent intake near ground level on the exposed south wall, a narrow window slot with the same effective flow area as the passive vent on the sheltered west wall, and a furnace flue pipe extending above roof level to act as an exhaust.
- **House 2**: with a passive inlet near ground level on the exposed south wall, an intermittently operated exhaust and supply fan to provide 0.2 ACH of background mechanical ventilation, and an open furnace flue to act as a passive and mechanical ventilation exhaust.
- **House 3**: with a passive ventilation intake near ground level on the exposed south wall, no flue, and exhaust through an open window with an effective flow area about 25% of the passive ventilation intake area.
- **House 4**: with no passive intakes, allowing natural background leakage and an open furnace flue to act as a reference for comparison purposes.
- **House 5**: with a passive ventilation inlet on the exposed south wall, an exhaust opening with about 25% of the passive intake area on the sheltered east wall, and a furnace flue as the primary passive exhaust.

Electrically operated dampers were used to cycle the passive ventilation inlets on the south walls through open and closed cycles over 4 hour, 6 hour and 24 hour periods. Construction details and ventilation characteristics of the five houses are summarized in the data sheets of Figures S-1 to S-5.

Figure S-1
Infiltration and Ventilation Characteristics
Masonry Unit 1



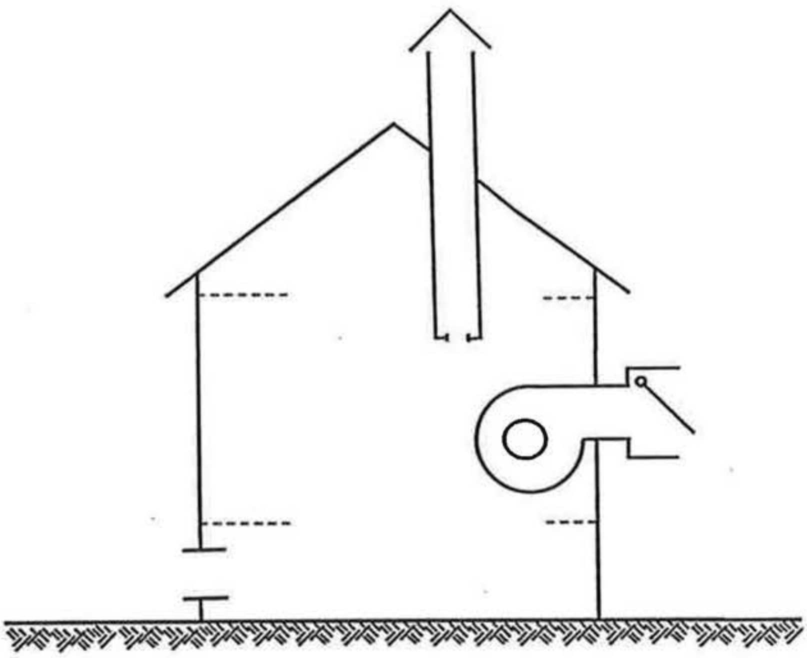
Envelope Construction and Distributed Leakage

The Masonry Unit had double wall construction with foamed-in-place urethane insulation between an inner concrete block wall and an outer wall of clay brick. The foamed-in-place insulation provides a tight seal around 5 windows, door, 13 electrical conduit pipes, and along the top of the basement wall. The inside of the concrete block wall has 8 surface mounted electrical outlet boxes. The major ceiling leakage sites consist of electrical conduit penetrations for 3 fluorescent light fixtures, and a 1 cm wide annular crack around the 20 cm O.D. flue pipe. The 15.2 cm inside diameter flue pipe had a 7.6 cm diameter restriction orifice at the bottom and a rain cap at the top. The restrictor orifice maintains the ratio of flue flow area to floor area about the same as a full sized house. With a distributed leakage area of 28.9 cm^2 envelope of the masonry unit had the tightest construction of all test houses.

Ventilation Configurations

A motorized damper on the passive ventilation intake pipe was operated in a 24 hour open/closed cycle at 12:00 (noon) each day. The flue exhaust pipe was equipped with a flow meter on the 7.6 cm diameter restriction orifice to continuously monitor exfiltration. The west sliding window was kept open to form a permanent slot with 1.1 cm width and 87.5 cm height. The neutral pressure level often passed across this window slot to produce counterflowing infiltration and exfiltration at the bottom and top of the slot.

Figure S-2
Infiltration and Ventilation Characteristics
Retrofit Unit 2



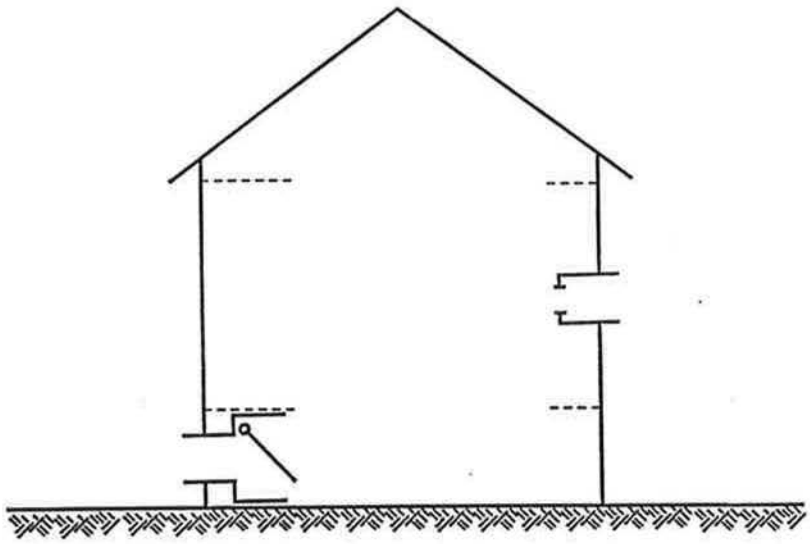
Envelope Construction and Distributed Leakage

The Retrofit Unit walls were insulated with fibreglass batts between 2x4 studs on 40.6 cm centers. The outside walls were covered with retrofitted 5.0 cm thick styrofoam board insulation behind the exterior plywood sheathing. A polyethylene vapour barrier behind the gypsum board interior walls passed under the bottom of the wood frame walls, and behind the exterior sheathing to cover the crack between the concrete basement wall and the wood frame wall above it. End plates over the floor joists had 7 penetrations for electrical conduits and for the sump drainage pipe. The vapour barrier was penetrated in 8 locations for electrical outlets in the walls, and by electrical terminal boxes for 3 fluorescent fixtures in the ceiling. The 20 cm O.D. flue pipe penetrating the ceiling had a 1 cm wide unsealed crack around it where it passed through the gypsum board ceiling.

Ventilation Configurations

The passive ventilation inlet pipe was kept permanently open, and a 7.6 cm restriction orifice on a flow meter was attached to the bottom of the flue. A mechanical ventilation fan mounted on a panel over the east window opening was operated in both supply and exhaust modes on 4 hour or 6 hour on-off cycles. When the fan was off the 3.33 cm diameter restriction orifice on the fan inlet pipe acted as a small local leakage site on the east window location.

Figure S-3
Infiltration and Ventilation Characteristics
Conservation Unit 3



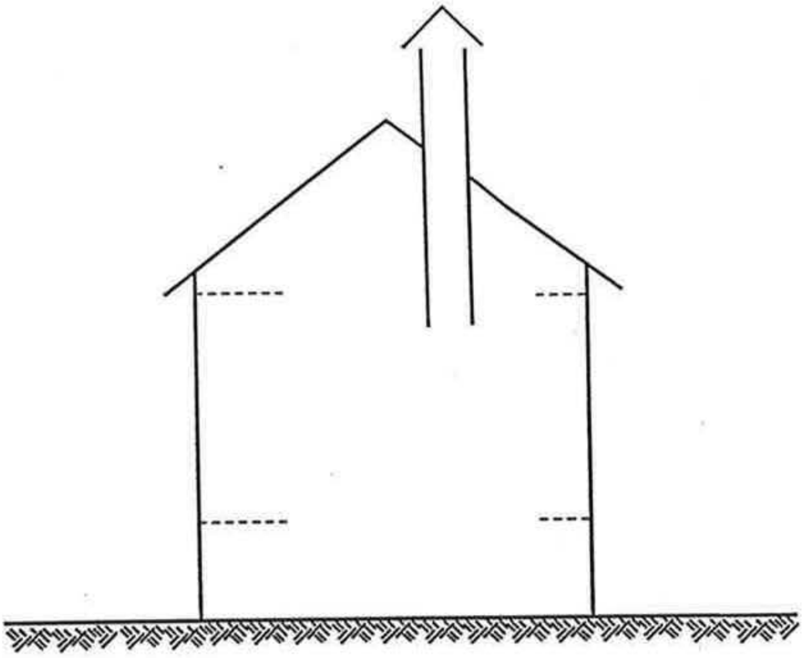
Envelope Construction and Distributed Leakage

The Conservation Unit used unconventional construction, with a polyethylene vapour barrier mounted on the outside of the uninsulated 2x4 stud wood frame wall to avoid penetrations of the vapour barrier by electrical outlets. Two layers of styrofoam board, each 10 cm thick, were glued in place with overlapping seams on the outside of the 2x4 stud wall, and then covered with exterior plywood sheathing. The basement walls were insulated with a single layer of styrofoam board 10 cm thick over the full height of the wall. The crack between the basement and wood frame walls was sealed by the exterior vapour barrier. The conservation unit was the only house with no flue pipe. The end plates on the floor joists had 7 penetrations for electrical conduit pipes and the basement sump drain.

Ventilation Configurations

A motorized damper on the passive ventilation inlet pipe operated in a 24 hour open/closed cycle, at 12:00 (noon) each day. The other passive ventilation site was a 7.6 cm diameter restriction orifice mounted in a panel over the fully open east side window of the house.

Figure S-4
Infiltration and Ventilation Characteristics
Solar Unit 4



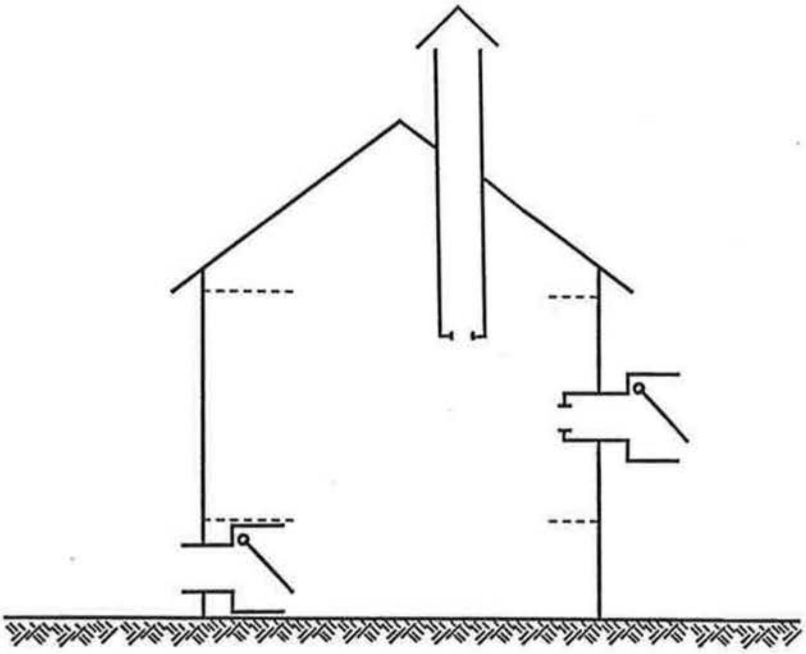
Envelope Construction and Distributed Leakage

The distinguishing feature of the Solar Unit was a south wall filled with six 0.9m wide by 1.8m high sealed double panel windows. The cracks around and between the window frames caused a significantly asymmetrical wall leakage distribution, with the majority of leakage on this south wall. The polyethylene vapour barrier on the inside of the wood frame walls had penetrations for 8 electrical outlets. There were no penetrations for ceiling fluorescent fixtures, so the only local ceiling leakage site was a 1 cm crack around the 20 cm O.D. flue pipe where it passed through the ceiling. The polyethylene vapour barrier passed under the bottom of the wood frame wall and behind the exterior sheathing to cover the crack between the concrete basement and the floor joists. The endplates on the floor joists had 7 penetrations for electrical conduits and the drain for the basement sump.

Ventilation Configurations

The Solar Unit was used to test ventilation in a house with two sizes of flue pipe, but without passive ventilation inlets. The passive ventilation inlet pipe was permanently sealed with a flange, and all windows were kept closed. The flue configuration was varied between an open 15.2 cm inside diameter unrestricted pipe and a 7.6 cm diameter orifice on a flow meter at the bottom of the flue. The unrestricted flue pipe had about 150% times the distributed envelope leakage area. With a restriction orifice in place, the flue had a leakage about 50% of the distributed envelope leakage.

Figure S-5
Infiltration and Ventilation Characteristics
Reference Unit 5



Envelope Construction and Distributed Leakage

The Reference Unit was constructed with typical 1980 residential housing standards. The 2x4 wood frame walls were insulated with fibreglass batts, with a polyethylene air-vapour barrier behind the gypsum board interior walls and ceiling. The only unconventional construction detail was to pass the air-vapour barrier under the floor of the wood frame wall, and carry it down over the joists to seal the crack at the top of the concrete basement wall. The box surrounding the floor joists had 7 penetrations for electrical conduit pipes and the sump drain pipe. The vapour barrier had 8 interior penetrations for electrical boxes in the walls, and 3 electrical boxes in the ceiling to serve the fluorescent light fixtures. The major ceiling leakage site was the 1 cm wide circular crack around the 200 cm O.D. flue pipe as it passed through the ceiling.

Ventilation Configurations

In the Reference Unit the three passive ventilation leakage sites were all equipped with flow meters to allow the distribution of ventilation flow rates to be measured. The passive ventilation inlet pipe was calibrated as a flow meter and operated for two heating seasons on a 4 hour open/closed cycle at 12:00 hours noon each day. For the last season of operation this was changed to a 24 hour open/closed cycle. A 7.6 cm diameter restriction orifice at the bottom of the flue pipe was monitored as a flow meter. The east window was fully open and connected to a metered 7.6 cm diameter orifice mounted on a pipe installed in a panel over the window.

After collecting the first year of data it became painfully obvious that the experiment had a major flaw. Passive ventilation was found to be strongly dependent on wind direction, with changes as large as a factor of four as the wind shifted from blowing directly on the exposed north and south walls to east and west winds along the sheltered line of houses. To study the influence of wind and temperature effects this sensitivity to wind direction required passive ventilation measurements to be sorted into narrow bins of relatively constant wind direction. This meant that with 16 different wind directions, an adequate selection of passive ventilation control strategies would require at least 10 years of continuous data to provide a sufficient number of points in each of the wind direction bins for a wide range of wind speed and temperature difference. Clearly, this was impossible.

To make more efficient use of the limited data set that could be collected over a three year period, it was decided that a computer model would be developed to predict combined passive ventilation and natural infiltration through background leakage. The computer model would then be used to test the feasibility of various passive ventilation strategies. The measurements at the test houses were used to refine and validate the ventilation computer model, rather than as direct estimates of passive ventilation effectiveness. To meet the need for a large number of measurements in each of 16 different wind directions, the passive ventilation configurations at the test houses were maintained in fully-open or closed state for periods of 12 to 24 hours. This computer modelling approach had the added advantage of allowing different types of construction and wind shelter to be studied, so that passive ventilation strategies could be developed for both single and two storey houses as well as row houses in town-house complexes.

Computer Model for Passive Ventilation

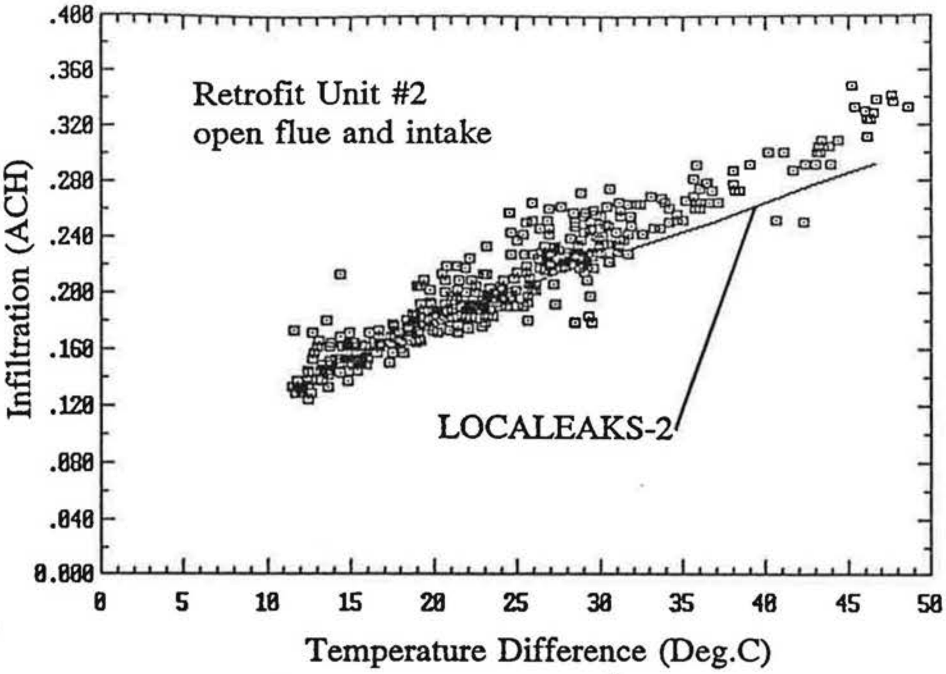
The flow through local leakage sites and passive ventilation intakes and exhausts is a non-linear process that depends (approximately) on the square root of the indoor-outdoor pressure difference across the leak. This indoor-outdoor pressure difference depends on wind speed, local wind shelter, and indoor-outdoor temperature difference. The computer model LOCALEAKS-2 determined the flow through distributed envelope leakage and intentional passive ventilation openings by first calculating the wind pressure on the exterior surfaces of the building. Several wind tunnel data sets measured by other investigators were used to determine wall and roof pressure coefficients for estimating this outdoor wind pressure. Adjustments were made to these wind effect pressures to account for local shelter from upwind buildings and obstacles. The indoor-outdoor temperature difference was used to add a stack effect pressure to the wind pressure. Then, a first guess was made for the indoor air pressure, and flow rates through the distributed leaks and each of the inlet and outlet ventilation openings were calculated. The total inflow was subtracted from the total outflow through all sites, and if the flows did not balance a new indoor air pressure was estimated and the process repeated until inflow and outflow rates balanced.

This computer model was based on EXACTAIM, a distributed leakage model used by Walker and Wilson (1990) to develop the Alberta Air Infiltration Model AIM-2. In order to accurately estimate passive ventilation EXACTAIM was modified to include changes in wind pressure coefficients with wind direction, and to provide realistic estimates of wind shelter effects in the downwind wakes of nearby buildings. Considerable effort was devoted to testing LOCALEAKS-2 over a wide range of ventilation locations, wind directions, and relative wind speed and temperature difference effects. The model was tested against air infiltration and passive ventilation data from all five test houses. In this extended summary, we will focus on a single house, Retrofit Unit #2 in its passive ventilation configuration. For these tests, the ground-level intake pipe on the south wall was open, and a standard domestic gas furnace flue with a 7.6 cm diameter restrictor orifice acted as the passive ventilation exhaust. The passive inlet pipe formed 36% of the total envelope flow leakage area, the flue with restrictor orifice contributed 20%, and the remaining 44% was distributed background leakage from vapour barrier holes, and cracks around the door, windows, ceiling and floor.

LOCALEAKS-2 requires an estimate of the fraction of distributed background leakage in each of the four walls, the ceiling, and at floor level. For Retrofit Unit #2 we estimated that 20% of the leakage was in the east wall, 20% in the west wall, 20% in the ceiling, and 20% at floor level. The north and south walls had no windows or doors and were each assigned 10% of the background leakage. Fortunately, the ventilation rate predictions were relatively insensitive to these rough estimates for background leakage, and changing any wall from 20% to 10% caused only a few percent change in total flow.

Passive ventilation measurements taken over a two year period were sorted to select hourly periods where passive ventilation was dominated by stack-effect, and a second set dominated by wind-effect. Figure S-6 shows a comparison of model predictions for 428 hours of stack-effect dominated flow with indoor-outdoor temperature differences larger than 10C and windspeeds less than 5.4 km/h. The agreement with LOCALEAKS-2 predictions is good, with an underprediction bias error of only -5%, and a root mean square "paired" scatter error of ±9% with bias removed from each hourly prediction.

Figure S-7 presents a comparison of model predictions with 902 hours of wind-effect dominated flow. This wind-dominated data was sorted to include windspeeds from 7.2 to 28.8 km/h, all with indoor-outdoor temperature differences less than 10C. Again, the model was in



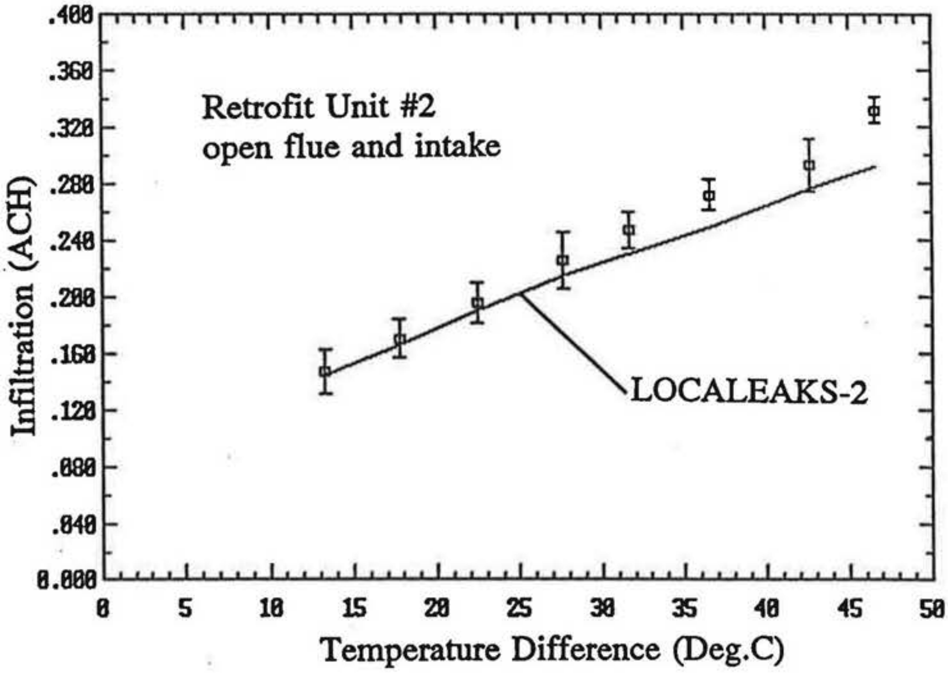
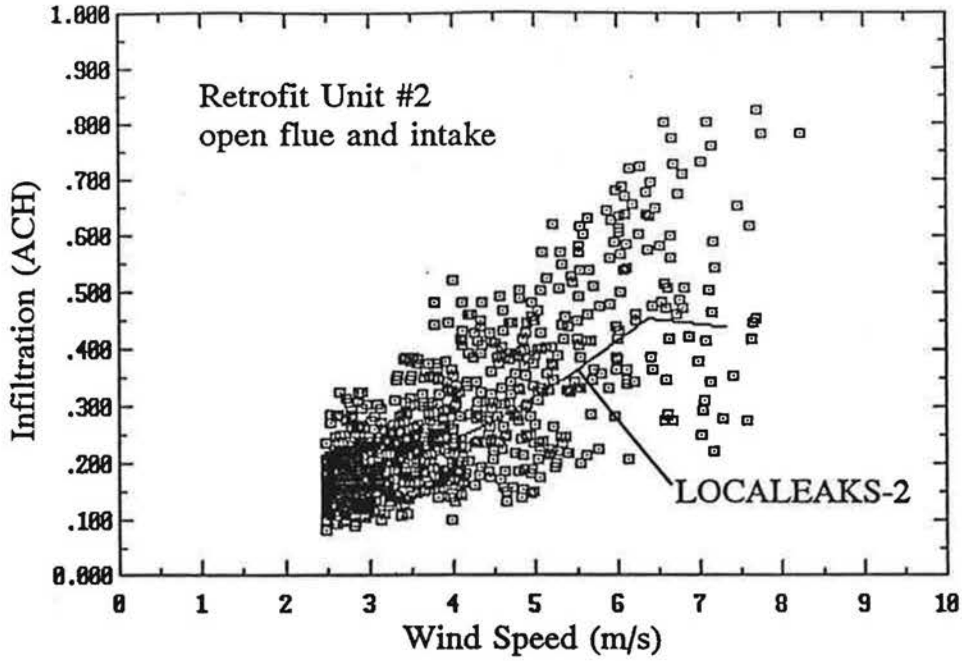


Figure S-6 Stack-effect passive ventilation of Retrofit Unit #2 with open flue and ground level intake pipe



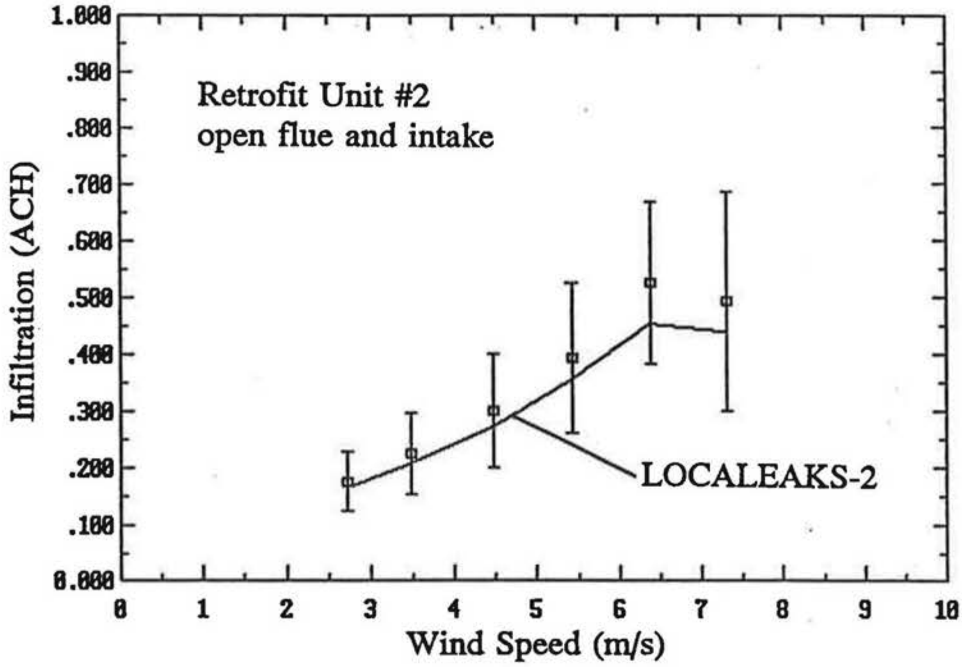


Figure S-7 Wind-effect passive ventilation of Retrofit Unit #2 with open flue and ground level intake pipe, for all wind directions reasonable agreement with measurements, showing an underprediction bias error of -9% and an RMS scatter error of ±22%.

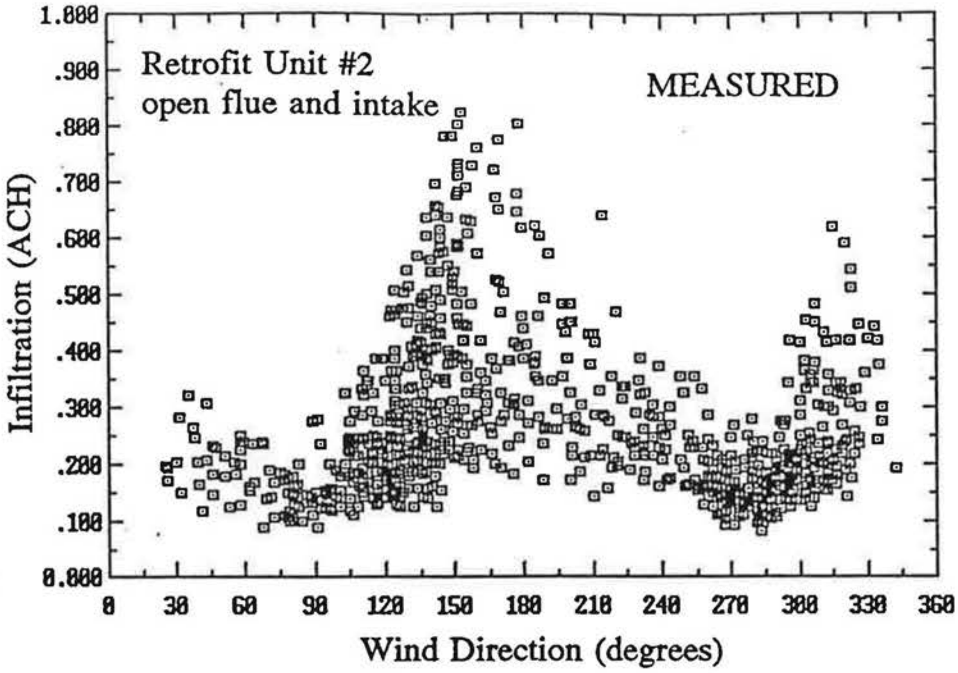
The wind-dominated ventilation shows a high degree of variability, with measured infiltration varying by a factor of four at any given windspeed. Figure S-8 shows that varying wind direction is the reason for this variability. Wind pressure coefficients are strongly dependent on wind direction, and on shelter provided by adjacent houses in the east-west row at the Alberta Home Heating Research Facility. In Figure S-8 the model shows its ability to simulate the effects of wind shelter and wind direction variation. Here the data is "unpaired", so that the predictions for an individual hour are not compared directly to the measured data in that same hour. This allows random variations in wind direction over each hour to be compensated by predictions from different hours with the same average wind direction. The unpaired model predictions are able to simulate a variation of about a factor of three in infiltration rate while the measured data experiences more than a factor of four variation at any given hourly average wind direction. This is a minor deficiency, and the model was judged to be adequate for predicting passive ventilation with varying wind direction and shelter from nearby buildings.

Detailed comparisons of bias, scatter and other model performance statistics are presented in PART 4 of this report, and additional figures for Retrofit Unit #2 are included in Appendix A. The final version of the model was capable of predicting the combined effects of passive ventilation and natural infiltration within ±10% over a monthly period, and to estimate the ventilation rate in any hour with a standard deviation of about 25% (i.e. within ±50% 9 times out of 10.) Once confidence had been established in the ability of the model to predict complex inlet and exhaust configurations on the test houses, it was then used to predict passive ventilation strategies for residential housing.

Case Studies of Passive Ventilation Strategies

The computer model LOCALEAKS-2 was used to test various passive intake and exhaust locations on three different types of houses, all with full ventilated basements:

- A small 100 m^2 floor area single story bungalow with exhaust and intakes distributed around its perimeter.
- A large 200 m^2 floor area two-storey house with high and low passive ventilation intake and exhaust locations.
- A large townhouse with 200 m^2 floor area located centrally in a row of identical units with common side walls, with leakage and passive ventilation sites on the front and back walls, and no leakage on the side walls connecting adjacent units.



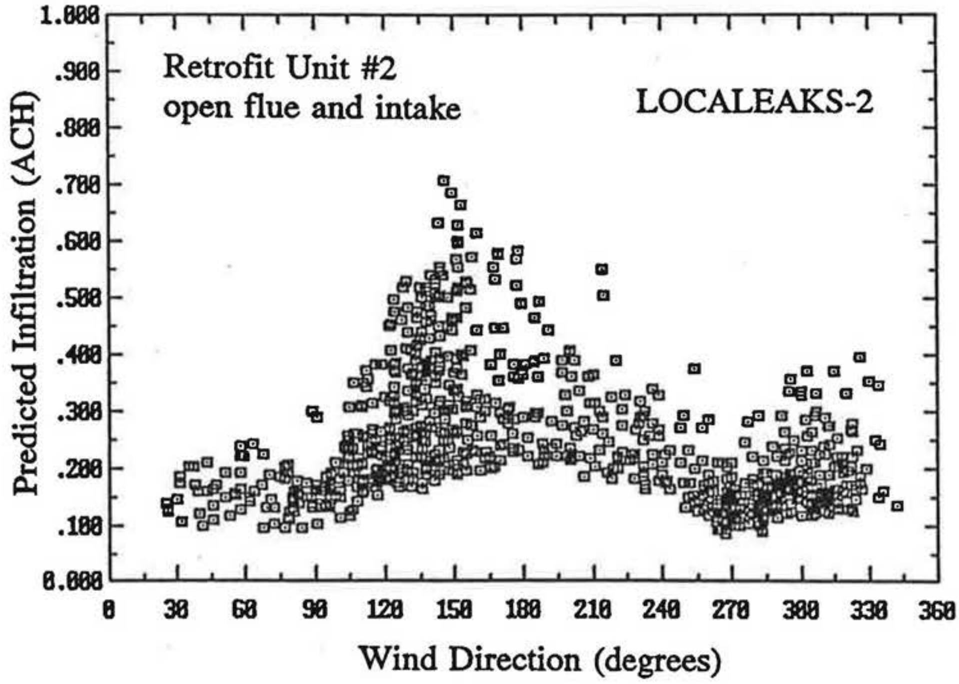


Figure S-8 Unpaired measured and predicted wind direction dependence of wind-effect passive ventilation of Retrofit Unit #2 with complete shelter by adjacent houses for 90° and 270°, and U_H = 2.5 to 8.0 m/s

In Alberta most houses are constructed with full basements, ventilated by a recirculating warm air gas furnace. Most houses are equipped with a furnace flue. However, some energy-efficient houses use condensing furnaces or flue dampers that essentially eliminate the furnace flue as a passive ventilation exhaust site. This possibility was accounted for by testing passive ventilation performance with and without a furnace flue. For configurations without a furnace flue, half the passive ventilation openings were located on the walls near ground level, and the other half were located near the upper ceiling level to take advantage of stack-effect infiltration from indoor-outdoor temperature differences. For houses with a flue, all passive ventilation sites were located near ground level with the flue serving as the only high level exhaust site.

Assuming seven occupants in the townhouse and two-storey house, and five occupants in the bungalow, ASHRAE 62-89 standard for minimum ventilation rates requires an air exchange of 0.25 ACH in the townhouse and two-storey house, and 0.27 ACH for the bungalow. Table S-1 presents calculated passive ventilation rates in one configuration for the bungalow. The complete range of annual weather conditions were simulated by dividing the year into summer, spring/fall, shoulder and winter seasons. The "shoulder" season between winter and spring, and fall and winter could also be thought of as mild winter, typical of a maritime climate. For each of the indoor-outdoor temperature difference seasons four different windspeeds were considered.

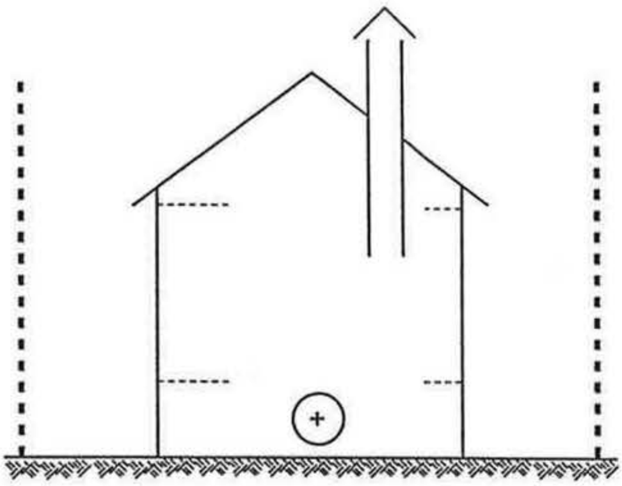
The results in Table S-1 illustrate the fundamental disadvantage of fixed area passive ventilation - its sensitivity to wind speed and wind direction. Here we see that relative to the 0.25 ACH requirement, the bungalow will be over-ventilated under high winds, and under-ventilated under low wind conditions. Detailed studies of other ventilator locations are presented in PART 5 of the report, and in Appendix B.

In addition to varying the location of passive ventilation openings and the effect of a furnace flue, the computer model tested the effect of wind shelter from nearby buildings. The following general conclusions were drawn from these computer simulations:

- Passive ventilation can be strongly dependent on wind speed, direction, and upwind sheltering by nearby buildings.
- Natural air infiltration with no passive vent opening will provide adequate ventilation of most houses in winter. The exception to this are townhouses with only two walls exposed (i.e. common side walls with other vents in a complex). Townhouses usually require supplementary passive vent openings to meet the ASHRAE ventilation standards.
- A standard furnace flue with its rain cap located above the roof ridge provides an efficient passive ventilation exhaust. Most single family dwellings in Alberta have an adequate built-in exhaust through their furnace flue. It is recommended that a false flue be

TABLE S-1 and B-15

Bungalow Ventilation Rate With One Passive Vent, Flue, Close Row Shelter



Background Leakage Area	67%
Flue Leakage Area	22%
Passive Vents Leakage Area	11%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.12	0.21	0.36	0.62
SPRING/FALL	10C	0.16	0.24	0.38	0.64
SHOULDER	0C	0.23	0.30	0.42	0.68
WINTER	-20C	0.35	0.41	0.51	0.76

Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.32 ACH
avg. 0.38 ACH
max. 0.47 ACH

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installed in electrically or hot-water heated dwellings to provide a reliable passive ventilation exhaust. The major advantage of exhaust through the furnace flue is that with its outlet above the roof ridge the flue is insensitive to wind direction, and is able to provide a consistent strong exhaust through a combination of unsheltered wind suction and buoyant stack effect.

- During spring and fall, passive ventilation will not be effective unless wind speeds are higher than about 10 km/h. Hourly average wind speeds often fall below this required limit, and produce inadequate passive ventilation. When the outdoor temperature is above 10 C it is expected that occupants will open windows to provide ventilation.
- Because townhouse units have common side walls with their neighbors, they have considerably smaller leakage areas relative to their floor area compared to detached bungalows and two-storey houses. This characteristic makes them prone to under-ventilation by natural infiltration.
- Air infiltration in townhouses is strongly dependent on wind direction, with a 50% variation above and below the average with no flue, and a 20% variation with a flue. From this, we conclude that townhouses are the type of construction most likely to benefit from the introduction of passive ventilation systems to increase natural ventilation.

Conclusions and Recommendations

Simulation of air infiltration and ventilation rates in bungalows, and two-storey detached and townhouse dwellings has led us to a number of conclusions on the best ventilation strategy for a compromise between providing adequate ventilation for indoor air quality, and avoiding over-ventilation and high energy costs in winter.

- Most detached single storey and two-storey houses are adequately ventilated in winter by natural air infiltration with no passive vent openings. Townhouses, with two walls common to adjacent units are usually not adequately ventilated by natural infiltration.
- Even with several large ground-level passive ventilation openings houses cannot be adequately ventilated in summer, and spring/fall seasons in light winds without using large open area vents that cause over-ventilation in winter.
- The major obstacle to adopting passive ventilation is an inlet damper control that is regulated not only by outdoor temperature, but also by windspeed. Such windspeed sensitive controllers are not commercially available, and are likely to be expensive and prone to malfunction if they use existing wind speed sensors.

The implication of the above conclusions is that even for passively ventilated houses, some supplementary form of ventilation is required in spring/fall and summer weather when indoor-outdoor temperature differences are less than 10C and winds are "light" to "moderate". Most occupants will open windows to provide supplementary ventilation under these mild weather conditions. If windows are opened in spring, summer and fall, passive ventilation inlets and exhausts with thermostatic dampers to close them during cold winter months provide a viable alternative to mechanical ventilation systems currently required by the CSA standard. However, if an idiot-proof system is required, supplementary mechanical supply ventilation in the form of a two-speed furnace fan should be considered. The fan should be operated continuously in its low-speed mode when the temperature is above freezing in order to draw air through a calibrated orifice in the combustion make-up air duct supplying the warm air furnace system.

Other issues that need to be addressed are methods for introducing the fresh air without producing cold uncomfortable drafts, and providing adequate mixing to deliver the air to the occupant's breathing zone. Future research should focus on developing combined wind speed and temperature controls to allow passive ventilation to function efficiently. Until wind speed sensitive controls are developed passive ventilation will over-ventilate by about 400% under high wind winter conditions in order to maintain adequate ventilation under light wind spring and fall conditions.

PART 1

PASSIVE VERSUS MECHANICAL VENTILATION

In the thousands of years since we first emerged from caves and began living in man made dwellings, the term "ventilation" has always meant natural passive ventilation caused by wind and weather. From the day when someone first knocked a hole in the roof to let out smoke, and left a gap under the animal hide covering the doorway to let in fresh air, there have been few changes in the way natural ventilation has been used. It is only recently that fans have been used to supplement natural ventilation of buildings. The modern concept of a tightly sealed house with all ventilation through intentional intake and exhaust openings on the building was developed in the last 100 years, and made practical by the development of effective air-vapour barriers in the last 30 years.

In the last century the major concern in designing ventilation systems for tight buildings has been the removal of moist indoor air to prevent structural water damage from condensation. It is only in the last 20 years that the requirement for fresh outdoor air to provide adequate indoor air quality has assumed equal importance to the control of moisture and nuisance odours. With the shift in emphasis from moisture and odour control to maintaining the health of occupants, ventilation designers are now required by building codes to ensure that a specified minimum fresh air ventilation rate is supplied **at all times** to the occupants. This requirement for assured ventilation to maintain indoor air quality has forced designers to supplement natural air infiltration and passive ventilation with mechanical ventilation using fans to exhaust and supply air.

The natural variability of passive ventilation caused by changes in wind and weather are viewed by regulatory agencies as too unreliable for providing minimum ventilation rates. Because no one can guarantee that passive ventilation through holes in the house envelope will produce a specified minimum ventilation rate under all weather conditions, passive ventilation has fallen out of favour as a means for ensuring indoor air quality. It is much easier to install an exhaust fan with a specified flow rating than to try and convince building code regulators that passive ventilation systems provide adequate ventilation for the vast majority of conditions.

Scope of the Study

The present study was carried out to determine whether passive ventilation through strategically placed openings in the building envelope is a viable alternative to mechanical exhaust ventilation to supply fresh outdoor air required to meet standards for indoor air quality. To evaluate passive ventilation strategies the study was carried out in three phases:

- A large data base of passive ventilation air exchange rates was collected using tracer gas measurements of air exchange rates in five test houses at the Alberta Home Heating Research Facility.
- A computer model was developed to predict the combined effect of natural infiltration through distributed leakage, passive ventilation through local inlets and outlets, and fan supply and exhaust flows. The model was refined and validated using the measured ventilation data base.
- The computer model was used to predict the contribution of passive ventilation strategies in one and two storey detached houses, and two storey townhouses typical of Canadian residences.

Previous studies have examined only a few specific test cases over a narrow range of weather conditions. Using a computer model rather than direct field tests it was possible to evaluate the variability in passive ventilation that would be caused by changes in wind sheltering by nearby buildings, and to test a variety of passive ventilation inlet and outlet configurations over a wide range of weather conditions.

Passive and Mechanical Ventilation Options

Is passive ventilation a viable alternative to mechanical supply and exhaust? Before trying to answer this question we must first define what we mean by "passive":

> **Passive ventilation operates by using the natural driving forces of wind and indoor-outdoor temperature difference without intervention by the occupants, and without externally powered controls.**

It is important to keep in mind that passive ventilation systems can make use of "passive controls" such as thermostatically controlled dampers operated by bimetallic springs. The only requirement is that the controls are neither electrically powered, nor require conscious operation by the occupant of the house. We will see later that these passive controls are essential in regulating inlet and outlet opening sizes over the wide range of wind and outdoor temperature conditions experienced in Alberta.

Ventilation is required to maintain indoor air quality, and to remove moisture and odours. The types of ventilation systems considered in this study are:

- **Totally Passive Systems:** Use local air inlets and exhaust ducts connected to kitchens and bathrooms. Inlet and outlet flow areas are fixed.

- **Controlled Passive Systems:** Flow areas of inlet and outlet passive vent openings are controlled by bimetallic thermostatic springs to avoid cold drafts and excessive energy consumption in winter, and to open wide in spring and fall to provide adequate ventilation when windows are closed.
- **Combined Passive and Mechanical Systems:** Mechanical exhaust is used to remove large transient sources of moisture and odour in kitchens and bathrooms, supplemented by a continuous passive ventilation system that provides base-flow requirements for indoor air quality.
- **Totally Mechanical Systems:** Intermittent fan exhaust to remove moisture and odour in kitchens and bathrooms is combined with continuous fan supply or exhaust to provide the base-flow indoor air quality requirements.

Most Canadian houses have occupant controlled intermittent mechanical ventilation to remove moisture and odours from kitchens and bathrooms. In this study we will assume that passive ventilation in Alberta houses is only required to provide fresh air for indoor air quality, and transient sources of moisture and odour are dealt with by intermittent exhaust fans. In contrast, passive ventilation systems designed for European housing use exhaust ducts that are located in kitchen and bathroom areas to avoid the need for any mechanical ventilation.

In choosing between the alternatives of passive and mechanical ventilation, the primary advantage that continuous mechanical ventilation offers is its ability to provide a fixed ventilation rate under all weather conditions. Balanced against this are a long list of disadvantages:

- Quiet reliable mechanical ventilation systems are expensive to install and maintain. Cheap systems tend to clog, vibrate and become noisy, and may be disconnected by the occupant to eliminate noise.
- Mechanical ventilation produces a continuous electrical energy demand, and exhaust-only systems simply dump this electrically generated heat outdoors.
- Mechanical ventilation controls are often incorrectly installed, and tend to go out of adjustment.

Passive ventilation also has several practical problems:

- The primary difficulty with passive ventilation is its strong variability with local wind conditions. This makes it difficult to guarantee a specified minimum ventilation rate at all times. On a calm spring or fall day with the same indoor and outdoor temperature, there will be no passive ventilation, and occupants must be intelligent enough to open windows.
- Totally passive systems require large inlet and outlet openings so that adequate ventilation is possible under spring and fall conditions when windows are still closed, and the

temperature-driven winter air infiltration rates are no longer present. Without some sort of active control dampers these large openings cause over-ventilation and cold drafts in winter.

Ventilation Requirements for Indoor Air Quality

Most houses heated with gas or oil have a flue, and provide makeup air for combustion through fresh air inlets in the furnace room or return air duct. The combination of a flue and combustion air supply inlet usually provide enough fresh air to meet indoor air quality standards when the furnace is operating regularly during the heating season. These combustion venting and makeup air requirements provide a unintended standard for air quality ventilation.

Over the past 10 years regulatory standards have been developed that require minimum ventilation rates in houses to ensure adequate indoor air quality. The two specific air quality ventilation standards that apply to Canadian houses are ASHRAE 62-89 "Ventilation for Acceptable Indoor Air Quality" and CSA preliminary standard F326.1-M1989 "Residential Mechanical Ventilation Requirements".

TABLE 1-1

Simplified Standards for Overall Minimum Fresh Air Requirements for Houses

Component	ASHRAE Standard 62-89	CSA Standard F326.1
Total Air Exchange Rate	0.35 ACH mechanical and natural	0.30 ACH mechanical
Intermittent Kitchen Exhaust	50 L/s (50 cfm)	50 L/s (50 cfm)
Intermittent Bathroom Exhaust	25 L/s (50 cfm) per bath	25 L/s (50 cfm) per bath

The ventilation requirements specified by the ASHRAE 62-89 and CSA F326.1 are summarized in Table 1-1. The simplified total air exchange rates of 0.35 ACH and 0.30 ACH are to be used if detailed room-by-room are not made. An important requirement of the CSA standard is that fresh air must be supplied to each room separately, and the designer can not rely simply on sucking air into the house at one point and exhausting it at another. This requirement can be met easily in most Alberta houses that use forced air recirculating heating systems.

However, in row-houses and apartments where hydronic (hot water) heat is used, the CSA requirement implies the need for an elaborate system of fresh air supply ducts.

The essential difference between these two standards is that ASHRAE 62-89 specifies the combined mechanical and natural ventilation rate should be no less than 0.35 air changes per hour (abbreviated ACH), while the CSA standard specifies that a fan **must** supply **mechanical** ventilation at a rate of 0.3 ACH. As pointed out in the review by Wilson (1990), this CSA standard is directed at new energy-conserving Canadian housing with very tight envelope construction, and negligible natural infiltration. However, studies by Kiel and Wilson (1987) and Wilson and Walker (1990) show natural ventilation adds almost linearly to mechanical ventilation, so that even a modest natural air change rate of 0.2 ACH would produce a combined fresh air ventilation rate of 0.5 ACH in a house that met the new CSA mechanical ventilation standard of 0.3 ACH. This suggests that the CSA standard may over-ventilate most houses in winter.

Canadian standard CSA F326.1 is based on a required air flow rate of 5.0L/s per room, with master bedrooms and basements requiring a higher rate of 10.0 L/s. In contrast, ASHRAE standard 62-89 sets a requirement based on the number of building occupants rather than the number of rooms. The required ASHRAE level of 7.5 L/s per person is converted to a building ventilation rate by assuming that there are N+1 occupants in a house with N bedrooms. Table 1-2 shows minimum ventilation rates calculated using these per-person and per-room requirements. When these "per room" or "per person" minimum rates are applied to typical single family houses several significant differences are apparent in the standards:

- The single family dwellings in Table 1-1 with full ventilated basements require less than 0.32 ACH to meet the ASHRAE 62-89 standard of 7.5 L/s per person. Most require less than 0.25 ACH. The additional ventilation to meet the overall 0.35 ACH simplified standard may reflect the U.S.A. norm of slab-on-grade construction (i.e. no basement), or requirement for additional basement ventilation to dilute radon entry.
- The "per room" ventilation in the Canadian standard CSA F326.1 requires fresh air supply by mechanical ventilation ranging from 0.24 to 0.44 ACH in single-storey houses with basements. These values vary considerably about the simplified minimum mechanical ventilation rate of 0.30 ACH in Table 1-1. For houses with an unheated crawlspace or slab-on-grade construction, the required rates range from 0.40 to 0.60 ACH from mechanical ventilation alone! These fresh air requirements seem rather high considering that they ignore the natural ventilation component of the house.

Because the CSA standard makes no allowance for passive ventilation, the present study focused on meeting an overall requirement of 0.2 to 0.3 ACH to meet the 7.5 L/s per person in ASHRAE Standard 62.89 for houses with full ventilated basements.

In addition, minimum ventilation rates should account for ventilation generated by occupant activity. The amount of this occupant-induced ventilation is difficult to assess, particularly because occupant behaviour varies greatly with local climate and culture. Stum (1988) estimated occupant exchange rates from opening doors and windows, and from clothes

Table 1-2

Required Minimum Air Exchange Rates for Typical Single Family Dwellings With Full Ventilated Basements

Number of Bedrooms N	Floor Area[a]		ASHRAE Standard 62-89 7.5 ℓ/s per occupant for (N+1) occupants		CSA Standard F326.1[b] 5.0 ℓ/s per room except 10.0 ℓ/s master bedroom 10.0 ℓ/s basement	
	ft²	m²	one storey ACH	two storey ACH	one storey ACH	two storey ACH
3	1000	93	0.24	0.32	0.44	0.58
3	1300	121	0.18	0.25	0.34	0.45
4	1800	167	0.17	0.22	0.27	0.35
4	2000	186	0.15	0.20	0.24	0.32

[a]excluding basement; wall height of 2.44 m for all levels assumed for active air volume
[b]kitchen, living room, family room, 2 bathrooms, basement, N bedrooms

dryers and intermittent kitchen and bath exhaust fans, contribute about 0.05 ACH to the daily average. Stum found that occupant-induced air change rates increased with the number of occupants. However, unlike several European studies, he observed that opening windows for winter ventilation was rare, with over 70% of the houses reporting that they never opened windows during the winter. This agrees with an informal survey conducted by Wilson in Edmonton, and indicates that both passive and mechanical ventilation systems must be designed to provide adequate fresh air supply with all windows closed during the cold winter months. In contrast, Kivsgaard et al. (1985) found that unoccupied sealed houses in Danish winter conditions experienced about 0.2 ACH, while occupied houses had about 0.5 ACH. During 75% of the heating season the outdoor temperature is above 0C in Denmark. The large occupant-included ventilation in occupied Danish houses is probably generated by window opening during the relatively mild Danish winter. This is quite different from Alberta, where very cold winters force occupants to keep windows shut tight to avoid cold drafts.

Comfortable ventilation requires the elimination of cold drafts caused by outdoor supply air. With mechanical systems this is accomplished by producing high velocity supply jets that mix with room air by turbulence. Passive ventilation inlets must rely on using multiple inlet locations near heating outlets or radiators to encourage mixing of cold inlet air with heated air in the room. Figures 1-1 and 1-2 show distributed inlets and exhausts used in Swedish housing. This mixing is particularly difficult to accomplish in well insulated houses where the heating system operates infrequently. During periods when the heat is off, passive ventilation inlets with pre-heaters (see Figure 1-2) still create cold air drafts as the cold air trickles across the floor.

Variability in wind direction can cause large changes in wind-induced passive ventilation. Some previous studies claim that this effect can be greatly reduced by a proper choice of inlet and outlet locations. For example, Johnson, Gaze and Brown (1985) found only a moderate sensitivity to wind speed using the system shown in Figure 1-3 with exhaust from a roof ridge ventilator. In contrast, Edwards and Irwin (1986) found that when the exhaust location was from a roof ventilator located about halfway down the sloping roof, a very strong dependence on wind speed and direction was observed.

Mechanical Ventilation Systems

A good description and analysis of several different types of mechanical ventilation systems is reported by Shaw (1985) in a study carried out at the Institute for Research in Construction at NRC, Ottawa. Shaw discusses three types of ventilation systems used in Canadian housing:

- **Balanced systems:** with an air-to-air heat exchanger, or separate supply and exhaust fans, systems of this type avoid problems of furnace flue backdrafting by providing separate fan supply air to balance the exhaust flow rate. Practical experience has shown that it is very difficult to balance the flow rates in a supply-exhaust system, and that they are costly to install and maintain.
- **Exhaust-only systems:** are the simple bath and kitchen exhaust fans found in most Canadian houses. Their operation can cause furnace flue backdrafting in tight houses, particularly when a clothes dryer is venting outdoors at the same time.
- **Supply-only systems:** outside air is drawn through an insulated pipe into the return air duct of a forced-air heating system. This system is inexpensive because it makes use of the furnace fan. This type of system does not provide adequate ventilation in spring and

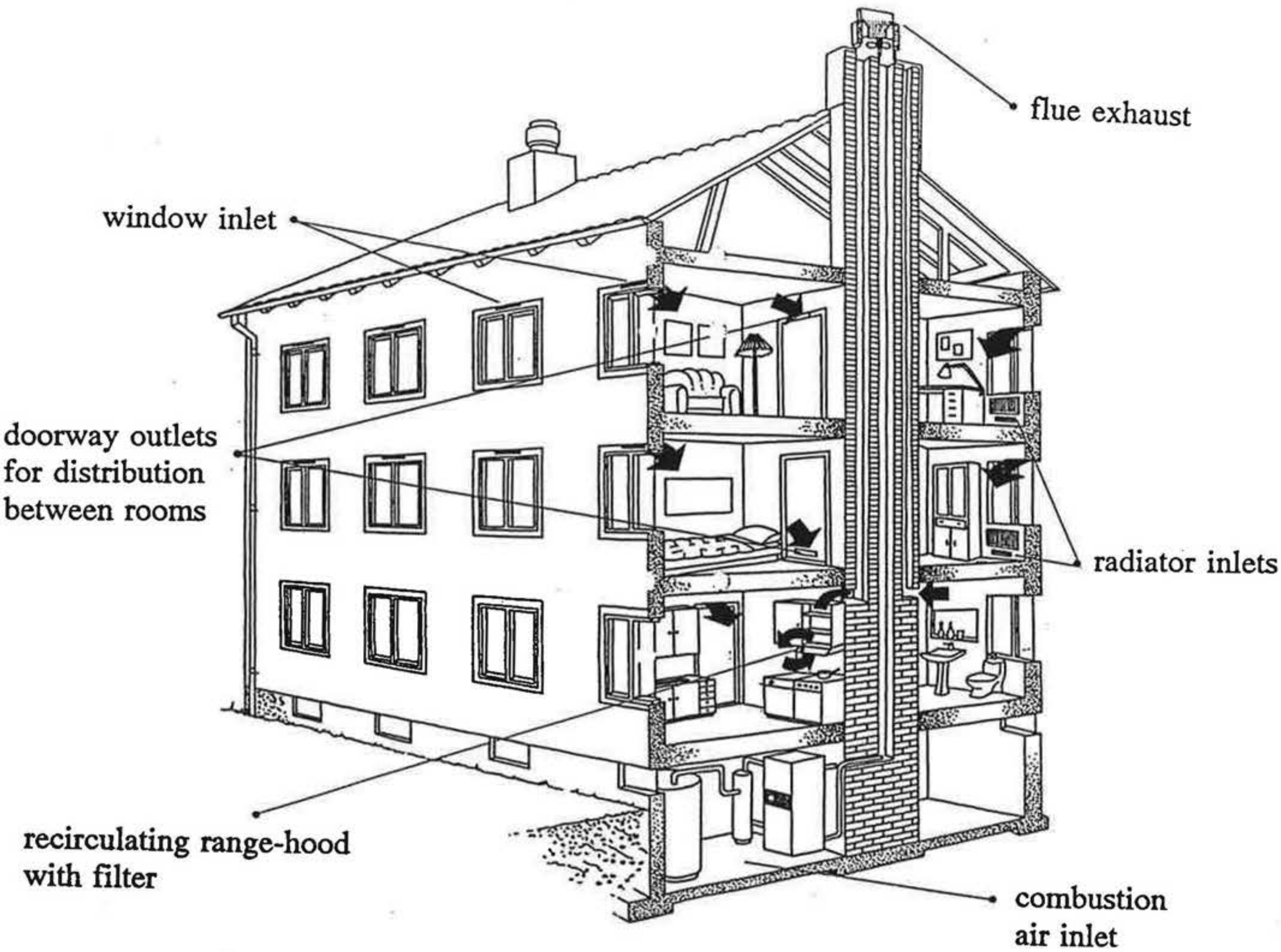


Figure 1-1 Distributed Passive Ventilation Inlets and Flue Exhaust System.
by: SPAR-VEN Systems, Kalmar, Sweden (1990).

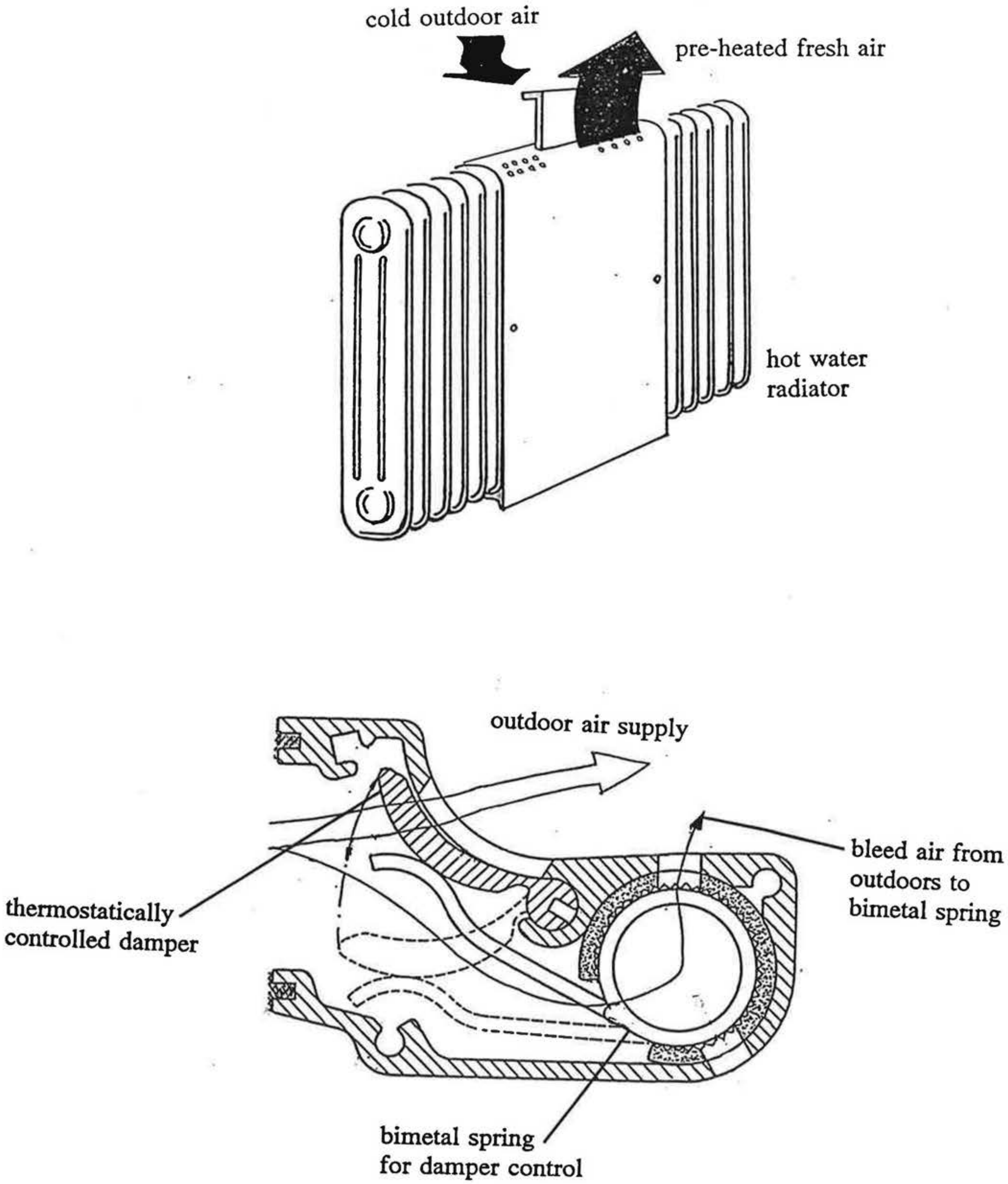


Figure 1-2 Preheater and Thermostatically Controlled Passive Ventilation Intake: VENT ···· System by NIKAB, Gallivar, Sweden (1990).

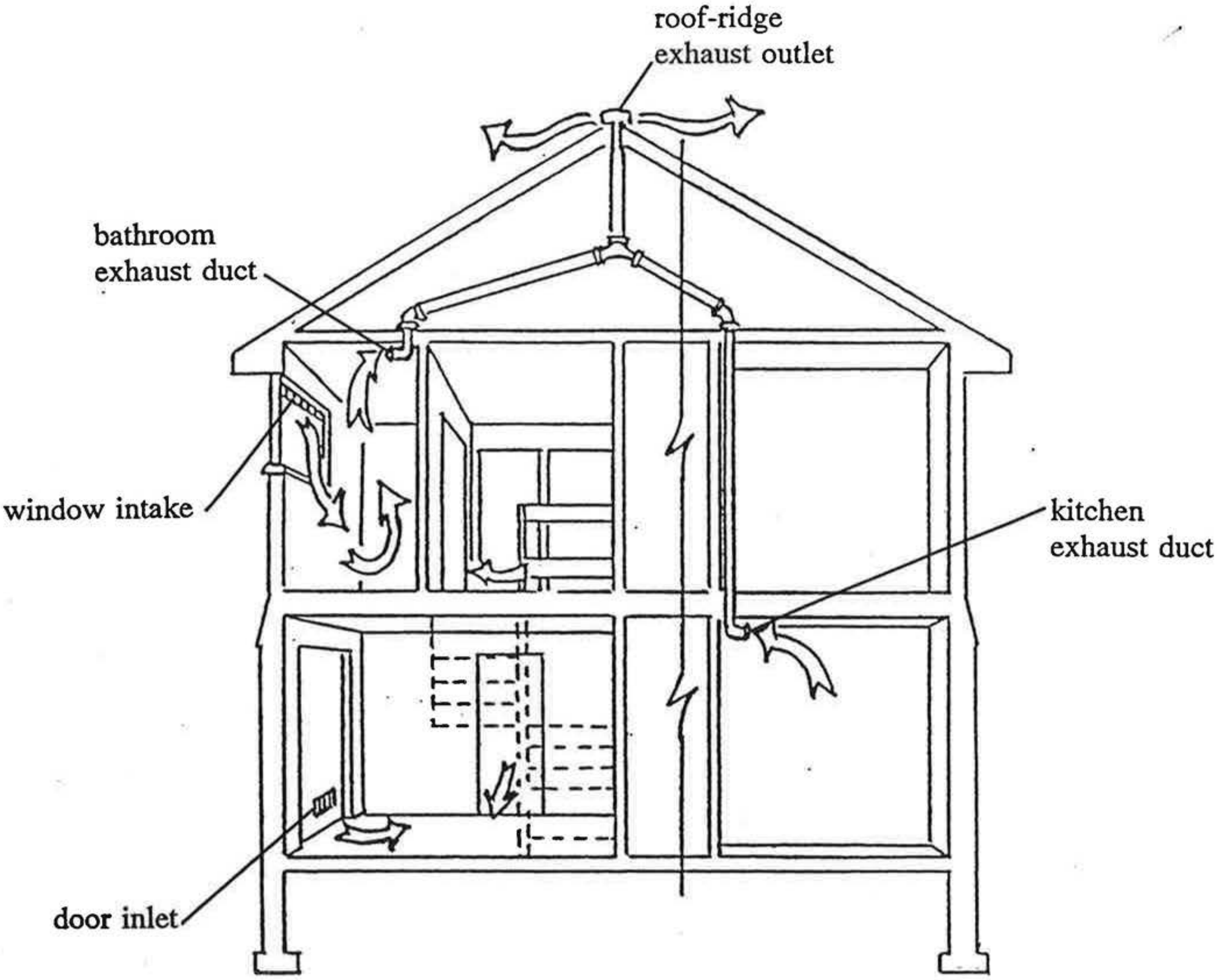


Figure 1-3 Totally Passive Ventilation System with Kitchen and Bathroom Exhaust Ducts. From Johnson, Gage and Brown (1985)

fall when outdoor temperature is about 5C to 10C, windows are closed, and the furnace fan is turned off or running infrequently. However, with a two-speed fan that operates at low speed when the burners are off, this supply-only system is a reliable, cheap way to maintain minimum ventilation rate.

Review of Previous Passive Ventilation Studies

The literature on passive ventilation stretches back several centuries. Reid (1844) showed how air shafts were designed to draw air through floor grills in the British Houses of Parliament to extract stale air. Billington's (1982) entertaining article showed clearly that engineers keep rediscovering passive ventilation concepts that have been applied centuries earlier. He also demonstrates that bad design is an ancient tradition, and quotes a 1894 article by Professor Jacob, a pathologist, who said

> "Real ventilation is so uncommon that the architect usually thinks this object has been obtained if some of the windows can be opened. Some think that the presence of ventilators ... ensures the required end. We may as well supply our house with water by making a trap door in the roof to admit rain".

The objective of our study is to show these deficiencies can be overcome by an intelligent choice for the location and size of the intake and exhaust openings. Billington also noted that one investigator suggested in 1906 that the newly invented electric fan be used to ventilate toilets, with a switch activated by sitting on the seat. All of this leads to the rather depressing conclusion that there are very few new ideas in ventilation.

British studies of passive ventilation have focused on totally passive systems with no flow controls. Johnson, Gaze and Brown (1985) found that inlet grills covering passive vents significantly restricted the flow. They demonstrated the need for large diameter exhaust pipes, of 110 mm in the kitchen, and 82.4 mm in the bathroom to produce flows of about 0.2 ACH for indoor-outdoor temperature differences of 15C and wind speeds of about 7 km/h. Although there was no specific discussion of wind direction effects, their study showed that under some circumstances increasing wind speed decreased passive ventilation rates, while under others the rates increased with increasing speed. The present investigation, with its large data base and computer simulation will show that this effect is related to varying wind direction and to the location of intake and exhaust points on the envelope of the building.

Another British study by Edwards and Irwin (1986) used a configuration similar to Figure 1-1, and found wind effects were dominant for temperature differences of 14C and wind speeds of 7 to 15 km/h. Under high wind conditions of 30 km/h flow reversals were observed with backdrafting down passive vent exhaust pipes. It was suggested attention be focused on the design and location of roof exhaust terminations to minimize backdrafting.

A theoretical study of passive ventilation was carried out by Etheridge and Sandberg (1984). They used a numerical solution of the inflow-outflow balance for mixed laminar and turbulent flow through openings in a building envelope to determine the flow sensitivity to the location of the holes, wind speed and temperature difference. When combining wind and stack effects they found that a ratio of the characteristic stack and wind pressures, defined in Equations (2-1) and (2-3) of Part II of this report, provided a useful measure of the relative importance of wind-driven and stack-driven flows. Their results demonstrate the value of such parametric studies, but because the wind speed was used to normalize variables in both the horizontal and vertical axes of their graphs they are difficult to interpret in practical terms. No effects of changing wind direction were discussed.

PART 2

PREDICTING PASSIVE VENTILATION FLOW

Passive ventilation differs from natural air infiltration because passive air inlet and outlet openings in the building envelope are intentional, and their flow areas may be controlled by dampers. To make intelligent choices for these inlet and outlet locations, we must first understand the influence of the driving pressures caused by "wind effect" and "stack effect" that generate passive ventilation flows.

Inflow-Outflow Balance

In a real house infiltration through distributed cracks and holes combines in a complex non-linear way with inflow through passive ventilation inlets and outlets. The computer flow model LOCALEAKS-2 was developed to account for this complex interaction by balancing total inflow with an equal total outflow to determine the combined infiltration and passive ventilation air change rate. To illustrate the way in which this balance is set, consider the simplest configuration: a single inlet-outlet pair with negligible background infiltration, shown in Figure 2-1. An analysis of this simple case will show the relative importance of variables such as inlet-to-outlet height separation h_{vent}, wind speed U_H, and indoor-outdoor temperature difference ΔT.

Most passive ventilation inlets and outlets behave like simple holes (rather than long thin cracks) with their physical cross sectional area A_{inlet} or A_{outlet} multiplied by a discharge coefficient C_d. Applying Bernoulli's equation to the inlet and outlet orifice holes produces the usual square-root dependence of flow rate Q m^3/s on pressure difference across the orifice. Referring to Figure 2-1,

$$Q_{inlet} = C_d\, A_{inlet}\left(\frac{2(P_{inlet}-P_{indoor})}{\rho_o}\right)^{0.5} \qquad (2\text{-}1)$$

$$Q_{outlet} = C_d\, A_{outlet}\left(\frac{2(P_{indoor}-P_{outlet})}{\rho_i}\right)^{0.5} \qquad (2\text{-}2)$$

where P_{indoor} and $P_{outdoor}$ are in pascals (Pa), ρ_o kg/m^3 is the outdoor air density, at the outdoor temperature T_o °K, and ρ_i is the indoor air density at the indoor air temperature T_i °K. The

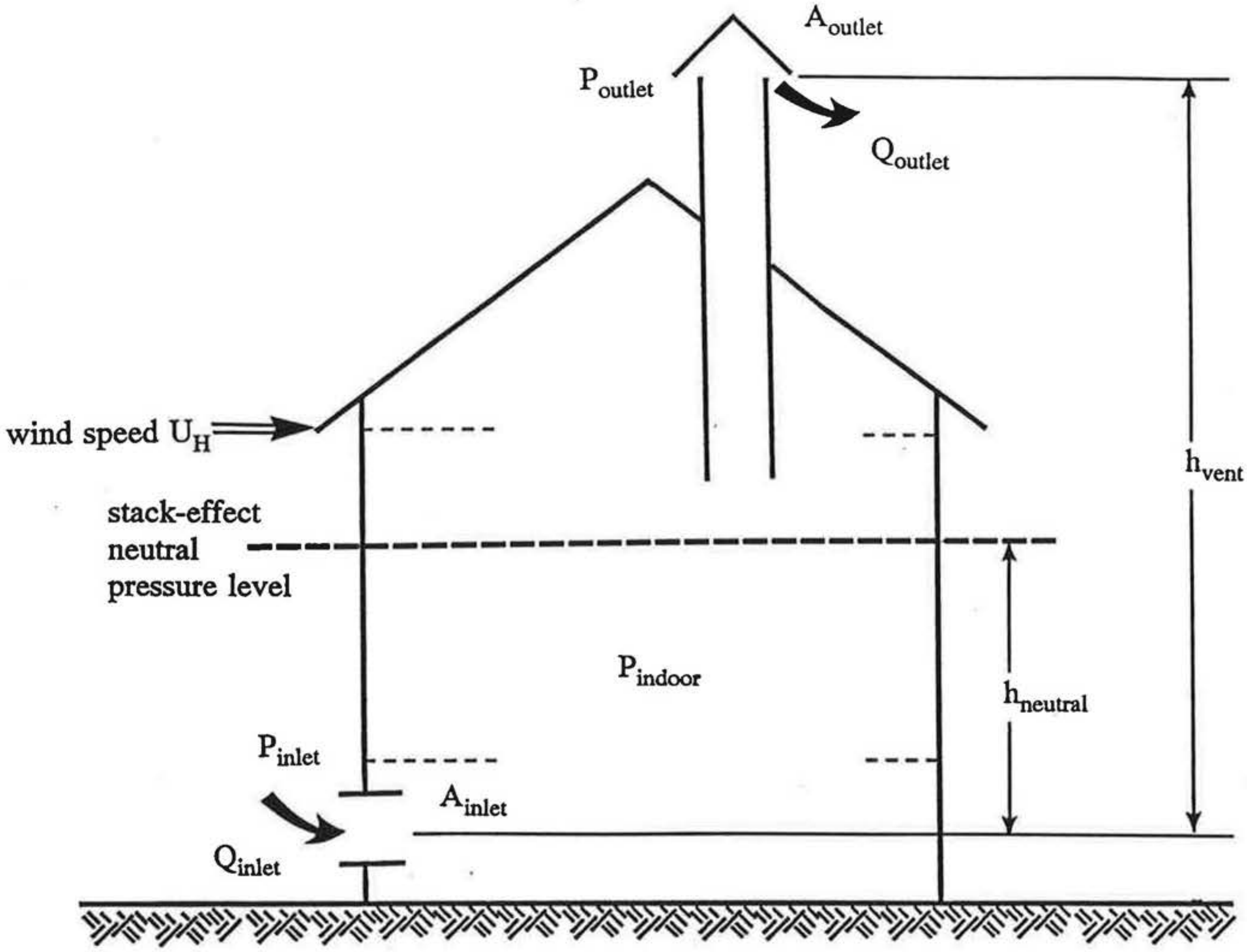


Figure 2-1 Passive Ventilation Inflow and Outflows for a House with a Furnace Flue as Outlet and a Single Wall Inlet.

fundamental requirement for all ventilation flow is that total inflow must balance total outflow, which in our simple case of an inlet-outlet pair is,

$$Q_{inlet} = Q_{outlet} \tag{2-3}$$

To avoid obscuring the basic relationships, we will assume that the indoor and outdoor air densities are equal, so that $\rho_o = \rho_i$, and both can be replaced by the average density ρ. In all situations of interest for passive ventilation, indoor-outdoor temperature differences are less than 30C so that ρ_o and ρ_i differ by less than 10%. Because flow Q varies as $\rho^{-0.5}$ in Equations (2-1) and (2-2), neglecting density differences causes at most a 5% error in flow rate Q.

The inflow-outflow balance of Equation (2-3) sets the indoor pressure P_{indoor} that must occur to keep the inflow equal to outflow. Taking the ratio of outlet to inlet area r defined by

$$r = \frac{A_{inlet}}{A_{outlet}} \tag{2-4}$$

the flow balance found by equating Equation (2-1) to (2-2) yields the indoor pressure

$$P_{indoor} = \frac{r^2 P_{inlet} + P_{outlet}}{1+r^2} \tag{2-5}$$

Using this in the inlet flow Equation (2-1),

$$Q_{inlet} = C_d\, A_{inlet} \left(\frac{2}{1+r^2}\right)^{0.5} \left(\frac{P_{inlet} - P_{outlet}}{\rho}\right)^{0.5} \tag{2-6}$$

One way to interpret this result is to imagine an inlet of constant area A_{inlet}, and a varying outlet area A_{outlet} that changes the area ratio, r. For Equation (2-6) we see that a very large outlet area will make r = 0 and produce 40% more flow than when the inlet and outlet areas were equal, with r = 1.0. However, when the outlet area is small, $r \rightarrow \infty$ and the flow rate is zero. With this small outlet the indoor pressure P_{indoor} in Equation (2-5) sets itself to the inlet pressure P_{inlet} and there is no pressure difference to drive the flow.

Because changing wind direction may cause the inlet to become the outlet if changing pressure reverses the flow, there is no advantage in choosing different sizes for passive vent holes. In the following analysis we will assume that the inlet and outlet are the same size, with

$A_{inlet} = A_{outlet}$, so that r = 1.0. Both areas will be replaced with the symbol A_{vent} to denote this equal-area configuration. Using this, Equation (2-6) becomes, for r = 1.0,

$$Q_{vent} = C_d \, A_{vent} \left(\frac{P_{inlet} - P_{outlet}}{\rho} \right)^{0.5} \tag{2-7}$$

Stack Effect

The difference between indoor and outdoor air temperature generates a buoyancy-induced pressure difference that causes warm indoor air to rise and exhaust from passive ventilation openings located on the upper portion of the building envelope. This exhaust flow is balanced by cold air being drawn through passive ventilation intakes located below the neutral level, shown on Figure 2-1, where indoor and outdoor pressures are equal.

The net driving pressure for stack-effect is linearly proportional to the height difference h_{vent} between the inlet and outlet, and to the difference in density between indoor air and outdoor air. For equal inlet and outlet areas $A_{inlet} = A_{outlet}$ in Figure 2-1, the neutral level height $h_{neutral} = 0.5\ h_{vent}$. The stack effect pressure difference ΔP_{stack} in pascals (Pa) for an inlet and outlet of equal size separated by a height h_{vent} an indoor-outdoor temperature difference $\Delta T = (T_i - T_o)$, and no wind pressure, is

$$P_{inlet} - P_{outlet} = \Delta P_{stack} = \rho_o g \, h_{vent} \, \frac{\Delta T}{T_i} \tag{2-8}$$

where $\rho_o \approx 1.1\ kg/m^3$ is the outdoor air density, $g = 9.8\ m/s^2$ is the acceleration of gravity, and $T_i = 293K\ (21C)$ is the indoor air temperature. Here, for simplicity we assume that distributed "background" leakage is negligible compared to flow through the passive ventilation inlet-outlet pair.

The driving pressure induced by stack effect is very small. For example, the average annual outdoor temperature in Alberta is about 1C, so the annual mean ΔT is about 20C. At this average temperature difference, a passive ventilation inlet and outlet separated by a 3 m height will produce $\Delta P_{stack} \approx 2.2$ Pa. Compare this to a typical bathroom or kitchen exhaust fan that produces 20 to 120 Pa, or to a furnace fan with a pressure rise of about 30 to 60 Pa.

To compensate for the small stack-effect pressure, passive vents must have large inlet and outlet areas. Because intake and exhaust holes usually behave like sharp edged openings with no viscous effects, Bernoulli's equation applies and flow rates are proportional to the square root of the pressure difference ΔP_{stack}. Using (2-8) in (2-7) for equal inlet and outlet areas

$$Q_{stack} = C_d\, A_{vent} \left(g\, h_{vent} \frac{\Delta T}{T_i} \right)^{0.5} \qquad (2\text{-}9)$$

where Q_{stack} is in the stack-effect passive ventilation rate through an equal inlet-outlet pair, each with area A_{vent}, and $C_d \approx 0.6$ is the discharge coefficient for a typical sharp-edged inlet or outlet.

It is important to note that stack-effect pressure depends only on the difference in elevation between the inlet and outlet points and not on the path travelled through the building. For example, Figure 2-1 shows an inlet mounted in a basement wall and exhaust up the furnace flue pipe that passes through the attic and ends above the roof ridge. For this configuration, the height h_{vent} in Equation (2-8) and (2-9) is the elevation difference between the basement inlet and the outlet at the top of the flue. A configuration of this type produces the largest stack-effect driving pressure for passive ventilation but has the disadvantage that incoming air through the basement wall inlet may short-circuit to the flue without providing fresh air ventilation for all rooms in the house.

Wind Effect

For three seasons of the year, spring, summer, and fall, wind-induced pressures are the dominant driving force for air infiltration and passive ventilation. Wind pressures are highly variable over the surface of a building; ranging from a large stagnation pressure on the upwind wall to moderate suction pressures on the sides, downwind wall and roof. To further complicate matters, these pressures are affected by local wind shelter from upwind obstacles. This shelter reduces the effective wind speed over some of the walls.

The effectiveness of wind-induced passive ventilation is strongly dependent on the choice of intake and outlet locations, the wind speed and direction, and sheltering by upwind obstructions. Although wind-driven ventilation has the greatest potential for providing adequate fresh air to maintain indoor air quality during spring and fall when windows are closed and temperature differences are small, these wind-effect flows are highly variable. When wind direction shifts, a passive vent intake on an upwind wall may suddenly become an exhaust point on a downwind wall. This variability has led government regulators to specify that mechanical rather than passive ventilation be used to assure indoor air quality.

The basic driving force for wind-driven ventilation is the stagnation pressure on the upwind wall. For a wind speed U_H m/s at roof eaves height in an unobstructed flow upwind of the building and an outdoor air density $\rho_o = 1.1$ kg/m^3 the wind-effect pressure difference for an unsheltered building is

$$P_{inlet} - P_{\infty} = C_{p,in} \frac{\rho_o U_H^2}{2} \tag{2-10}$$

where $C_{p,in}$ is the wall or roof wind pressure coefficient at the inlet location, and P_{∞} is the atmospheric (i.e. barometric) pressure in pascals (Pa) measured far enough from the building that wind-induced pressure changes caused by flow patterns around the building are negligible.

The wind-effect pressure difference ΔP_{wind}, for equal inlet and outlet areas can be calculated from Equation (2-5) with $r = 1.0$, using Equation (2-10) for P_{inlet} and a similar equation for P_{outlet} with its pressure coefficient $C_{p,out}$

$$P_{inlet} - P_{outlet} = \Delta P_{wind} = (C_{p,in} - C_{p,out}) \frac{\rho_o U_H^2}{2} \tag{2-11}$$

where ΔP_{wind} in pascals (Pa), $\rho_o = 1.1$ kg/m^3 is the outdoor air density, and U_H m/s is the wind speed at eaves height. Using Equation (2-11) in the flow Equation (2-7),

$$Q_{wind} = C_d A_{vent} \left(\frac{\rho_o C_{p,in} - C_{p,out}}{2} \right)^{0.5} U_H \tag{2-12}$$

The most significant difference between wind-effect and stack-effect flows in Equations (2-9) and (2-12) is that Q_{stack} is proportional to the square root of indoor-outdoor temperature difference, $\Delta T^{0.5}$, in contrast to the linear proportionality of Q_{wind} to wind speed U_H. A factor of two increase in ΔT and U_H will produce a 40% change in Q_{stack} and a 100% change in Q_{wind}. This implies that stack effect is a more reliable source of passive ventilation, because with changing weather conditions it varies much less than wind effect.

Wind pressure coefficients vary greatly over each wall (and the roof). As the wind direction swings through 360°, the pressure coefficient C_p at a fixed location and switches from positive (stagnation) to negative (suction). This variation makes it difficult to choose optimum locations for passive ventilation inlets and outlets without the use of a computer flow model to test alternatives.

For a wall inlet, and an outlet through the flue (with its rain cap at $C_{p,out} = -0.5$), the inlet-outlet pressure coefficient difference ($C_{p,in}$ - $C_{p,out}$) varies from about 0.2 to 1.2 as the wind direction changes through 360°. A typical average over all wind directions is about ($C_{p,in}$ - $C_{p,out}$) = 0.5. The annual mean airport wind speed at Alberta locations is approximately $U_{airport}$

≈ 15 km/hr. Using these values in Equation (2-11) for an unsheltered building with $U_H = U_{airport}$ yields an annual average value of $\Delta P_{wind} \approx 4.8$ Pa. Although this is more than double the annual mean stack effect pressure difference of $\Delta P_{stack} \approx 2.2$ Pa, shelter from upwind obstructions can reduce the wind-effect pressure by a factor of three, making $\Delta P_{wind} \approx 1.6$ Pa. From these calculations we see that stack and wind effects are often of equal importance in passive ventilation. Because these two effects interact in a highly nonlinear way, a combined stack and wind-effect flow balance is required to deal with both effects simultaneously.

LBL and AIM-2 Distributed Leakage Infiltration Models

The preceding analysis for passive ventilation considered the simplest possible configuration: a single inlet and a single outlet in an otherwise perfectly tight building envelope. Although this idealization is useful to estimate the influence of inlet and outlet locations and wind pressure coefficients on wind and stack effect, real houses are much more complicated. In a real house a significant fraction of the fresh air required for indoor air quality comes from distributed unintentional leakage sites between the walls and foundation, in the ceiling, and around windows, doors and other holes in the air-vapour barrier.

Instead of using a single pair of holes passive ventilation could be modelled by approximating the inlet and outlet flow areas as distributed leakage spread over the walls, ceiling or floor. This distributed-leakage approach forms the theoretical foundation on which our model LOCALEAKS-2 was built to account for the sensitivity of passive ventilation to wind direction, inlet and outlet location, and local wind shelter.

The formulation of LOCALEAKS-2 begins with the pioneering work of Sherman (1980) and Sherman and Grimsrud (1980) who developed the LBL air infiltration model at Lawrence Berkeley Laboratories. The LBL model approximates a real building by distributing all envelope leakage (including passive vent holes) as uniform porosity over walls, ceiling and floor of the building. To account for the relative importance of wind and stack effects, Sherman divided the total building leakage into three user-specified fractions, at ceiling level, floor level and in the walls. All leakage was approximated as a uniformly distributed array of small holes each behaving like an orifice with flow rate proportional to the square root of pressure difference between indoors and outdoors.

The major appeal of the LBL model was its use of explicit functions for wind and stack effect flow factors. These functions were developed by Sherman (1980) by solving the non-linear flow equations for a wide range of leakage distribution fractions in walls, ceiling and floor, and fitting these solutions with physically realistic algebraic approximating equations. Using these approximations air infiltration can be estimated by simple direct calculation without the need for finding a solution to the non-linear flow-balance equations.

Walker and Wilson (1989) developed the Alberta Air Infiltration Model AIM-2 using the same techniques Sherman employed for the LBL model. In AIM-2 a separate furnace or fireplace or flue was added to the distributed leakage sites, and a more realistic flow model with $Q = C(\Delta P)^n$ was used. The variable flow exponent ranged from n = 0.5 for leakage dominated by sharp edged holes to n = 1.0 for laminar flow leakage through long, thin straight cracks. More realistic assumptions were made for wind-effect pressures at attic and floor level in AIM-2 to improve the LBL model. Like the LBL model AIM-2 developed approximating functions to fit the calculations of a numerical solution to the infiltration-exfiltration flow balance equations. Measured air infiltration at the Alberta Home Heating Research Facility demonstrated that AIM-2 gave considerably better estimates than the LBL model for a house with a flue.

Both AIM-2 and the LBL model are limited to houses with an approximately square plan-form and uniform wind shelter over all walls. This uniform shelter requirement means that the upwind obstacles must be large enough to provide the same shelter over the entire house even when the wind comes from a 45° angle rather than perpendicular to the upwind wall. AIM-2 and the LBL model approximate local passive ventilation inlets and outlets by distributing their leakage uniformly over all four walls of the building. LOCALEAKS-2 was developed to deal with sensitivity of shelter to wind direction, specific locations for passive ventilation inlets and outlets, and the interaction of natural ventilation with fan supply and exhaust flows.

LOCALEAKS-2 Ventilation and Infiltration Model

The LOCALEAKS-2 air infiltration model was specifically designed to simulate flow through passive ventilation inlets and outlets. Because the model is based on a numerical solution of the non-linear inflow-outflow balance, approximations and simplifications that were required to produce closed-form equations for the LBL and AIM-2 models are no longer necessary. The basic features of the model are summarized below:

- **Building Shape**: The building plan form is approximated as a rectangle with a user-specified length, width and height. For split level houses the user must estimate the floor-area weighted average of the two ceiling heights above grade level, and use this average value as input.
- **Distributed Leakage**: The unintentional "background" leakage through cracks and holes is distributed by the user in six separate locations: ceiling, floor, and each of the four walls. The default condition is a "uniform" leakage distribution in the four walls, with the fraction of total background leakage assigned to each wall according to its length.

The uniformly distributed ceiling leakage excludes fireplace and furnace flues. The pressure-flow relationship is given by

$$Q = C_{dist}(\Delta P)^{n_{dist}} \tag{2-13}$$

where the flow coefficient C_{dist} for the distributed leakage and exponent n_{dist} are found from a fan pressurization test, or estimated from similar construction types. The same value of n_{dist} is used for all sites, and the flow coefficient is

$$C_{dist} = C_{ceiling} + C_{floor} + C_{wall1} + C_{wall2} + C_{wall3} + C_{wall4} \tag{2-14}$$

with wall, ceiling and floor level leaks user-specified. The fraction in each of these sites is based on pure guesswork. For modern Canadian detached houses a reasonable estimate is to put 20% in the ceiling, 20% in the floor, and 15% in each of the four walls. The flow coefficients C are directly proportional to the leakage flow areas A_L in each wall.

- **Local Leakage Sites:** The user may specify any number of local leakage sites at floor level, in the ceiling, and in the walls. The default assumption for these sites is that they act like sharp edged orifice holes with $n_{local} = 0.5$ and an effective flow area of C_dA_{local}, where C_d is the discharge coefficient and A_{local} is the flow area of an opening. A value of $C_d = 0.6$ is used for short pipes and holes, and $C_d = 0.56$ is used for a furnace or fireplace flue with a raincap. Alternately, the user may specify the flow coefficient C_{local} and n_{local} in $Q = C_{local}(\Delta P)^{n_{local}}$ for each local leakage site. LOCALEAKS-2 uses a single averaged wind pressure coefficient for each wall of the building, so that only the height above grade of each local leakage site needs to be specified, rather than its specific location on a wall.
- **Doors and Windows:** The leakage from an open door or open window is often formed by a tall thin slot. A tall slot may cross the neutral level pressure plane shown in Figure 2-1, causing outflow through the portion of the slot above the neutral plane and inflow below it. To account for this LOCALEAKS-2 requires the user to specify the height and width and door and windows leakage openings, and uses the counterflow mixing theory of Wilson and Keil (1990) to calculate inflow and outflow rates separately for the portions of the leak above and below the neutral pressure plane.
- **Furnace and Fireplace Flues:** Flues are treated as a local leak orifice with a flow area A_{local} equal to the smallest restricted area of the flue pipe. LOCALEAKS-2 automatically reverses the flow in the flue to produce backdrafting if the indoor air pressure falls below that at the flue cap outlet. The height of the flue top above grade level is specified by

the user, and the flue is assumed to be filled with room-temperature air, or outdoor air, depending on whether the flue is in normal operation or backdrafting. An option also exists for an user-specified flue gas temperature to simulate warm air rising up a heated flue after furnace shutoff. In the present passive ventilation study the flue was assumed to be full of room air to estimate minimum ventilation rates in spring and fall.

- **Wind Pressure Coefficients**: Two different sets of wall-averaged wind pressure coefficients are used in the model. For an isolated building the wall-averaged coefficients of Akins, Peterka and Cermak (1979) were chosen. These isolated-building coefficients were also used by Sherman (1980) in the LBL model, and by Walker and Wilson (1989) in AIM-2. However, for a row of houses nearby buildings suppress the side-wall flow separations that occur on an isolated building. For houses in a closely-spaced row along a street, or for an inside unit of a town-house complex, side-wall pressure coefficients will be less negative than for an isolated building. The model accounts for this by using the two different sets of coefficients discussed in PART 4. The variation of pressure coefficient with wind direction was estimated using a polynomial in sines and cosines to fit the variation found by Akins, Peterka and Cermak (1979) and Wiren (1984).
- **Floor, Attic and Crawlspace Wind Pressures**: The user-specified floor level leakage is assumed to be distributed as a uniform crack around the perimeter that experiences the same wind pressure as the wall above it. The pressure coefficient of a ventilated crawlspace or attic is approximated by the mean of the four wall pressure coefficients. These wall pressure coefficients are weighted using user-specified fractions for the attic or crawlspace ventilator open area on each of the four sides and the roof.
- **Wind Shelter from Adjacent Buildings**: The wind shelter from neighbouring buildings is simulated using a new wind-shadow technique with adjustments for distance from the upwind obstacle and the variability caused by atmospheric turbulence over each one hour interval. Using the wind-shadow sheltering model, a shelter coefficient S_w is derived for 360 different wind directions on each of the four walls and roof of the building. This shelter coefficient is used to reduce the effective speed U_H in the flow approaching the building to produce an effective wind speed $U_{eff} = S_w U_H$ used to calculate the wind pressure on each wall.
- **Supply and Exhaust Fans**: The simplest type of mechanical ventilation is a high pressure centrifugal fan that produces a constant flow rate regardless of the wind and stack effect pressures. To simulate this type of fan the user simply specifies a fixed supply or exhaust flow rate to the house. The model is also capable of simulating real fan characteristics using a user-specified pressure-flow characteristic of the fan, and its

location on one of the building walls. The model then uses the indoor-outdoor pressure difference at this point on the building envelope to calculate the pressure supplied by the fan. This fan flow rate becomes part of the inflow-outflow balance used to determine the correct value of the indoor pressure at which inflows and outflows are equal.

- **Solution for Flowrate:** The inflow and outflow rates are solved for each of the local leakage sites and the distributed leaks for a specified value of wind speed, direction and indoor and outdoor temperature. Referring to Figure 2-1 the indoor pressure P_{indoor} must lie between the stagnation pressure on the upwind wall and the wake suction pressure on the downwind wall. As a first guess, LOCALEAKS-2 assumes that $(P_{indoor} - P_\infty) = 0$ where P_∞ is the atmospheric pressure in the wind approaching the building site. Using this first estimate, the mass inflow and outflow rates are calculated for each leak. The next iteration for indoor pressure is chosen as $(P_{indoor} - P_\infty) = +1000$ Pa if total inflow exceeds outflow, and -1000 Pa if outflow exceeds inflow. Succeeding iterations use the method of bisection, in which P_{indoor} for the next iteration is reduced by half the difference between the last two iterations. This bisection continues until the sign of the next inflow-outflow rate changes, after which the iterations step in the opposite direction until the net inflow and outflow balance.

PART 3

PASSIVE VENTILATION MEASUREMENTS

To test the ability of the computer model to predict combined infiltration from distributed leakage, passive ventilation from local openings, and mechanical ventilation from fan exhaust and supply, a wide range of experiments was carried out over a three year period at the Alberta Home Heating Research Facility. These experiments, combined with baseline infiltration data from previous years, showed that the effectiveness of passive ventilation is strongly dependent on the location of intake and exhaust openings relative to wind direction. In addition, wind shelter from nearby buildings strongly influences the sensitivity of passive ventilation to small changes in wind speed and direction. To validate and refine the computer model to account for wind speed, shelter and direction sensitivity, it was necessary to collect several thousand hours of ventilation measurements for each passive ventilation configuration in order to be able to sort the data into narrow bins of wind speed, indoor-outdoor temperature difference, and wind direction.

Air Leakage and Ventilation Characteristics of Test Houses

The Alberta Home Heating Research Facility is made up of six permanent test houses with poured concrete basements, and a seventh mobile home trailer unit modified for a study of drying rates of residential wall construction panels. Their construction is described in Gilpin et. al. (1980). The six unoccupied test houses have been continuously monitored since 1980 for building envelope energy losses and air infiltration and ventilation rates. The units are shown in the photographs of Figure 3-1 and 3-2, with the Masonry Unit #1 on the right in Figure 3-1, and on the left in Figure 3-2. Construction dimensions relevant to infiltration and ventilation are listed in Table 3-1.

The houses have been used to test gas furnace efficiency, air infiltration and ventilation, envelope heat losses, moisture migration and accumulation, active and passive solar heating strategies, and radiant floor heating systems. Continuous monitoring of building air exchange using tracer gases has been used to develop methods for predicting flow rates through open doors and windows, and for the interaction of air infiltration flow with exhaust and supply flow from fans.

Table 3-1

Construction Dimensions of AHHRF Test Houses

Component	Value	Remarks
basement floor thickness	10 cm	poured concrete slab on 0.0152 cm polyethylene sheet
basement wall height above basement floor	230 cm	poured concrete 20 cm thick, wall extends 50 cm above grade
floor joist depth	19 cm	wood floor joists rest on basement walls and support room walls
room wall height	244 cm	wood frame walls (except Masonry Unit #1) 4.1x9.2 cm studs on 40.6 cm centers with 1.3 cm drywall inside, 1.1 cm plywood exterior
flue top height above room floor	440 cm	flue top located at same height as the roof ridge
outside building dimensions	670x730 cm	long dimension on north and south walls. Conservation Unit #3 is 710x770 cm
inside floor dimensions	650x712 cm	plywood floor covered with rubber backed carpeting
inside floor area	46.3 m^2	about 1/2 to 1/3 floor area of typical 1 story house
total volume inside envelope	228 m^3	neglecting volume of equipment, floor joists and partition walls
net active air exchange volume	220 m^3	varies by ±2% depending on equipment and furnishings
envelope area	126 m^2	inside air-vapour barrier including basement wall above grade (0.5 m)

As shown in Figure 3-1 and 3-2, the houses are situated in a closely-spaced, east-west line with about 2.6 m separation between their side walls. The units are numbered from west to east (right to left in Figure 3-2). False end walls, with a height of 3.7 m but without roof gable peaks, were constructed beside the end houses of the line (Masonry Unit #1 and Moisture Unit

Figure 3-1 North side of test houses looking east along row from Masonry Unit 1 showing rain-capped flues and end wall wind shielding barrier.

Figure 3-2 South side of test houses looking east along row from Masonry Unit 1.

#6) to provide wind shelter and solar shading similar to that experienced by interior houses in the row. Only five of the six houses (excluding Moisture Unit #6) were used in the passive ventilation study.

All test houses have full poured concrete basements and polyethylene air-vapour barriers in walls and ceilings. The door on the east side of each house has flexible weatherstrip around its outside edges. Figure 3-3 shows the door in Reference Unit #5. Construction dimensions common to all test houses are summarized in Table 3-1. With the exception of the Masonry Unit #1, described in Kostiuk and Dale (1985), the other four houses used in the passive ventilation study are all of wood frame construction with 4.1 x 9.2 cm studs on 40.6 centers (2x4 studs on 16" centers) with 1.3 cm painted drywall on the interior and 1.0 cm plywood exterior sheathing. The inside area of 46.3 m^2 is about one-third to one-half the floor area of a typical single storey home. The asphalt shingled roof on all six houses is supported by wood roof trusses with their ends elevated 0.61 m above the ceiling by attic wall extensions. These elevated roof trusses were used to accommodate thick ceiling insulation, and to provide easy access to the attic space.

In addition to having a smaller floor area, the test modules differ from a standard house in that they have no plumbing or sewer drains, and no interior partition walls except for an entryway with an open interior doorway, shown in Figure 3-4 and 3-5. The absence of interior walls promotes air mixing, and allows the house to be treated as a single air exchange zone. The houses are heated electrically with a centrifugal fan shown in Figure 3-12, distributing air through under-floor ducts to the main-floor room. The fan in the electric heater operates continuously, recirculating 4.5 house interior volumes per hour to ensure complete mixing of air infiltration with indoor air tagged with SF_6 tracer gas. Air from the upstairs outlets returns to the basement through the large open stairwell shown in Figure 3-5. To avoid basement air stratification, a fan intake is located near the basement floor, and another intake is close to the ceiling see (Figure 3-12).

A standard mercury switch room thermostat located on the room side of the entryway wall maintains the interior temperature at 22C ± 0.5C during the heating season. In summer, the fan continues to circulate air through the house, and room temperature is governed by ventilation and heat gains through the walls and windows. Summer indoor temperature rarely differs by more than ±5C from the outdoor air.

With the exception of Conservation Unit #3, all test houses have a standard double walled 15.2 cm ID natural gas furnace flue pipe that acts as the major exfiltration site. This unheated flue begins about 145 cm above the basement floor and passes through the roof to terminate in a rain cap at the level of the roof ridge (see Figures 3-6, 3-5 and 3-1). Except in rare cases of backdrafting the unheated flue was full of room temperature air, making it equivalent to a leakage

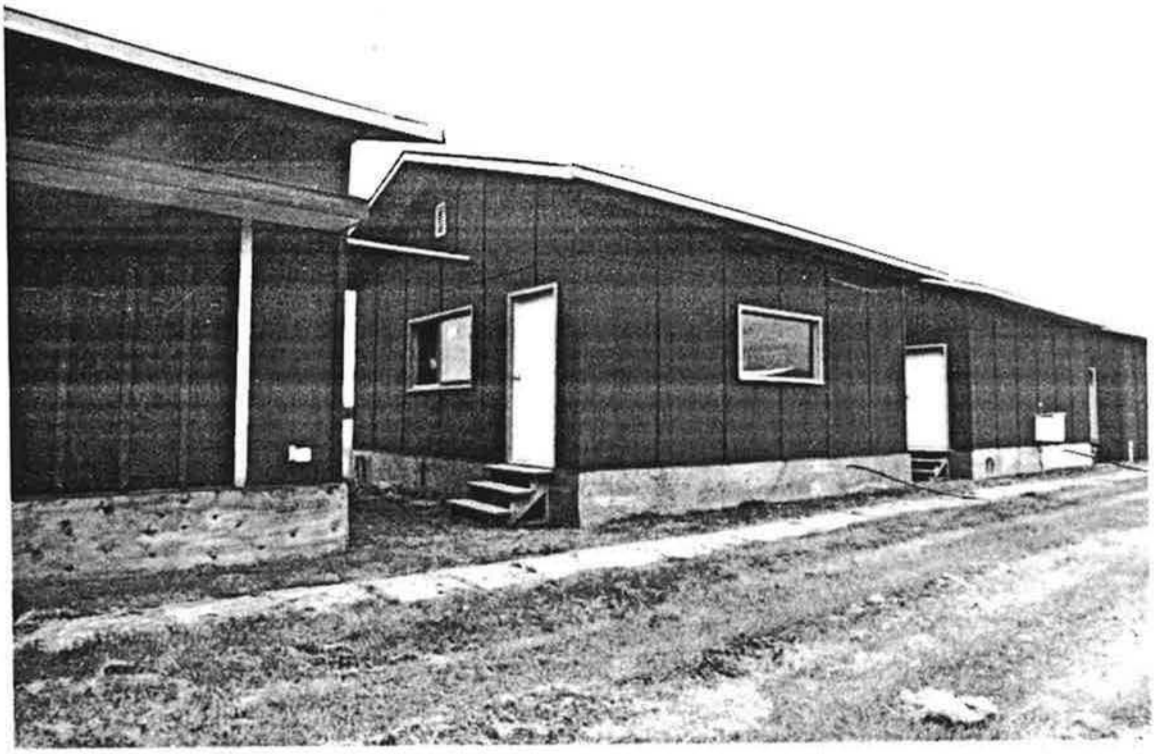


Figure 3-3 Reference Unit 5 from north-east showing plywood sheathing over vapour barrier on concrete basement.

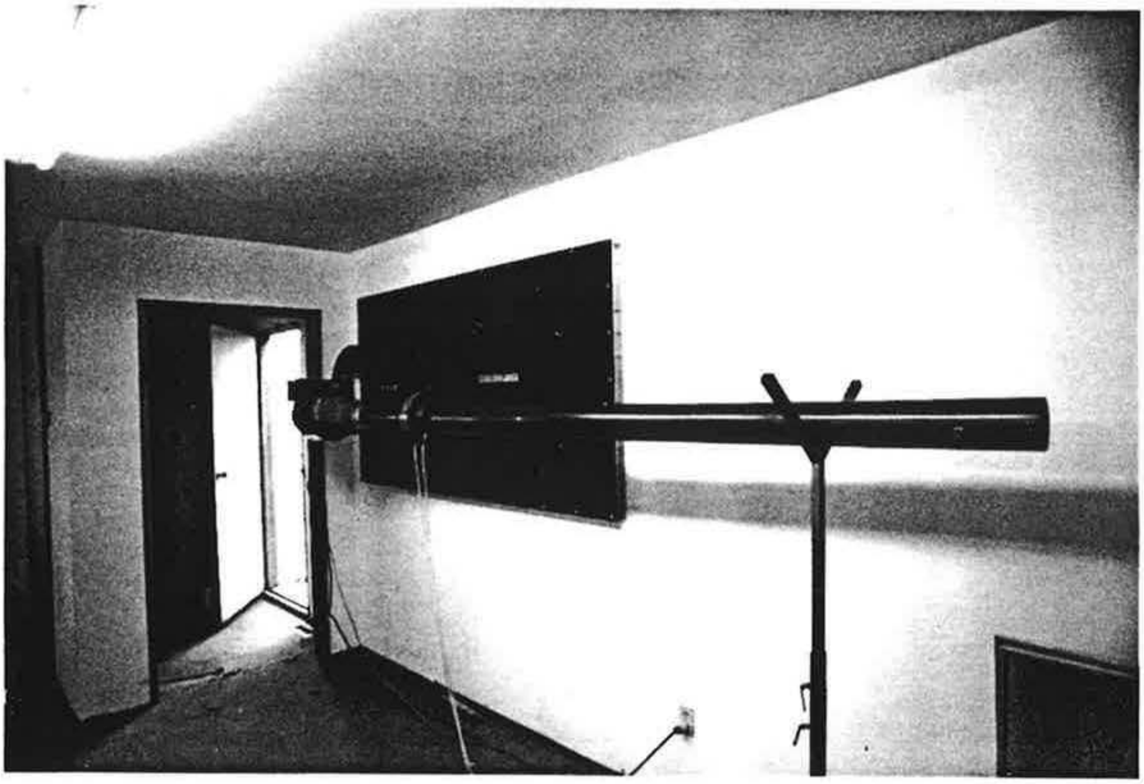


Figure 3-4 Entryway and mechanical ventilation fan in Retrofit Unit 2.

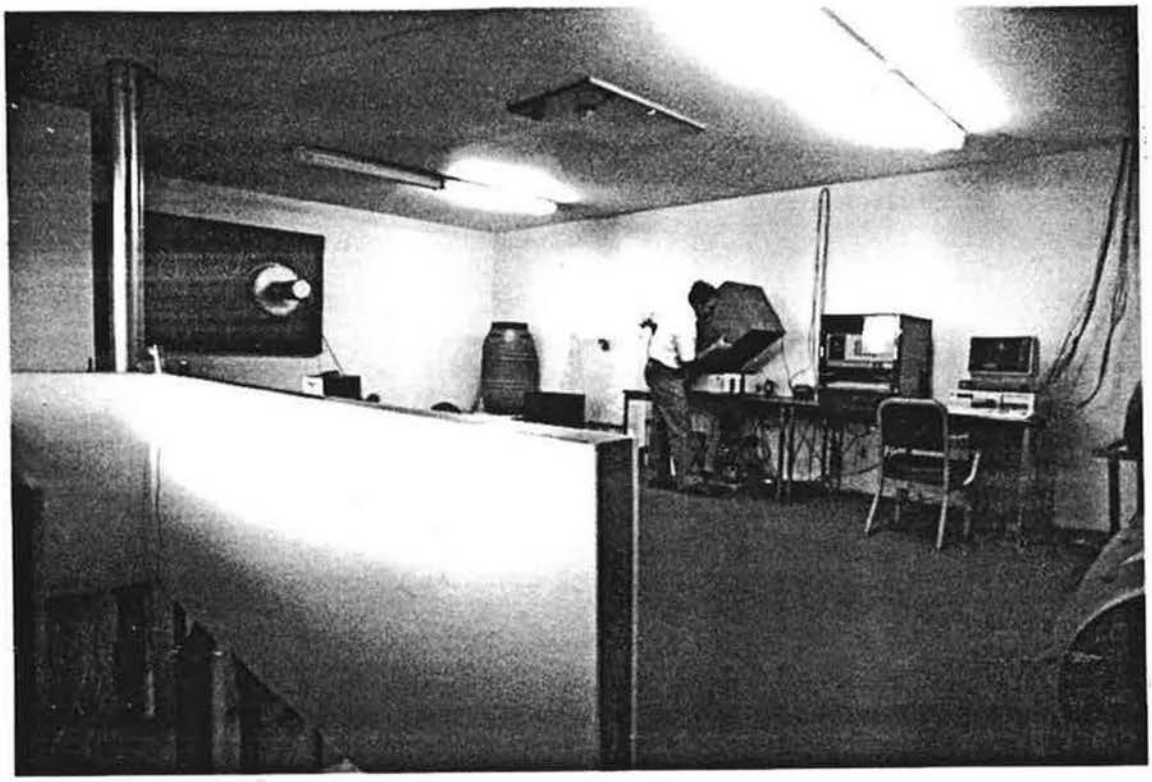


Figure 3-5 Main level of Reference Unit 5 with tracer gas concentration measurement and control system, flow meter on panel over east window, and open stairwell to basement.

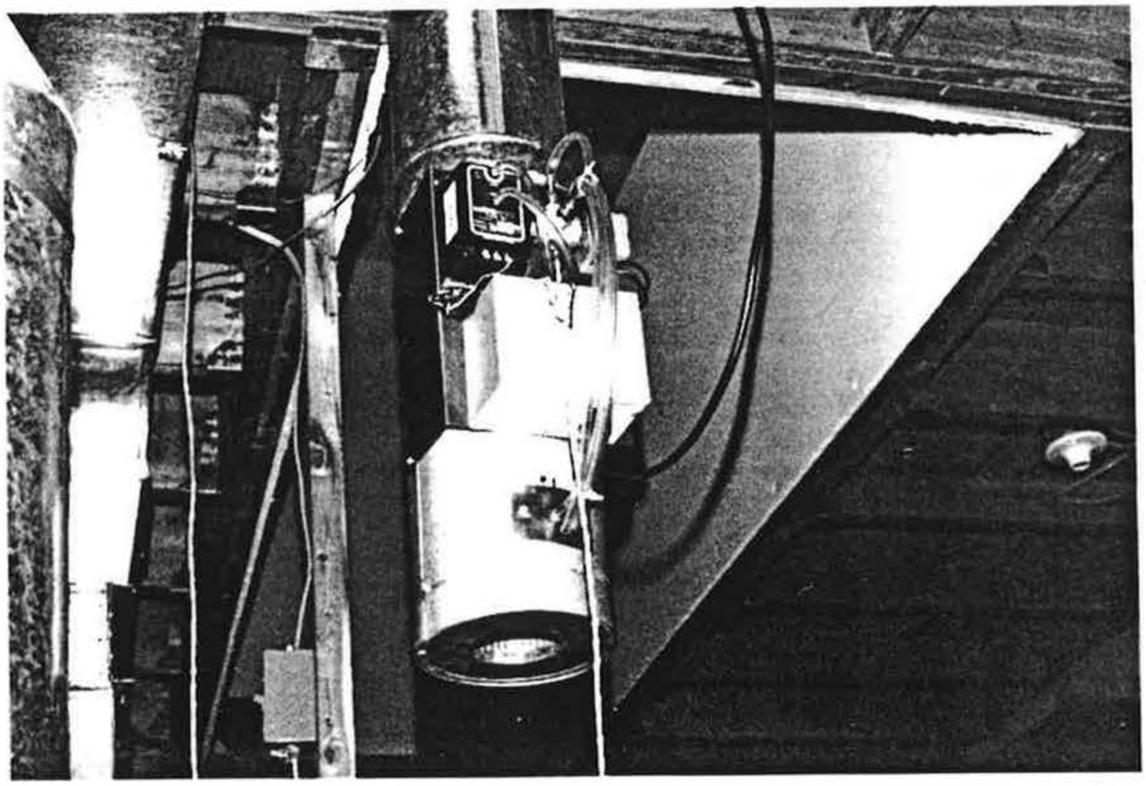


Figure 3-6 Flue flow meter with SETRA capacitative pressure transducer and zeroing solenoid valve, view from basement into open stairwell in Reference Unit 5.

site with the same flow resistance located at a height above the ceiling equal to the distance from the ceiling to the rain cap at roof ridge height. To limit flue exfiltration, the bottom of the flue was fitted with a 7.6 cm diameter sharp edged restrictor orifice, shown in Figure 3-6.

The air infiltration configuration of each house is summarized in Table 3-2, and discussed in detail in the following sections.

Open Windows

In autumn and spring, when outdoor temperature is greater than about 10C, passive ventilation systems would usually be supplemented by occupant opening of windows. To determine how window opening influences passive ventilation two different open-window configurations were investigated. The first was a 1.1 cm opening of the horizontal sliding window in the west wall of Masonry Unit #1 to form a narrow vertical slot. Under calm conditions when the neutral pressure level (where indoor and outdoor pressures are equal) was near the mid-height of the room, this slot acted as an exfiltration site at its top, and an infiltration site at the bottom. This configuration provided a test of the computer model in predicting counterflow through an opening.

The second type of window opening shown in Figure 3-7, 3-8 and 3-9 was a 7.6 cm diameter orifice mounted in the east wall window of Conservation Unit #3 and Reference Unit #5. These local leakage sites on the sheltered east walls allowed the computer model LOCALEAKS-2 to be tested for its ability to predict flow through sheltered passive ventilation intakes.

Passive Ventilation Inlet

To take advantage of stack effect caused by indoor-outdoor temperature difference, a passive ventilation inlet pipe was located near ground level on the center of the exposed south wall of the test houses. This location produced the largest stack effect height difference between the inlet pipe and the exfiltration outlet at the top of the furnace flue.

The south wall inlet was constructed from a flanged 15.2 cm ID PVC pipe sealed into a wooden panel set in the concrete basement wall, as shown in Figure 3-10. The inlet was covered with window screen clamped behind the flange, as shown in Figure 3-10. Inside each house, the passive vent inlet was connected through a motorized damper to a 3m long pipe shown in Figure 3-11. At the indoor end of the pipe, an upturned elbow was located above the basement ceiling level fan air intake to ensure that passive intake air was sucked into the recirculating fan and mixed completely with tracer gas tagged air in the house.

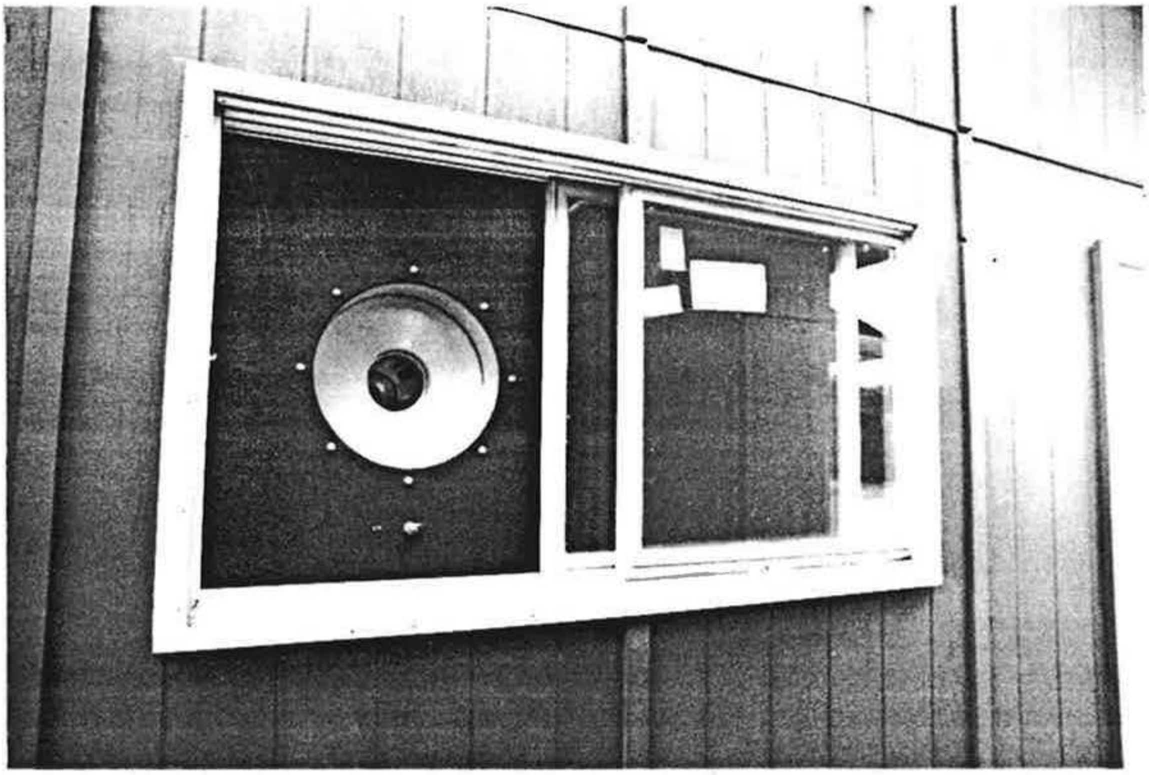


Figure 3-7 Open east window of Reference Unit 5 covered with interior panel containing restrictor orifice and flow meter.

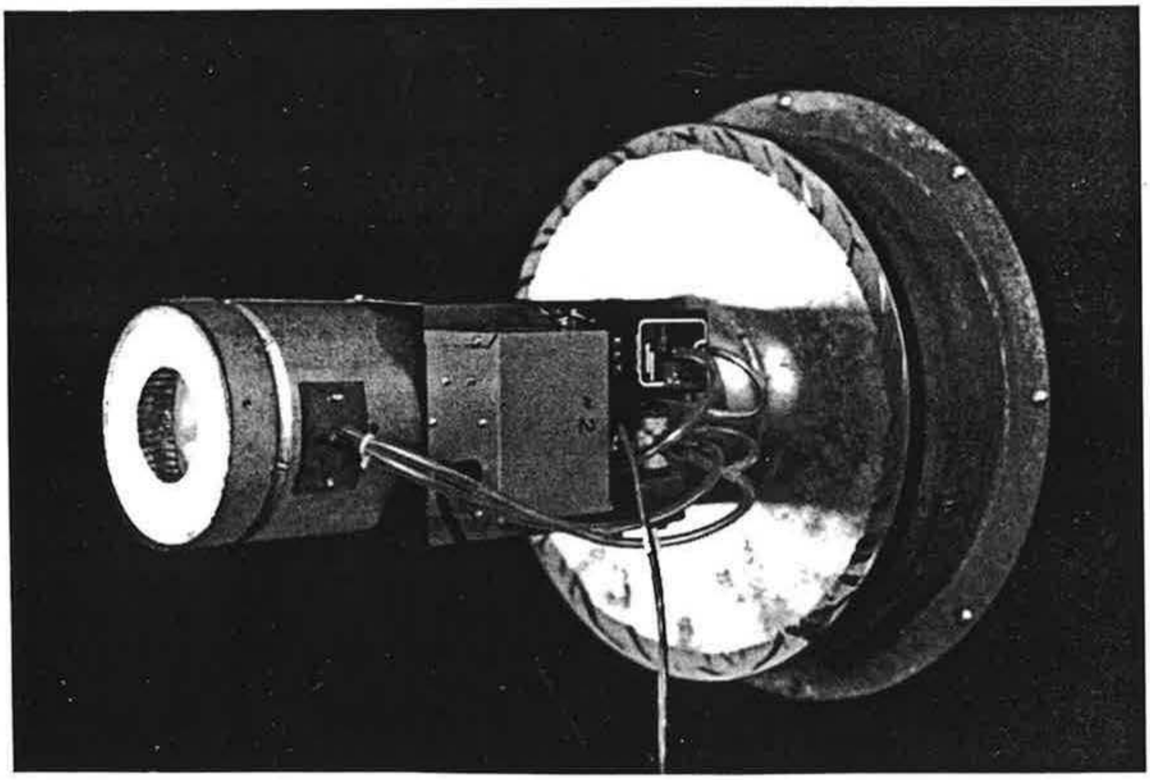


Figure 3-8 Flow meter and 7.6 cm I.D. restrictor orifice on east window panel of Reference Unit 5.

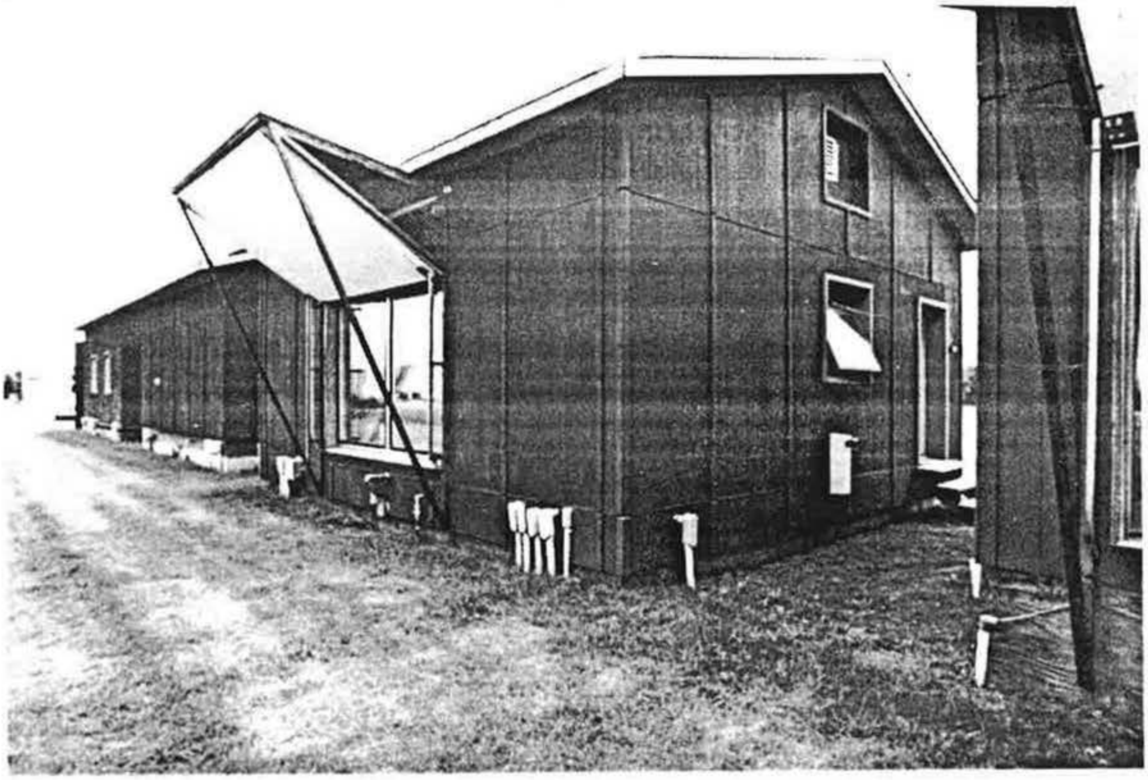


Figure 3-9 Conservation Unit 3 from south-east showing open window (with restrictor orifice on interior panel) and door on east side, shaded window and electrical conduct penetrations on south side

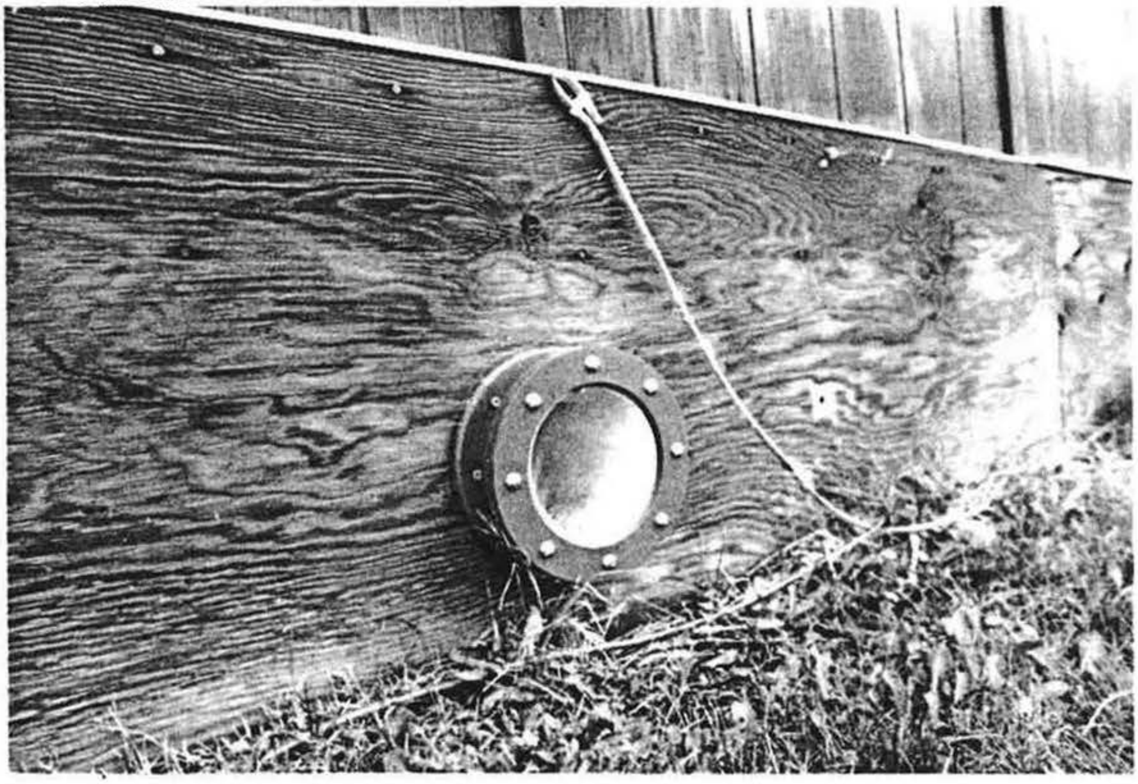


Figure 3-10 Screened inlet of 15 cm I.D. passive vent pipe on center of south wall of Reference Unit 5.

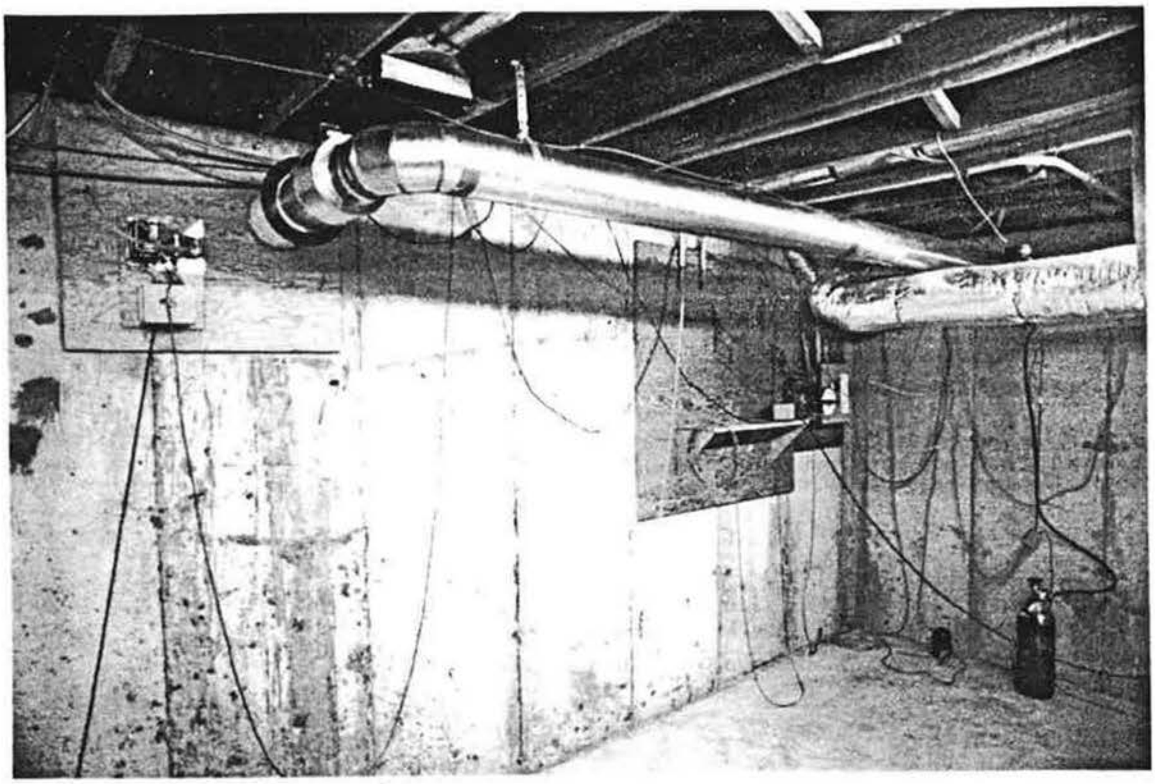


Figure 3-11 Passive ventilation inlet pipe and flow meter pressure transducer on south basement wall of Reference Unit 5, showing 15.2 cm I.D. pipe to circulating fan inlet.

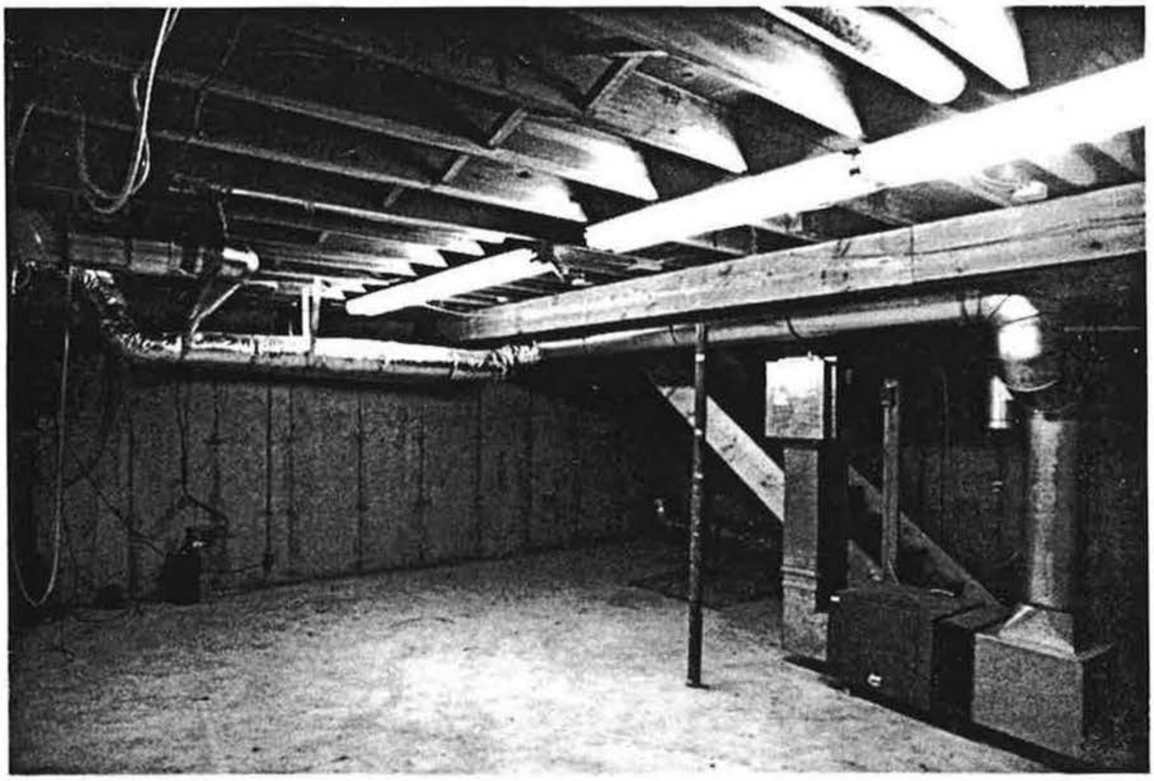


Figure 3-12 Circulating fan and electric heater in basement of Reference Unit 5.

The pressure-flow characteristic of the ground level inlet pipe was measured in the laboratory by blowing air from a test chamber through the screened pipe and damper assembly. The inflow to the test chamber was monitored with a standard ASME orifice meter. For pressure differences from 1 Pa to 35 Pa the pressure-flow characteristic was within ± 1% of orifice flow through an equivalent sharp edged hole with a diameter of 15.4 cm and a discharge coefficient of C_d = 0.32. The equivalent orifice area of the passive intake pipe was about twice as large as the 7.6 cm diameter restrictor orifice in the flue that acts as the major passive vent outlet site.

Distributed Envelope Leakage

In addition to intentional passive ventilation leakage sites each house had a leakage distribution of small cracks and holes created unintentionally during construction. The major unintentional leakage sites are: the crack between the wall sill plate and the top of the concrete basement wall; vapour barrier penetrations by electrical conduits and outlet boxes, flue pipes and plumbing vents; and cracks around the frames of windows and doors.

This distributed unintentional leakage was measured using a variable speed fan and flow meter connected to a 45.7 cm diameter hole in the plywood panel that is permanently mounted over the east window of each house. The fan pressurization panels were also used to mount the window vent restrictor orifices, and the mechanical ventilation fan (see Figures 3-4, 3-5, 3-7 and 3-8). To account for "valving action" of flexible leakage paths (such as door weatherstrip), leakage tests were carried out with the fan sucking air in and pressurizing the house, and with the fan blowing air out to depressurize the house.

In addition to pressure differences of 10 Pa to 70 Pa required to meet the ASTM (1982) and CGSB (1986) fan pressurization test requirements, the pressure-flow characteristic of the house envelope was measured at low pressures of 1 Pa to 10 Pa where actual wind and stack effects are dominant. To reduce errors from wind pressure fluctuations, the fan system was controlled by a microcomputer that made measurements only during calm periods. Pressurization tests were carried out if the average wind speed in the previous hour was less than a preset upper limit that ranged between 0.5 m/s to 1.5 m/s. (Most pressurization tests used the upper limit of 1.5 m/s during the measurement.) After each 100 second average at a pressure setting, the fan was shut off and a motorized damper on the window panel was closed to record a 100 second zero-flow indoor-outdoor pressure difference. These zero-flow pressures were subtracted from the pressurization measurement to correct for any offset caused by residual wind and stack effect. This procedure greatly reduced the variability caused by pressure fluctuations from varying wind speed and direction during a test. Errors due to wind pressure fluctuations are discussed in Modera and Wilson (1989).

The results from a large number of pressurization tests are summarized in Table 3-3, where the pressure-flow characteristic of each house has been fitted to the power law

$$Q = C(\Delta P)^n \tag{3-1}$$

where C is a flow coefficient dependent on leakage flow area and n is an exponent that characterizes the type of leak. The exponent n must lie between n = 0.5 for flow through sharp edged holes to n = 1.0 for laminar flow through long, thin, straight cracks. Because the ensemble of cracks and holes that make up a leakage distribution usually vary widely in their size and shape, the value of n lies between the limits $0.5 \leq n \leq 1.0$. Measurements for short pipes by Kreith and Eisenstadt (1957) suggest n = 0.67 for laminar flow in short cracks typical of envelope construction leakage sites. The values in Table 3-3 are from tests with windows closed and the flue and passive intake sealed to leave only distributed "background" leakage.

The combined wind and stack effect pressures across a leakage site usually lie in the range from 1 Pa to 10 Pa. With this in mind, Sherman (1980) suggested that leakage could be expressed as an equivalent ideal orifice leakage area A_L with discharge coefficient C_d = 1.0 at a reference pressure of 4.0 Pa. Equating the pressure-flow characteristic of (3-1) to the orifice flow equation at a specified reference pressure ΔP_{ref}, and an air density ρ kg/m^3,

$$Q = C\Delta P_{ref}^n = A_L\left(\frac{2\Delta P_{ref}}{\rho}\right)^{0.5} \tag{3-2}$$

from which

$$A_L = C\left(\frac{\rho}{2}\right)^{0.5}\Delta P_{ref}^{n-0.5} \tag{3-3}$$

Values of this leakage area A_L for the distributed unintentional "background" leakage are given in Table 3-3 for ΔP_{ref} = 4.0 Pa.

Mechanical Ventilation

Depressurization of a house by intermittent operation of kitchen and bathroom exhaust fans, and clothes dryers, can have a strong effect on passive ventilation flow rates. As a test of the ability of the computer model LOCALEAKS-2 to simulate combined mechanical and passive ventilation, an exhaust fan was operated intermittently in Retrofit Unit #2. A centrifugal fan with a constant speed AC motor sucked indoor air through a standard ASME orifice flow meter and

Table 3-2

Infiltration and Ventilation Characteristics of Test Houses

House	Polyethylene Air Vapour Barrier Thickness	Double Glazed Windows (% floor area)	South Facing Windows (% floor area)	Flue Pipe and Restriction Orifice		Passive Ventilation Openings	
				inside pipe diameter	restriction orifice diameter	Ground Level Pipe on South Side	Open Windows
1 Masonry	0.0152 cm	21%	7%	15.2 cm	7.6 cm metered orifice	24 hour open/closed cycle	west side 1.1 cm wide 87.5 cm high slot
2 Retrofit	0.0102 cm	12%	none	15.2 cm	7.6 cm metered orifice	open	none
3 Conservation	0.0152 cm	14%	11%	none	none	24 hour open/closed cycle	east side 7.6 cm dia. orifice
4 Solar	0.0152 cm	25%	23%	15.2 cm	7.6 cm metered orifice	closed	none
5 Reference	0.0102 cm	12%	none	15.2 cm	7.6 cm metered orifice	4 hr and 24 hr open/closed cycles metered pipe	east side 7.6 cm dia. metered orifice

Table 3-3

Distributed Background Envelope Leakage from Fan Pressurization Tests
With Flue and Passive Vent Intake Sealed, Windows Closed

$Q = C(\Delta P)^n$

House	Year	PRESSURIZATION			DEPRESSURIZATION		
		Flow Coefficient C $m^3/(s \cdot Pa^n)$	Flow Exponent n	Leakage Area A_L cm^2 at 4 Pa	Flow Coefficient C $m^3/(s \cdot Pa^n)$	Flow Exponent n	Leakage Area A_L cm^2 at 4 Pa
1 - Masonry[1]	1986	0.00403	0.705	41.5	0.00384	0.706	39.6
	1987	0.00250	0.763	27.9	0.00274	0.740	29.6
2 - Retrofit	1987	0.00664	0.745	72.3	0.00730	0.739	78.8
3 - Conservation	1987	0.00845	0.560	71.1	0.00861	0.581	74.6
4 - Solar	1987	0.00684	0.712	71.0	0.00592	0.742	64.1
5 - Reference	1988	0.00937	0.625	86.3	0.00970	0.661	93.6

[1]Leakage characteristics in House #1 from 1986 used for model validation with house sealed, and with open 7.6 cm flue orifice. Pressurization tests from 1987 were used for validation with passive inlet pipe, flue and open window.

exhausted it outdoors. As shown in Figure 3-4, the exhaust fan was mounted in the same window panel used for fan pressurization leakage tests.

The pressure drop through the fan and orifice system was about 160 Pa, of which about 140 Pa was across the orifice. This large pressure drop through the exhaust system maintained a constant flow rate, independent of the small wind and stack effect induced pressures, which were always less than 20 Pa. The 3.33 cm diameter flow meter orifice was sized to produce a flow rate of 7.3 L/s (44 m^3/h), yielding a mechanical air exchange rate of about 0.20 ACH. The exhaust fan was operated in four hour and six hour on-off cycle times. When the fan was off, the metering orifice with its discharge coefficient of $C_d = 0.6$ produced an equivalent leakage area of 5.2 cm^2, adding about 7% to the background leakage area of 76 cm^2.

Air Exchange Measurements

The total amount of outside air brought in by combined natural infiltration, passive ventilation, and fan exhaust was measured using a tracer gas system that injected sulphur hexaflouride, SF_6, to maintain a constant concentration in each of the test houses. The total volume of tracer gas, injected eight times each hour, is proportional to the amount of outside air that enters the house and is brought up to the 5.0 ppm setpoint. The gradual decrease of concentration in each of the 7.5 min periods between injections was accounted for in the data analysis to determine a true hourly average concentration, typically 4.8 ppm. Two independent Miran 103 infra-red gas analyzers were used to monitor the tracer gas concentration. The analyzers were located in Retrofit Unit #2 and Reference Unit #5, and monitored the house in which they were located and the house on either side. By locating the analyzer in the centre of the three-house group, the length of sample lines and the time required to draw a representative gas sample was kept to a minimum.

The requirement for continuous unattended operation of the gas analyzer over periods of several months required special operation and calibration techniques to obtain accurate measurements. These techniques were developed during several frustrating years of instrument malfunction and signal drift. Finally, each of the gas analyzers was enclosed in a temperature controlled box, shown being lifted in Figure 3-5, and maintained at 30C ± 0.2C using an electric heater with a proportional voltage controller monitoring a thermistor inside the box. A small fan circulated air inside the box, and a vent hole in the box allowed some room air to leak in to maintain sufficient heat loss for the temperature controller to operate properly. The enclosure temperature of 30C was chosen to allow effective control during summer conditions when room temperature rose above the winter thermostat set point of 22C. If the instrument enclosure temperature deviated by more than ± 1.0C from the 30C set-point, the measurements were flagged to indicate the possibility of concentration measurement error.

The MIRAN 103 detectors used infra-red absorption along a 20m light beam path obtained by multiple reflections of an infra-red source from gold front-surfaced mirrors. Infrared absorption generates a non-linear response, with output voltage proportional to the logarithm of SF_6 concentration. However, over the small range from 4.5 ppm to 5.0 ppm at which the tracer concentration is maintained in the houses, the analyzer response was almost linear with concentration. The gas analyzers were calibrated over this range by preparing a 5.00 ppm gas sample in which 0.5 ml of pure SF_6 was injected by syringe into 100 litres of filtered outdoor air pumped through a dry gas meter into a plastic sample bag. The concentration calibration was made by drawing 25 litres of this mixture through the analyzer to thoroughly purge its internal 2.5 litre volume. Then, a second calibration sample was mixed to produce 4.50 ppm SF_6 concentration to provide the second calibration point. Linear interpolation between these two analyzer voltage readings was used to determine the room air tracer concentration during system operation.

To provide a continuous check on analyzer accuracy and drift, an outdoor air background and reading and a bottled calibration gas reference reading were taken automatically using computer controlled solenoid valves on the analyzer sampling manifold. A zero reading was taken once each day by drawing an outdoor air sample through a filter at the meterological tower and along sample lines to each of the instruments. This reading gave a check on the instrument zero setting, and on the presence of background contaminants (such as ammonia-based fertilizers) that occasionally produced an apparent false tracer-gas reading in the incoming outdoor air. Once a day, calibration gas was injected from a pressurized bottle with 4.75 ppm to provide a reading in the control range to check for analyzer drift. The overall voltage drift of the analyzers caused an uncertainty of about ± 1% in the measured tracer concentration, and in the calculated air exchange rate. The fluctuation in analyzer cal-gas reading was about 0.5% per month, with a slowly-varying random cycle of about four months.

Tracer gas to maintain the houses at the average 4.8 ppm level was injected from a bottle of pure SF_6 by pulsing a pair of closely spaced solenoid valves to produce puffs of tracer gas, each with a volume of about 3.5 cm^3 at room pressure. The injectors were calibrated by pulsing them 300 times to produce about 1000 cm^3 of gas, measured by bubbling the tracer gas through water into an inverted graduated cylinder.

A micro-computer data acquisition system monitoring the two analyzers was used to control the number of pulsed injections of tracer gas required to maintain the concentration at a setpoint of 5.0 ppm in each of the houses. To assure complete mixing of the tracer gas with building air, the tracer gas injector was mounted in the ceiling-level return air duct in the basement. The automated sampling system monitored the tracer concentration in each house for 2.5 minutes, with a return period of 7.5 minutes, to produce eight sets of injection pulses per hour in each house. This 7.5 minute return period allowed ample time for the previous series of injections to mix completely within the house volume, and allowed the necessary time for the infra-red analyzer to draw a sample from the two other houses. By monitoring and injecting tracer gas eight times per hour, the indoor concentration was maintained within ±0.1 ppm of the hourly average 4.8 ppm. The sum of the number of tracer gas injections was recorded for each hour.

An uncertainty analysis of the injection and concentration measuring systems indicated that the standard deviation in measured infiltration rate was ±2.5% of the air exchange rate, added to an absolute error of ± 0.0025 ACH. This corresponds to a measurement uncertainty standard deviation of about ±3% at typical air exchange rate of 0.3 ACH. For random variations this implies a range of about ±6% to encompass 95% of data scatter due to uncertainty. Measurement uncertainty was much smaller than the hour-to-hour natural variability of the air infiltration rate. The injector resolution of ±0.0025 ACH is clearly evident in the measured infiltration data plotted in Figure 3-13.

Passive Ventilation Flow Rates

Air infiltration and passive ventilation computer models can predict a correct overall air exchange rate but still produce large inaccuracies, and even incorrect flow directions, through individual passive ventilation leakage sites. To test the accuracy of the computer model LOCALEAKS-2, it was essential to measure local flow rates through passive ventilation intake and exhaust sites. The infiltration and ventilation configurations of each of the test houses are summarized in Table 3-4. These different arrangements were designed to provide a wide range of variables to test the model's capability.

To monitor these flow rates, the flue and window openings were connected to a specially designed orifice flow-meter. This flow-meter, shown in Figures 3-6 and 3-8, was constructed by cutting a precise 7.6 cm diameter hole in a sheet metal cap at the end of a 61 cm long section of 15.2 cm I.D. gas furnace flue vent pipe. The orifice flow meters were calibrated using a standard ASME orifice to calculate their pressure-flow characteristics in both the forward and reverse flow directions. The accuracy of these calibrations was about ±3%. The differential pressure between room air outside the orifice and flow inside the pipe was monitored using a sensitive diaphragm pressure transducer (SETRA model 264). Flow meter differential pressure readings were often as small as 5 Pa. To produce accurate readings, the pressure transducer was

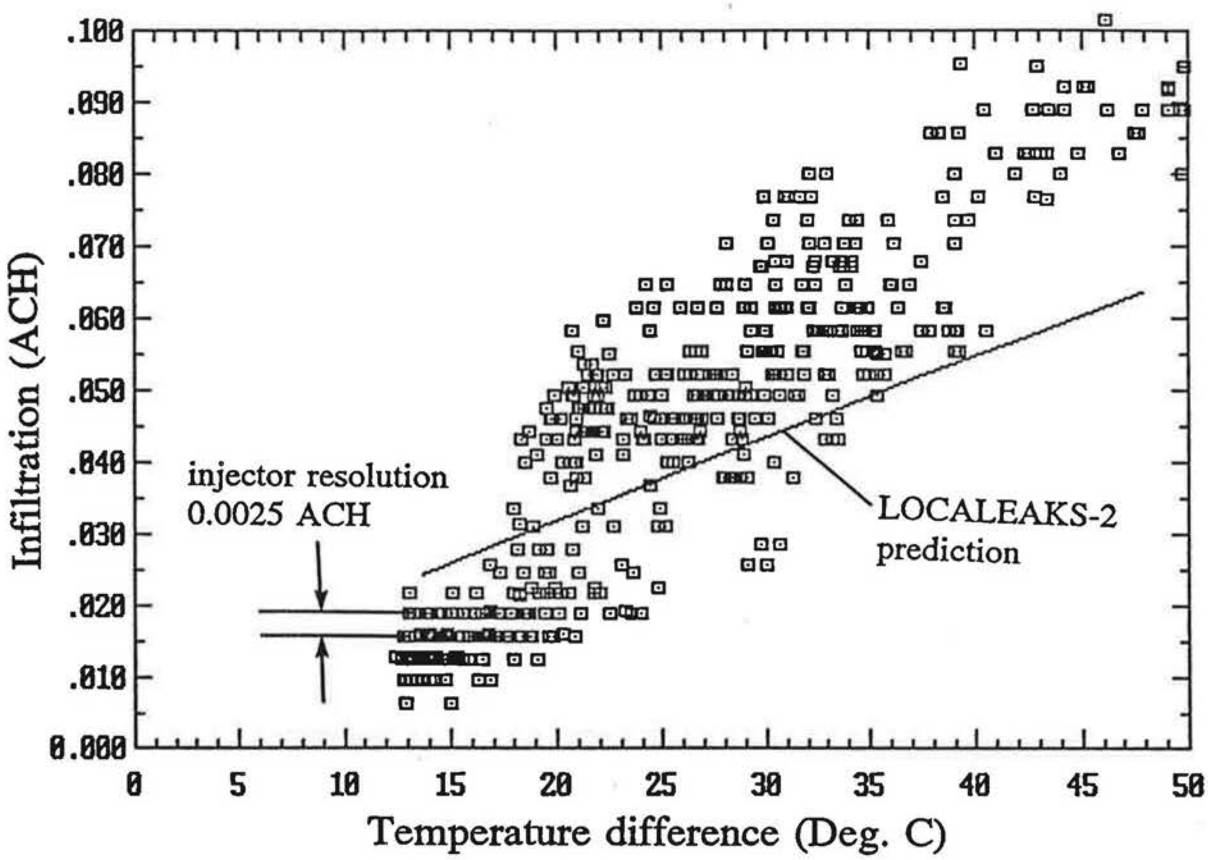


Figure 3-13 Effect of Tracer Gas Pulse Injector Resolution on Measured Air Infiltration in Masonry Unit #1, Sealed Configuration

Table 3-4

Location and Equivalent Leakage Area[a] of Infiltration and Ventilation Sites

House	A_d Distributed Background Leakage[c] cm^2	Normalized Distributed[e] Leakage cm^2/m^2	A_f Flue @Z=450cm[d] cm^2	A_p Passive Vent Inlet[b] cm^2	A_w Open Window[b] cm^2	Window Configuration
1 Masonry	38.8 (1986) 27.5 (1987)	0.26	33.7 metered orifice	59.3 at Z=-32 cm	57.8 at Z=153 cm	open west window 1.1 cm wide, 87.5 cm high slot on sliding plane
2 Retrofit	72.2	0.57	33.7 metered orifice	59.3 at Z=-38 cm	none	all windows closed
3 Conservation	69.8	0.55	no flue	59.3 at Z=-40 cm	30.4 at Z=160 cm	open west window connected to 7.6 cm dia. sharp edged orifice
4 Solar	64.8	0.51	closed	closed	none	all windows closed
5 Reference	86.2	0.68	33.7 metered orifice	59.3 metered pipe at Z=-32 cm	30.4 metered orifice at Z=156 cm	open east window connected to 7.6 cm dia. sharp edged orifice on flow meter

(a)Leakage area at 4.0 Pa reference pressure difference with air density $\rho = 1.10\ kg/m^3$
(b)Height Z above (+) or below (-) floor level to center of leakage site
(c)Average of pressurization and depressurization values at 4.0 Pa reference pressure
(d)For upflow: when flue backdrafts outside air enters at Z = -105 cm below floor level
(e)Normalized with Envelope area of 118 m^2

mounted on a rigid metal bracket on the side of the flow meter, as shown in Figure 3-6, and its zero pressure reading was measured once each day by using a computer controlled three-way solenoid valve to connect the input to the output pressure tap, and disconnect the flow meter. The pressure transducer output amplifier was modified by adding a resistance-capacitance filter with a time constant of about 1 minute. In operation, the differential pressure from the transducer was read at 2.5 minute intervals, and the 1.0 minute time constant of the averaging filter made these readings representative of the previous 2.0 minute interval.

Reversals in flow direction were monitored by converting each of the 24 readings per hour to equivalent flow rate, and storing separate averages for positive and negative differential pressures. For air exchange rate, it is important to account for these flow reversals, because a leakage site that has an average flow of zero over an hour may act as an effective inlet for part of the time and an outlet for the remainder, causing a significant net air exchange.

In addition to these window and flue flow meters, the basement inlet pipe on Reference Unit #5 was instrumented with the same type of pressure transducer system to monitor flow rate. The pressure transducer on the basement inlet pipe measured the indoor-outdoor pressure difference between the outside wall beside the inlet and the indoor pressure at the same elevation, as shown in Figures 3-10, and 3-11. Using the equivalent orifice area of the inlet pipe, the flow rate was calculated and stored in the same way as the flow meters.

Wind Measurement

Computer predictions of air exchange rate require an accurate estimate of the wind at roof eaves height in the unobstructed flow approaching the building. These measurements were obtained using a pair of 10 m high meteorological towers located midway along the row of houses, 19.5 m from the north and south faces of the row. The wind speed and direction at 10 m height was measured with low-friction cup anemometers and rotating direction vanes on both towers, with the data acquisition system recording values from the tower upwind of the houses. There was usually little difference in the 10m wind speeds and directions on the two towers, and the two readings were useful mainly to increase system reliability by providing an extra set of wind instruments.

Wind speeds and directions were measured 24 times an hour (at 2.5 minute intervals) and averaged to produce one hour average values. Both the mean and standard deviation of these 24 readings for wind speed and direction were recorded. In addition, east and north vector components of each of the 24 readings were calculated, and stored as mean-squared averages over the hour. These mean-square values could then be used to compute the standard deviation of wind speed, and to calculate a true average wind-run direction.

The cup anemometers and wind vanes were calibrated in the large 1.2 m by 2.4 m cross section wind tunnel in the Department of Mechanical Engineering at the University of Alberta. A pitot-static probe connected to a diaphragm pressure transducer was used as the standard. Internal friction on the DC anemometer cup generator, and in the shaft bearings limited the starting speed to about 0.3 m/s during calibration. Under cold weather operating conditions, the starting speed may have been as high as 0.5 m/s. This starting speed offset produced a small bias by overpredicting the amount of time that calm wind conditions occurred. The anemometer was recalibrated periodically, and revised calibration equations were used to convert the instrument voltage reading to equivalent wind speed. Using these calibrations, the wind speed uncertainty has a standard deviation of about ±1.5% added to an absolute uncertainty of about ±0.2 m/s.

For use in the LOCALEAKS-2 air infiltration model the wind speeds at 10 m height were converted to an equivalent wind speed at the 3.0 m roof eaves height of the test houses using power-law velocity profile with an exponent $U \propto Z^{0.16}$ typical of rural terrain.

Site Terrain and Wind Shelter

The flat exposed test site is located on rural agricultural farm land, with fields planted in forage and cereal crops in summer, becoming snow covered stubble in winter. Windbreaks of mixed poplar and spruce trees cross the landscape at intervals of a few kilometres. One of these windbreak rows with 20 meter high trees is located parallel to the line of the houses about 250 m to the north, and another windbreak lies 100m to the northeast. A low tree row with 3 meter height runs perpendicular to the line of the buildings to the southwest. The houses are totally exposed to south and east winds. Wind shelter from man-made structures is dominated by two-storey storage and machinery buildings located about 50 m to the northeast.

Because wind speeds are measured close to the row of buildings, wind shelter from trees and nearby buildings is accounted for directly in the wind measurements. Shelter from adjacent houses in the row, and from the false end wall beside Masonry Unit #1 was estimated by developing theoretical wind shelter adjustments to the LOCALEAKS-2 ventilation and infiltration model.

PART 4

COMPUTER MODEL VALIDATION

The objective of the model validation was to use measured data to test and refine LOCALEAKS-2 to produce a realistic simulation of both air infiltration through distributed leakage, and passive ventilation through a combination of intake and exhaust pipes, with distributed background leakage. When using experimental data to refine a theoretical model, there is a danger that the model will be tuned to match specific data sets, and in so doing, sacrifice both its generality and its credibility. Here, we will try to state clearly the physical basis of the refinements made, and limit them to the bare minimum required to improve the realism of LOCALEAKS-2.

A rational evaluation of the strengths and weaknesses of the passive ventilation model was made possible by the large data base available for testing. Over the three year project, more than 100,000 hours of air infiltration and meteorological data were recorded in the five test houses. This large data base allowed separate tests of wind-effect and stack-effect dominated ventilation, and made possible an accurate estimate for the effect of varying wind direction and shelter by adjacent buildings.

Sorted Data Sets

For a given air infiltration or passive ventilation leakage configuration, air flow is dependent on three critical variables:

- **Stack-effect,** buoyancy-driven flow, dependent on indoor-outdoor temperature difference ΔT.
- **Wind-effect,** stagnation pressure-driven flow, dependent on wind speed of the unobstructed approach flow U_H.
- **Shelter and orientation effects** caused by wakes from upwind buildings and flow pattern changes dependent on wind direction angle θ.

To test these effects separately, the data was sorted into two types

- stack-effect dominated with ΔT = 10C to 50C and $U_H < 1.5$ m/s
- wind-effect dominated with U_H = 2.0 to 9.0 m/s and $\Delta T < 10$C

Sorted data sets were generated for each house in both a low leakage "infiltration" configuration, and a high leakage "passive ventilation" configuration. The effect of wind direction and shelter was dealt with by a secondary sorting of each of these data sets into wind direction bins.

House Leakage Configurations

To provide a wide range of leakage distributions, four of the five houses were set up in both a background leakage "infiltration" configuration and a "passive ventilation" configuration with intake pipes, flues and open windows added to the distributed background leakage. The relative leakage in each of these configurations was calculated using the data in Table 3-4 and is summarized in Table 4-1. Solar Unit #4 was tested in a single leakage configuration, with its flue sealed, and all leakage formed by distributed unintentional sites in the walls, ceiling, and the crack around floor level. Because most wall leakage in Solar Unit #4 is concentrated in the exposed south wall with its six double-glazed window units, House #4 provided a challenging test for LOCALEAKS-2 to predict wind direction dependence of air infiltration.

Each house generated four data sets, for the two different leakage configurations, and for stack and wind dominated flows. These 19 data sets ranged in size from 96 hours to 1035 hours in size, and totalled 10,399 hours of data, about 10% of the total available data set. The remaining 90% of the data was for other leakage configurations, and for periods when wind and stack pressures were equally important.

Table 4-1

Relative Distribution of Leakage for Test Houses

House	Configured for Infiltration "sealed"		Configured for Passive Ventilation			
	Distributed Background[(a)]	Flue	Distributed Background[(a)]	Flue	Intake Pipe	Window
1-Masonry	100%	closed	15%	19%	34%	32%
2-Retrofit	68%	32%	44%	20%	36%	closed
3-Conservation	100%	none	44%	none	37%	19%
4-Solar	100%	closed	-	-	-	-
5-Retrofit	100%	closed	41%	16%	28%	15%

[(a)] Leakage area at 4.0 Pa reference pressure, air density $\rho = 1.10$ kg/m^3, see Table 3-4

Background Leakage Distribution

One of the major uncertainties in using any air infiltration model is specification of the distribution of unintentional "background" leakage sites on the building envelope. These leakage sites are mostly invisible, and strongly dependent on construction details. The amount of total leakage in each of the walls, ceiling and floor is determined mostly by guesswork. Because this distribution is user-specified, model performance can be improved by making a judicious choice.

To provide a rational foundation for estimating leakage distributions, the fraction assigned to each wall was based roughly on the length of cracks around windows and doors. A sealed window was assumed to have less leakage than one that could be opened. Table 4-2 gives the distributed background leakage distribution for each of these houses based on these crack-length rules. Blank walls with no windows or doors were assigned 5% to 10% of the total leakage to account for construction flaws and vapour-barrier penetrations by electrical fittings.

Table 4-2

Assumed Background Leakage Distributions for AHHRF Test Houses

Background Leakage Location	House				
	Masonry Unit #1	Retrofit Unit #2	Conservation Unit #3	Solar Unit #4	Reference Unit #5
North Wall #1	5%	10%	10%	5%	10%
South Wall #2	5%	10%	30%	30%	10%
East Wall #3	10%	20%	30%	20%	20%
West Wall #4	0%	20%	10%	5%	20%
Floor Level	20%	20%	10%	20%	20%
Ceiling	50%	20%	10%	20%	20%

Model Refinements

The first attempt at constructing a model capable of predicting wind direction and shelter effects on passive ventilation through large local openings was LOCALEAKS-1. This original version used a purely empirical function to describe wind shelter effects for a row of houses. The function used a polynomial in sines and cosines that smoothly varied the wind-shelter coefficient S_w with wind angle. This coefficient reduces the effective windspeed to S_wU_H; with S_w=1.0 for unsheltered north and south winds, and S_w = 0.5 for complete shelter by adjacent houses in east or west winds.

Preliminary testing of this empirical wind shelter factor produced large errors in passive ventilation flow as the wind shifted slightly from the completely sheltered east or west directions. To improve model performance and provide a physical basis for wind shelter, a theoretical windshadowing model was developed. This shelter model uses the momentum-deficit decay of three-dimensional wake flows to simulate shelter by adjacent buildings. The new theory still requires an empirical estimate of the maximum shelter provided by a closely spaced adjacent building. Figure 4-1 shows a wind direction plot of the shelter coefficient generated by the wind-shadow theory. Predicted values of shelter coefficients gave significantly better agreement with air infiltration and passive ventilation measurements.

A final adjustment to LOCALEAKS-1 to produce LOCALEAKS-2 was an adjustment of side-wall pressure coefficients. For an isolated building, this side-wall pressure coefficient is about C_p = -0.65, based on wind-tunnel measurements by Akins, Peterka and Cermak (1979). When this value was used, LOCALEAKS-1 showed poor performance in predicting flow rates through the south wall inlet pipe and east wall open window. To improve model performance for local leakage sites it was necessary to use a side-wall pressure coefficient of -0.20. The physical justification for this change is that the upwind house in a closely-spaced row, or the houses on either side, channel the flow and prevent large flow separations and strong streamline curvature from occurring on side-walls. This reduced upwind corner flow separation region results in more parallel streamline flow along the sides of a closely spaced row, and produces a lower suction pressure because streamline curvature is reduced. This explanation seems plausible, and helped put our consciences at rest when we defined two different types of side wall pressure coefficients shown in Table 4-3.

Table 4-3

Wall-Averaged Wind Pressure Coefficients C_p for Wind Direction Normal to the Upwind Wall

Shelter Configuration	C_p Pressure Coefficient		
	Upwind Wall	Side Walls	Downwind Wall
Isolated House	+0.60	-0.65	-0.30
In-Line Closely-Spaced Row	+0.60	-0.20	-0.30

The two refinements made to the model for wind shelter and side wall pressure coefficients were motivated by observed poor performance with model predictions. However, these differences were used as the basis for developing physically realistic model enhancements, and not as a

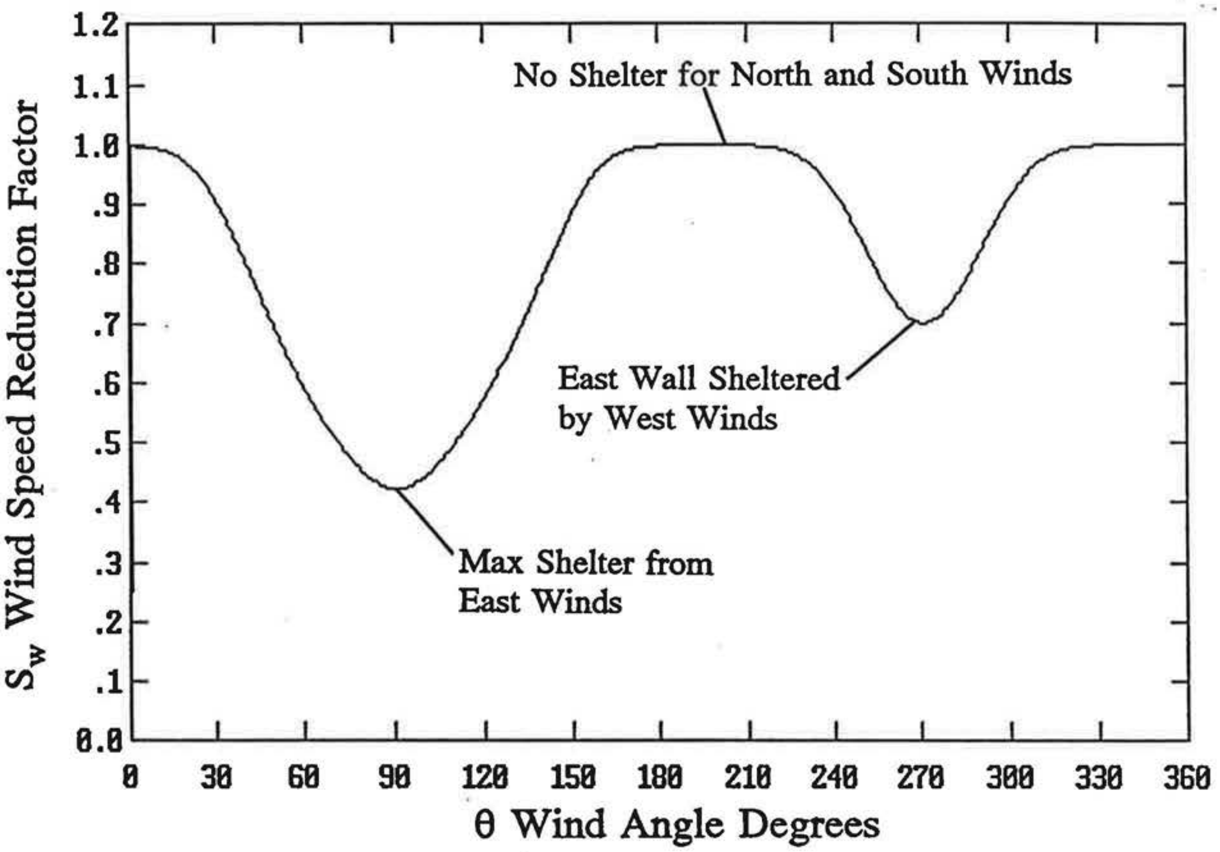


Figure 4-1 Wind-Shadow Shelter Coefficients for the East Wall of a Test House

means of tuning the model with empirical coefficients to produce a good fit to the measured ventilation rates.

Model Performance Statistics

The performance of LOCALEAKS-2 for stack-effect and wind-effect dominated flow was evaluated by two factors; the tendency of the model to underpredict or overpredict the average infiltration in a data set, and its variability in predicting each of the hourly measurements. The under-prediction or over-prediction bias, and the random scatter error were calculated using all the hourly measurements in a sorted data set.

The average bias error, B, of the predictions was calculated for N hourly values from predicted and measured flow rates Q using

$$B = \frac{1}{N} \sum_{j=1}^{N} \left(Q_{predicted,j} - Q_{measured,j}\right) \tag{4-1}$$

The random error from hour to hour is defined by the scatter, S, calculated as the root mean square difference between the predicted and measured values, with the average bias error B subtracted from **each** predicted value

$$S = \left[\frac{1}{N-1} \sum_{j=1}^{N} \left(\left(Q_{predicted,j} - B\right) - Q_{measured,j}\right)^2\right]^{0.5} \tag{4-2}$$

The bias and scatter are expressed as percentage errors in Table 4-4 and 4-5 using the mean measured flow rate.

Model performance statistics are summarized in Tables 4-4 and 4-5 for stack-effect and wind-effect dominated flows in both low leakage "infiltration", and high leakage "passive ventilation" configurations. This bewildering array of model performance statistics led us to the following conclusions:

- There was no significant difference in bias or scatter errors between stack-effect and wind-effect dominated flows.
- For low-leakage "infiltration" configurations the over or under-prediction bias was an average of ±5%, with an overall +1% overprediction for all five houses.
- For high-leakage "passive ventilation" configurations LOCALEAKS-2 tended to underpredict the ventilation rate, with an average -15% bias error for the four houses.

Table 4-4

Stack-Effect Dominated LOCALEAKS-2 Model Performance Statistics

Parameter	Test House								
	Masonry #1		Retrofit #2		Conservation #3		Solar #4	Reference #5	
Local Leakage Sites	sealed	pipe+ window+flue	flue	pipe+flue	sealed	pipe+window	sealed	sealed	pipe+window +flue
Measured Average Infiltration ACH	0.043	0.247	0.117	0.206	0.055	0.239	0.042	0.075	0.238
Predicted Average Infiltration ACH	0.038	0.189	0.123	0.200	0.058	0.144	0.036	0.079	0.234
Prediction Bias Error	-12%	-23%	+6%	-5%	+5%	-40%	-15%	+6%	-2%
Prediction Scatter RMS Error	±34%	±29%	±10%	±9%	±15%	±44%	±20%	±11%	±10%
Average ΔT Indoor-Outdoor	26C	23C	22C	24C	23C	23C	15C	26C	23C
Average U_H Wind Speed	0.90 m/s	0.92 m/s	0.98 m/s	0.92 m/s	0.89 m/s	0.94 m/s	0.90 m/s	1.1 m/s	0.91 m/s
Number of Hours	524	274	96	428	916	290	141	461	415

Table 4-5

Wind-Effect Dominated LOCALEAKS-2 Model Performance Statistics

Parameter	Test House								
	Masonry #1		Retrofit #2		Conservation #3		Solar #4	Reference #5	
Local Leakage Sites	sealed	pipe+ window+ flue	sealed	pipe +flue	flue	pipe +window	sealed	sealed[a]	pipe+window +flue
Measured Average Infiltration ACH	0.030	0.306	0.164	0.266	0.061	0.205	0.079	0.106	0.297
Predicted Average Infiltration ACH	0.030	0.254	0.158	0.241	0.076	0.186	0.059	0.103	0.282
Prediction Bias Error	0%	-17%	-	-9%	+26%	-9%	-25%	-3%	-5%
Prediction Scatter RMS Error	±33%	±27%	±18%	±22%	±45%	±41%	±47%	±19%	±18%
Average ΔT Indoor-Outdoor	6.6C	5.4C	5.6C	5.0C	5.0C	4.0C	5.3C	16.4C	5.3C
Average U_H Wind Speed	4.0 m/s	3.9 m/s	4.1 m/s	3.9 m/s	4.0 m/s	3.9 m/s	3.9 m/s	4.0 m/s	3.9 m/s
Number of Hours	1035	628	286	902	916	645	988	432	962

[a]combined wind and stack effects; no summer data available

- The average root mean square (RMS) scatter error of paired hourly measured and predicted values was about ±25% for both low leakage and high leakage configurations. This implies that an individual hourly prediction would be within ±50% of the measured value 9 times out of 10, for a normal error distribution and no bias.

The major failure of LOCALEAKS-2 was its inability to predict stack-effect dominated passive ventilation in Conservation Unit #3. (Detailed plots of binned and hourly infiltration data for Conservation Unit #3 are included in Appendix A.) Performance statistics in Table 4-4 show that the model under-predicted stack-effect dominated ventilation by 40%. The cause of this underprediction was window exhaust pipe flow fluctuations caused by wind turbulence over the hourly averaging periods. Because Unit #3 has no flue, the neutral pressure plane (see Figure 2-1) is close to the window exhaust location. Wind fluctuations over the one hour averaging periods caused this neutral level to fluctuate up and down, inducing a pulsating inflow and outflow. The predicted value from LOCALEAKS-2 using hourly average windspeed assume a constant height for the neutral pressure plane, and misses pulsating outflow and inflow pumping. In applying LOCALEAKS-2 to houses with passive ventilation exhausts on the walls, and no flue, this tendency to drastically underpredict actual infiltration rates might be accounted for by adding about 40% or 0.1 ACH (whichever is smaller) to predicted values.

Model performance for stack-effect dominated "infiltration" and "passive ventilation" leakage configurations is shown in Figures 4-2 and 4-3 for Reference Unit #5. Each hourly value is shown on the top graph, and binned data with bars for one standard deviation in each 5C bin are shown below. The model predictions are in good agreement with measurements, although there is considerable scatter, possibly due to wind effects. This is surprising, because the data for stack-dominated flow was sorted to exclude average windspeeds larger than 1.5 m/s.

Wind-dominated infiltration and passive ventilation in Unit #5 are shown in Figures 4-4 and 4-5. The mean values at each windspeed are in good agreement with averaged hourly predictions from LOCALEAKS-2. However, infiltration rates at any given windspeed vary by a factor of four, indicating sensitivity to wind direction. The strong sensitivity of both low leakage (infiltration) and high-leakage (passive ventilation) flows to wind direction is shown in Figures 4-6 and 4-7. This variability is due to the combined effect of wind direction on pressure coefficients and to direct wind shelter from adjacent houses in the row. The large peak in measured and predicted infiltration rates for south-east winds (θ=135°) was caused by a combination of higher windspeeds from this direction, and the presence of dominant leakage sites around the door and window on the east wall.

The data plots in Figures 4-6 and 4-7 show good agreement when predicted and measured unpaired hourly values are compared. The predicted infiltration rates have the correct trend, but

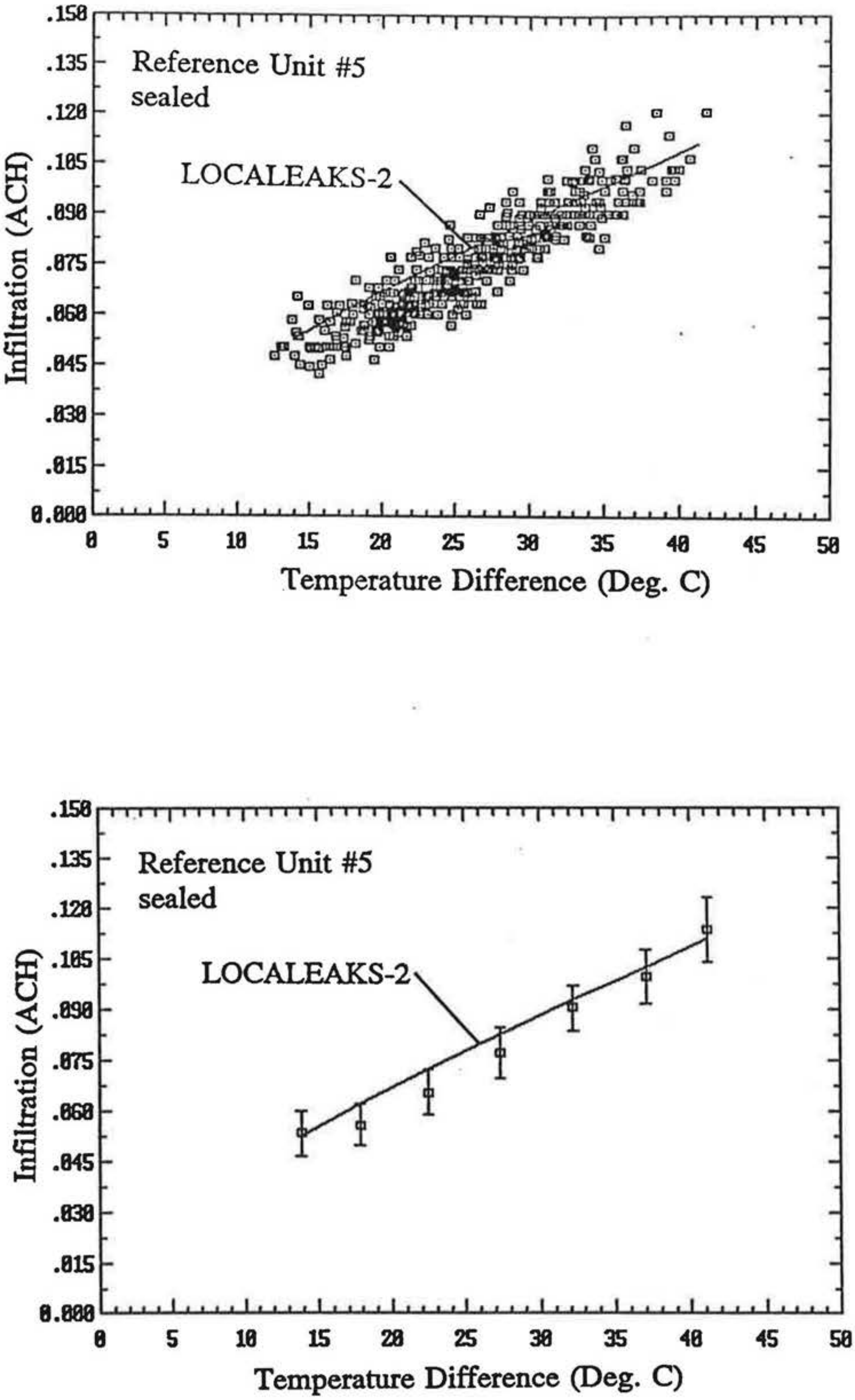
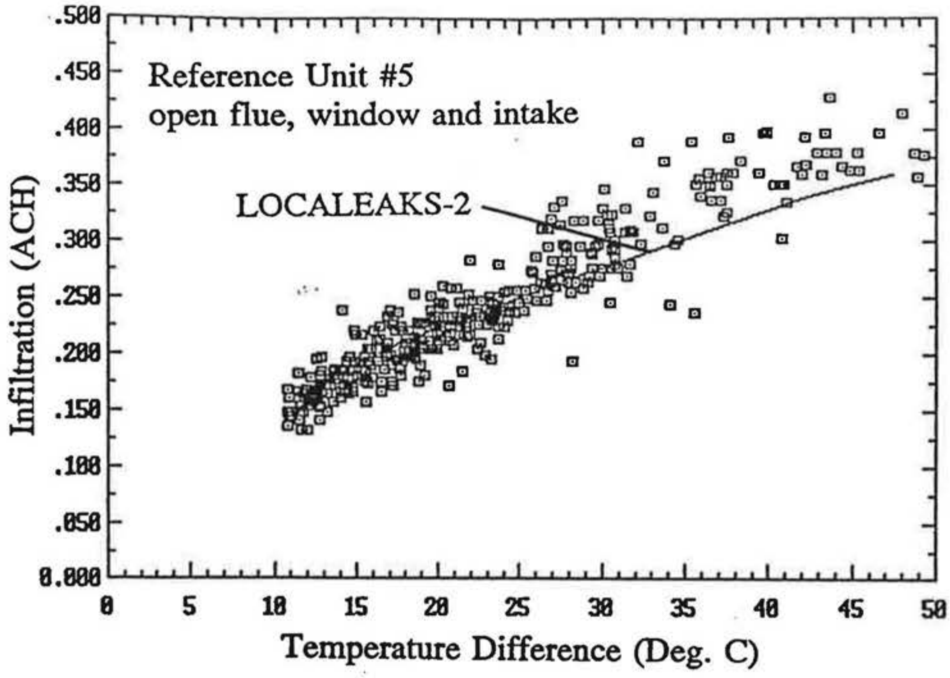


Figure 4-2 Stack-effect infiltration into sealed Reference Unit #5



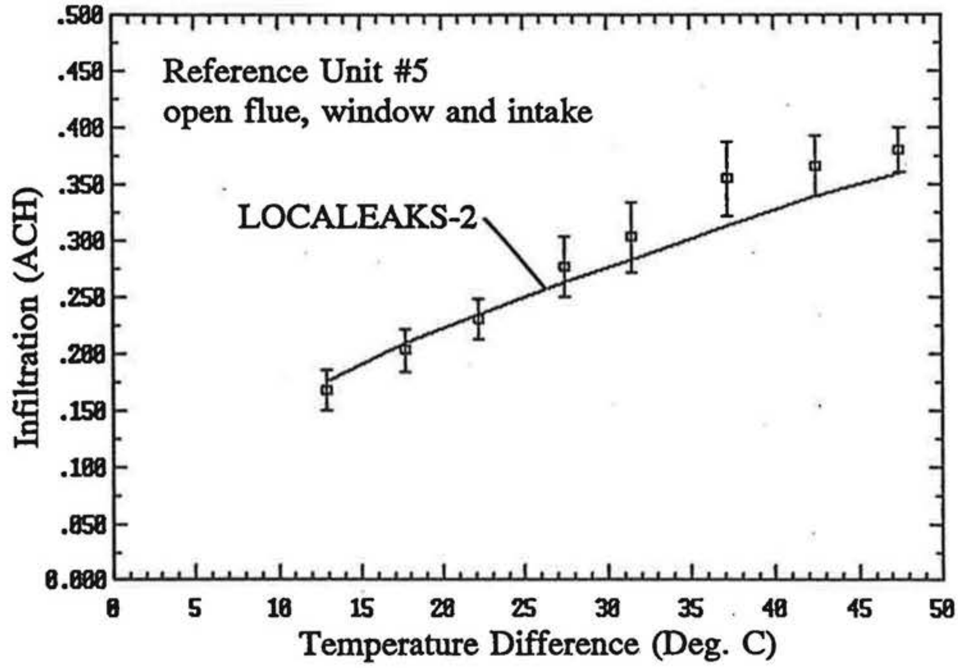
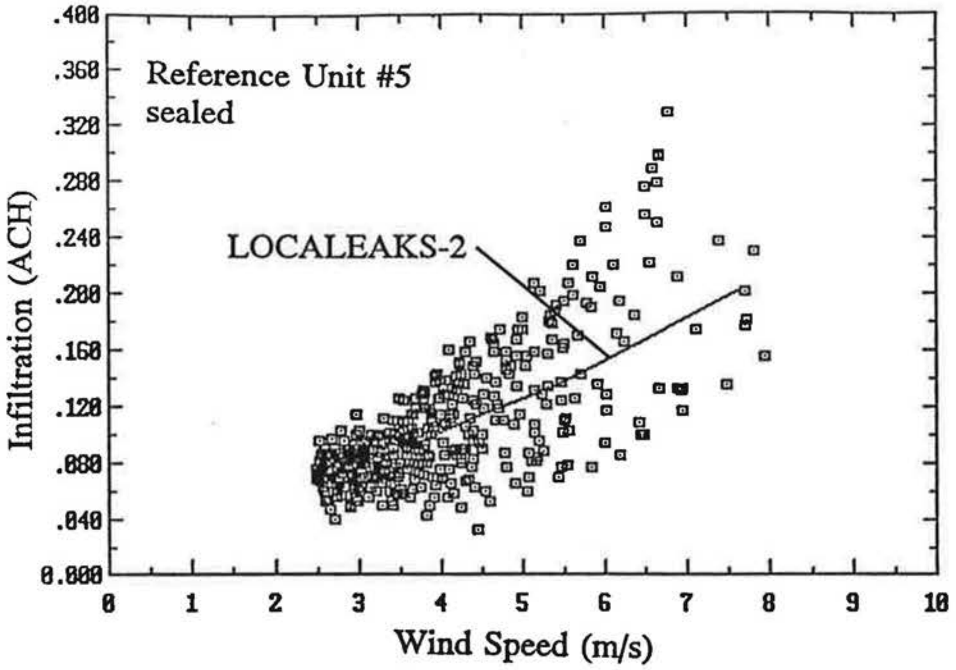


Figure 4-3 Stack-effect passive ventilation of Reference Unit #5 with open flue, window orifice and ground level intake pipe



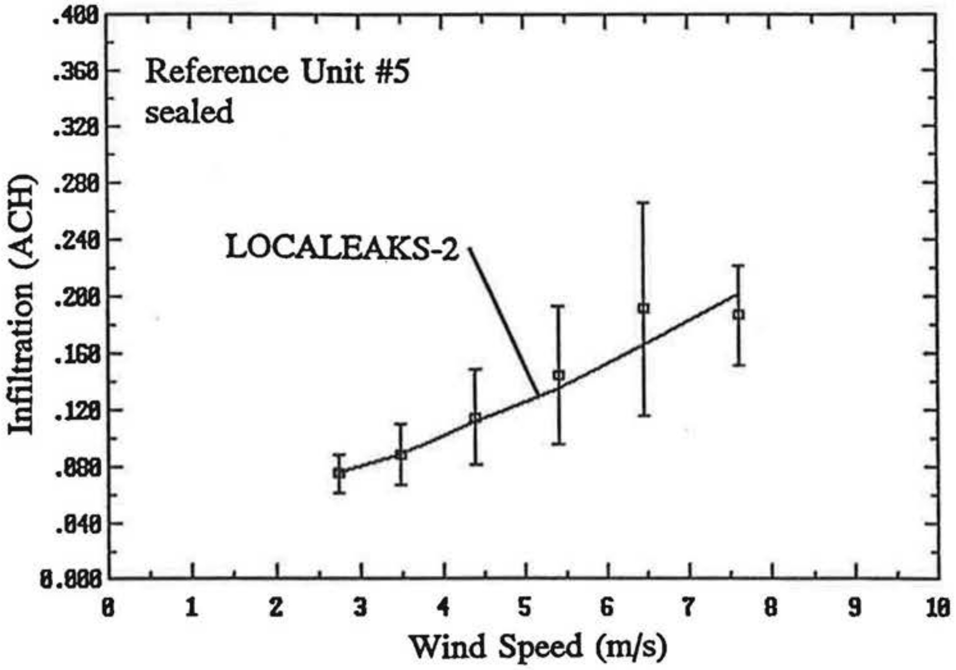
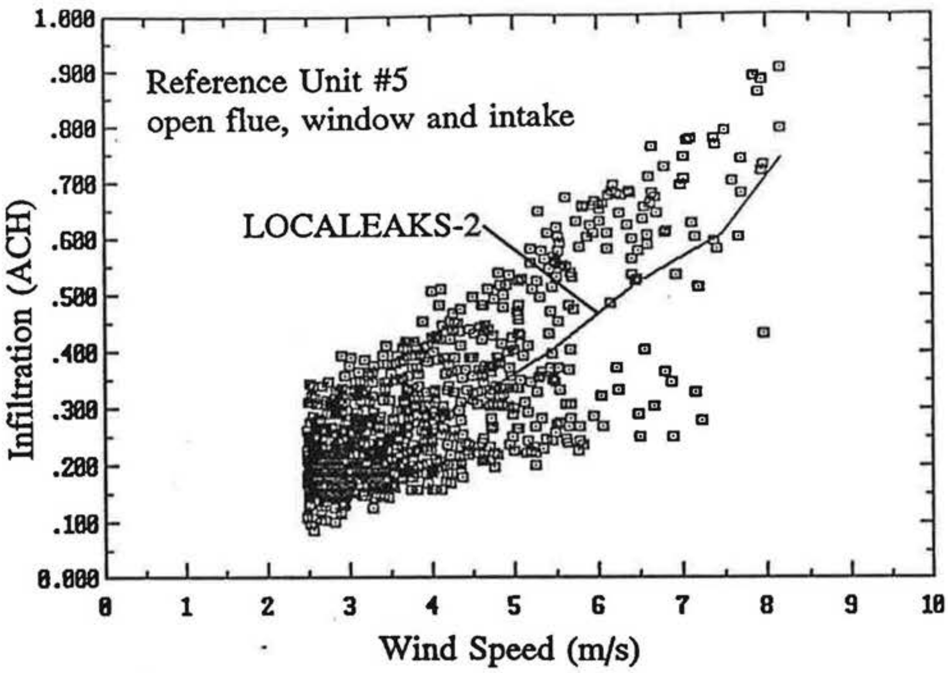


Figure 4-4 Wind-effect infiltration into sealed Reference Unit #5, for all wind directions



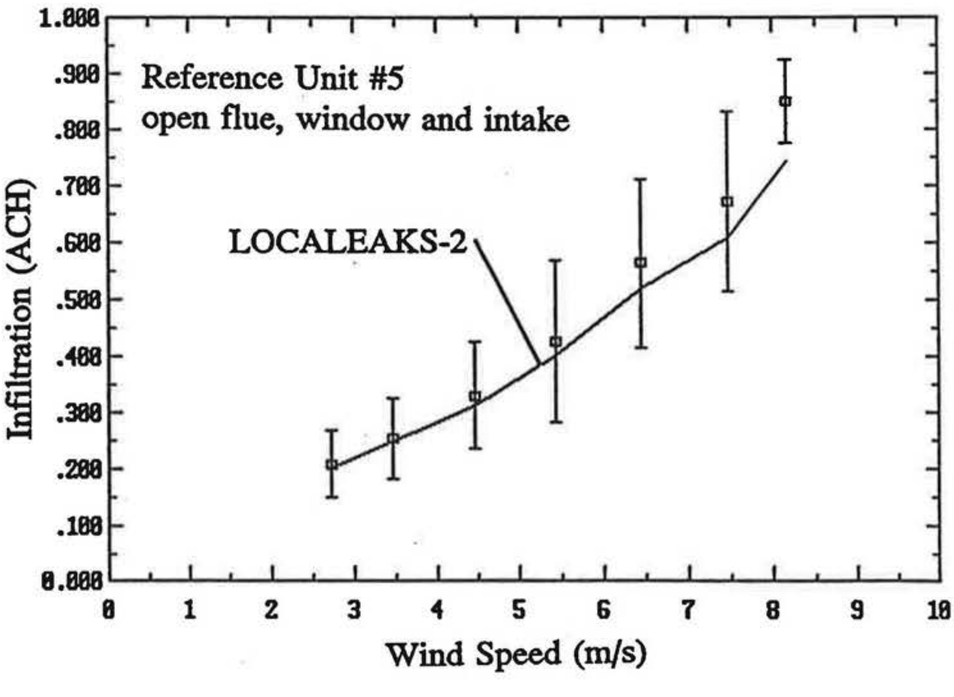


Figure 4-5 Wind-effect passive ventilation of Reference Unit #5 with open flue, window orifice and ground-level intake pipe, for all wind directions

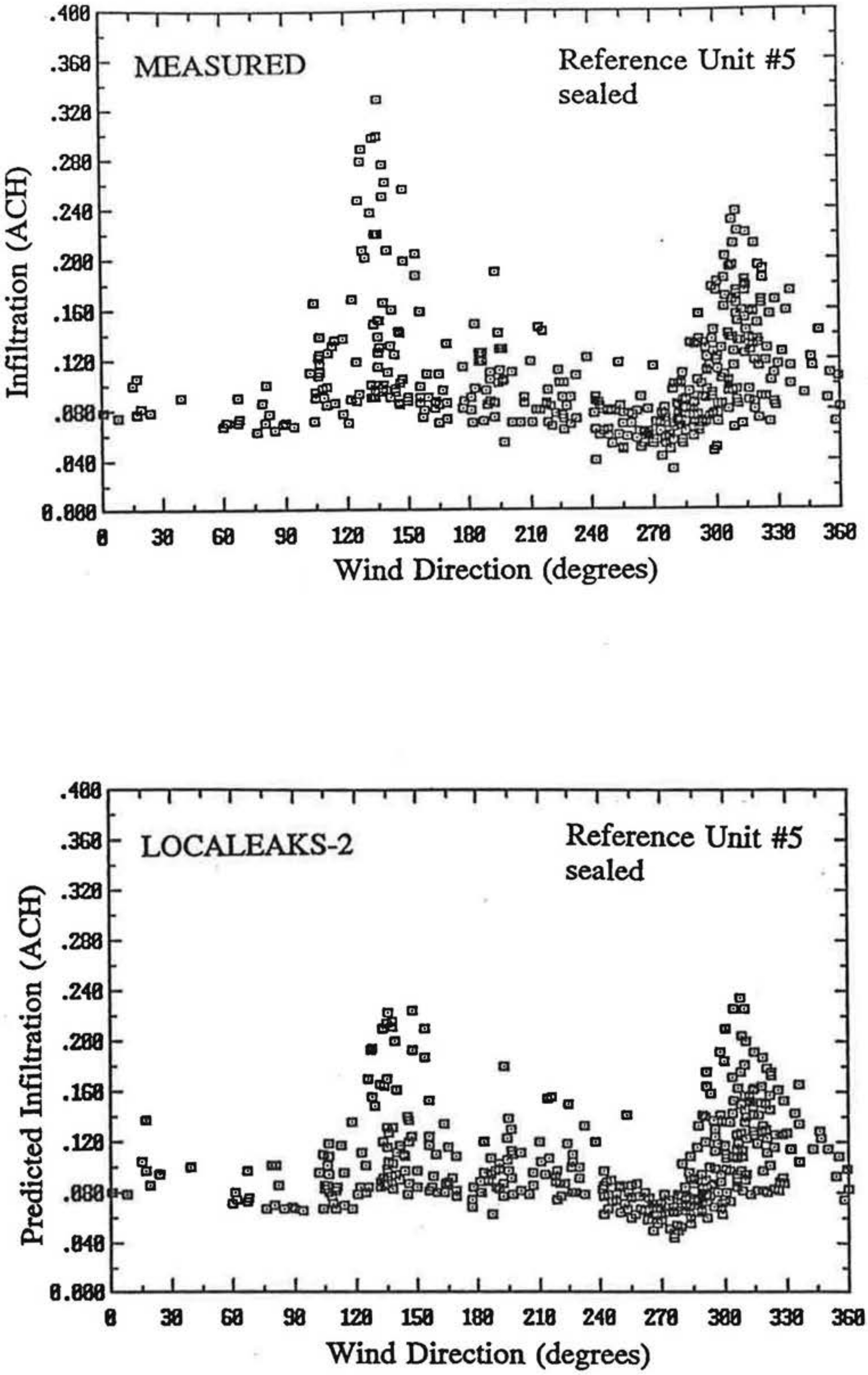
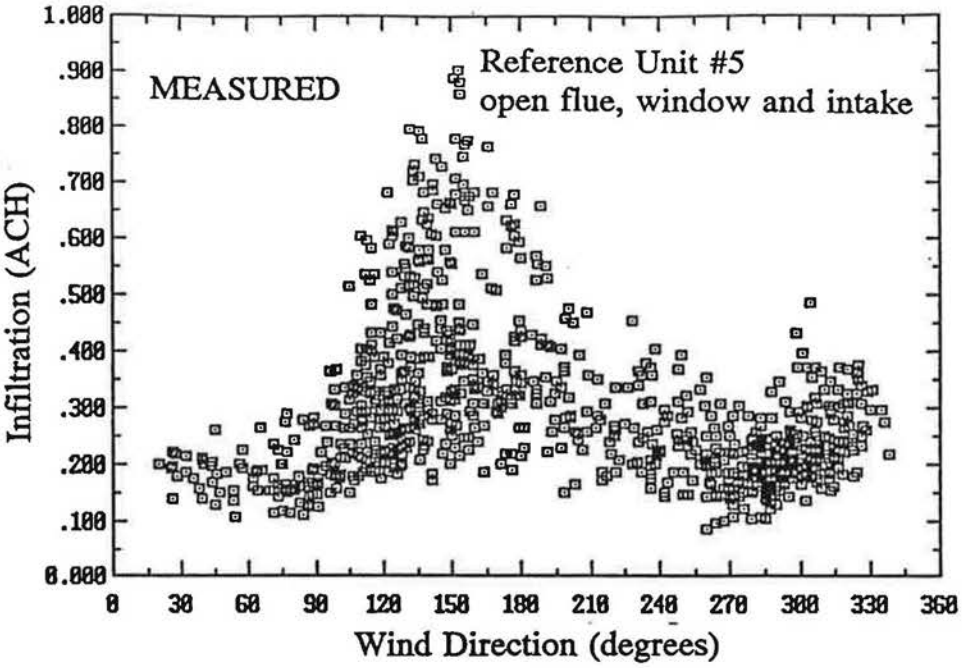


Figure 4-6 Unpaired measured and predicted wind direction dependence of wind-effect infiltration into Reference Unit #5 with complete shelter by adjacent houses for 90° and 270°, and U_H = 2.5 to 8.0 m/s



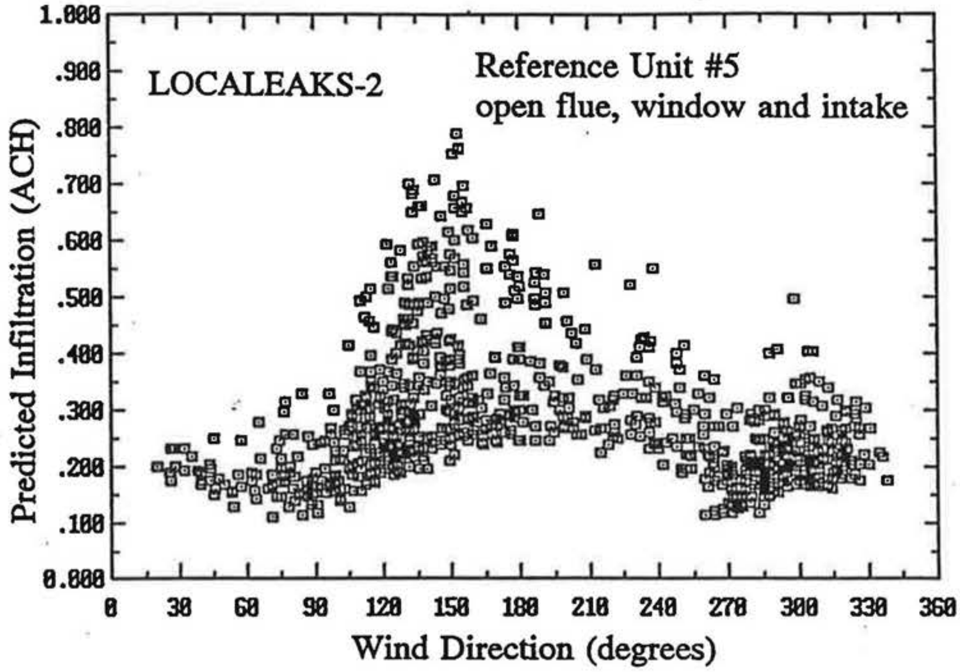
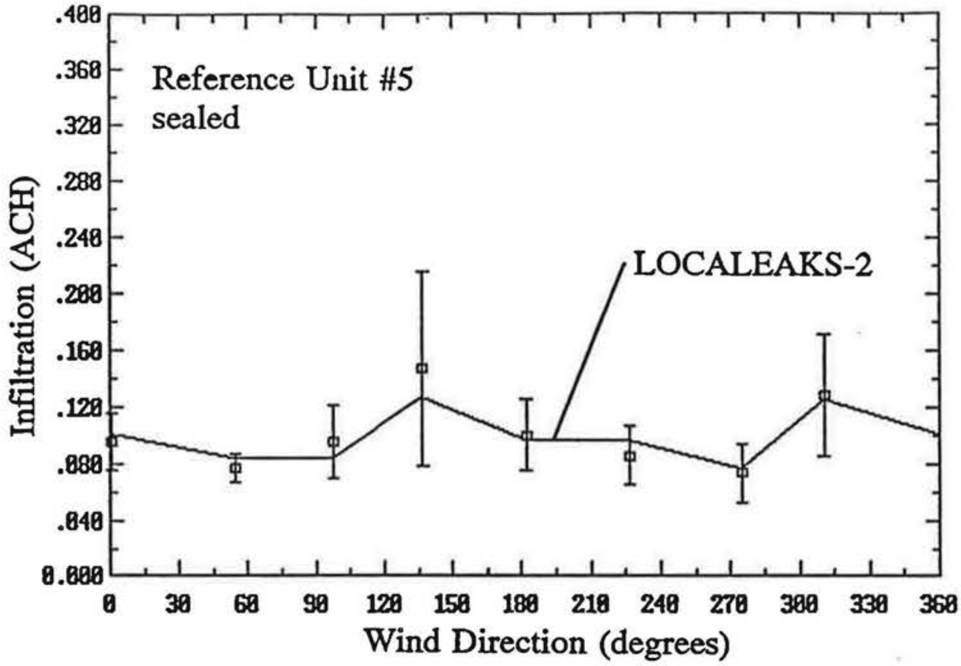


Figure 4-7 Unpaired measured and predicted wind direction dependence of wind-effect passive ventilation of Reference Unit #5 with complete shelter by adjacent houses for 90°C and 270°, and U_H = 2.5 to 8/0 m/s

fail to follow the low and high extremes because they are smoothed over one hour averaging times.

The wind-shadow shelter model used in LOCALEAKS-2 successfully follows the variation of infiltration with wind direction, as shown by the binned data in Figures 4-8 and 4-9 for "infiltration" and "passive ventilation" configurations. The plots at the bottom of these figures show hour-by-hour paired prediction errors for wind-dominated infiltration. It is encouraging to note that scatter in the data is relatively uniform for all wind directions.

Similar data comparisons for other test houses are included in Appendix A. From these correlations and model performance statistics we concluded that LOCALEAKS-2 is an accurate and reliable model for predicting air infiltration and passive ventilation. In the final section of the report, LOCALEAKS-2 is used to test strategies for locating and sizing passive ventilation intakes and exhausts to obtain reliable minimum ventilation rates.



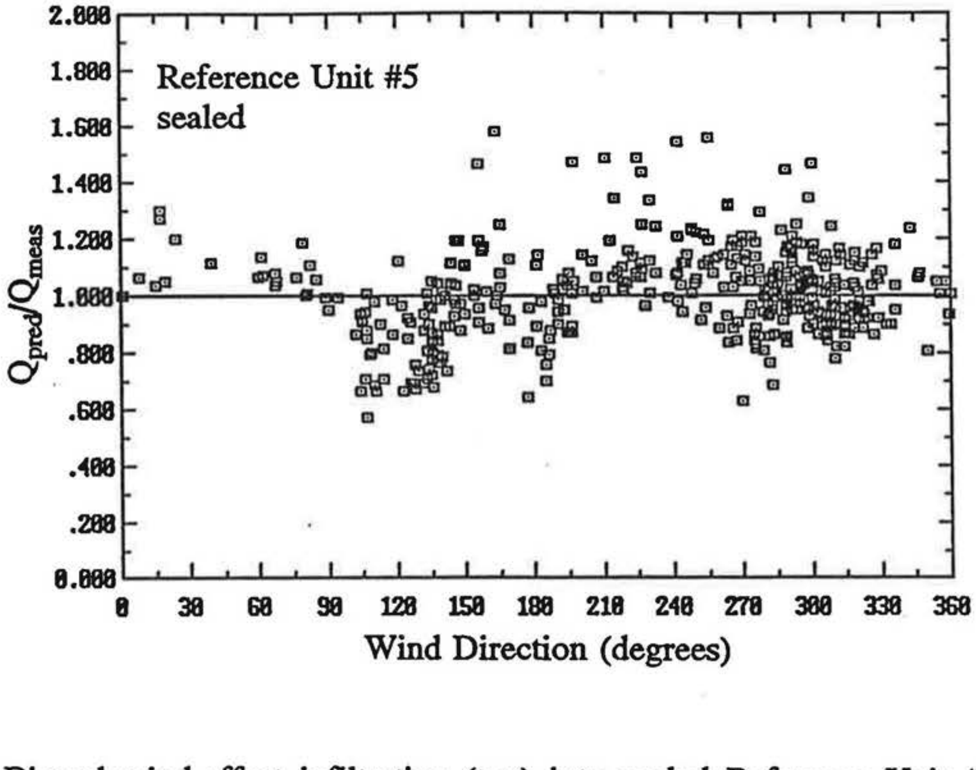
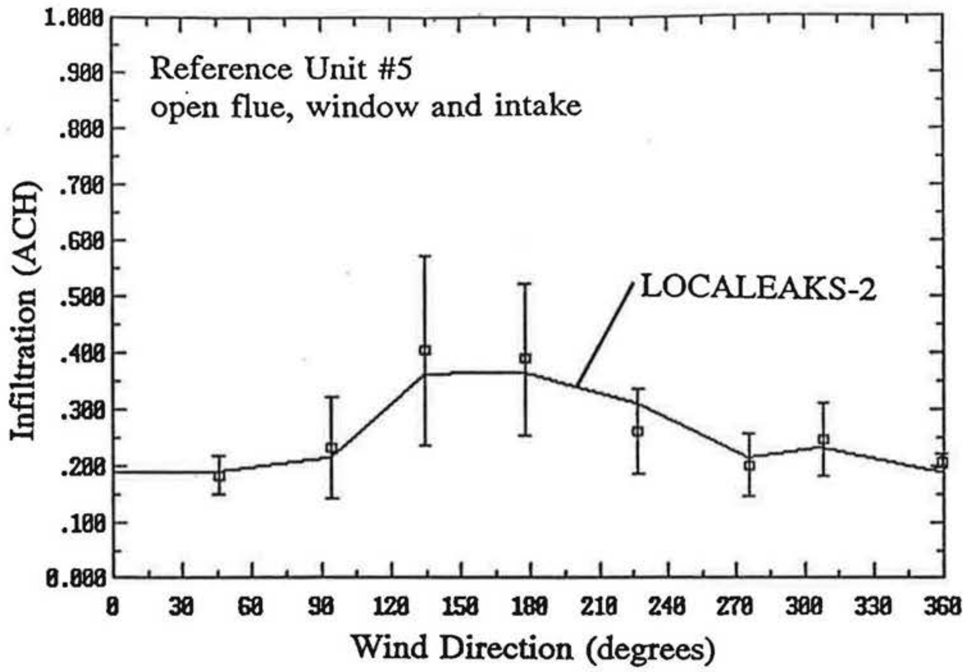


Figure 4-8 Binned wind-effect infiltration (top) into sealed Reference Unit #5, and paired prediction errors (bottom) with complete shelter by adjacent houses for 90° and 270°, and U_H = 2.5 to 8.0 m/s



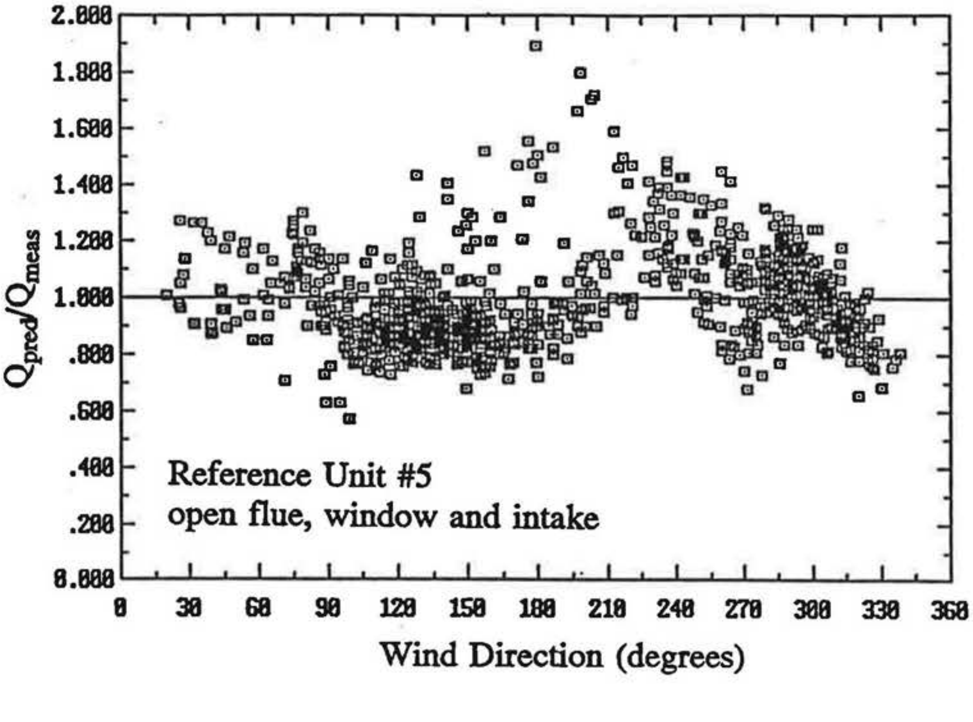


Figure 4-9 Binned wind-effect passive ventilation (top) into Reference Unit #5, and paired prediction errors (bottom) with complete shelter by adjacent houses for 90°and 270°, and U_H = 2.5 to 8.0 m/s

PART 5
CASE STUDIES OF PASSIVE VENTILATION PERFORMANCE

Natural ventilation by air infiltration and intentional passive intakes and exhausts is complicated by its simultaneous dependence on several variables. The air exchange rate depends on the type of building, its background leakage distribution, the location of passive intakes and exhausts, local wind shelter by nearby buildings, and the interaction of stack and wind effect pressures. By using LOCALEAKS-2 we were able to isolate the effects of each of these variables and determine how they interact, and which are most important in providing adequate ventilation for indoor air quality. In this section we will examine the effect of changing passive ventilation openings and surrounding wind shelter for three different house types, typical of new Canadian construction.

Case Study House Configurations

In Alberta the vast majority of houses are constructed with full basements, ventilated by a recirculating warm air gas furnace. Most houses are equipped with a 15.2 cm ID furnace flue. However, some energy-efficient houses use condensing furnaces or flue dampers that essentially eliminate the furnace flue as a passive ventilation exhaust site. This possibility was accounted for by testing passive ventilation performance with and without a furnace flue. For configurations without a furnace flue, half the passive ventilation openings were located on the walls near ground level, and the other half were located near the upper ceiling level to take advantage of stack-effect infiltration from indoor-outdoor temperature differences. For houses with a flue, all passive ventilation sites were located near ground level with the flue serving as the only high exhaust site.

Three case-study configurations were developed to simulate a small single-storey bungalow, a large two-storey house, and a townhouse located centrally in a row of identical units with common sidewalls. The construction and background leakage details of these hypothetical case-study houses is presented in Table 5-1. The townhouse was deliberately chosen to have the same 200 m^2 floor area as the two-storey house so that direct comparisons could be made for the effect of the different leakage distribution caused by the presence of sealed common walls between adjacent units in the townhouse complex. In reality, most townhouses are somewhat smaller than this, with a floor area ranging from 100 m^2 to 150 m^2. The large size of the townhouse was accounted for by specifying that it (and the two-storey house) had seven occupants, while the small bungalow had only five occupants. Table 5-1 shows that the

Table 5-1

Construction and Leakage Details of Case-Study Houses with Ventilated Basements

Parameter	Case Study House Type		
	Bungalow	Two-Storey	Townhouse
Number of storeys	1	2	2
Number of Occupants	5	7	7
Basement wall height above grade	0.5 m	0.5 m	0.5 m
Room wall heights	2.44 m	2.44 m	2.44 m
Eaves height above grade	3.0 m	5.5 m	5.5 m
Inside dimensions	10 m x 10 m	10 m x 10 m	10 m x 10 m
Floor area above grade	100 m^2 (1076 ft^2)	200 m^2 (2153 ft^2)	200 m^2 (2153 ft^2)
Envelope area including basement wall above grade	220 m^2	320 m^2	210 m^2 excluding common walls
Active air exchange volume	500 m^3	750 m^3	750 m^3
Background leakage area A_{L4} with n = 0.67	306 cm^2	578 cm^2	306 cm^2
Background leakage at floor level	25%	15%	15%
Background leakage in walls	50%	70%	15%
Background leakage at ceiling level	25%	15%	70%
Optional 15.2 cm furnace flue leakage area A_{L4} with n = 0.50	102 cm^2	102 cm^2	102 cm^2
Optional passive vent leakage area A_{L4} with n = 0.50 for each 10.2 cm I.D. opening	49 cm^2	49 cm^2	49 cm^2
Minimum ventilation rate for ASHRAE 62-89 7.5 ℓ/s per person standard	0.27 ACH	0.25 ACH	0.25 ACH

Table 5-2

Background Leakage Areas For New Canadian Housing[a]

Location	Number of Houses Tested	Leakage Area Normalized by Envelope Area (cm^2/m^2)		
		Mininum	Average	Maximum
Winnipeg	20	0.42	0.91	1.47
Regina	10	0.55	1.05	1.69
Quebec City	20	0.78	1.17	1.93
Saskatoon	10	0.67	1.20	2.01
Montreal	20	0.65	1.31	2.36
Edmonton	8	0.47	1.32	2.33
Halifax	14	0.70	1.36	2.32
Fredericton	10	0.81	1.49	3.08
St. John's	10	1.31	1.75	2.24
Toronto	30	1.18	1.92	2.69
Ottawa	20	1.34	2.07	2.79
Vancouver	20	1.27	2.87	4.79
Total Sample	192	0.42	1.61	4.79

[a]From Hamlin, Forman and Lubun (1990)

Table 5-3

Normalized Background Leakage of Passive Ventilation Case-Study Houses Compared to Others

Description	Leakage Area Normalized by Envelope Area cm^2/m^2		
	minimum	average	maximum
U of Alberta Test Houses	0.26	0.51	0.68
New-Canadian Houses[(a)]	0.42	1.61	4.79
Case-Study Bungalow	-	1.39	-
Case-Study Two-Storey	-	1.81	-
Case-Study Townhouse	-	1.46	-

[(a)]From Hamlin, Forman and Lubin (1990)

ASHRAE 62-89 standard for minimum ventilation rates requires an air exchange of 0.25 ACH in the townhouse and two-storey house, and 0.27 ACH for the bungalow.

The distributed background leakage caused by unintentional holes and cracks is highly variable in real houses. Table 5-2 lists measured background leakage areas reported by Hamlin, Forman and Lubun (1990) for new Canadian housing. Each particular group of houses showed a variability of about a factor of two in background leakage area (with furnace flue sealed). Table 5-3 shows that the background leakage area chosen for the case-study houses is typical of the average of new Canadian housing.

It is interesting to note in Table 5-3 that the test houses used to validate the LOCALEAKS-2 ventilation model were much tighter than the average of new Canadian houses. Tight houses such as these, with sparsely distributed leakage sites concentrated around doors and windows represent the most difficult test for computer simulation, and we expect that when LOCALEAKS-2 is applied to real houses it will have less bias and scatter than was observed during the model validation studies in Part 4 of this report.

Shelter, Weather, and Passive Vent Configurations

To evaluate passive ventilation over a wide range of construction and weather conditions five independent variables were identified: the classifications within each of these five variables are summarized below:

House Types:

- **bungalow:** 100 m^2 (1076 ft^2) above-grade floor area
- **two-storey:** 200 m^2 (2153 ft^2) above-grade floor area
- **townhouse:** 200 m^2 (2153 ft^2) above-grade floor area

Shelter Configurations:

- **unsheltered:** Isolated house with no nearby buildings or obstacles to reduce windspeed
- **close-row shelter:** with identical units on either side, and unsheltered front and back.
- **uniform shelter:** heavy shielding by nearby buildings and obstacles on all sides reduces effective windspeed to 50% of the unsheltered case.

Outdoor Temperature: (indoor temperature T_{in} = 20C, $\Delta T = T_{in} - T_{out}$)

- **summer:** T_{out} = 15C ΔT = 5C
- **spring/fall:** T_{out} = 10C ΔT = 10C
- **shoulder seasons:** T_{out} = 0C ΔT = 20C
- **winter:** T_{out} = -20C ΔT = 40C

Windspeeds: (at house eaves height, for unsheltered approach flow)

- **light:** U_H = 1.0 m/s (3.6 km/h)
- **moderate:** U_H = 3.0 m/s (10.8 km/h)
- **strong:** U_H = 4.0 m/s (14.4 km/h)
- **high:** U_H = 5.0 m/s (18.0 km/h)

Passive Vent Configurations: (all vents 10.2 cm (4.0") ID pipes)

- no vents (except optional flue, if present)
- 1 vent
- 2 vents on 2 unsheltered sides
- 2 vents on close-row sheltered side
- 4 vents on 4 unsheltered sides
- 4 vents on 2 close-row sheltered sides

The case of warm summer weather with equal indoor and outdoor temperatures was not considered. In warm summer conditions it may safely be assumed that occupants will open windows to maintain required ventilation rates. Another important point is that hourly averaged windspeeds are very seldom completely calm, and "light" wind conditions are often perceived as "calm". Even when airport meteorological stations report "calm" winds, there is often a light wind present, at too low a level to turn the cups of the met station anemometer.

To assess variability with wind direction air exchange rates were calculated using LOCALEAKS-2 for 16 standard compass directions (N, NNE, NE, E ... etc.) and combined to determine a "360° average" with equal weighting for each wind direction. To avoid generating an unmanageable mass of tabulated data, the results presented here list wind direction variability only for strong winds in spring/fall seasons. (U_H=4 m/s at unsheltered eaves height with an indoor-outdoor temperature difference of ΔT=10C). The variability under these conditions is typical of values found for the same leakage distribution and wind shelter in other seasons and at other windspeeds.

A complete set of ventilation rate calculations is tabulated in Appendix B for all the configurations listed above. Most of the results show the same trends and lead to the same conclusions. Here, we will focus on infiltration and passive ventilation in a bungalow, and elaborate later on the minor differences between this single storey house and the two-storey and townhouse configurations.

Bungalow Infiltration With No Passive Vents

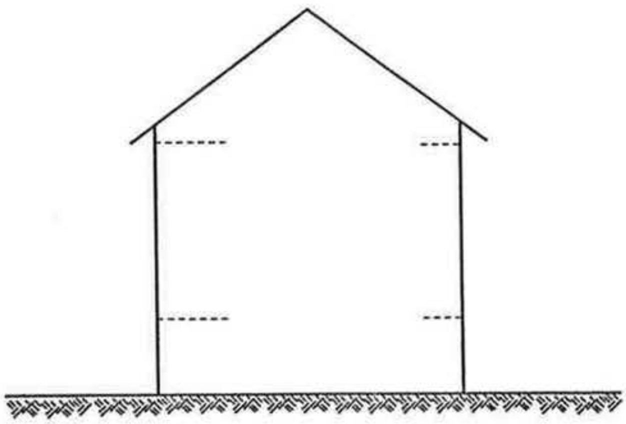
Tables 5-4 and 5-5 show air infiltration rates for an unsheltered bungalow with and without a furnace flue. Using the ASHRAE 62-89 minimum ventilation rate standard of 0.27 ACH, it is apparent in Table 5-4 that a bungalow without a flue will be under-ventilated in all seasons for light and moderate winds. When a furnace flue is added, Table 5-5 shows that under-ventilation occurs in summer, spring/fall and shoulder seasons with light and moderate winds. From this, it is clear that passive ventilation openings are required to meet the minimum ventilation rate standard in all seasons.

Three important observations can be made from the infiltration values in Tables 5-4 and 5-5. The first is that when the shelter (or in this case lack of shelter) is uniform in all wind directions, air infiltration remains relatively constant with wind direction. Both with and without a flue, the house showed a variation of less than 10% about the mean value with changing wind direction for a building with square plan form.

The second observation emphasizes a fundamental problem of using passive ventilation. At a given outdoor temperature, air infiltration and natural ventilation are strongly dependent on wind speed. For the unsheltered bungalow in Tables 5-4 and 5-5 a factor of five increase in speed from "light" to "high" causes more than a factor of three increase in infiltration rate during the critical "shoulder" season when temperatures are near freezing. Even with heavy uniform

TABLE 5-4 and B-1

Bungalow Ventilation Rates With No Passive Vents, No Flue, No Shelter



Background Leakage Area	100%
Flue Leakage Area	0%
Passive Vents Leakage Area	0%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.05	0.14	0.26	0.49
SPRING/FALL	10C	0.07	0.15	0.27	0.50
SHOULDER	0C	0.10	0.17	0.29	0.52
WINTER	-20C	0.17	0.21	0.33	0.57

Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.26 ACH
avg. 0.27 ACH
max. 0.30 ACH

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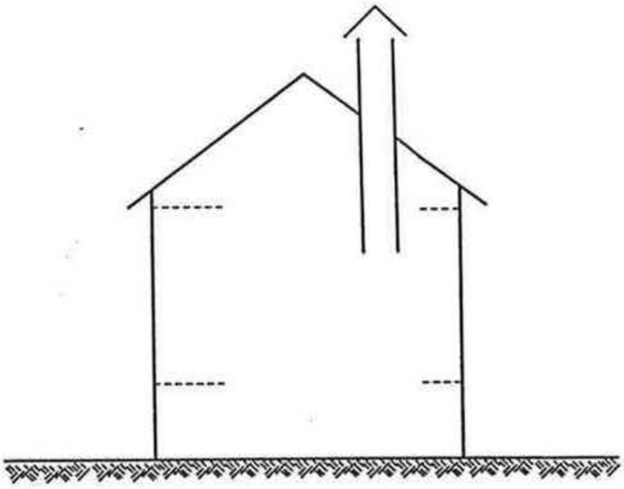
TABLE 5-5 and B-11

Bungalow Ventilation Rates With No Passive Vents, Flue, No Shelter



Background Leakage Area	75%
Flue Leakage Area	25%
Passive Vents Leakage Area	0%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.10	0.19	0.33	0.59
SPRING/FALL	10C	0.14	0.21	0.35	0.60
SHOULDER	0C	0.21	0.25	0.38	0.64
WINTER	-20C	0.32	0.36	0.46	0.71

Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.33 ACH
avg. 0.35 ACH
max. 0.36 ACH

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shelter that effectively reduces the wind speed by a factor of two, the sensitivity of infiltration to wind speed still causes more than a factor of two increase in the infiltration rate during this shoulder season. This wind speed sensitivity does not augur well for providing controlled passive ventilation.

Thirdly, the air exchange rates in Tables 5-4 and 5-5 show that most modern houses in Canada are already adequately ventilated in winter by background infiltration. Supplementary ventilation of any kind (mechanical or passive) is required only in the spring/fall seasons, and marginally in the shoulder seasons for light and moderate winds.

A standard furnace flue with its raincap located above the roof ridge provides an efficient passive ventilation exhaust site. The major advantage of exhaust through the furnace flue with its outlet above the roof ridge is that the flue is insensitive to wind direction, and can provide a consistent strong exhaust through a combination of unsheltered wind suction and buoyant stack effect. For this reason we will focus most of our attention in the following sections on houses with flues. The passive ventilation performance of houses without flues, using passive vent openings near grade level and high on the wall, are tabulated in Appendix B.

Wind Shelter Effects

One of the most surprising results of the LOCALEAKS-2 simulations was the insensitivity to wind direction of air exchange rates with and without passive ventilation openings. Table 5-6 and 5-7, for a bungalow with a flue and no passive ventilation openings, shows that changing wind direction only causes about a 10% variation about the average with both closely-spaced row shelter, and heavy uniform shelter. What is even more surprising, is that this lack of wind direction sensitivity persists when two passive vents are installed close to grade level on opposite walls. If these two passive vents are placed on the exposed walls, wind direction variability causes the ventilation rate to vary by about 20% above and below its mean value (see Table 5-8). When the passive vent openings are moved to the sheltered sides between adjacent buildings in the closely spaced row (see Table 5-9), the 360° average air exchange rate decreases by only 5%, and the same 20% variability about the mean persists!

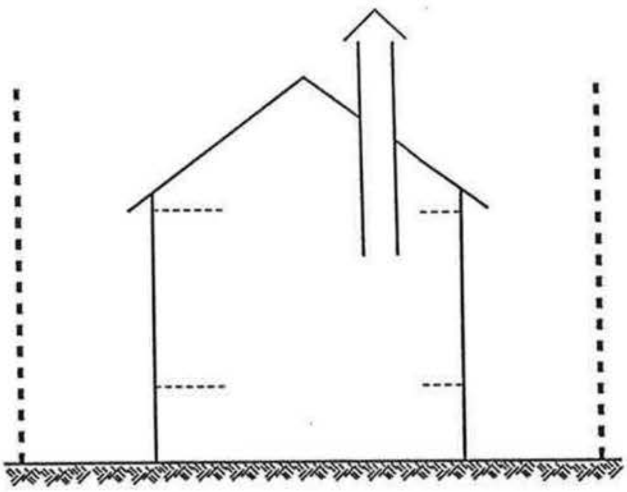
Because the directional effects of wind shelter are relatively small, we will focus our attention on buildings with heavy, uniform wind shelter that reduces the eaves-height windspeed by a factor of two. Other shelter configurations are tabulated in Appendix B.

Bungalow With Multiple Passive Vents

Adding more passive ventilation openings only partially solves the problem of under-ventilation at low windspeeds in spring and fall. Tables 5-10, 5-11 and 5-12 show the effect of

TABLE 5-6 and B-12

Bungalow Ventilation Rates With No Passive Vents, Flue, Close Row Shelter



Background Leakage Area	75%
Flue Leakage Area	25%
Passive Vents Leakage Area	0%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.10	0.18	0.31	0.55
SPRING/FALL	10C	0.14	0.21	0.33	0.57
SHOULDER	0C	0.21	0.27	0.37	0.60
WINTER	-20C	0.32	0.37	0.46	0.68

Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.30 ACH
avg. 0.33 ACH
max. 0.36 ACH

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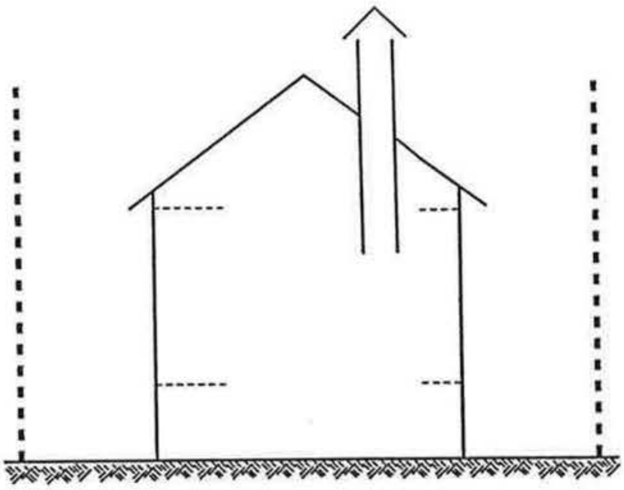
TABLE 5-7 and B-13

Bungalow Ventilation Rates With No Passive Vents, Flue, Uniform Shelter, S_w=0.5



Background Leakage Area	75%
Flue Leakage Area	25%
Passive Vents Leakage Area	0%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature Tout For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.10	0.18	0.28	0.46
SPRING/FALL	10C	0.14	0.21	0.30	0.48
SHOULDER	0C	0.21	0.26	0.35	0.52
WINTER	-20C	0.32	0.36	0.44	0.60

Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.29 ACH
avg. 0.30 ACH
max. 0.31 ACH

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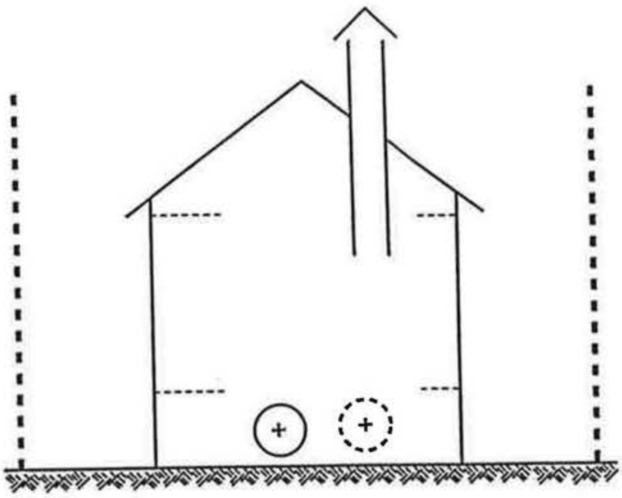
TABLE 5-8 and B-19

Bungalow Ventilation Rates With Two Passive Vents, Flue, Close Row Shelter



Background Leakage Area	61%
Flue Leakage Area	20%
Passive Vents Leakage Area	19%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.13	0.24	0.41	0.70
SPRING/FALL	10C	0.18	0.26	0.43	0.72
SHOULDER	0C	0.26	0.33	0.47	0.75
WINTER	-20C	0.39	0.44	0.55	0.83

Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.34 ACH
avg. 0.43 ACH
max. 0.49 ACH

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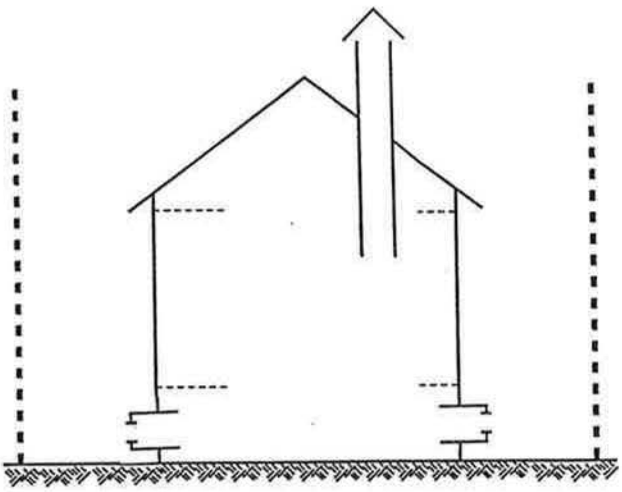
TABLE 5-9 and B-21

Bungalow Vent Rates With Two Sheltered Passive Vents, Flue, Close Row Shelter



Background Leakage Area	61%
Flue Leakage Area	20%
Passive Vents Leakage Area	19%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.13	0.25	0.39	0.67
SPRING/FALL	10C	0.18	0.25	0.41	0.68
SHOULDER	0C	0.26	0.32	0.44	0.72
WINTER	-20C	0.39	0.44	0.53	0.80

Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.34 ACH
avg. 0.41 ACH
max. 0.45 ACH

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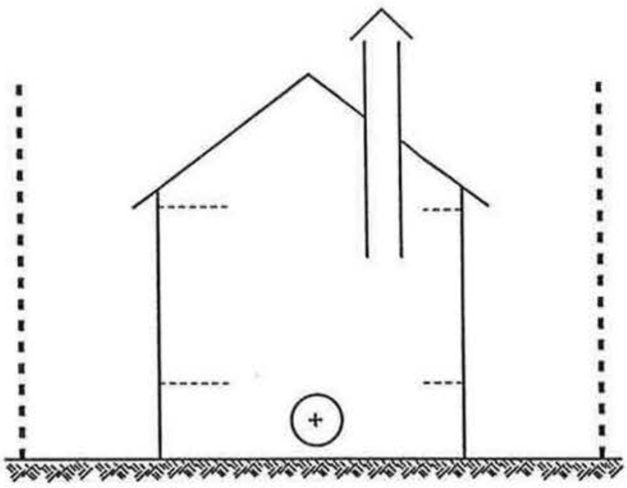
TABLE 5-10 and B-16

Bungalow Ventilation Rates With One Passive Vent, Flue, Uniform Shelter, S_w=0.5



Background Leakage Area	67%
Flue Leakage Area	22%
Passive Vents Leakage Area	11%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature Tout For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.11	0.19	0.30	0.49
SPRING/FALL	10C	0.16	0.23	0.33	0.51
SHOULDER	0C	0.23	0.29	0.38	0.55
WINTER	-20C	0.35	0.39	0.47	0.64

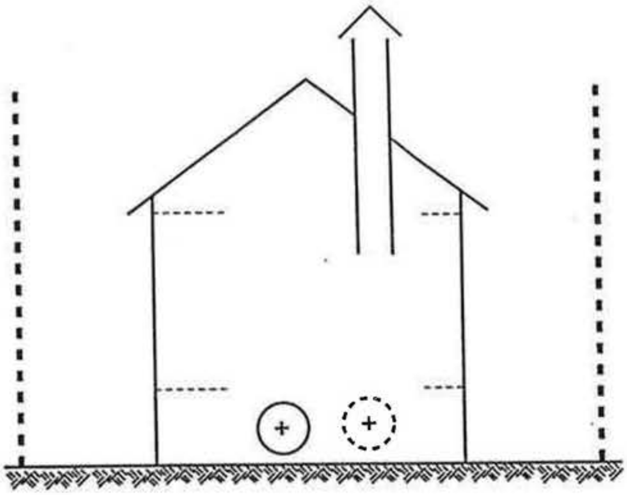
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.31 ACH
avg. 0.33 ACH
max. 0.34 ACH

BUF1LO.DAT

TABLE 5-11 and B-20

Bungalow Ventilation Rates With Two Passive Vents, Flue, Uniform Shelter, S_w=0.5



Background Leakage Area	61%
Flue Leakage Area	20%
Passive Vents Leakage Area	19%

Natural Ventilation Rate ACH (360° average)

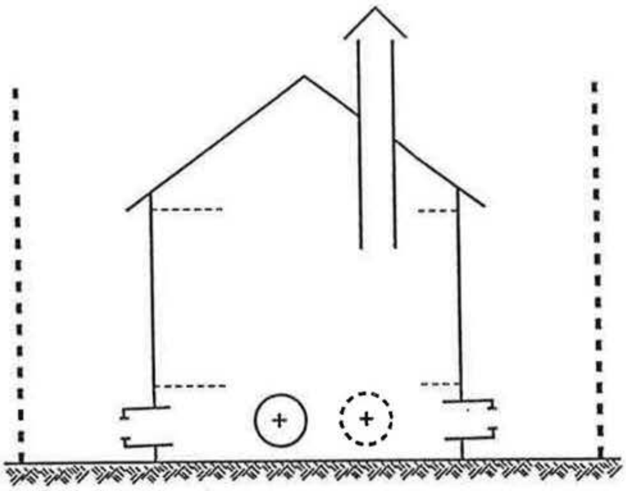
Season	Outdoor Temperature Tout For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.12	0.21	0.32	0.52
SPRING/FALL	10C	0.18	0.24	0.35	0.54
SHOULDER	0C	0.25	0.31	0.40	0.58
WINTER	-20C	0.39	0.43	0.51	0.67

Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C min. 0.32 ACH
avg. 0.35 ACH
max. 0.36 ACH

BUF2LO.DAT

TABLE 5-12 and B-24

Bungalow Ventilation Rates With Four Passive Vents, Flue, Uniform Shelter, S_w=0.5



Background Leakage Area	51%
Flue Leakage Area	17%
Passive Vents Leakage Area	32%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature Tout For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.14	0.23	0.36	0.58
SPRING/FALL	10C	0.20	0.27	0.39	0.61
SHOULDER	0C	0.30	0.35	0.44	0.65
WINTER	-20C	0.44	0.48	0.56	0.73

Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.37 ACH
avg. 0.39 ACH
max. 0.39 ACH

BUF4LO.DAT

having one, two and four passive vent openings near ground level for a bungalow with uniform wind shelter that reduces the approach wind at eaves height by a factor of two. Comparing these results to Table 5-7 for the same house with no passive vent openings, shows that placing a 10.2 cm diameter pipe near ground level on each of the four walls, increases the high wind ventilation rate by about 20%, and the light wind rate by about 40%. We see in Table 5-12 that even with these four large openings the bungalow is under-ventilated in spring and fall for light wind conditions. The results are encouraging, in that ground-level passive vents add 40% to the light wind ventilation rates where it is needed, while increasing high wind rates by only 20% where extra ventilation is an energy liability.

However, comparing Table 5-7 with 5-12, it is clear that effective passive ventilation requires some control mechanism that is sensitive to wind speed as well as to indoor-outdoor temperature difference in order to avoid over-ventilation in high wind winter conditions. At present, there appears to be no cost-effective device for providing this wind-speed sensitive control of passive vent flow area.

Two-Storey House Ventilation

A two-storey house is easier to passively ventilate than a single storey bungalow. In a two-storey house, stack-effect pressures are proportional to ceiling height, and so are typically twice as great as in a bungalow. This increases natural infiltration and ventilation under light wind conditions in spring/fall and summer. Tables 5-13 and 5-14 show ventilation rates in a heavily sheltered two-storey house with no passive vent openings, with and without a flue present. The open flue causes about a 50% increase in air infiltration for all windspeeds and all seasons of the year.

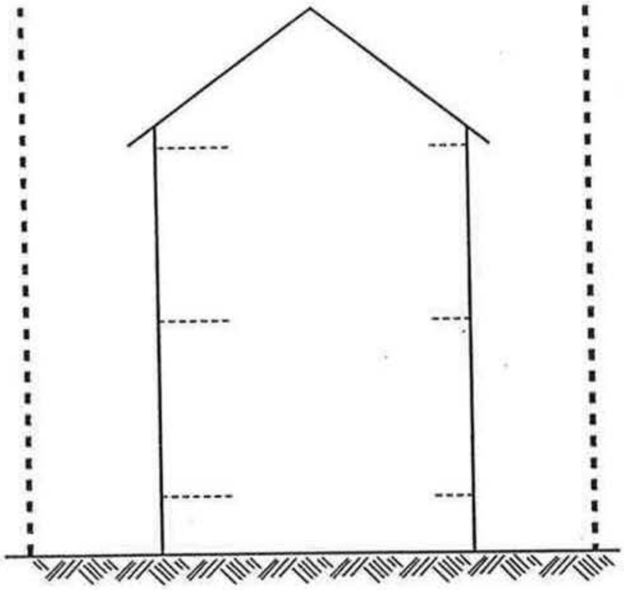
The ventilation rate required to meet ASHRAE standard 62-89 is 0.25 ACH (see Table 5-1). Table 5-14 shows that natural infiltration into a typical two-storey house without passive vents exceeds the minimum required rate for most of the year. The house is under-ventilated only in summer, and in the spring/fall seasons with light and moderate winds.

Adding passive ventilation openings near ground level on each of the four walls adds about 20% to the high wind winter ventilation rate, and 30% to the spring/fall light wind ventilation. However, even with these four large openings, the two-storey house will be under-ventilated in spring/fall for light winds, and in summer for both light and moderate winds.

Because the two-storey house has a larger stack effect than the bungalow, it is less susceptible to varying windspeeds. Even so, ventilation rates with four passive vents shown in Table 5-15 have a factor of two increase in ventilation rate as the windspeed increases by a factor of five from "light" to "high". Again, this implies that if passive ventilation areas are sized to

TABLE 5-13 and B-27

Two Storey Ventilation Rates With No Passive Vents, No Flue, Uniform Shelter, S_w=0.5



Background Leakage Area	100%
Flue Leakage Area	0%
Passive Vents Leakage Area	0%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.07	0.10	0.18	0.32
SPRING/FALL	10C	0.11	0.13	0.19	0.33
SHOULDER	0C	0.18	0.19	0.23	0.35
WINTER	-20C	0.29	0.30	0.33	0.42

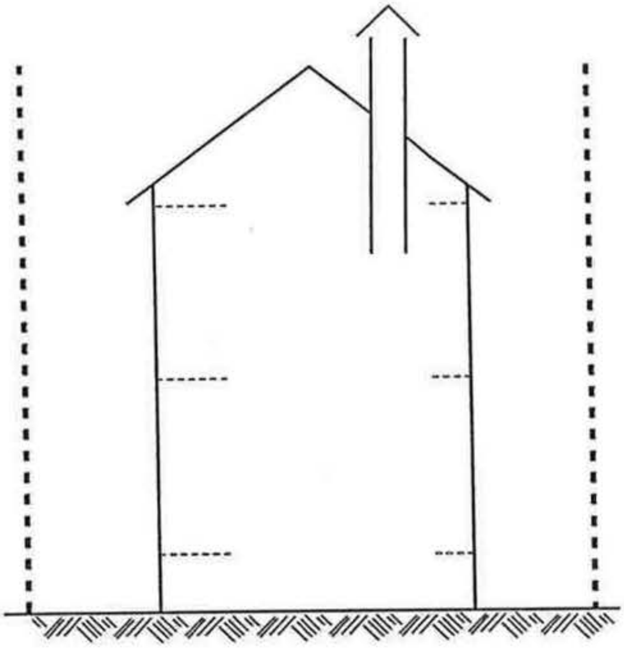
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.19 ACH
avg. 0.19 ACH
max. 0.19 ACH

2SN0VENT.DAT

TABLE 5-14 and B-37

Two Storey Ventilation Rates With No Passive Vents, Flue, Uniform Shelter, S_w=0.5



Background Leakage Area	85%
Flue Leakage Area	15%
Passive Vents Leakage Area	0%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.11	0.17	0.26	0.44
SPRING/FALL	10C	0.17	0.21	0.30	0.46
SHOULDER	0C	0.26	0.29	0.36	0.51
WINTER	-20C	0.41	0.43	0.48	0.62

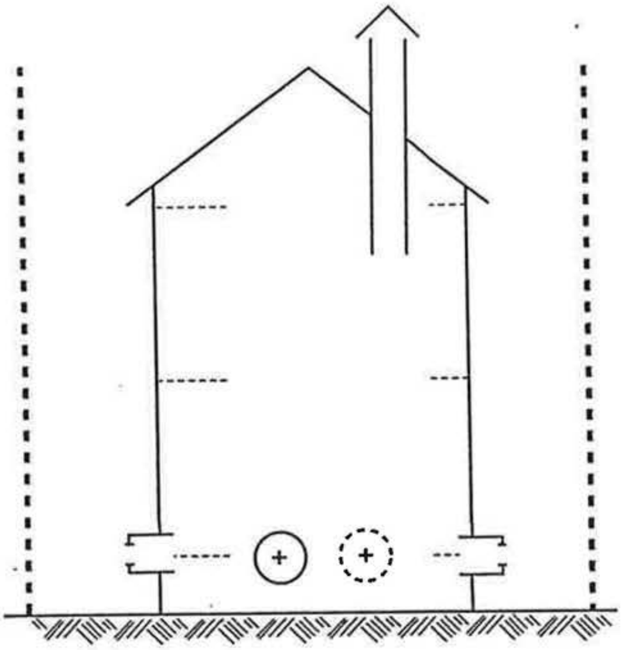
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.29 ACH
avg. 0.30 ACH
max. 0.30 ACH

2SF0VENT.DAT

TABLE 5-15 and B-48

Two Storey Ventilation Rates With Four Passive Vents, Flue, Uniform Shelter, S_w=0.5



Background Leakage Area	66%
Flue Leakage Area	12%
Passive Vents Leakage Area	22%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.15	0.21	0.32	0.54
SPRING/FALL	10C	0.22	0.27	0.35	0.57
SHOULDER	0C	0.34	0.37	0.44	0.60
WINTER	-20C	0.52	0.54	0.59	0.73

Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.35 ACH
avg. 0.35 ACH
max. 0.36 ACH

2SF4LO.DAT

maintain indoor air quality under light wind conditions in spring/fall, the two-storey house will be over-ventilated by about a factor of two under high wind conditions.

Townhouse Ventilation

Because townhouse units have common side walls with their neighbors, they have considerably smaller leakage area as a fraction of their floor area compared to detached bungalows and two-storey houses. This characteristic makes them prone to under-ventilation by natural infiltration. Tables 5-16 and 5-17 show infiltration rates for a townhouse unit with no passive vents, with and without a flue. Here, the 360°-averaged air exchange fails to meet the 0.25 ACH ASHRAE 62-89 standard (see Table 5-1) except in winter with strong or high winds.

Air infiltration in townhouses is strongly dependent on wind direction, with a 50% variation above and below the average with no flue, and a 20% variation with a flue. From this, we conclude that townhouses are the type of construction most likely to benefit from the introduction of passive ventilation systems to increase natural ventilation.

Table 5-18 shows the effect of adding two passive vent openings near ground level on the exposed front and back walls of the case-study townhouse. With two passive vents, the ventilation rate increases considerably, and meets the 0.25 ACH standard except in spring/fall and shoulder seasons for light and moderate winds. Although more passive ventilation openings (and an extra flue) could be added, the factor of two or three increase in air exchange rate that occurs as the windspeed increases by a factor of five from "light" to "high" shows that the townhouse would pay a significant energy penalty due to over-ventilation under high wind winter conditions. Again, a method for controlling passive ventilation openings with varying windspeed is required to develop an energy-efficient system.

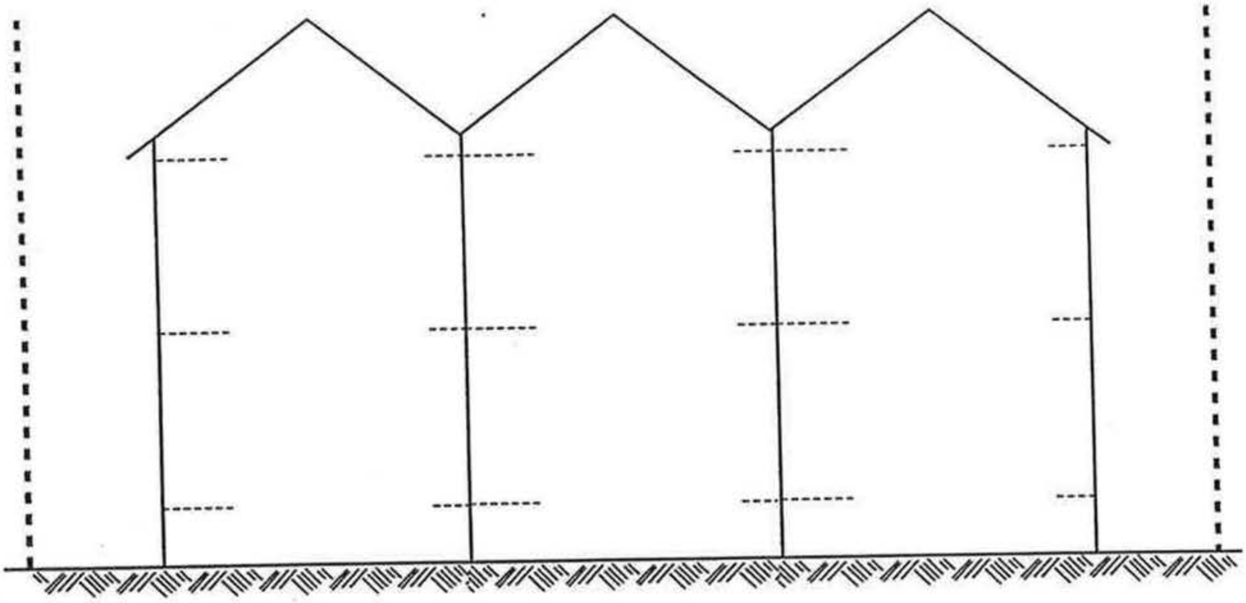
Conclusions and Recommendations

Simulation of air infiltration and ventilation rates in bungalows, and two-storey detached and townhouse dwellings has led us to a number of conclusions on the best ventilation strategy for a compromise between providing adequate ventilation for indoor air quality, and avoiding over-ventilation and high energy costs in winter.

- Our first conclusion is that most detached single storey and two-storey houses are adequately ventilated in winter by natural air infiltration with no passive vent openings. Townhouses, with two walls common to adjacent units are usually not adequately ventilated by natural infiltration.

TABLE 5-16 and B-49

Townhouse Ventilation Rates With No Passive Vents, No Flue, Close Row Shelter



Background Leakage Area	100%
Flue Leakage Area	0%
Passive Vents Leakage Area	0%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.04	0.09	0.17	0.31
SPRING/FALL	10C	0.06	0.10	0.18	0.32
SHOULDER	0C	0.09	0.12	0.19	0.34
WINTER	-20C	0.15	0.17	0.22	0.37

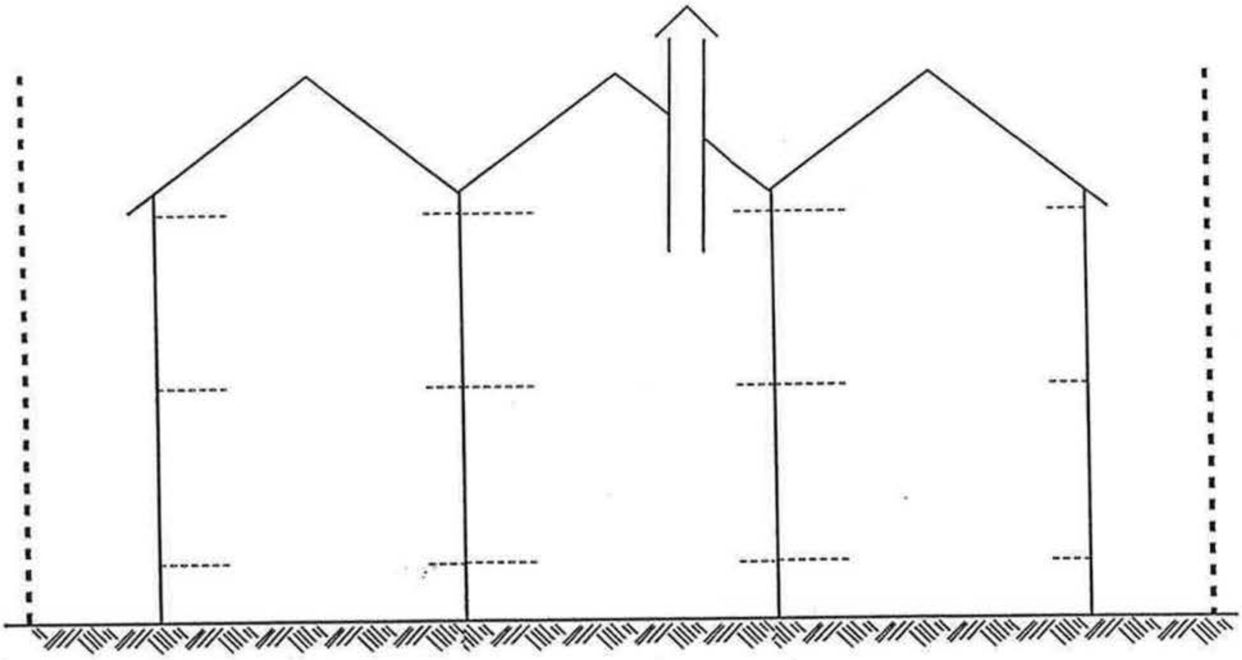
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.08 ACH
avg. 0.18 ACH
max. 0.26 ACH

THN0VENT.BDT
(BASEMENT)

TABLE 5-17 and B-51

Townhouse Ventilation Rates With No Passive Vents, Flue, Close Row Shelter



Background Leakage Area	75%
Flue Leakage Area	25%
Passive Vents Leakage Area	0%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.08	0.15	0.25	0.44
SPRING/FALL	10C	0.12	0.18	0.27	0.45
SHOULDER	0C	0.17	0.22	0.31	0.48
WINTER	-20C	0.27	0.31	0.38	0.54

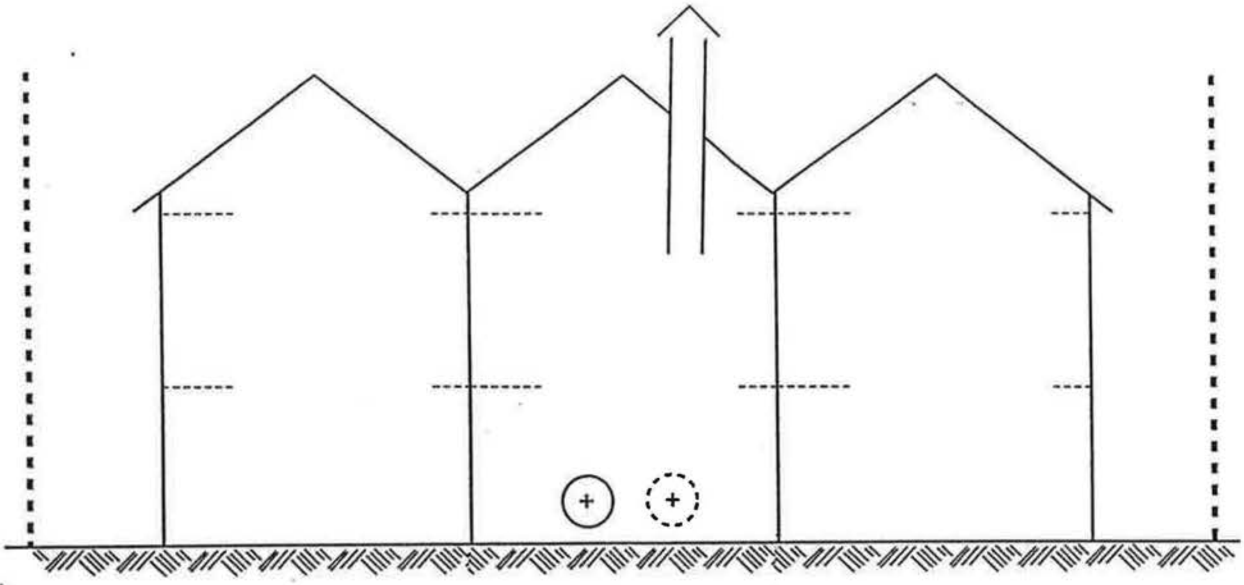
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.22 ACH
avg. 0.27 ACH
max. 0.33 ACH

THF0VENT.BDT
(BASEMENT)

TABLE 5-18 and B-53

Townhouse Ventilation Rates With Two Passive Vents, Flue, Close Row Shelter



Background Leakage Area	61%
Flue Leakage Area	20%
Passive Vents Leakage Area	19%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.11	0.18	0.30	0.52
SPRING/FALL	10C	0.15	0.21	0.32	0.54
SHOULDER	0C	0.22	0.26	0.36	0.57
WINTER	-20C	0.33	0.36	0.44	0.63

Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.23 ACH
avg. 0.32 ACH
max. 0.41 ACH

THF2LO.BDT
(BASEMENT)

- The second conclusion is that even with several large ground-level passive ventilation openings houses cannot be adequately ventilated in summer, and spring/fall seasons in light winds without using large open area vents that cause over-ventilation in winter.
- The major obstacle to adopting passive ventilation is an inlet damper control that is regulated not only by outdoor temperature, but also by windspeed. Such windspeed sensitive controllers are not commercially available, and are likely to be expensive and prone to malfunction if they use existing wind speed sensors.

The implication of the above conclusions is that even for passively ventilated houses, some supplementary form of ventilation is required in spring/fall and summer weather when indoor-outdoor temperature differences are less than 10C and winds are "light" to "moderate". Most occupants will open windows to provide supplementary ventilation under these mild weather conditions. However, if an idiot-proof system is required, supplementary mechanical ventilation in the form of a two-speed furnace fan should be considered. The fan should be operated continuously in its low-speed mode when the temperature is above freezing in order to draw air through a calibrated orifice in the combustion make-up air duct supplying the warm air furnace system.

From the standpoint of effectively controlling passive ventilation, the results in Tables 5-8 and 5-9 are discouraging. Moving a pair of passive vents from exposed front and back walls of a house to sheltered side wall locations for houses in a closely-spaced row has less than 5% effect on reducing the strong variation of flow-rate with wind speed. In the "shoulder" seasons when outdoor temperatures are near freezing, both sheltered and unsheltered passive vent configurations show almost a factor of three increase in air infiltration rate as the windspeed increases by a factor of five from "light" to "high" speeds for houses in a closely spaced row with unsheltered front and rear exposures.

Future research should focus on developing combined wind speed and temperature controls to allow passive ventilation to function efficiently. Until wind speed sensitive controls are developed passive ventilation will over-ventilate by about 400% under high wind winter conditions in order to maintain adequate ventilation under light wind spring and fall conditions. At present, there is no "hole for all seasons".

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APPENDIX A

SUPPLEMENTARY MODEL VALIDATION TESTS

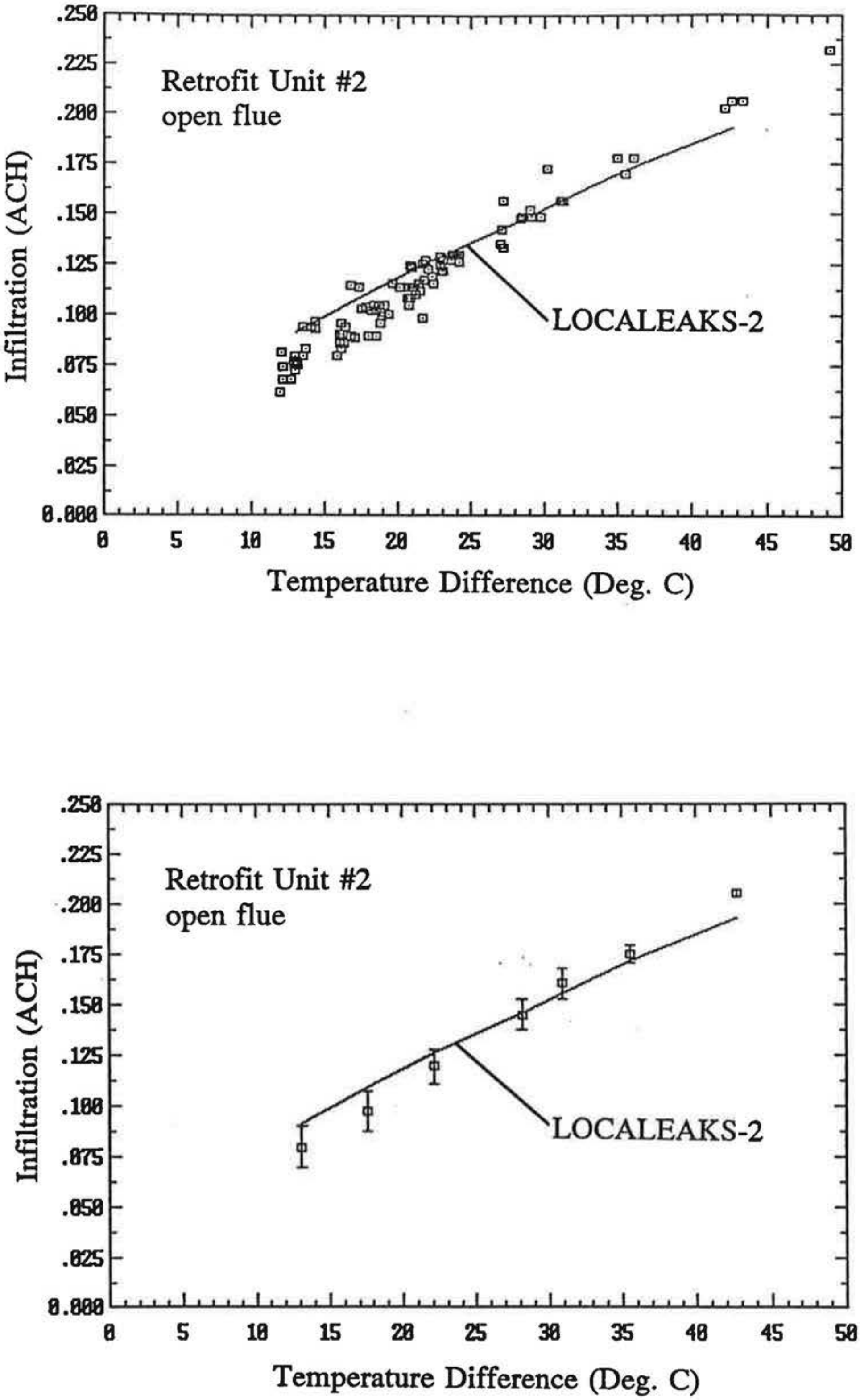


Figure A-1 Stack-effect infiltration into Retrofit Unit #2 with open flue

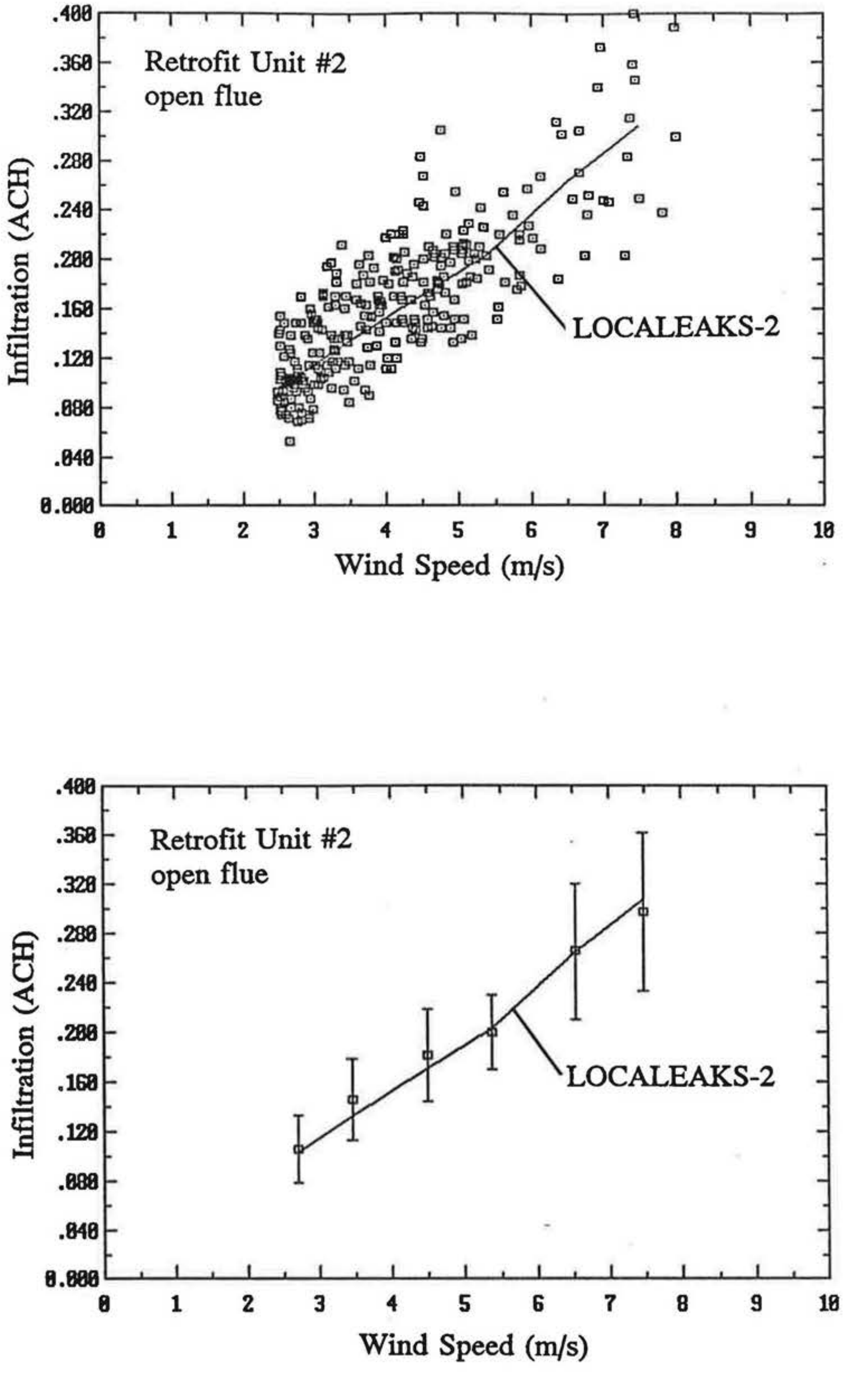
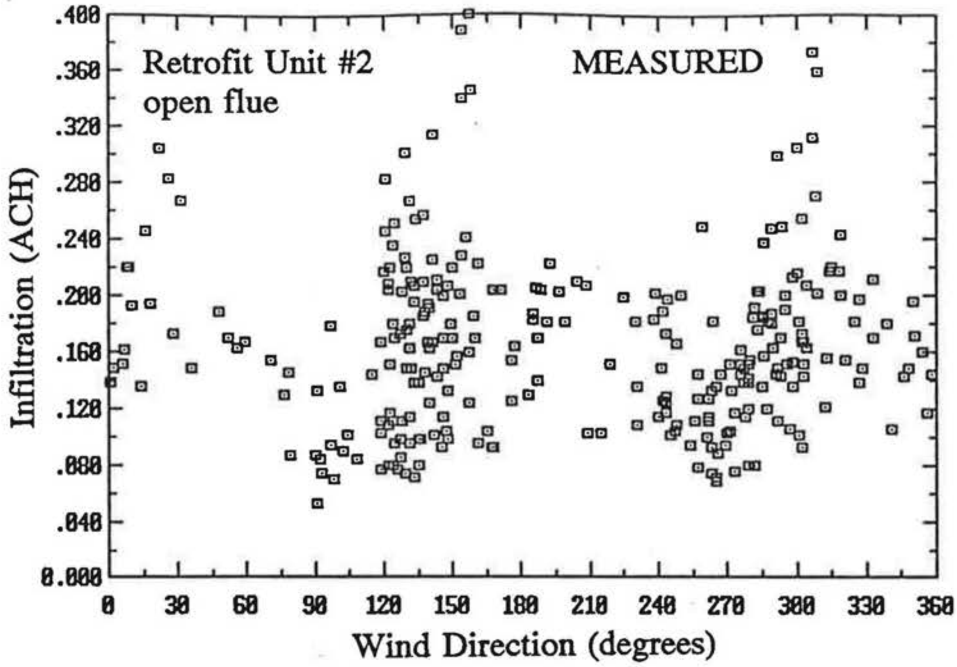


Figure A-2 Wind-effect infiltration into Retrofit Unit #2 with open flue, for all wind directions



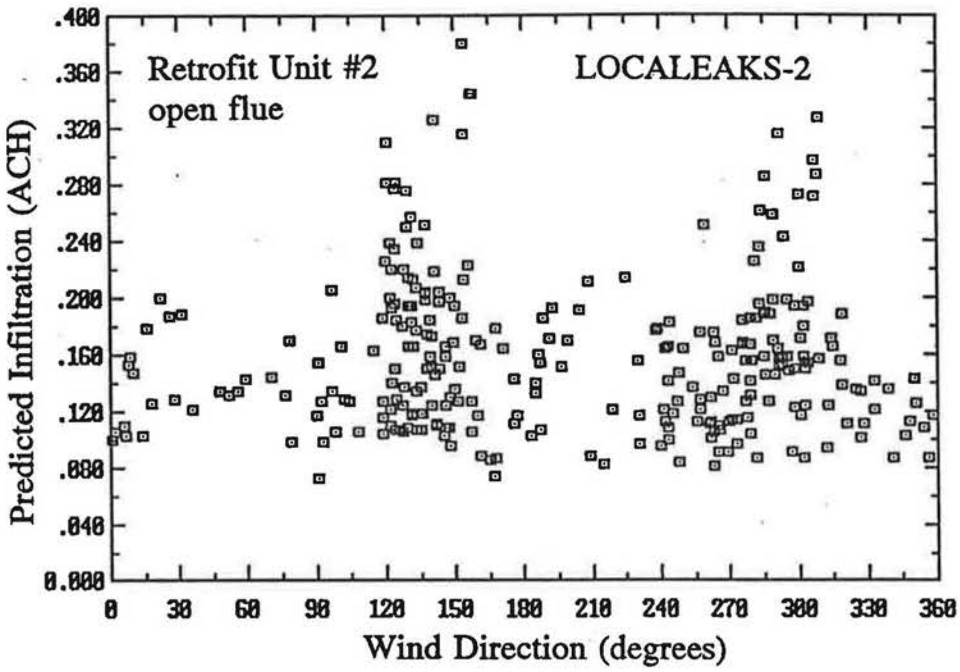
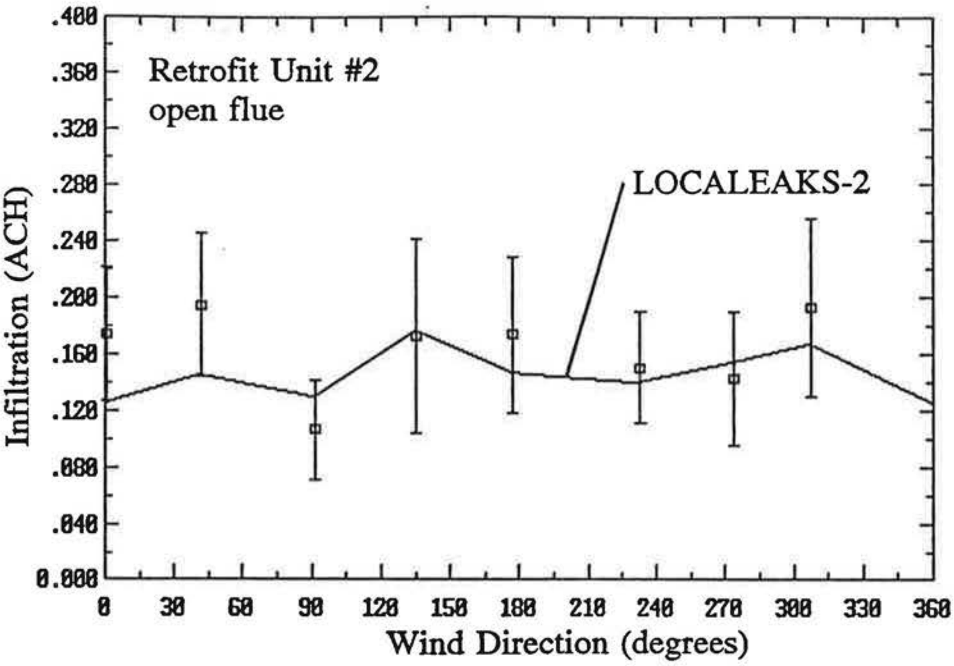


Figure A-3 Unpaired measured and predicted wind direction dependence of wind-effect infiltration into Retrofit Unit #2 with complete shelter by adjacent houses for 90° and 270°, and U_H = 2.5 to 8.0 m/s.



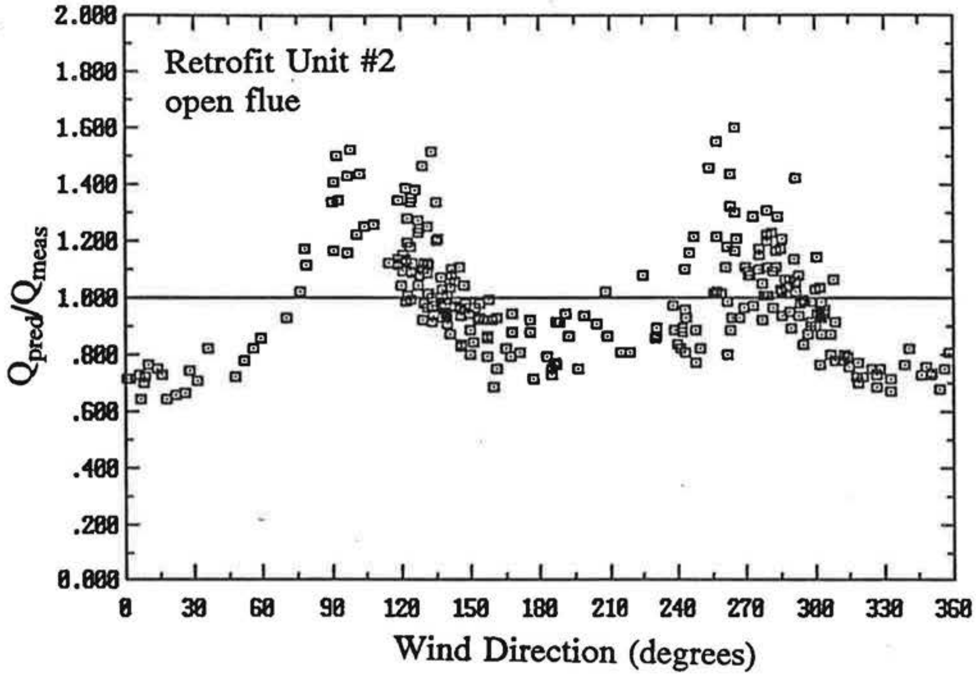
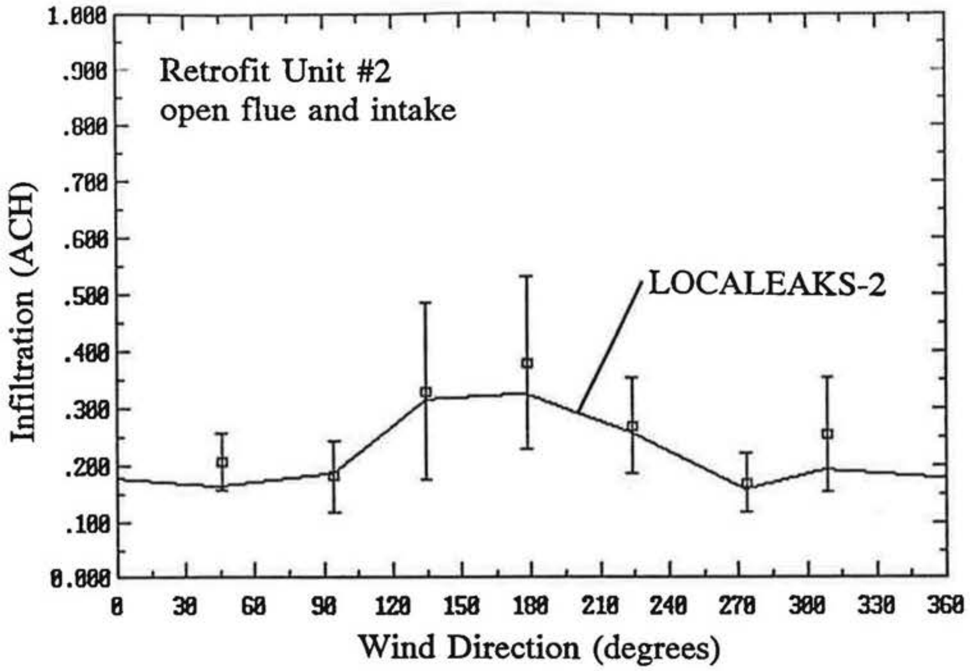


Figure A-4 Binned wind-effect infiltration (top) into Retrofit Unit #2 and paired prediction errors (bottom) with complete shelter by adjacent houses for 90° and 270°, and U_H = 2.5 to 8.0 m/s



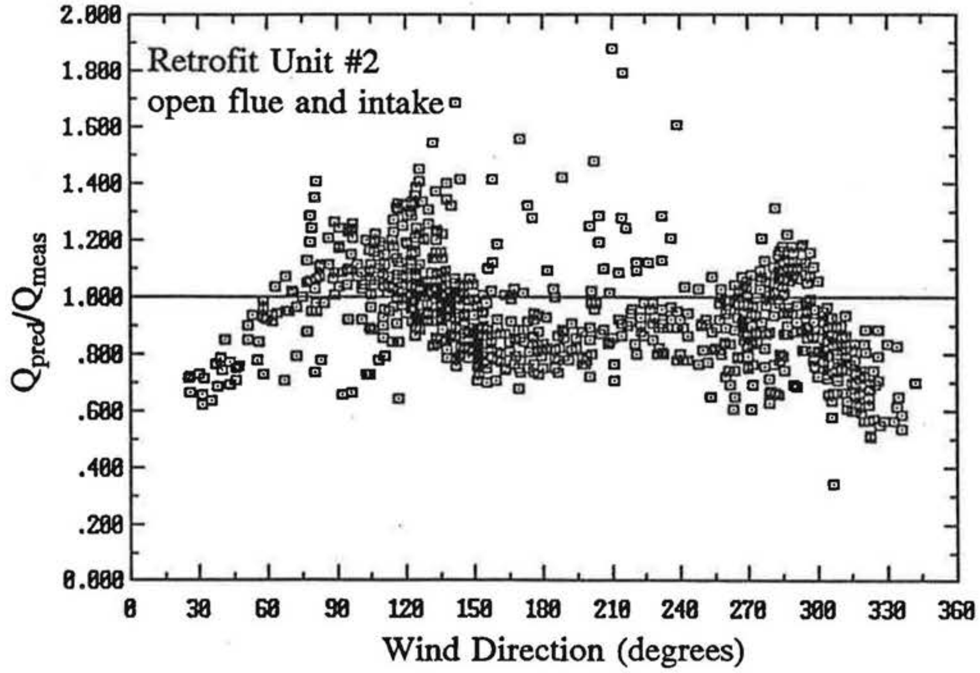
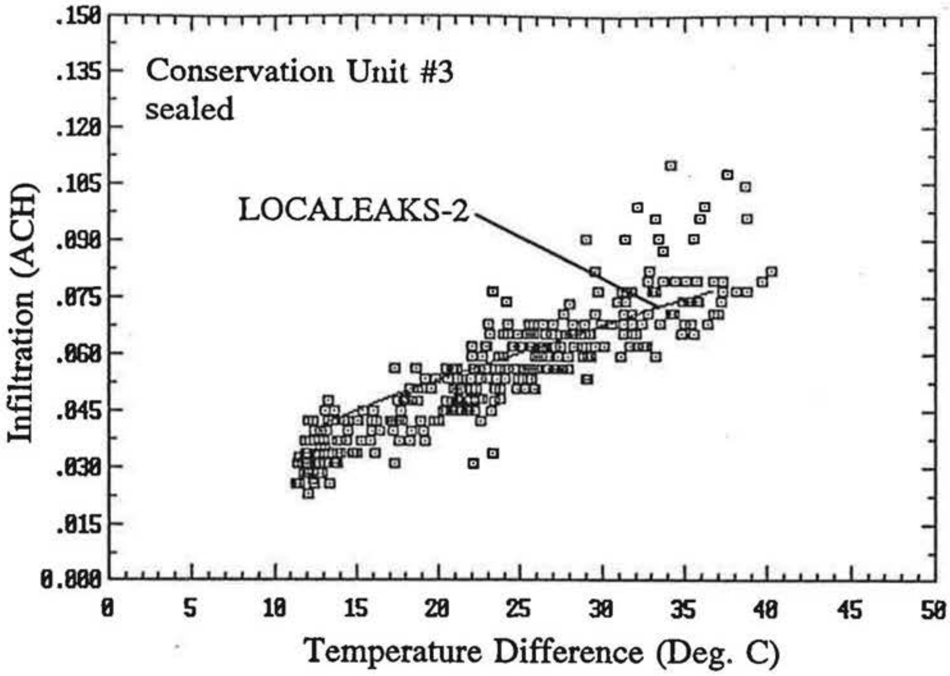


Figure A-5 Binned wind-effect passive ventilation (top) into Retrofit Unit #2, and paired prediction errors (bottom) with complete shelter by adjacent houses for 90° and 270°, and U_H = 2.5 to 8.0 m/s



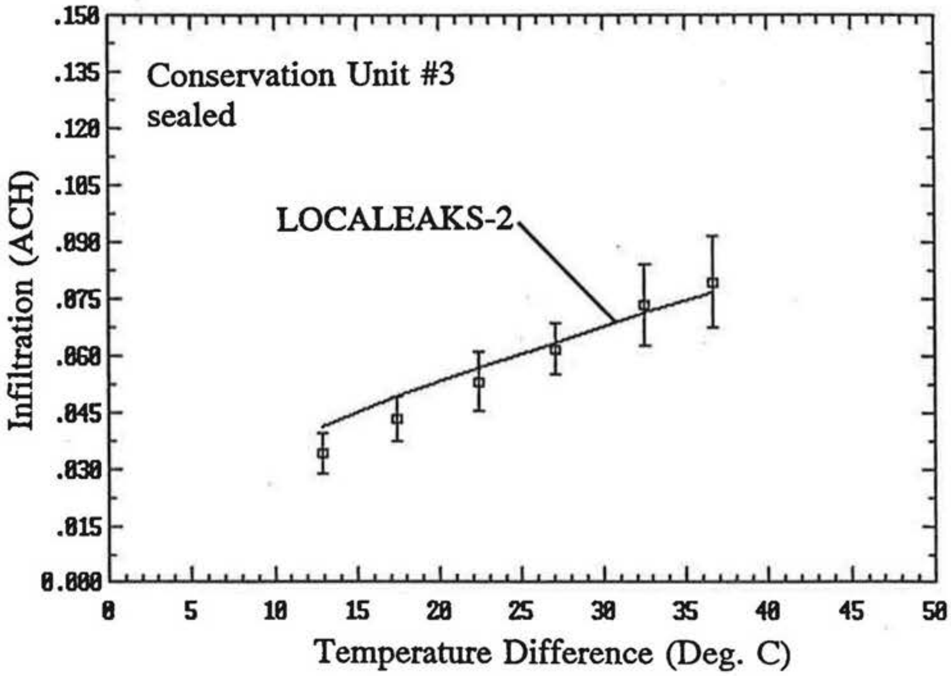
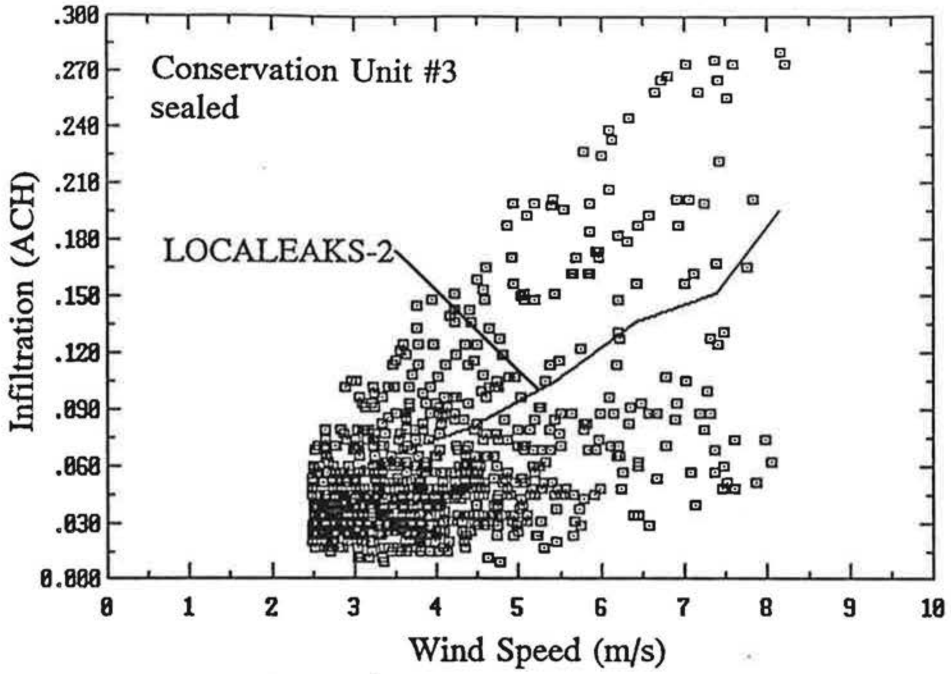


Figure A-6 Stack-effect infiltration into sealed Conservation Unit #3



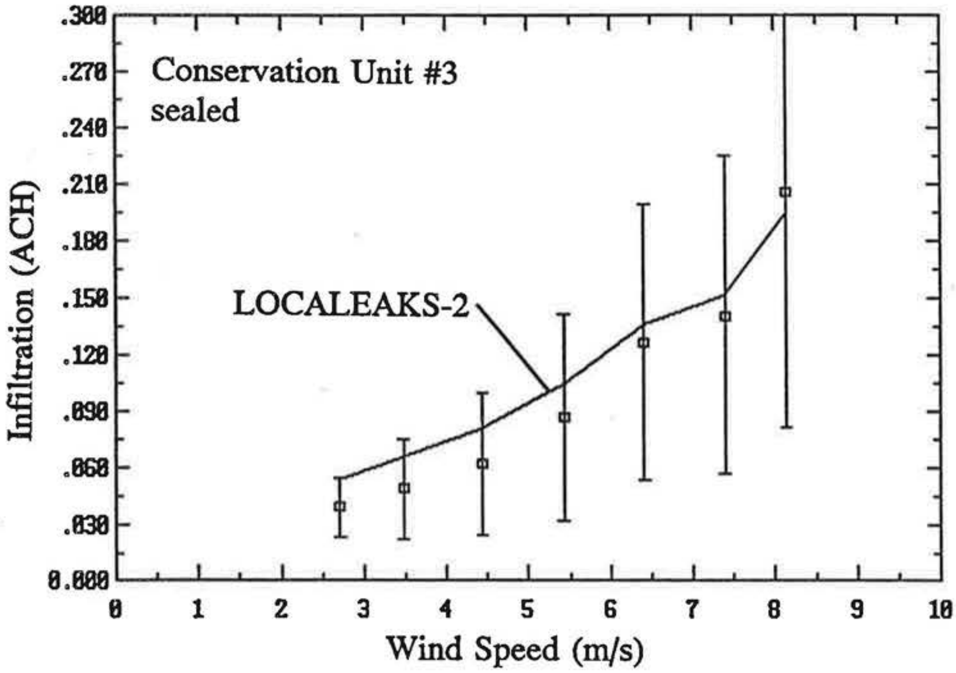
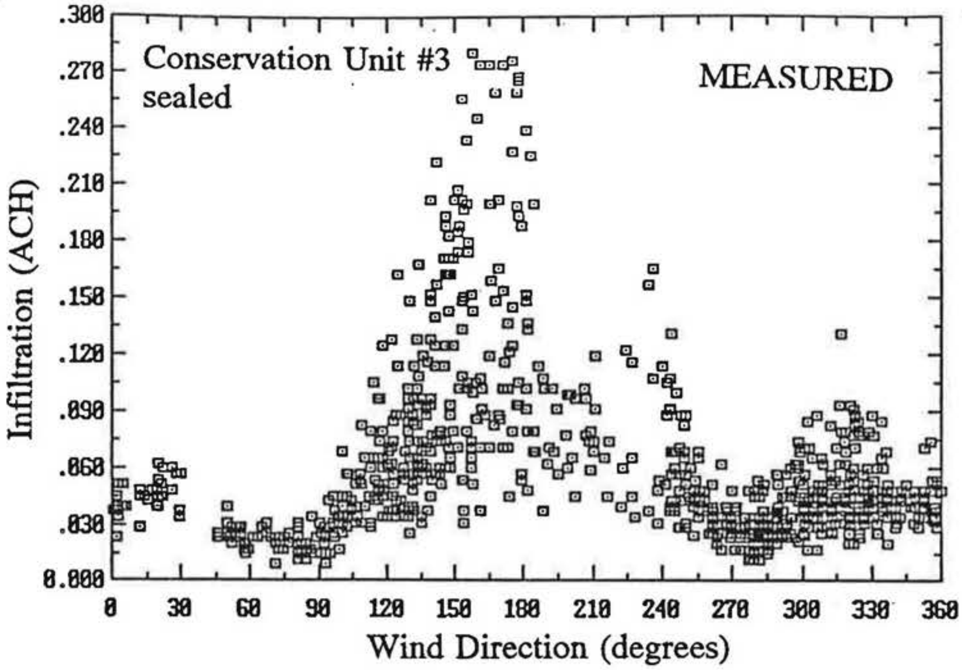


Figure A-7 Wind-effect infiltration into sealed Conservation Unit #3, for all wind directions



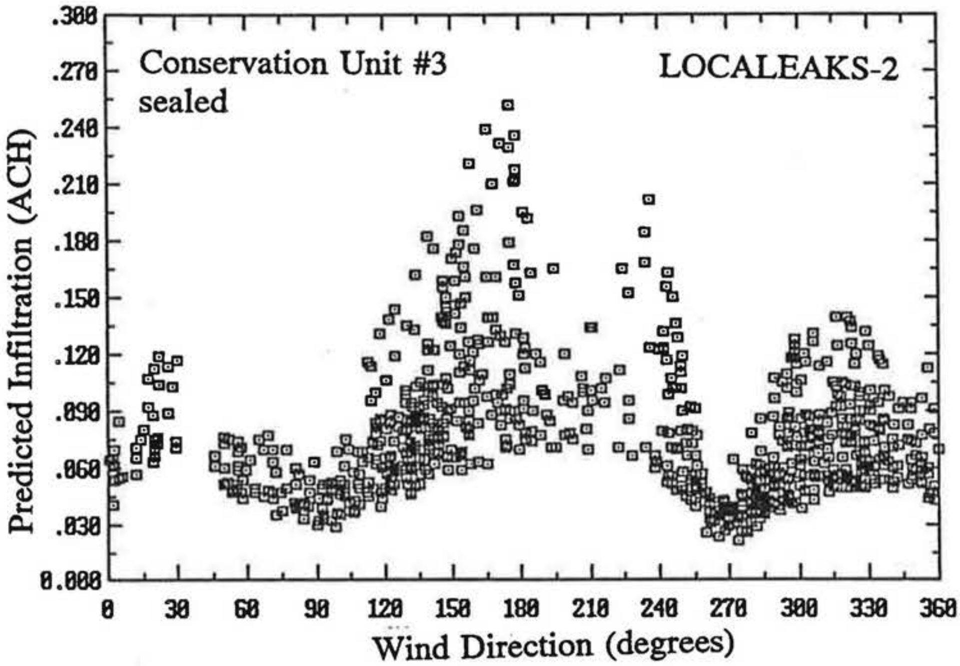
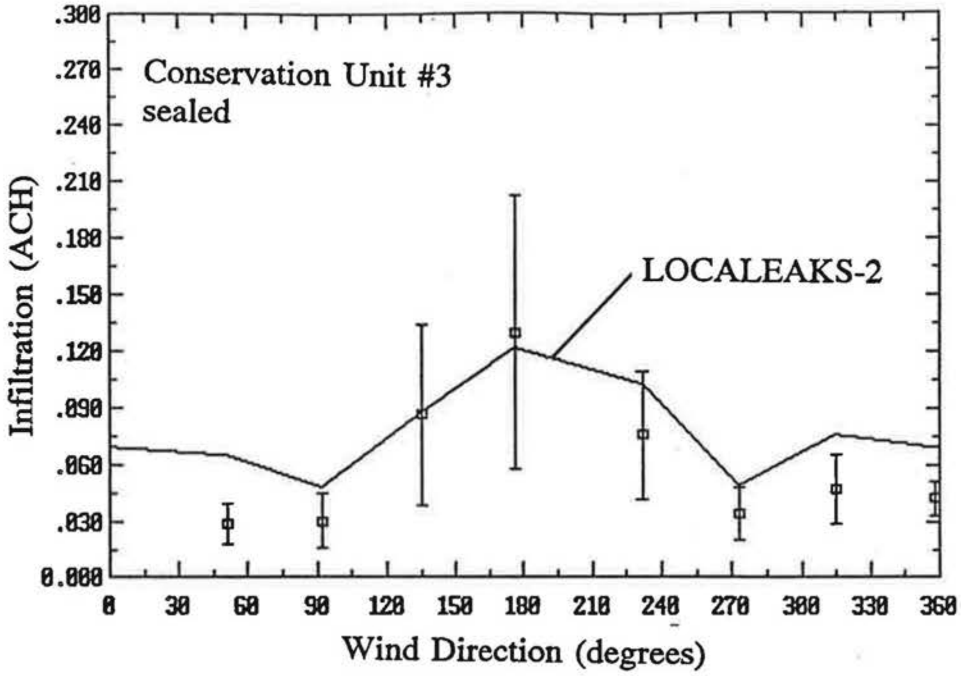


Figure A-8 Unpaired measured and predicted wind direction dependence of wind-effect infiltration into sealed Conservation Unit #3 with complete shelter for 90° and 270°, and U_H = 2.5 to 8.5 m/s



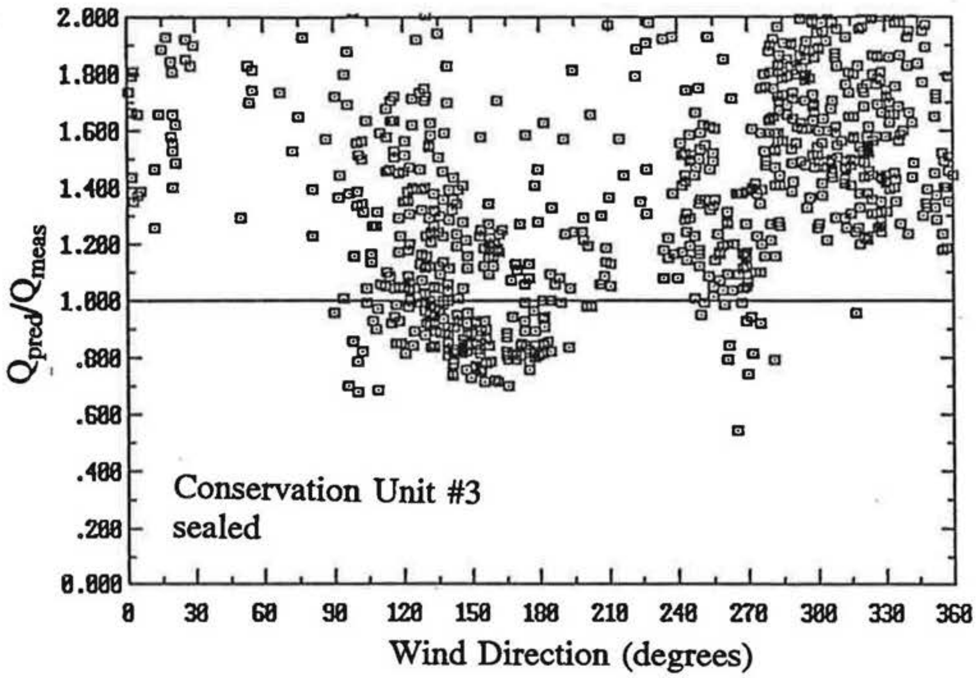
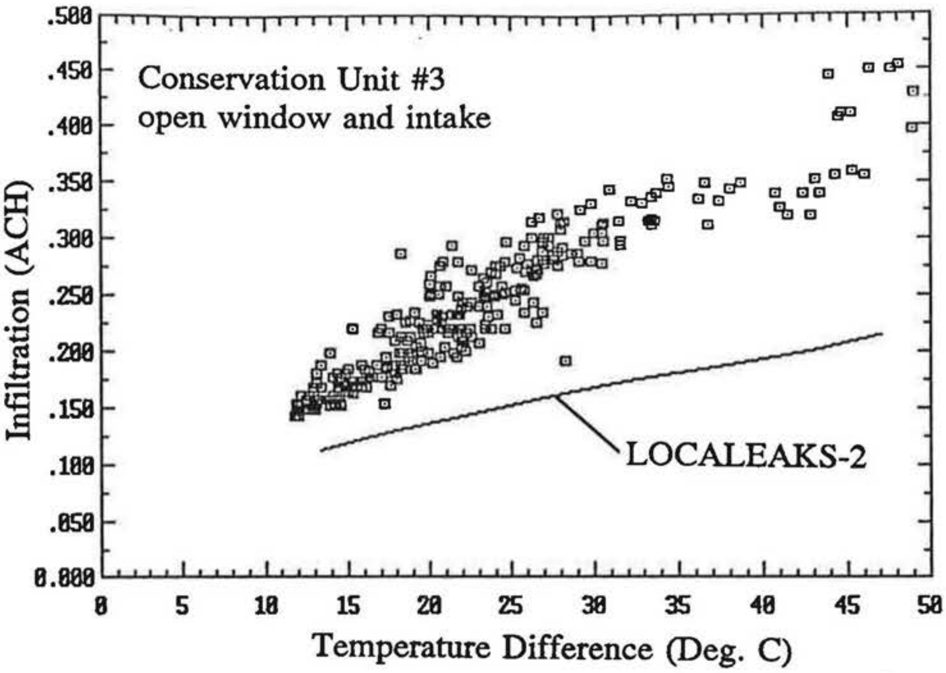


Figure A-9 Binned wind-effect infiltration (top) into sealed Conservation Unit #3, and paired prediction errors (bottom) with complete shelter by adjacent houses for 90° and 270° and U_H = 2.5 to 8.5 m/s



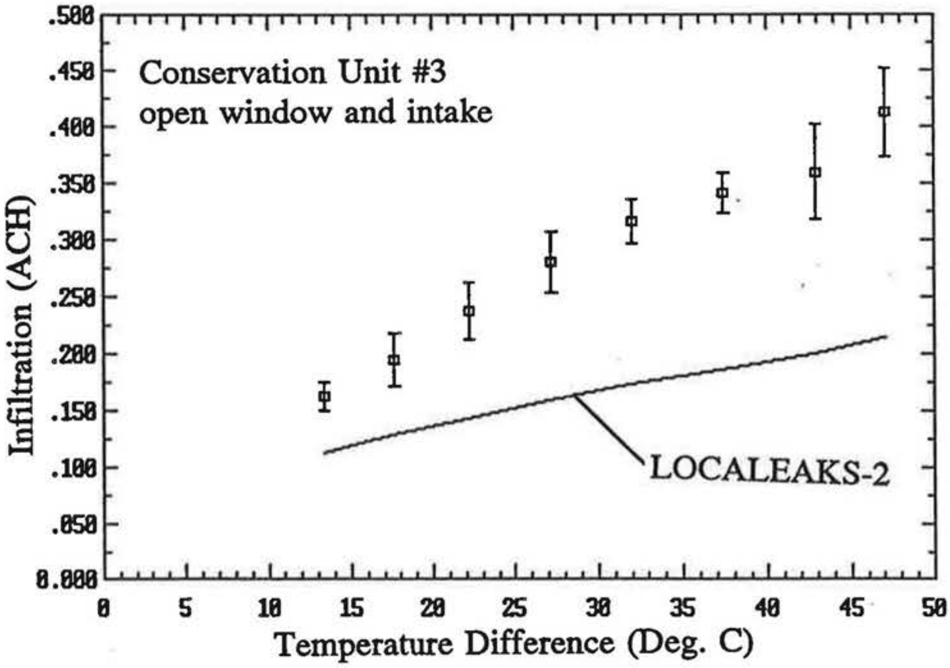
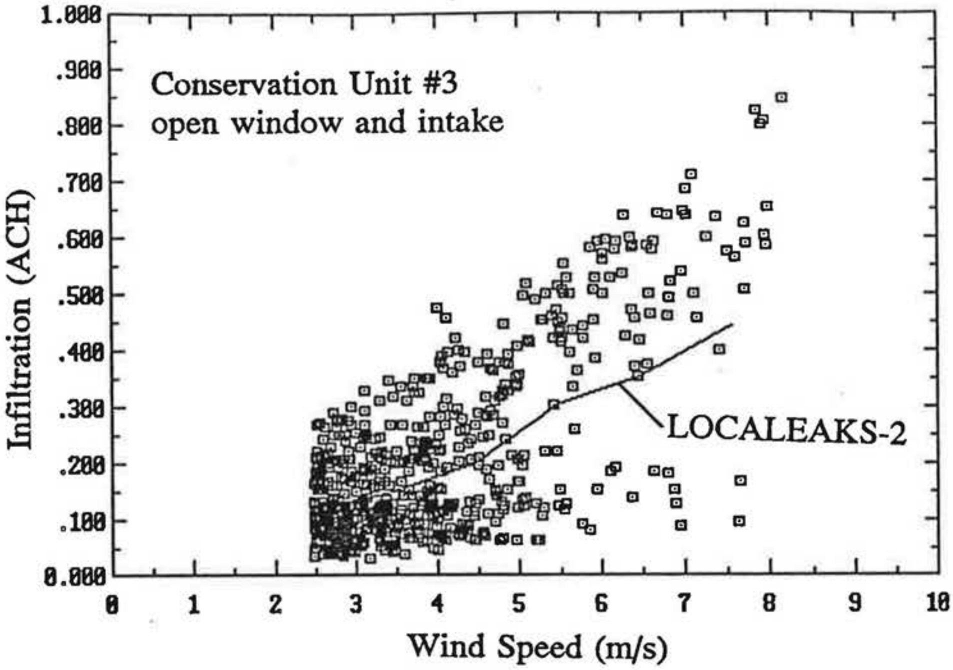


Figure A-10 Stack-effect passive ventilation into Conservation Unit #3 with open window orifice and ground-level intake pipe



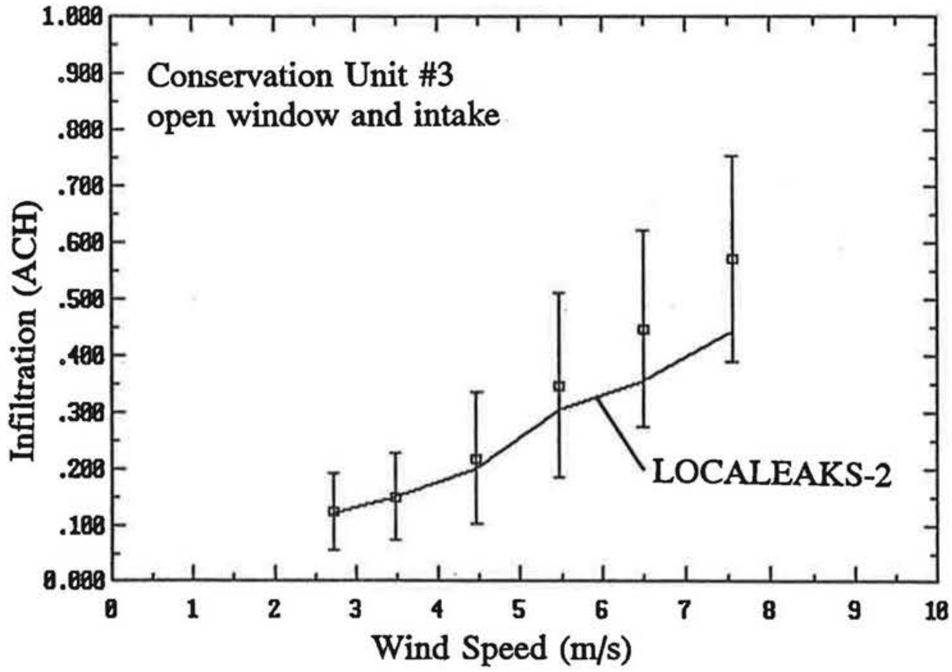
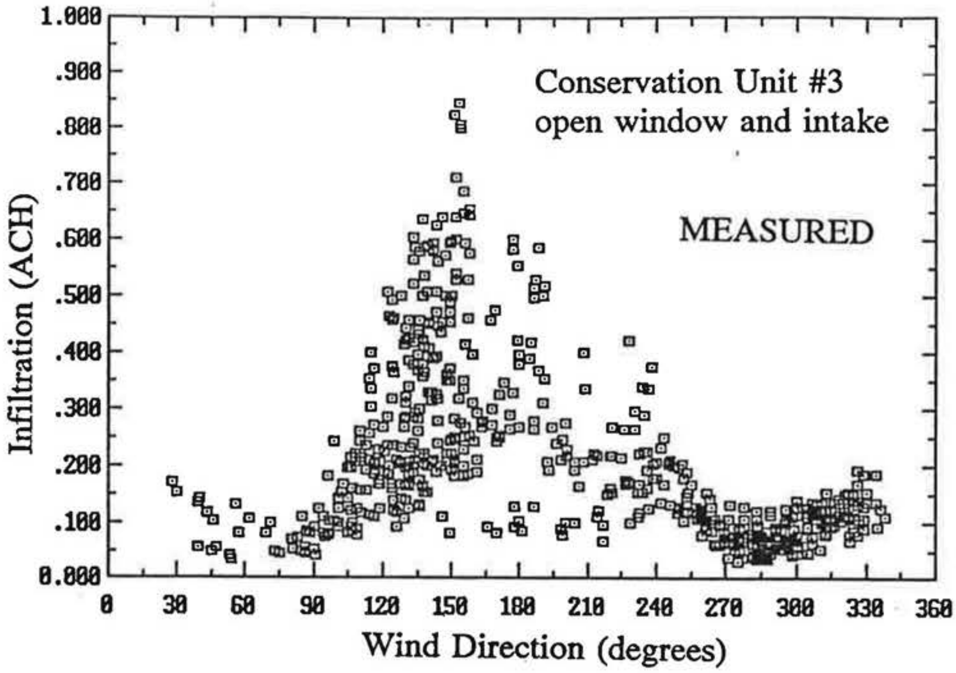


Figure A-11 Wind-effect passive ventilation of Conservation Unit #3 with open window orifice and ground level intake pipe, for all wind directions



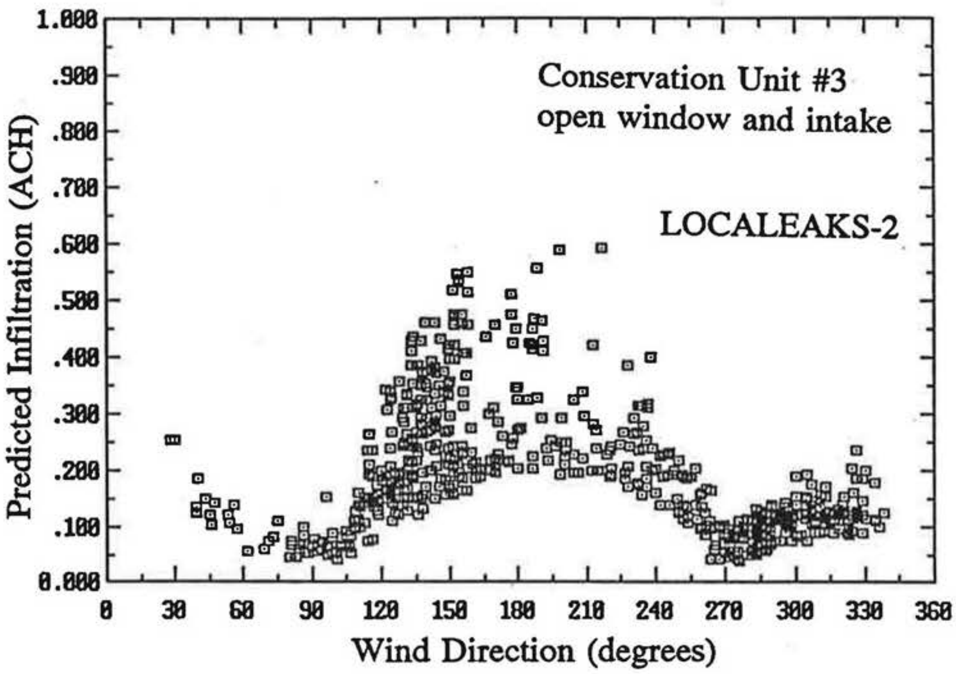
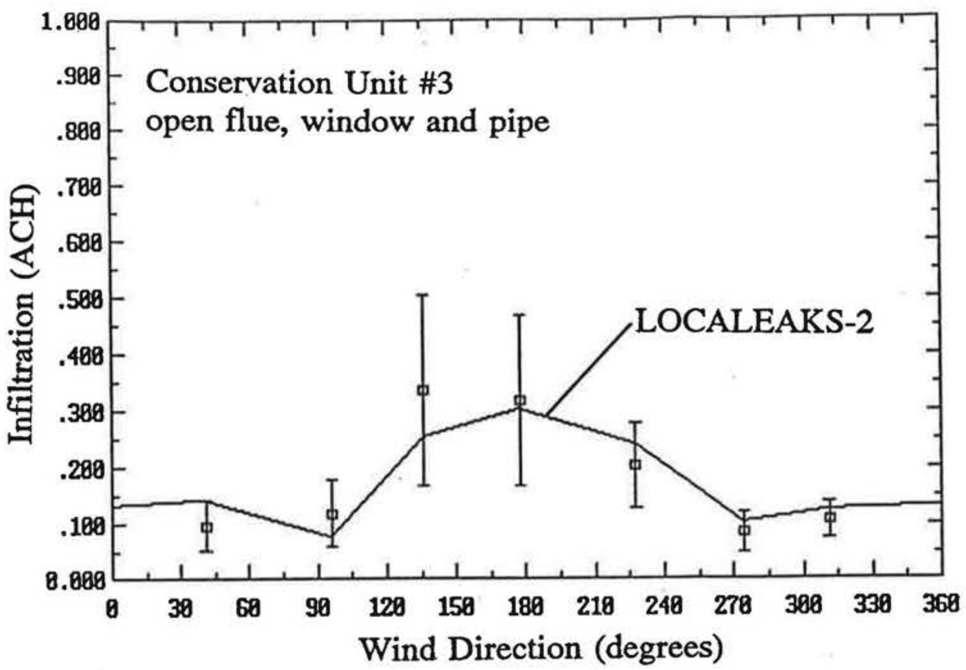


Figure A-12 Unpaired measured and predicted wind direction dependence of wind-effect passive ventilation of Conservation Unit #3 for complete shelter for 90° and 270°, and U_H = 2.5 to 8.0 m/s



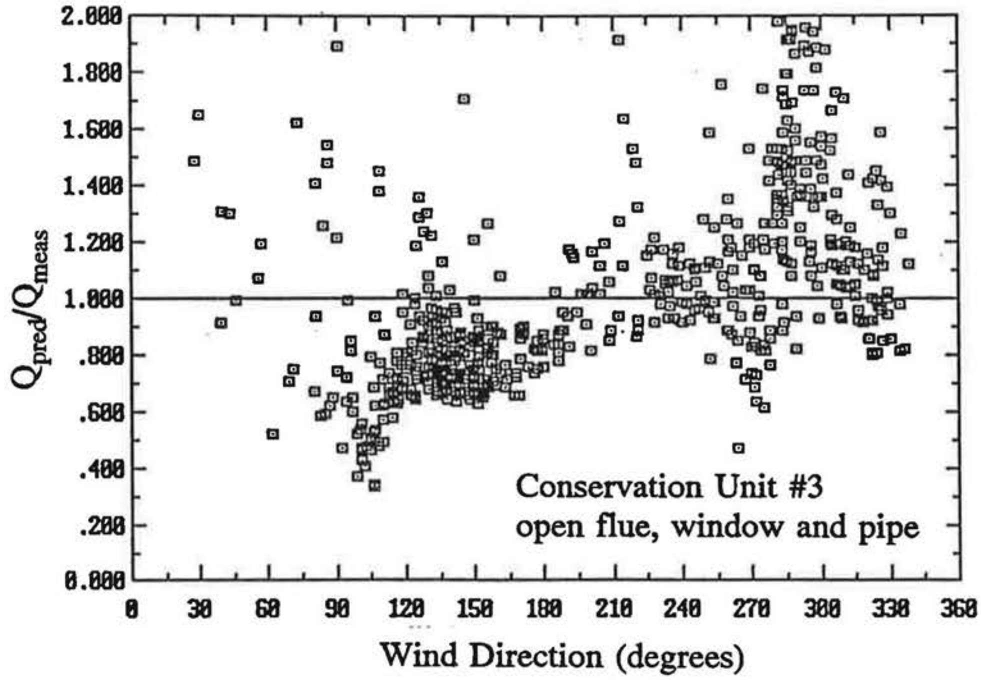
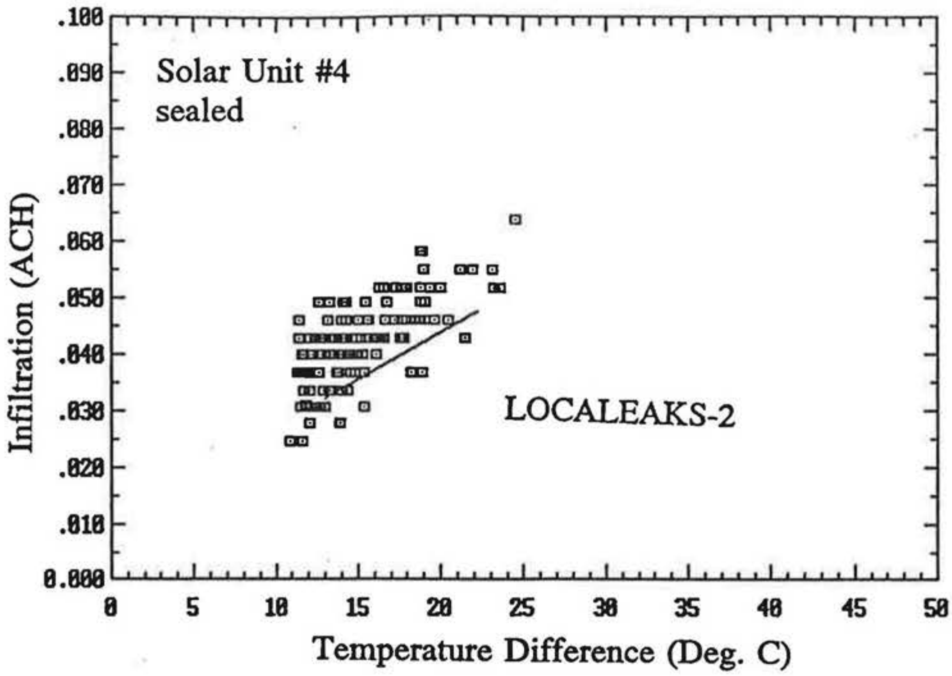


Figure A-13 Binned wind-effect passive ventilation (top) of Reference Unit #5, and paired prediction errors (bottom) with complete shelter by adjacent houses for 90° and 270°, and U_H = 2.5 to 8.0 m/s



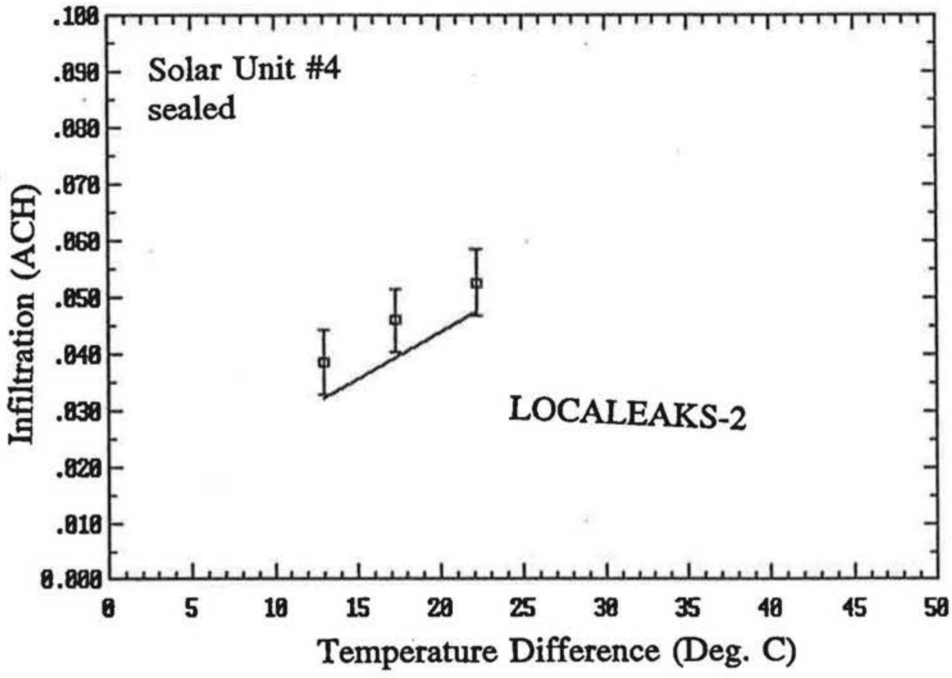
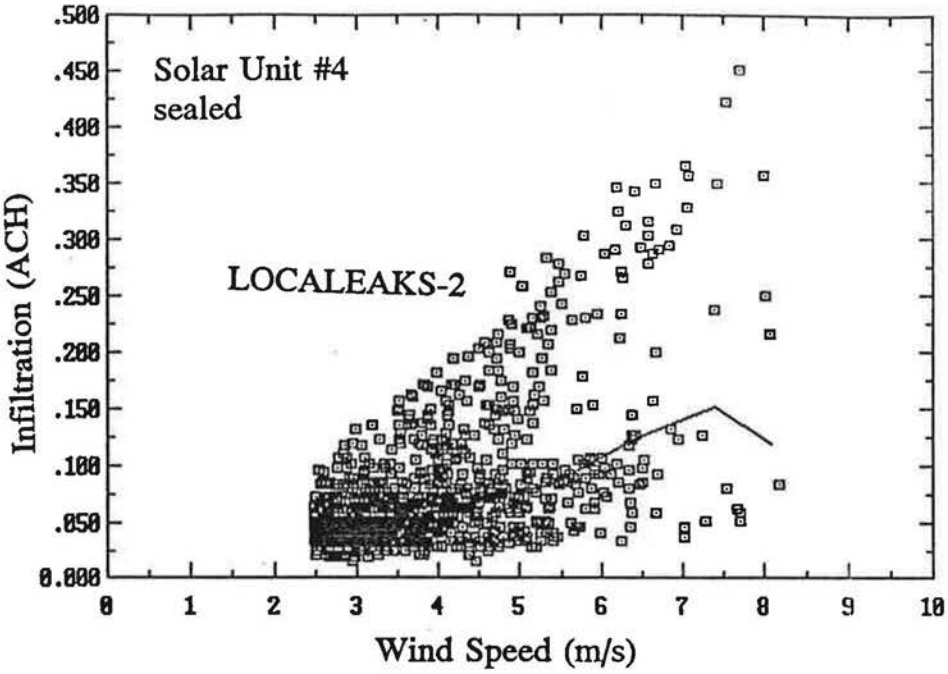


Figure A-14 Stack-effect infiltration into sealed Solar Unit #4



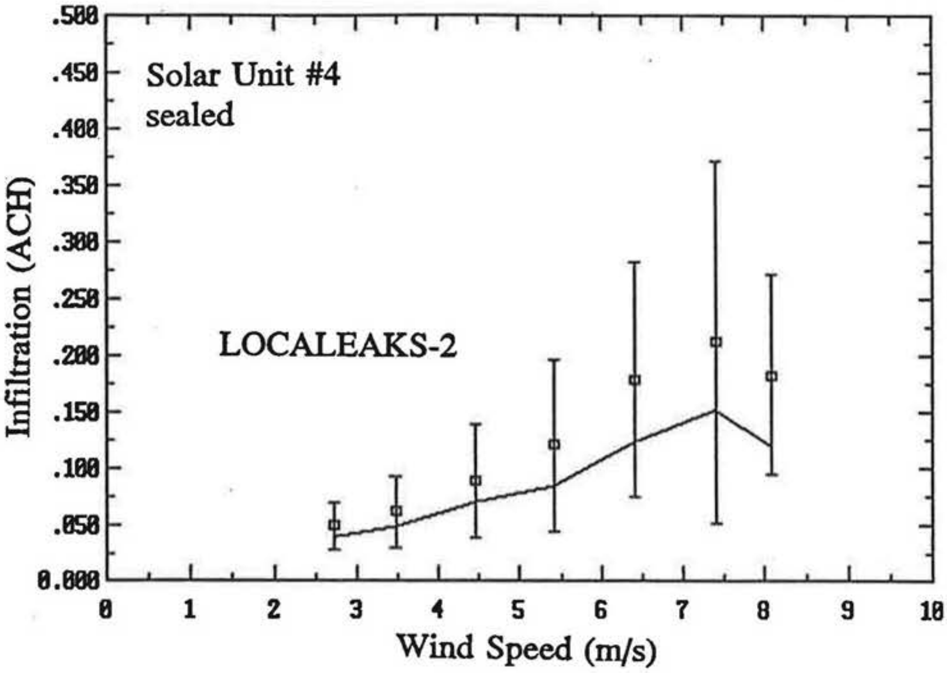


Figure A-15 Wind-effect infiltration into sealed Solar Unit #4 for all wind directions

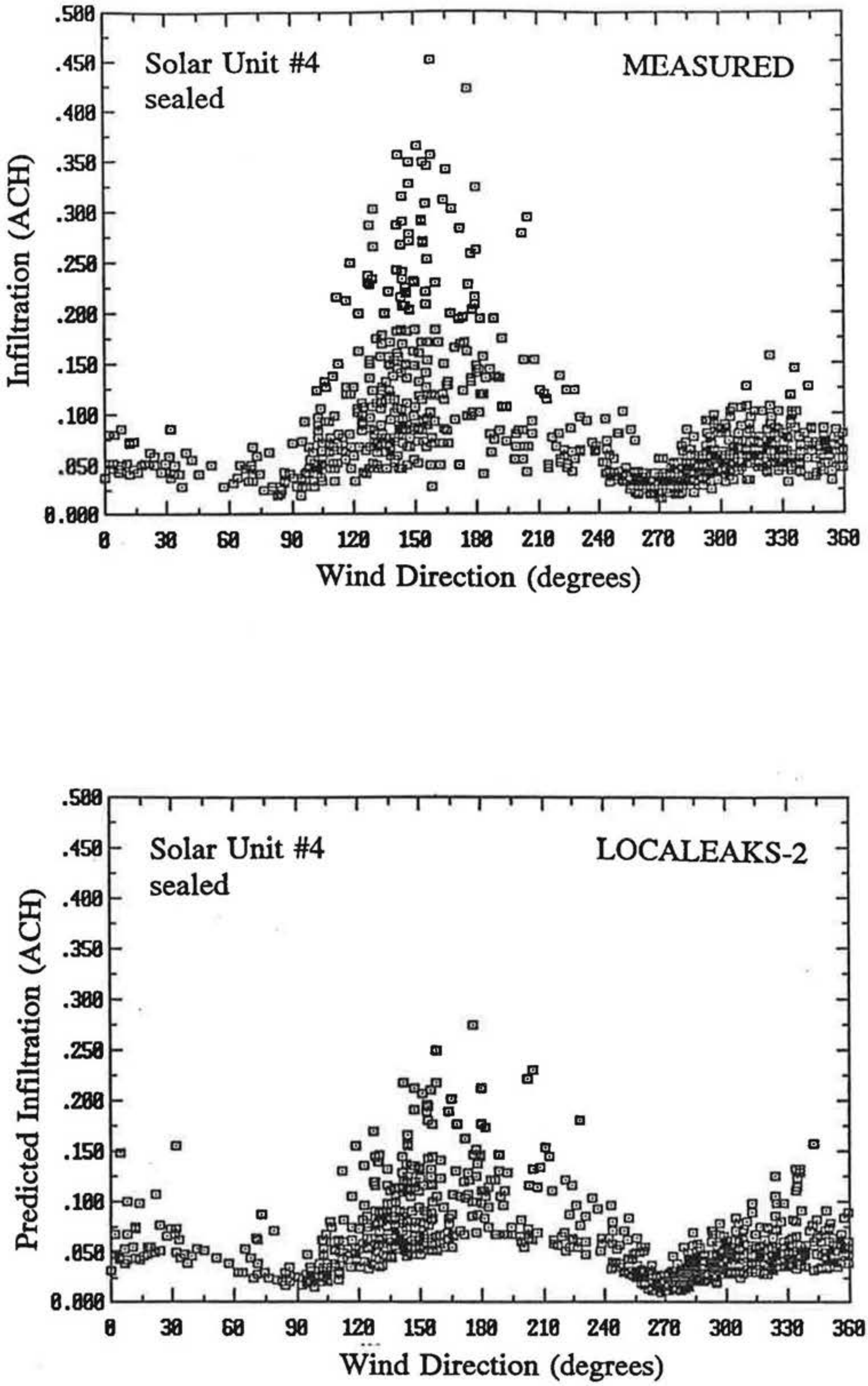
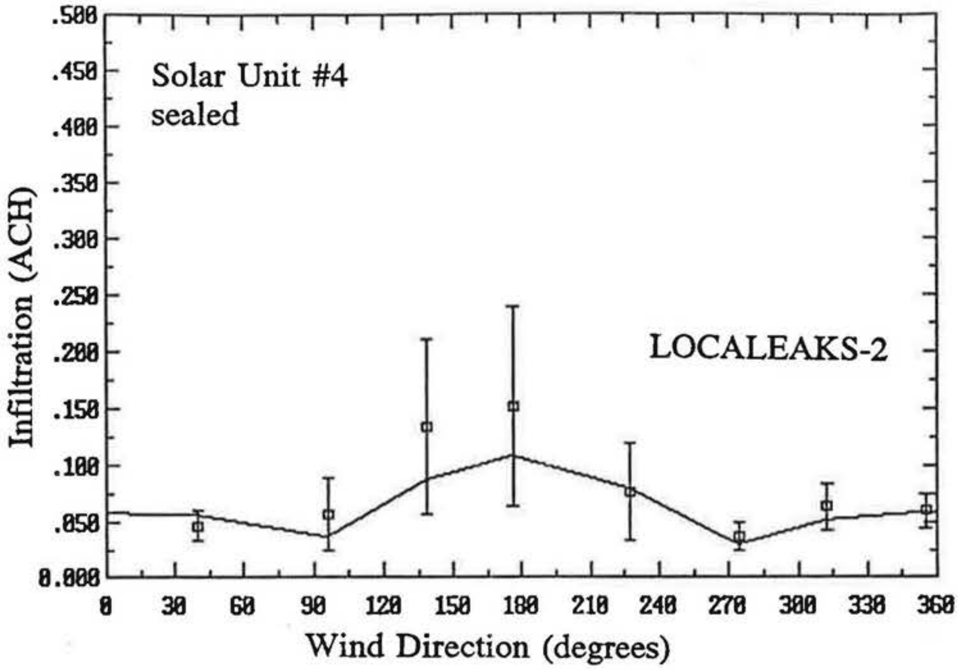


Figure A-16 Unpaired measured and predicted wind direction dependence of wind-effect infiltration into sealed Solar Unit #4 with complete shelter by adjacent houses for 90° and 270°, and U_H = 2.5 to 8.0 m/s



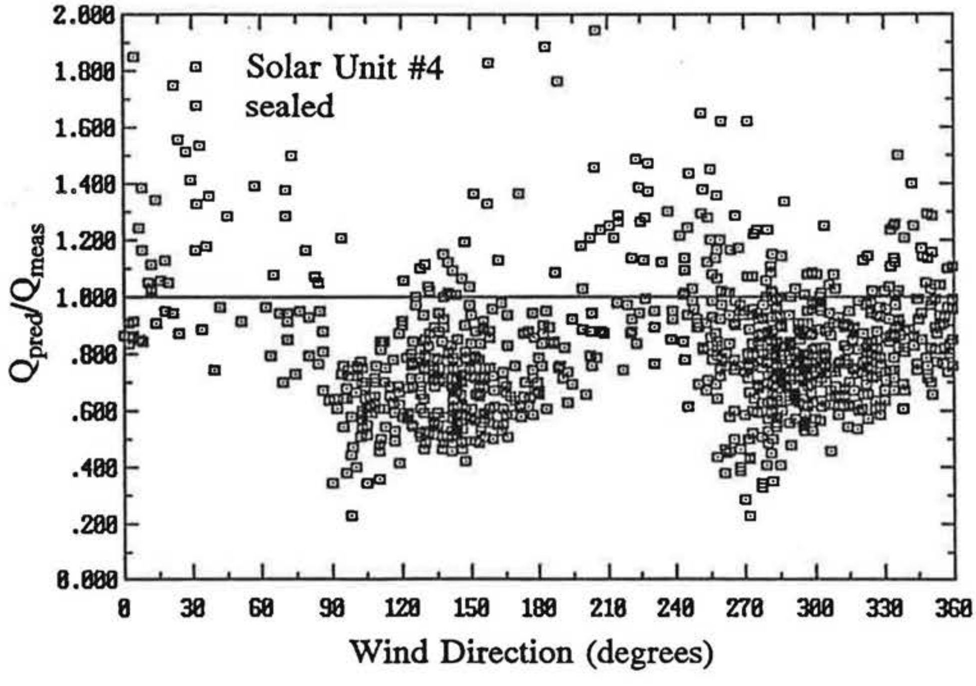


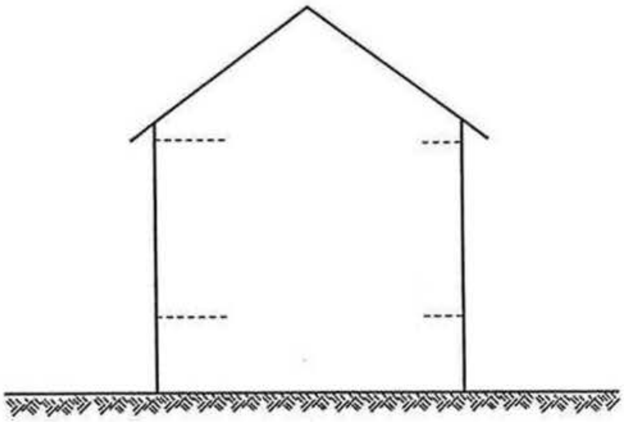
Figure A-17 Binned wind-effect air infiltration (top) into sealed Solar Unit #4, and paired prediction errors (bottom) with complete shelter by adjacent houses for 90° and 270°, and U_H = 2.5 to 8.0 m/s

APPENDIX B

TABULATED VENTILATION RATES FOR PASSIVE VENTILATION CONFIGURATIONS

TABLE 5-4 and B-1

Bungalow Ventilation Rates With No Passive Vents, No Flue, No Shelter



Background Leakage Area	100%
Flue Leakage Area	0%
Passive Vents Leakage Area	0%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.05	0.14	0.26	0.49
SPRING/FALL	10C	0.07	0.15	0.27	0.50
SHOULDER	0C	0.10	0.17	0.29	0.52
WINTER	-20C	0.17	0.21	0.33	0.57

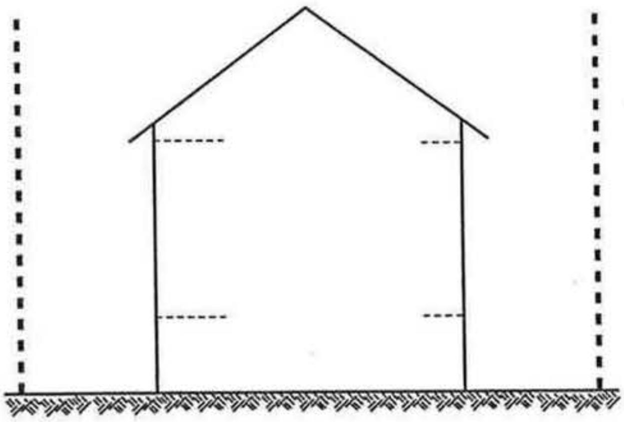
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.26 ACH
avg. 0.27 ACH
max. 0.30 ACH

BUN0VENT.DAT

TABLE B-2

Bungalow Ventilation Rates With No Passive Vents, No Flue, Close Row Shelter



Background Leakage Area	100%
Flue Leakage Area	0%
Passive Vents Leakage Area	0%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.05	0.12	0.22	0.42
SPRING/FALL	10C	0.07	0.13	0.23	0.42
SHOULDER	0C	0.10	0.15	0.25	0.44
WINTER	-20C	0.17	0.20	0.29	0.49

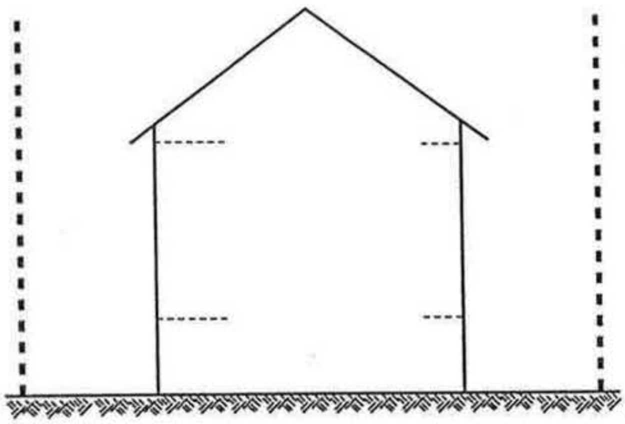
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.14 ACH
avg. 0.23 ACH
max. 0.29 ACH

BUN0VENT.DAT

TABLE B-3

Bungalow Ventilation Rates With No Passive Vents, No Flue, Uniform Shelter, S_w=0.5



Background Leakage Area	100%
Flue Leakage Area	0%
Passive Vents Leakage Area	0%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature Tout For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.04	0.08	0.14	0.26
SPRING/FALL	10C	0.07	0.09	0.15	0.27
SHOULDER	0C	0.10	0.12	0.17	0.28
WINTER	-20C	0.17	0.19	0.22	0.32

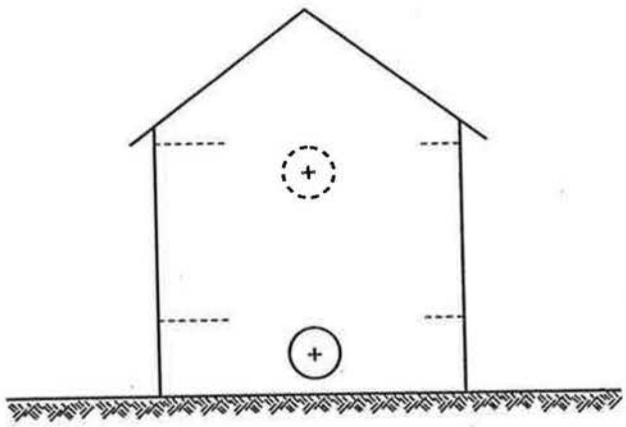
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.14 ACH
avg. 0.15 ACH
max. 0.15 ACH

BUN0VENT.DAT

TABLE B-4

Bungalow Ventilation Rates With Two Passive Vents, No Flue, No Shelter



Background Leakage Area	76%
Flue Leakage Area	0%
Passive Vents Leakage Area	24%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.07	0.20	0.36	0.65
SPRING/FALL	10C	0.10	0.20	0.37	0.66
SHOULDER	0C	0.15	0.22	0.39	0.68
WINTER	-20C	0.24	0.28	0.43	0.73

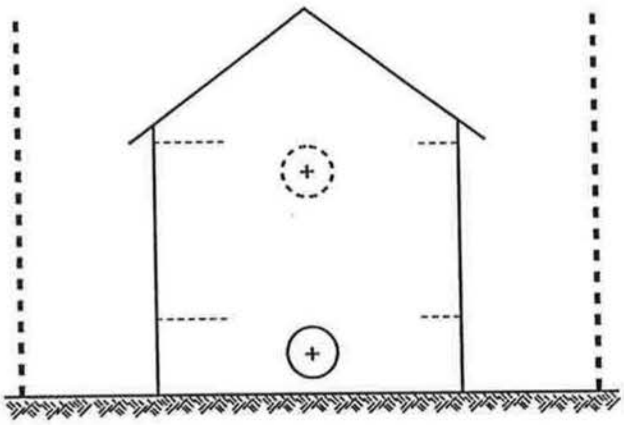
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.31 ACH
avg. 0.37 ACH
max. 0.41 ACH

BUN2LOHI.DAT

TABLE B-5

Bungalow Ventilation Rates With Two Passive Vents, No Flue, Close Row Shelter



Background Leakage Area	76%
Flue Leakage Area	0%
Passive Vents Leakage Area	24%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.07	0.17	0.31	0.56
SPRING/FALL	10C	0.10	0.18	0.32	0.57
SHOULDER	0C	0.15	0.20	0.34	0.59
WINTER	-20C	0.24	0.27	0.38	0.64

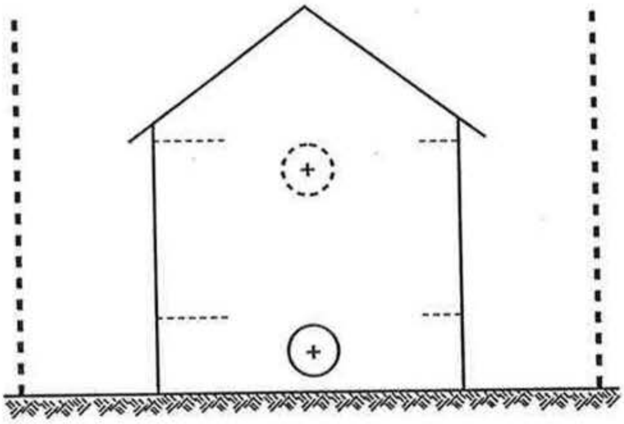
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.17 ACH
avg. 0.32 ACH
max. 0.41 ACH

BUN2LOHI.DAT

TABLE B-6

Bungalow Ventilation Rates With Two Passive Vents, No Flue, Uniform Shelter, S_w=0.5



Background Leakage Area	76%
Flue Leakage Area	0%
Passive Vents Leakage Area	24%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature Tout For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.07	0.11	0.19	0.33
SPRING/FALL	10C	0.10	0.13	0.20	0.34
SHOULDER	0C	0.15	0.17	0.22	0.36
WINTER	-20C	0.24	0.26	0.29	0.40

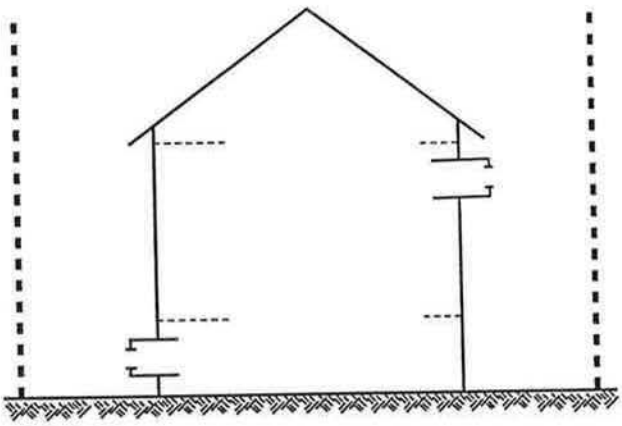
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.17 ACH
avg. 0.20 ACH
max. 0.22 ACH

BUN2LOHI.DAT

TABLE B-7

Bungalow Ventilation Rates With Two Sheltered Passive Vents, No Flue, Close Row Shelter



Background Leakage Area	76%
Flue Leakage Area	0%
Passive Vents Leakage Area	24%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.07	0.16	0.29	0.52
SPRING/FALL	10C	0.10	0.17	0.30	0.53
SHOULDER	0C	0.15	0.19	0.32	0.55
WINTER	-20C	0.24	0.27	0.36	0.61

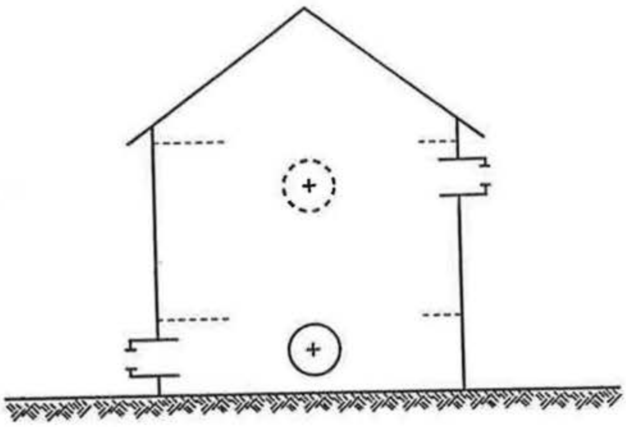
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.18 ACH
avg. 0.30 ACH
max. 0.37 ACH

BUN2LOHI.SDT

TABLE B-8

Bungalow Ventilation Rates With Four Passive Vents, No Flue, No Shelter



Background Leakage Area	61%
Flue Leakage Area	0%
Passive Vents Leakage Area	39%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.09	0.25	0.45	0.79
SPRING/FALL	10C	0.14	0.26	0.46	0.80
SHOULDER	0C	0.20	0.29	0.48	0.82
WINTER	-20C	0.32	0.35	0.54	0.90

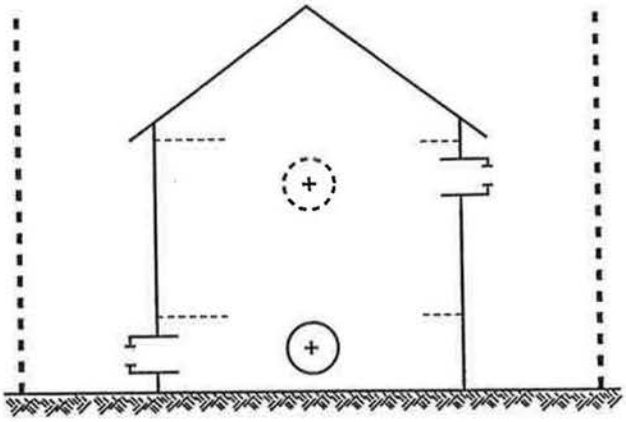
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.41 ACH
avg. 0.46 ACH
max. 0.53 ACH

BUN4LOHI.DAT

TABLE B-9

Bungalow Ventilation Rates With Four Passive Vents, No Flue, Close Row Shelter



Background Leakage Area	61%
Flue Leakage Area	0%
Passive Vents Leakage Area	39%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.09	0.21	0.38	0.67
SPRING/FALL	10C	0.14	0.22	0.39	0.68
SHOULDER	0C	0.21	0.25	0.41	0.70
WINTER	-20C	0.32	0.34	0.45	0.75

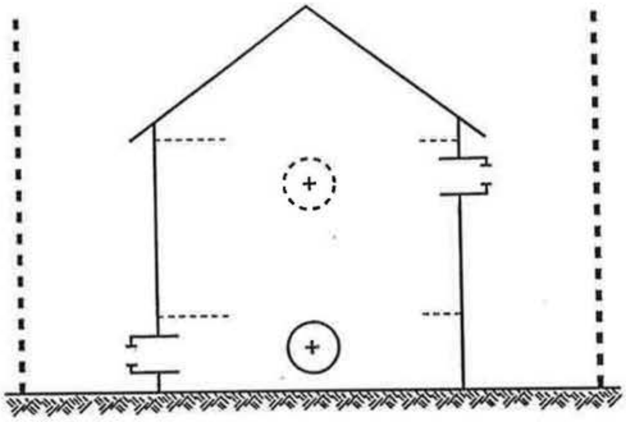
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.22 ACH
avg. 0.39 ACH
max. 0.50 ACH

BUN4LOHI.DAT

TABLE B-10

Bungalow Ventilation Rates With Four Passive Vents, No Flue, Uniform Shelter, S_w=0.5



Background Leakage Area	61%
Flue Leakage Area	0%
Passive Vents Leakage Area	39%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature Tout For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.09	0.14	0.24	0.41
SPRING/FALL	10C	0.14	0.16	0.25	0.42
SHOULDER	0C	0.20	0.22	0.27	0.44
WINTER	-20C	0.32	0.33	0.36	0.49

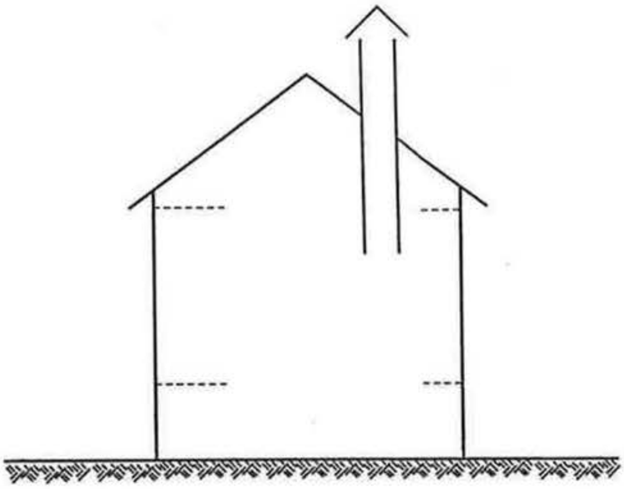
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.23 ACH
avg. 0.25 ACH
max. 0.28 ACH

BUN4LOHI.DAT

TABLE 5-5 and B-11

Bungalow Ventilation Rates With No Passive Vents, Flue, No Shelter



Background Leakage Area	75%
Flue Leakage Area	25%
Passive Vents Leakage Area	0%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.10	0.19	0.33	0.59
SPRING/FALL	10C	0.14	0.21	0.35	0.60
SHOULDER	0C	0.21	0.25	0.38	0.64
WINTER	-20C	0.32	0.36	0.46	0.71

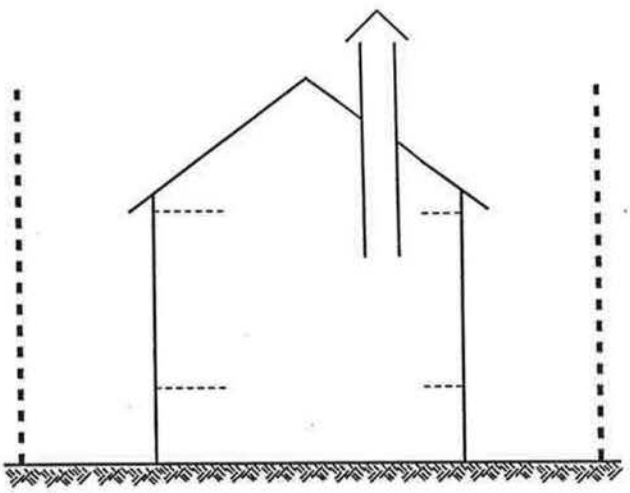
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.33 ACH
avg. 0.35 ACH
max. 0.36 ACH

BUF0VENT.DAT

TABLE 5-6 and B-12

Bungalow Ventilation Rates With No Passive Vents, Flue, Close Row Shelter



Background Leakage Area	75%
Flue Leakage Area	25%
Passive Vents Leakage Area	0%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.10	0.18	0.31	0.55
SPRING/FALL	10C	0.14	0.21	0.33	0.57
SHOULDER	0C	0.21	0.27	0.37	0.60
WINTER	-20C	0.32	0.37	0.46	0.68

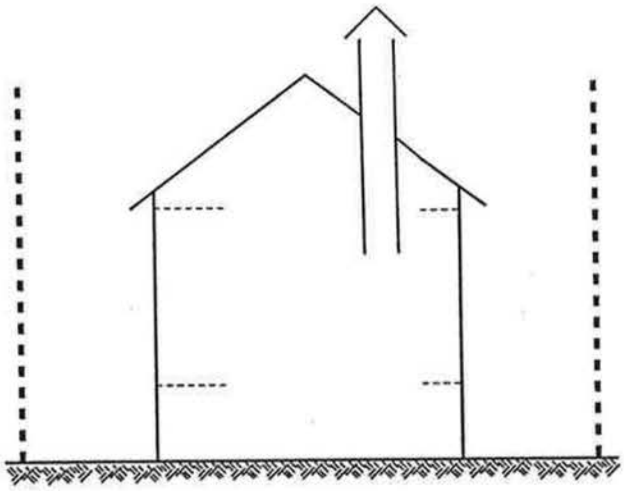
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.30 ACH
avg. 0.33 ACH
max. 0.36 ACH

BUF0VENT.DAT

TABLE 5-7 and B-13

Bungalow Ventilation Rates With No Passive Vents, Flue, Uniform Shelter, S_w=0.5



Background Leakage Area	75%
Flue Leakage Area	25%
Passive Vents Leakage Area	0%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature Tout For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.10	0.18	0.28	0.46
SPRING/FALL	10C	0.14	0.21	0.30	0.48
SHOULDER	0C	0.21	0.26	0.35	0.52
WINTER	-20C	0.32	0.36	0.44	0.60

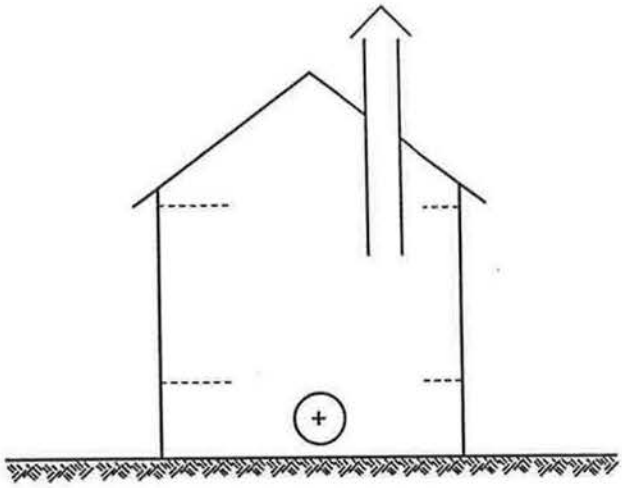
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.29 ACH
avg. 0.30 ACH
max. 0.31 ACH

BUF0VENT.DAT

TABLE B-14

Bungalow Ventilation Rates With One Passive Vent, Flue, No Shelter



Background Leakage Area	67%
Flue Leakage Area	22%
Passive Vents Leakage Area	11%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.11	0.22	0.38	0.68
SPRING/FALL	10C	0.16	0.24	0.40	0.69
SHOULDER	0C	0.23	0.29	0.43	0.72
WINTER	-20C	0.35	0.40	0.51	0.80

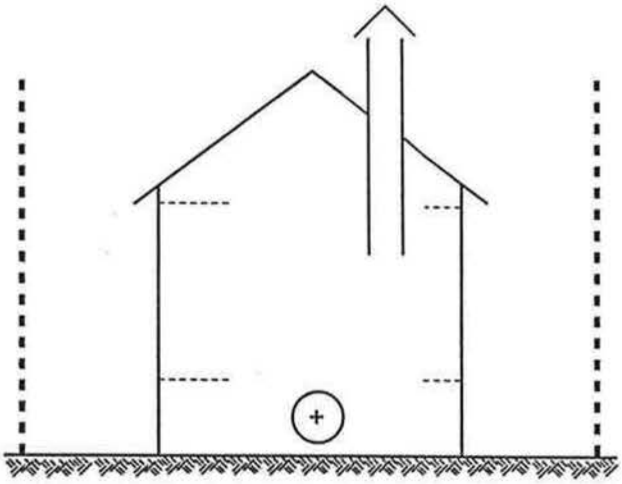
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.35 ACH
avg. 0.40 ACH
max. 0.47 ACH

BUF1LO.DAT

TABLE S-1 and B-15

Bungalow Ventilation Rate With One Passive Vent, Flue, Close Row Shelter



Background Leakage Area	67%
Flue Leakage Area	22%
Passive Vents Leakage Area	11%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.12	0.21	0.36	0.62
SPRING/FALL	10C	0.16	0.24	0.38	0.64
SHOULDER	0C	0.23	0.30	0.42	0.68
WINTER	-20C	0.35	0.41	0.51	0.76

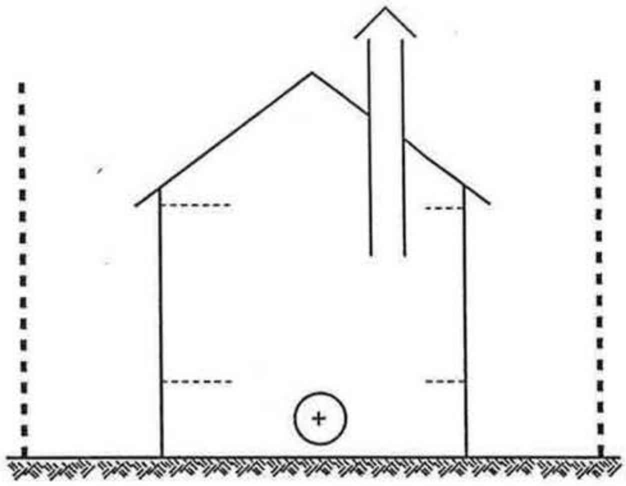
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.32 ACH
avg. 0.38 ACH
max. 0.47 ACH

BUF1LO.DAT

TABLE 5-10 and B-16

Bungalow Ventilation Rates With One Passive Vent, Flue, Uniform Shelter, S_w=0.5



Background Leakage Area	67%
Flue Leakage Area	22%
Passive Vents Leakage Area	11%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature Tout For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.11	0.19	0.30	0.49
SPRING/FALL	10C	0.16	0.23	0.33	0.51
SHOULDER	0C	0.23	0.29	0.38	0.55
WINTER	-20C	0.35	0.39	0.47	0.64

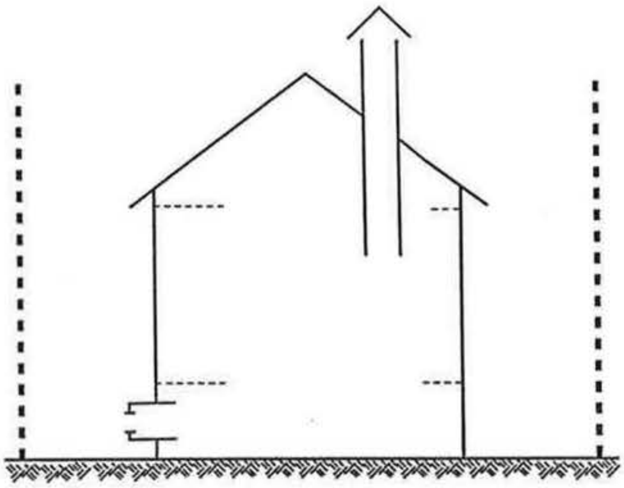
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.31 ACH
avg. 0.33 ACH
max. 0.34 ACH

BUF1LO.DAT

TABLE B-17

Bungalow Ventilation Rates With One Sheltered Passive Vent, Flue, Close Row Shelter



Background Leakage Area	67%
Flue Leakage Area	22%
Passive Vents Leakage Area	11%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.11	0.20	0.35	0.60
SPRING/FALL	10C	0.16	0.24	0.37	0.62
SHOULDER	0C	0.23	0.30	0.41	0.66
WINTER	-20C	0.35	0.41	0.50	0.74

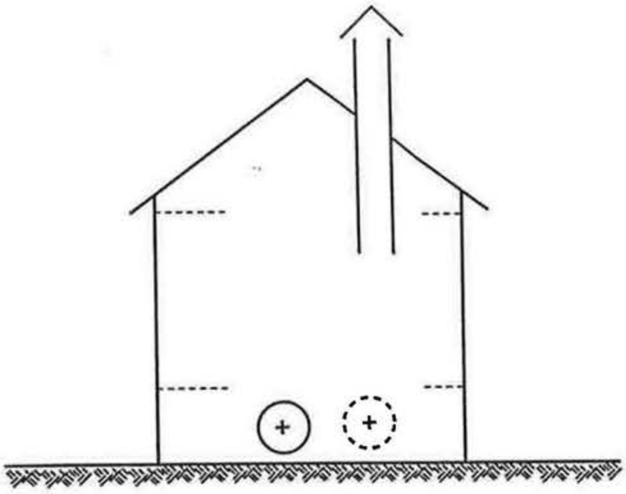
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.31 ACH
avg. 0.37 ACH
max. 0.44 ACH

BUF1LO.SDT

TABLE B-18

Bungalow Ventilation Rates With Two Passive Vents, Flue, No Shelter



Background Leakage Area	61%
Flue Leakage Area	20%
Passive Vents Leakage Area	19%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.13	0.25	0.43	0.75
SPRING/FALL	10C	0.17	0.27	0.45	0.77
SHOULDER	0C	0.25	0.32	0.49	0.80
WINTER	-20C	0.38	0.43	0.56	0.88

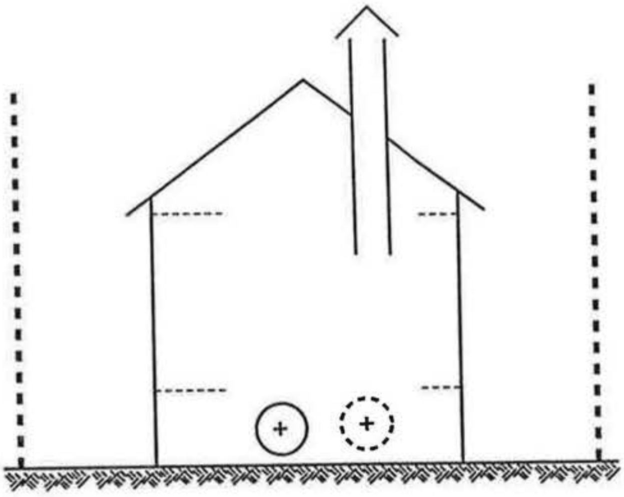
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.41 ACH
avg. 0.45 ACH
max. 0.48 ACH

BUF2LO.DAT

TABLE 5-8 and B-19

Bungalow Ventilation Rates With Two Passive Vents, Flue, Close Row Shelter



Background Leakage Area	61%
Flue Leakage Area	20%
Passive Vents Leakage Area	19%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.13	0.24	0.41	0.70
SPRING/FALL	10C	0.18	0.26	0.43	0.72
SHOULDER	0C	0.26	0.33	0.47	0.75
WINTER	-20C	0.39	0.44	0.55	0.83

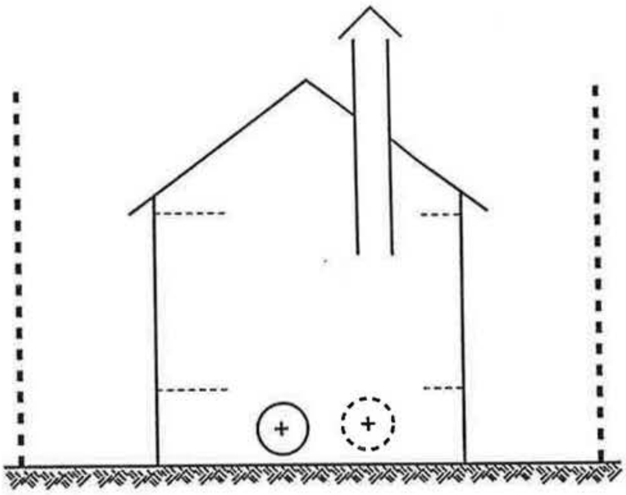
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.34 ACH
avg. 0.43 ACH
max. 0.49 ACH

BUF2LO.DAT

TABLE 5-11 and B-20

Bungalow Ventilation Rates With Two Passive Vents, Flue, Uniform Shelter, S_w=0.5



Background Leakage Area	61%
Flue Leakage Area	20%
Passive Vents Leakage Area	19%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature Tout For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.12	0.21	0.32	0.52
SPRING/FALL	10C	0.18	0.24	0.35	0.54
SHOULDER	0C	0.25	0.31	0.40	0.58
WINTER	-20C	0.39	0.43	0.51	0.67

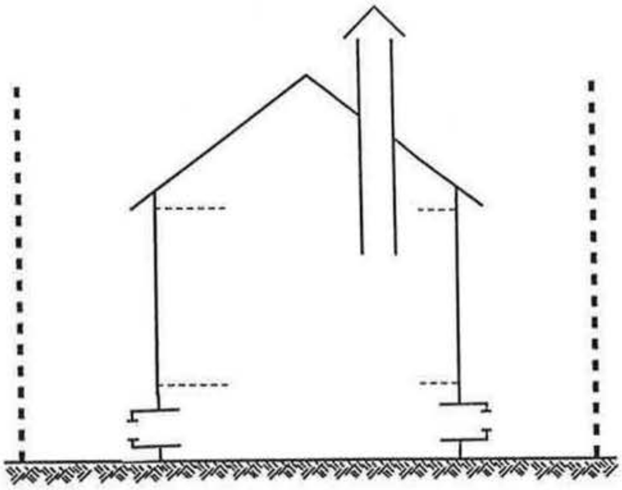
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.32 ACH
avg. 0.35 ACH
max. 0.36 ACH

BUF2LO.DAT

TABLE 5-9 and B-21

Bungalow Vent Rates With Two Sheltered Passive Vents, Flue, Close Row Shelter



Background Leakage Area	61%
Flue Leakage Area	20%
Passive Vents Leakage Area	19%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.13	0.25	0.39	0.67
SPRING/FALL	10C	0.18	0.25	0.41	0.68
SHOULDER	0C	0.26	0.32	0.44	0.72
WINTER	-20C	0.39	0.44	0.53	0.80

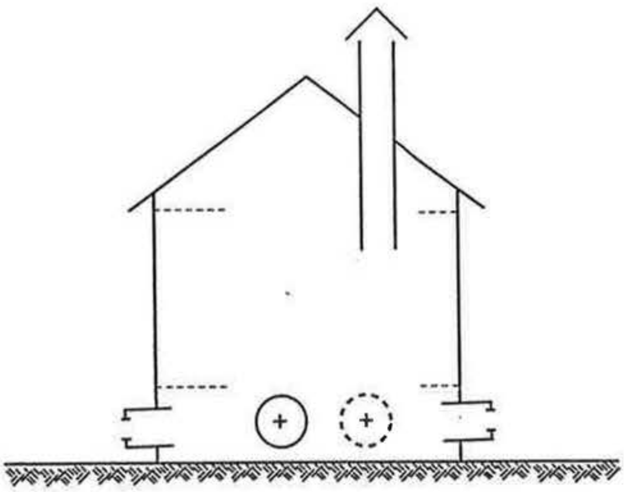
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.34 ACH
avg. 0.41 ACH
max. 0.45 ACH

BUF2LO.SDT

TABLE B-22

Bungalow Ventilation Rates With Four Passive Vents, Flue, No Shelter



Background Leakage Area	51%
Flue Leakage Area	17%
Passive Vents Leakage Area	32%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.14	0.31	0.53	0.91
SPRING/FALL	10C	0.20	0.33	0.54	0.93
SHOULDER	0C	0.29	0.38	0.59	0.96
WINTER	-20C	0.44	0.48	0.68	1.05

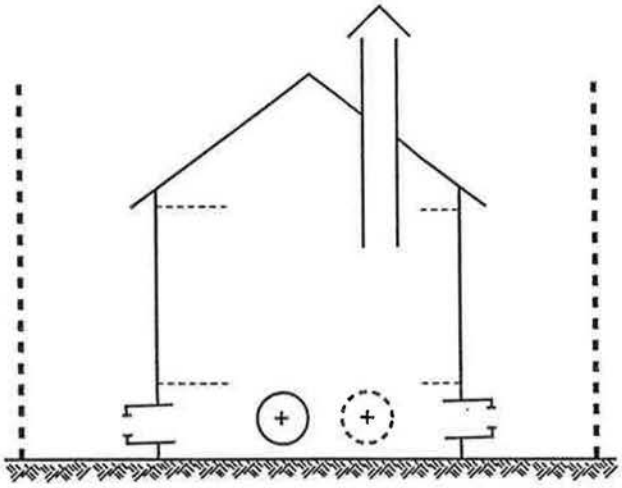
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.52 ACH
avg. 0.54 ACH
max. 0.60 ACH

BUF4LO.DAT

TABLE B-23

Bungalow Ventilation Rates With Four Passive Vents, Flue, Close Row Shelter



Background Leakage Area	51%
Flue Leakage Area	17%
Passive Vents Leakage Area	32%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.15	0.28	0.48	0.81
SPRING/FALL	10C	0.20	0.31	0.50	0.83
SHOULDER	0C	0.30	0.36	0.54	0.87
WINTER	-20C	0.44	0.49	0.62	0.95

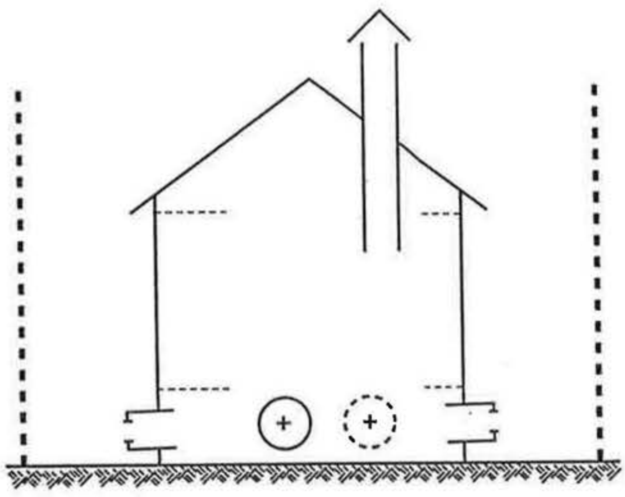
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.37 ACH
avg. 0.50 ACH
max. 0.58 ACH

BUF4LO.DAT

TABLE 5-12 and B-24

Bungalow Ventilation Rates With Four Passive Vents, Flue, Uniform Shelter, S_w=0.5



Background Leakage Area	51%
Flue Leakage Area	17%
Passive Vents Leakage Area	32%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature Tout For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.14	0.23	0.36	0.58
SPRING/FALL	10C	0.20	0.27	0.39	0.61
SHOULDER	0C	0.30	0.35	0.44	0.65
WINTER	-20C	0.44	0.48	0.56	0.73

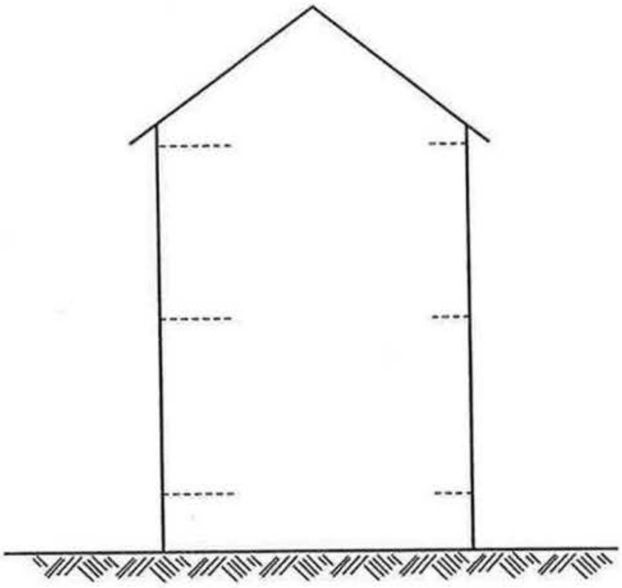
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.37 ACH
avg. 0.39 ACH
max. 0.39 ACH

BUF4LO.DAT

TABLE B-25

Two Storey Ventilation Rates With No Passive Vents, No Flue, No Shelter



Background Leakage Area	100%
Flue Leakage Area	0%
Passive Vents Leakage Area	0%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.07	0.19	0.36	0.67
SPRING/FALL	10C	0.11	0.21	0.37	0.68
SHOULDER	0C	0.18	0.24	0.40	0.72
WINTER	-20C	0.29	0.33	0.47	0.79

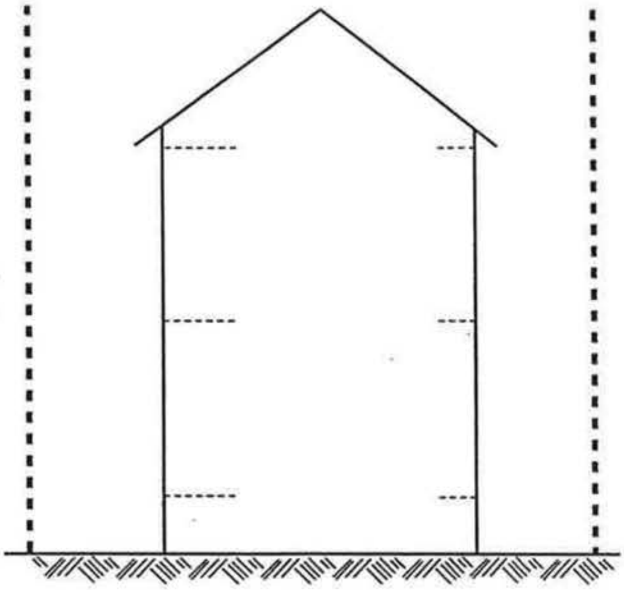
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.35 ACH
avg. 0.38 ACH
max. 0.41 ACH

2SN0VENT.DAT

TABLE B-26

Two Storey Ventilation Rates With No Passive Vents, No Flue, With Close Row Shelter



Background Leakage Area	100%
Flue Leakage Area	0%
Passive Vents Leakage Area	0%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.07	0.15	0.29	0.53
SPRING/FALL	10C	0.11	0.17	0.30	0.55
SHOULDER	0C	0.18	0.21	0.33	0.57
WINTER	-20C	0.29	0.31	0.39	0.79

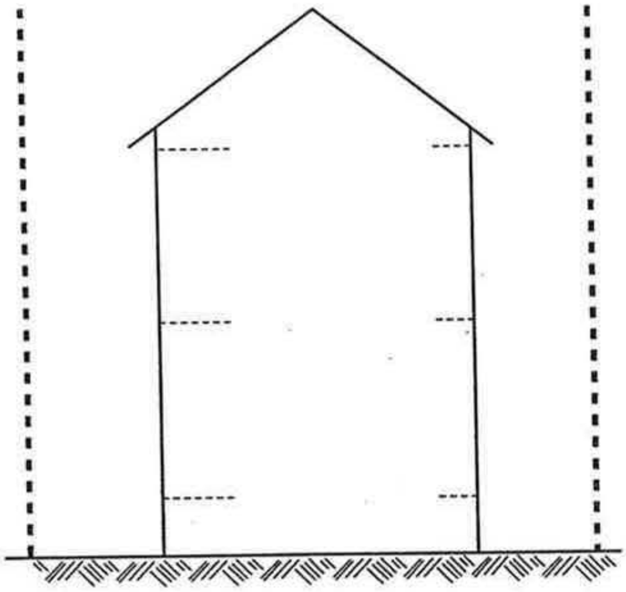
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.17 ACH
avg. 0.30 ACH
max. 0.38 ACH

2SN0VENT.DAT

TABLE 5-13 and B-27

Two Storey Ventilation Rates With No Passive Vents, No Flue, Uniform Shelter, S_w=0.5



Background Leakage Area	100%
Flue Leakage Area	0%
Passive Vents Leakage Area	0%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.07	0.10	0.18	0.32
SPRING/FALL	10C	0.11	0.13	0.19	0.33
SHOULDER	0C	0.18	0.19	0.23	0.35
WINTER	-20C	0.29	0.30	0.33	0.42

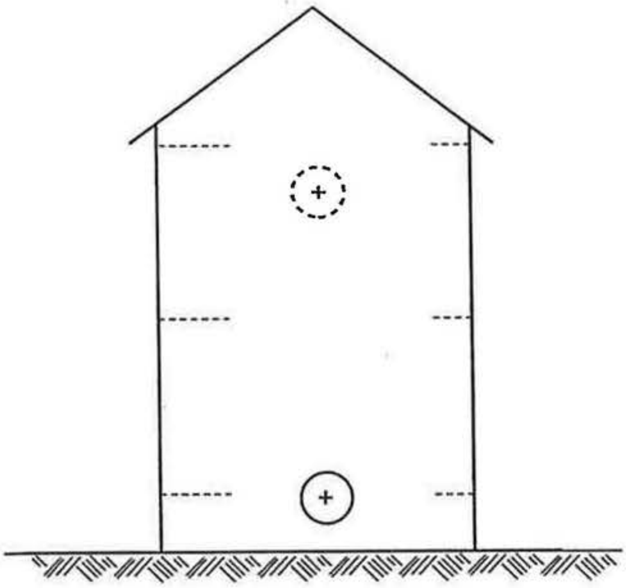
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.19 ACH
avg. 0.19 ACH
max. 0.19 ACH

2SN0VENT.DAT

TABLE B-28

Two Storey Ventilation Rates With Two Passive Vents, No Flue, No Shelter



Background Leakage Area	86%
Flue Leakage Area	0%
Passive Vents Leakage Area	14%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.09	0.23	0.43	0.77
SPRING/FALL	10C	0.14	0.24	0.44	0.79
SHOULDER	0C	0.22	0.28	0.47	0.82
WINTER	-20C	0.36	0.39	0.54	0.90

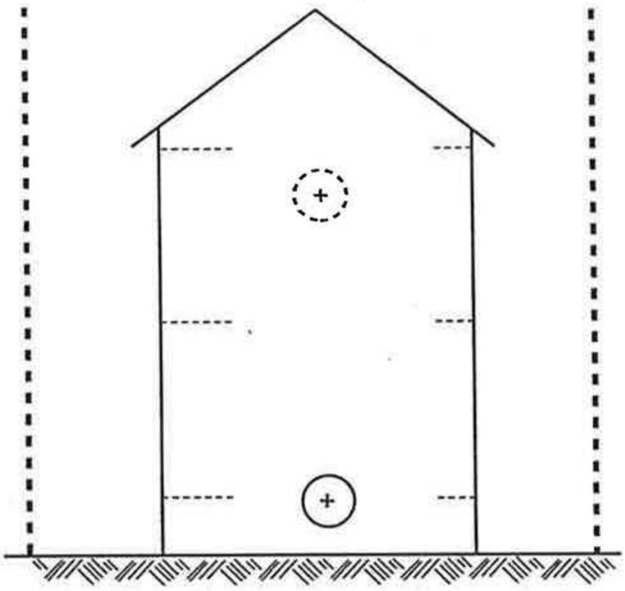
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.38 ACH
avg. 0.44 ACH
max. 0.49 ACH

2SN2LOHI.DAT

TABLE B-29

Two Storey Ventilation Rates With Two Passive Vents, No Flue, Close Row Shelter



Background Leakage Area	86%
Flue Leakage Area	0%
Passive Vents Leakage Area	14%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.09	0.19	0.35	0.63
SPRING/FALL	10C	0.14	0.20	0.36	0.64
SHOULDER	0C	0.22	0.25	0.39	0.67
WINTER	-20C	0.36	0.38	0.46	0.73

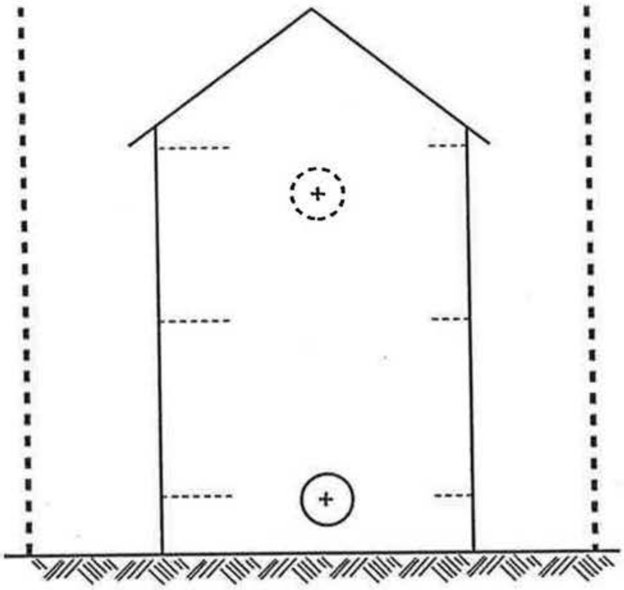
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.20 ACH
avg. 0.36 ACH
max. 0.47 ACH

2SN2LOHI.DAT

TABLE B-30

Two Storey Ventilation Rates With Two Passive Vents, No Flue, Uniform Shelter, S_w=0.5



Background Leakage Area	86%
Flue Leakage Area	0%
Passive Vents Leakage Area	14%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.09	0.12	0.21	0.37
SPRING/FALL	10C	0.14	0.16	0.22	0.38
SHOULDER	0C	0.22	0.23	0.28	0.41
WINTER	-20C	0.36	0.37	0.39	0.49

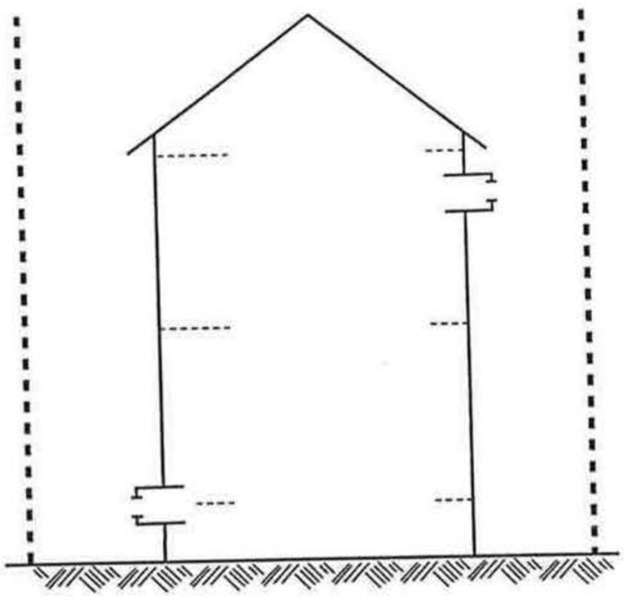
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.20 ACH
avg. 0.22 ACH
max. 0.24 ACH

2SN2LOHI.DAT

TABLE B-31

Two Storey Ventilation Rates With Two Sheltered Passive Vents, No Flue, Close Row Shelter



Background Leakage Area	86%
Flue Leakage Area	0%
Passive Vents Leakage Area	14%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.09	0.18	0.33	0.60
SPRING/FALL	10C	0.14	0.20	0.35	0.62
SHOULDER	0C	0.22	0.25	0.37	0.64
WINTER	-20C	0.36	0.38	0.45	0.71

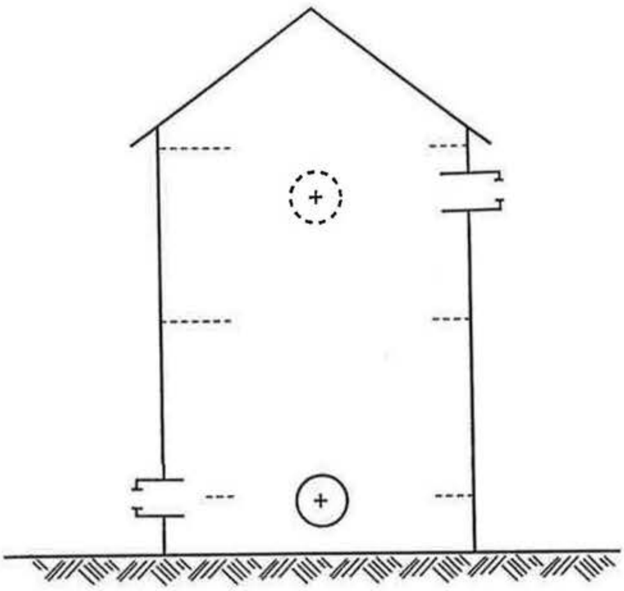
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.19 ACH
avg. 0.35 ACH
max. 0.44 ACH

2SN2LOHI.SDT

TABLE B-32

Two Storey Ventilation Rates With Four Passive Vents, No Flue, No Shelter



Background Leakage Area	75%
Flue Leakage Area	0%
Passive Vents Leakage Area	25%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.12	0.27	0.49	0.87
SPRING/FALL	10C	0.17	0.29	0.50	0.88
SHOULDER	0C	0.27	0.33	0.54	0.92
WINTER	-20C	0.42	0.45	0.61	1.00

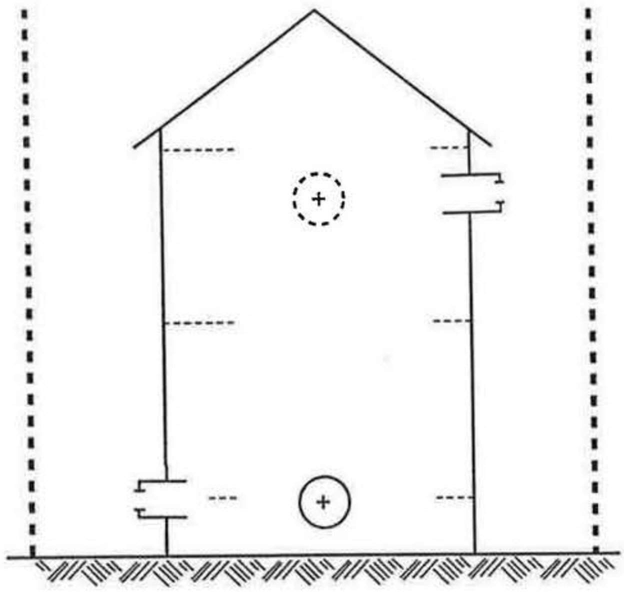
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.46 ACH
avg. 0.50 ACH
max. 0.56 ACH

2SN4LOHI.DAT

TABLE B-33

Two Storey Ventilation Rates With Four Passive Vents, No Flue, Close Row Shelter



Background Leakage Area	75%
Flue Leakage Area	0%
Passive Vents Leakage Area	25%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.12	0.22	0.39	0.70
SPRING/FALL	10C	0.17	0.23	0.40	0.71
SHOULDER	0C	0.26	0.30	0.43	0.74
WINTER	-20C	0.42	0.44	0.52	0.80

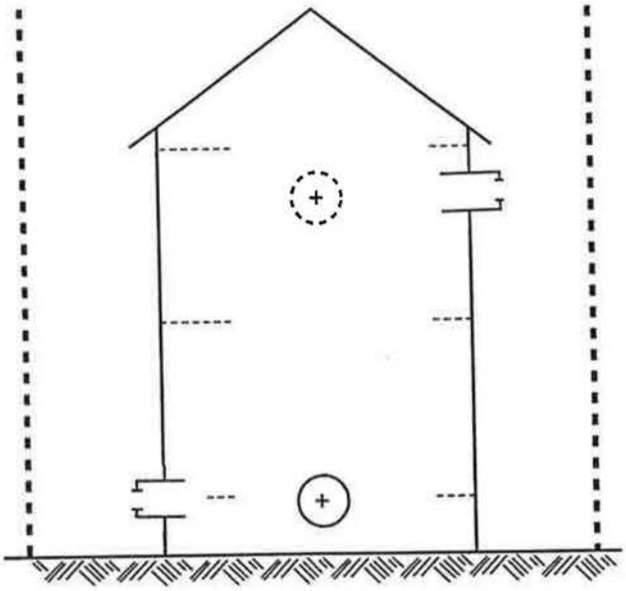
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.22 ACH
avg. 0.40 ACH
max. 0.53 ACH

2SN4LOHI.DAT

TABLE B-34

Two Storey Ventilation Rates With Four Passive Vents, No Flue, Uniform Shelter, S_w=0.5



Background Leakage Area	75%
Flue Leakage Area	0%
Passive Vents Leakage Area	25%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.11	0.15	0.24	0.42
SPRING/FALL	10C	0.17	0.19	0.26	0.43
SHOULDER	0C	0.27	0.28	0.32	0.46
WINTER	-20C	0.42	0.43	0.46	0.55

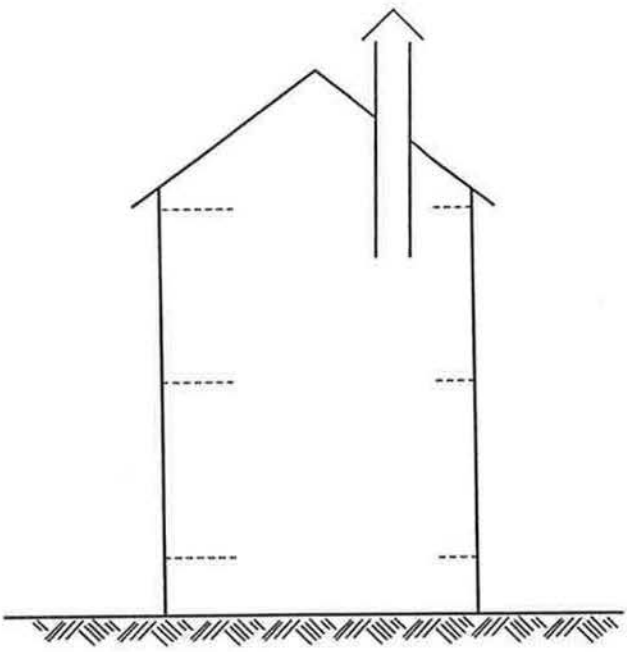
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.21 ACH
avg. 0.26 ACH
max. 0.28 ACH

2SN4LOHI.DAT

TABLE B-35

Two Storey Ventilation Rates With No Passive Vents, Flue, No Shelter



Background Leakage Area	85%
Flue Leakage Area	15%
Passive Vents Leakage Area	0%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.12	0.23	0.42	0.75
SPRING/FALL	10C	0.17	0.26	0.44	0.77
SHOULDER	0C	0.26	0.32	0.48	0.82
WINTER	-20C	0.41	0.45	0.58	0.91

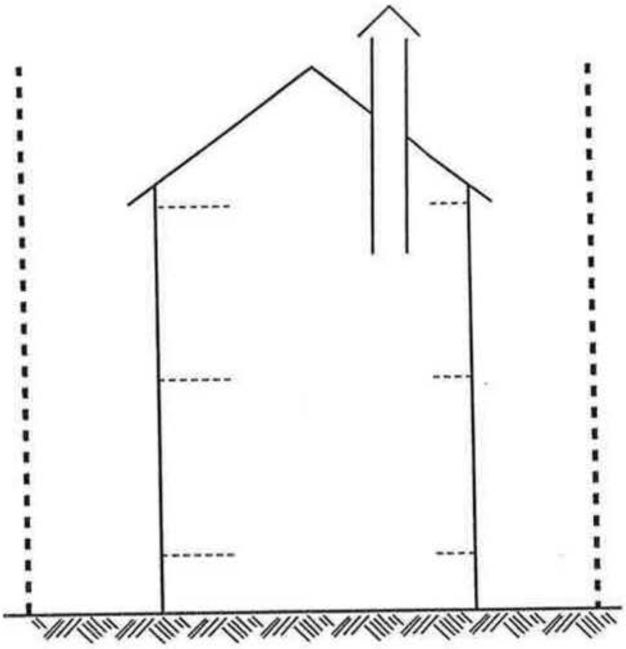
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.42 ACH
avg. 0.44 ACH
max. 0.48 ACH

2SF0VENT.DAT

TABLE B-36

Two Storey Ventilation Rates With No Passive Vents, Flue, Close Row Shelter



Background Leakage Area	85%
Flue Leakage Area	15%
Passive Vents Leakage Area	0%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.11	0.21	0.36	0.64
SPRING/FALL	10C	0.17	0.24	0.38	0.66
SHOULDER	0C	0.26	0.31	0.43	0.70
WINTER	-20C	0.41	0.44	0.54	0.79

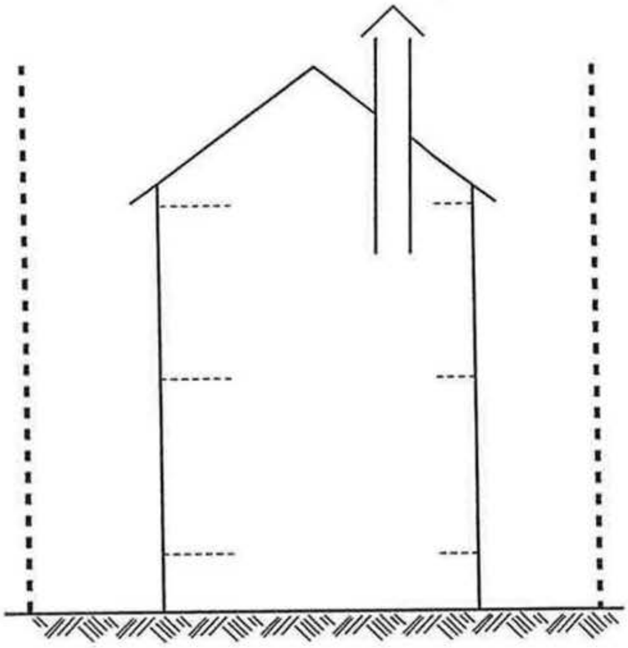
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.28 ACH
avg. 0.38 ACH
max. 0.45 ACH

2SF0VENT.DAT

TABLE 5-14 and B-37

Two Storey Ventilation Rates With No Passive Vents, Flue, Uniform Shelter, S_w=0.5



Background Leakage Area	85%
Flue Leakage Area	15%
Passive Vents Leakage Area	0%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.11	0.17	0.26	0.44
SPRING/FALL	10C	0.17	0.21	0.30	0.46
SHOULDER	0C	0.26	0.29	0.36	0.51
WINTER	-20C	0.41	0.43	0.48	0.62

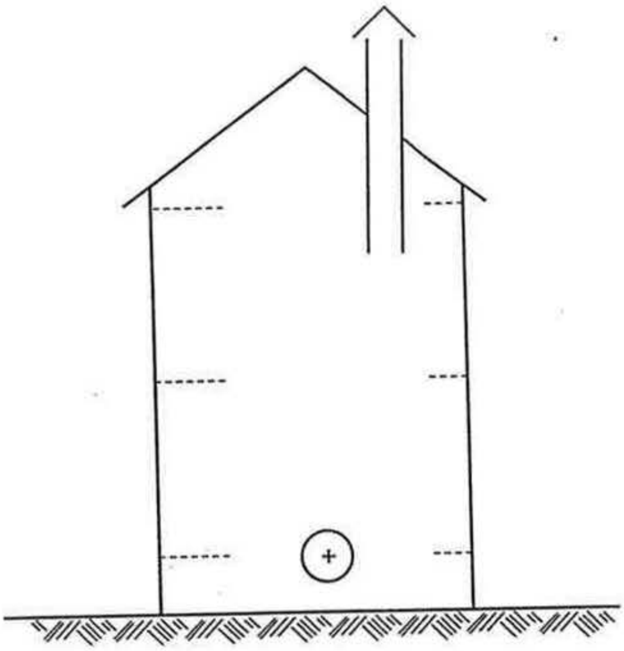
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.29 ACH
avg. 0.30 ACH
max. 0.30 ACH

2SF0VENT.DAT

TABLE B-38

Two Storey Ventilation Rates With One Passive Vent, Flue, No Shelter



Background Leakage Area	79%
Flue Leakage Area	14%
Passive Vents Leakage Area	7%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.13	0.25	0.45	0.81
SPRING/FALL	10C	0.18	0.28	0.47	0.83
SHOULDER	0C	0.28	0.34	0.52	0.87
WINTER	-20C	0.44	0.48	0.61	0.96

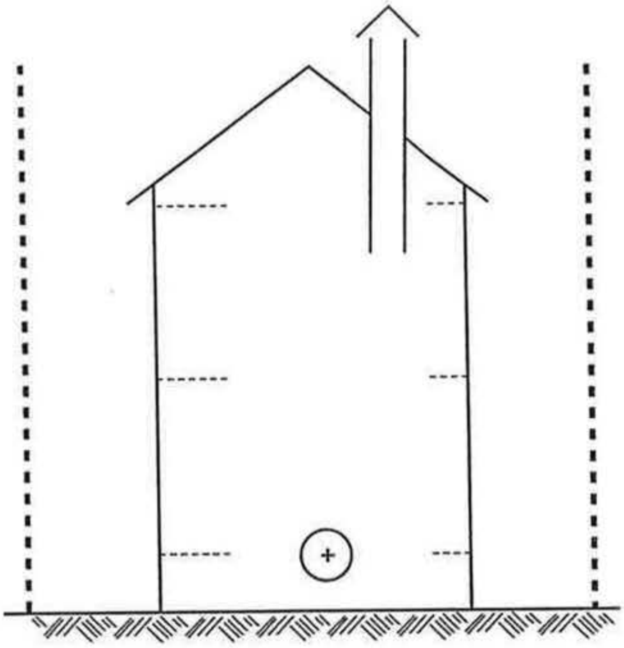
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.43 ACH
avg. 0.47 ACH
max. 0.53 ACH

2SF1L0.DAT

TABLE B-39

Two Storey Ventilation Rates With One Passive Vent, Flue, Close Row Shelter



Background Leakage Area	79%
Flue Leakage Area	14%
Passive Vents Leakage Area	7%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.13	0.23	0.39	0.68
SPRING/FALL	10C	0.18	0.26	0.41	0.71
SHOULDER	0C	0.28	0.33	0.46	0.75
WINTER	-20C	0.44	0.47	0.57	0.84

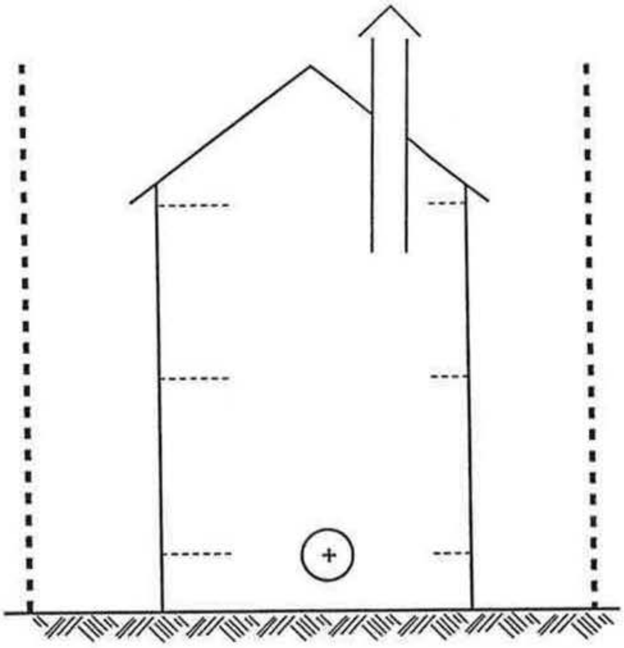
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.29 ACH
avg. 0.41 ACH
max. 0.52 ACH

2SF1LO.DAT

TABLE B-40

Two Storey Ventilation Rates With One Passive Vent, Flue, Uniform Shelter, S_w=0.5



Background Leakage Area	79%
Flue Leakage Area	14%
Passive Vents Leakage Area	7%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.12	0.18	0.28	0.46
SPRING/FALL	10C	0.18	0.23	0.31	0.49
SHOULDER	0C	0.28	0.31	0.38	0.53
WINTER	-20C	0.44	0.46	0.51	0.64

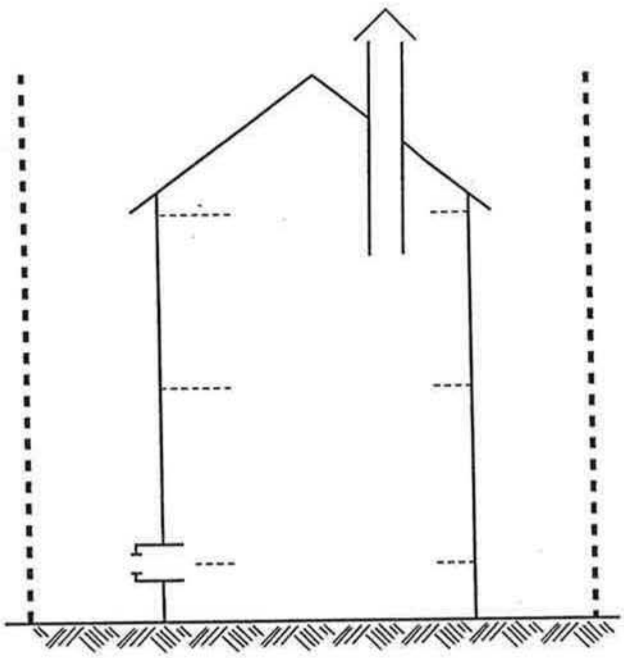
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.30 ACH
avg. 0.31 ACH
max. 0.32 ACH

2SF1LO.DAT

TABLE B-41

Two Storey Ventilation Rates With One Sheltered Passive Vent, Flue, Close Row Shelter



Background Leakage Area	79%
Flue Leakage Area	14%
Passive Vents Leakage Area	7%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.13	0.22	0.38	0.67
SPRING/FALL	10C	0.18	0.26	0.41	0.69
SHOULDER	0C	0.28	0.33	0.45	0.74
WINTER	-20C	0.44	0.47	0.56	0.83

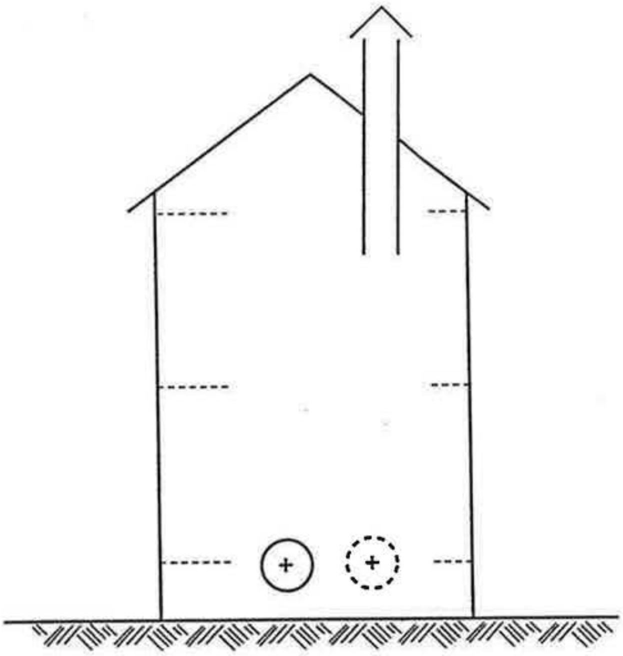
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.29 ACH
avg. 0.41 ACH
max. 0.50 ACH

2SF1LO.SDT

TABLE B-42

Two Storey Ventilation Rates With Two Passive Vents, Flue, No Shelter



Background Leakage Area	74%
Flue Leakage Area	13%
Passive Vents Leakage Area	13%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.14	0.27	0.49	0.86
SPRING/FALL	10C	0.20	0.30	0.50	0.88
SHOULDER	0C	0.30	0.37	0.55	0.92
WINTER	-20C	0.47	0.51	0.65	1.01

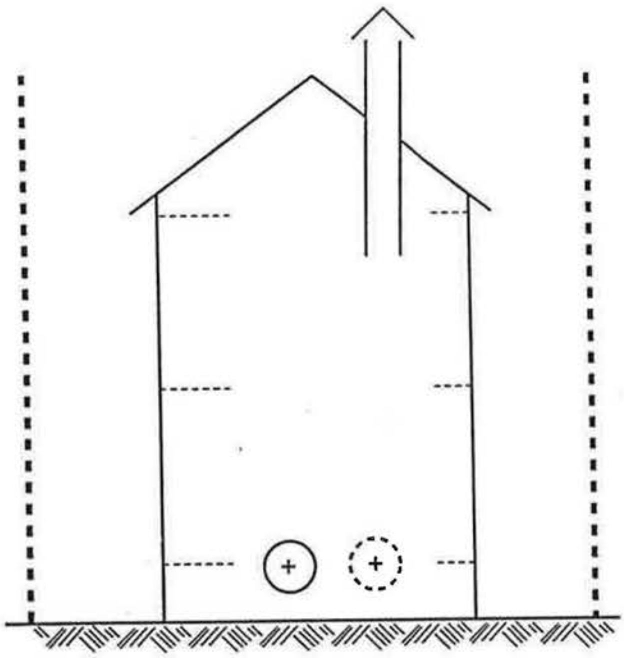
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.46 ACH
avg. 0.50 ACH
max. 0.55 ACH

2SF2LO.DAT

TABLE B-43

Two Storey Ventilation Rates With Two Passive Vents, Flue, Close Row Shelter



Background Leakage Area	74%
Flue Leakage Area	13%
Passive Vents Leakage Area	13%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.14	0.24	0.42	0.73
SPRING/FALL	10C	0.20	0.27	0.44	0.75
SHOULDER	0C	0.30	0.35	0.50	0.80
WINTER	-20C	0.47	0.50	0.60	0.89

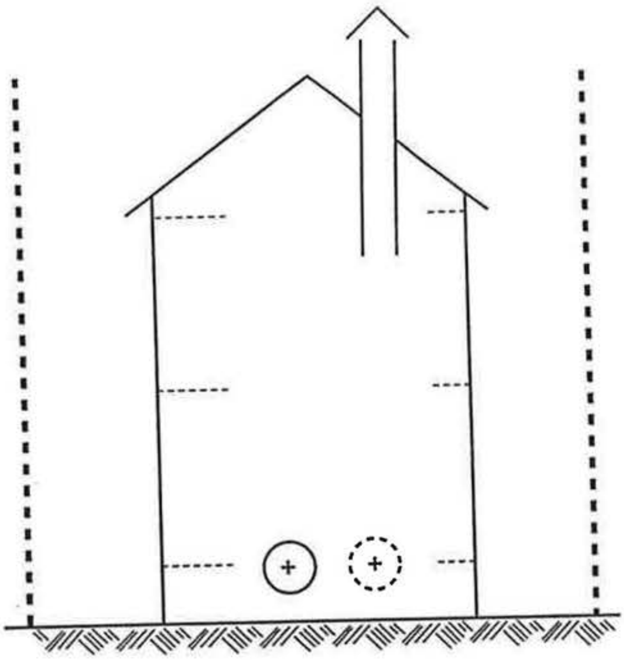
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.30 ACH
avg. 0.44 ACH
max. 0.53 ACH

2SF2LO.DAT

TABLE B-44

Two Storey Ventilation Rates With Two Passive Vents, Flue, Uniform Shelter, S_w=0.5



Background Leakage Area	74%
Flue Leakage Area	13%
Passive Vents Leakage Area	13%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.13	0.19	0.29	0.49
SPRING/FALL	10C	0.20	0.24	0.33	0.51
SHOULDER	0C	0.30	0.33	0.40	0.56
WINTER	-20C	0.47	0.49	0.54	0.68

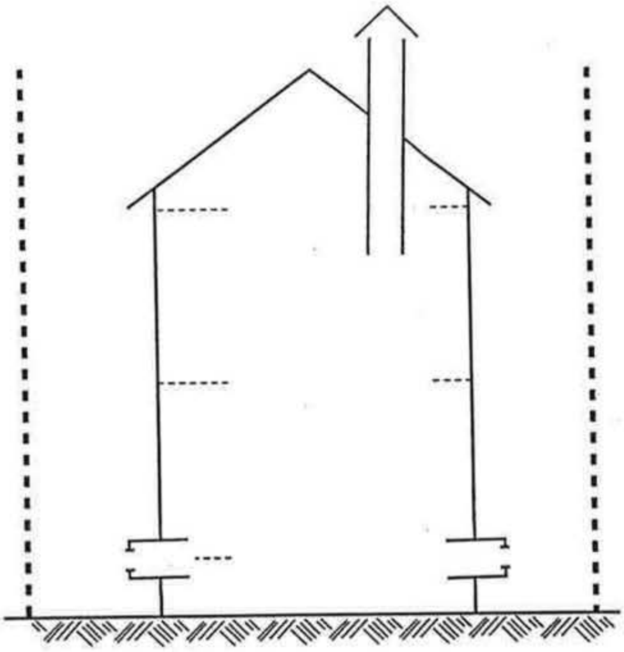
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.31 ACH
avg. 0.33 ACH
max. 0.34 ACH

2SF2LO.DAT

TABLE B-45

Two Storey Ventilation Rates With Two Sheltered Passive Vents, Flue, Close Row Shelter



Background Leakage Area	74%
Flue Leakage Area	13%
Passive Vents Leakage Area	13%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.13	0.23	0.41	0.70
SPRING/FALL	10C	0.20	0.27	0.43	0.73
SHOULDER	0C	0.30	0.35	0.48	0.78
WINTER	-20C	0.47	0.50	0.59	0.87

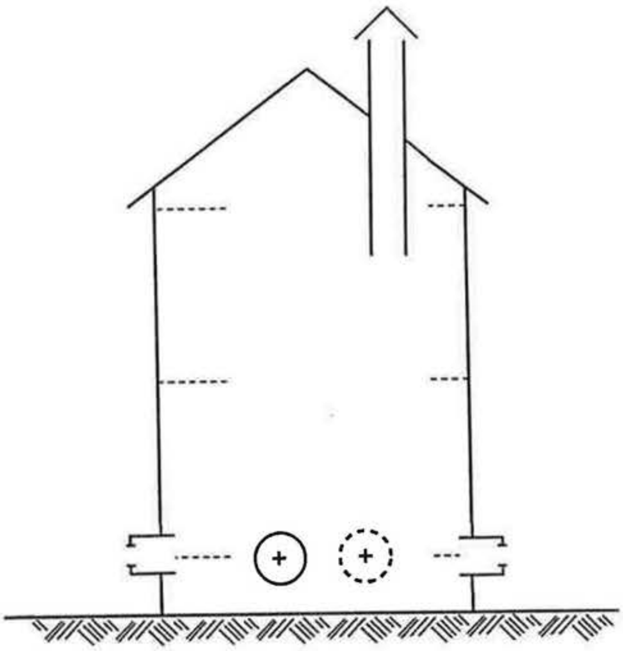
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.31 ACH
avg. 0.43 ACH
max. 0.51 ACH

2SF2LO.SDT

TABLE B-46

Two Storey Ventilation Rates With Four Passive Vents, Flue, No Shelter



Background Leakage Area	66%
Flue Leakage Area	12%
Passive Vents Leakage Area	22%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.15	0.31	0.55	0.96
SPRING/FALL	10C	0.22	0.34	0.57	0.98
SHOULDER	0C	0.34	0.40	0.62	1.03
WINTER	-20C	0.52	0.56	0.72	1.12

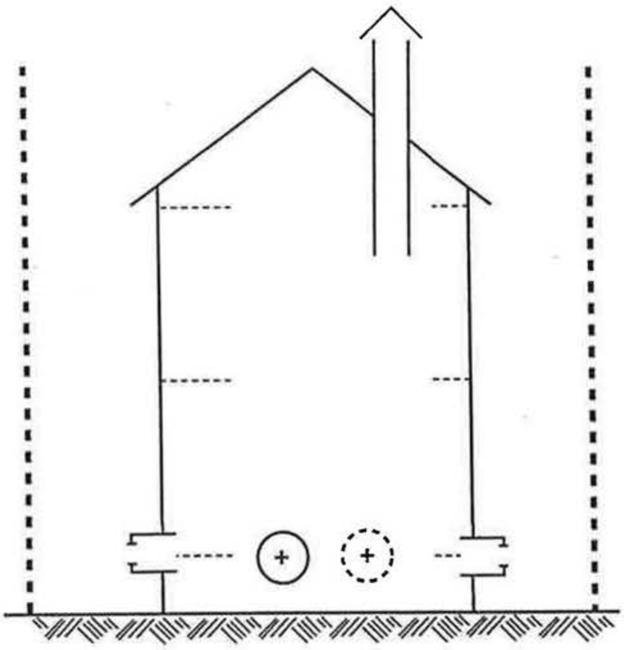
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.54 ACH
avg. 0.57 ACH
max. 0.62 ACH

2SF4LO.DAT

TABLE B-47

Two Storey Ventilation Rates With Four Passive Vents, Flue, Close Row Shelter



Background Leakage Area	66%
Flue Leakage Area	12%
Passive Vents Leakage Area	22%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.15	0.27	0.46	0.80
SPRING/FALL	10C	0.22	0.30	0.49	0.82
SHOULDER	0C	0.34	0.39	0.54	0.87
WINTER	-20C	0.52	0.56	0.65	0.97

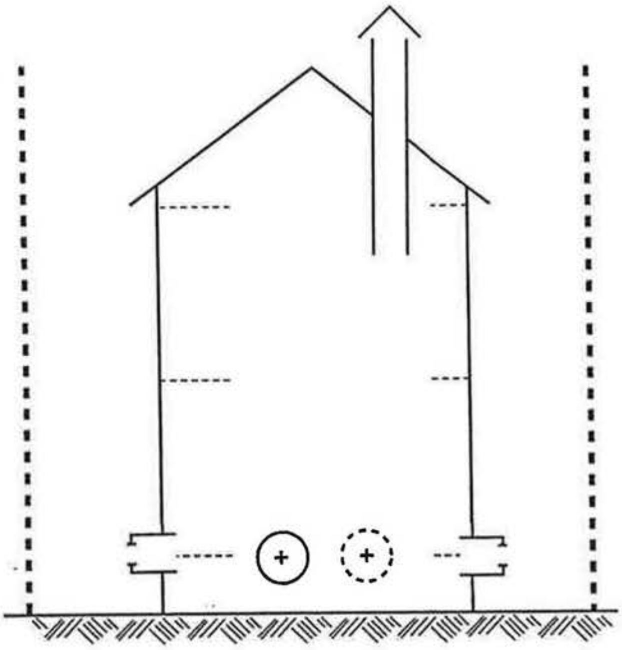
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.33 ACH
avg. 0.49 ACH
max. 0.59 ACH

2SF4L0.DAT

TABLE 5-15 and B-48

Two Storey Ventilation Rates With Four Passive Vents, Flue, Uniform Shelter, S_w=0.5



Background Leakage Area	66%
Flue Leakage Area	12%
Passive Vents Leakage Area	22%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.15	0.21	0.32	0.54
SPRING/FALL	10C	0.22	0.27	0.35	0.57
SHOULDER	0C	0.34	0.37	0.44	0.60
WINTER	-20C	0.52	0.54	0.59	0.73

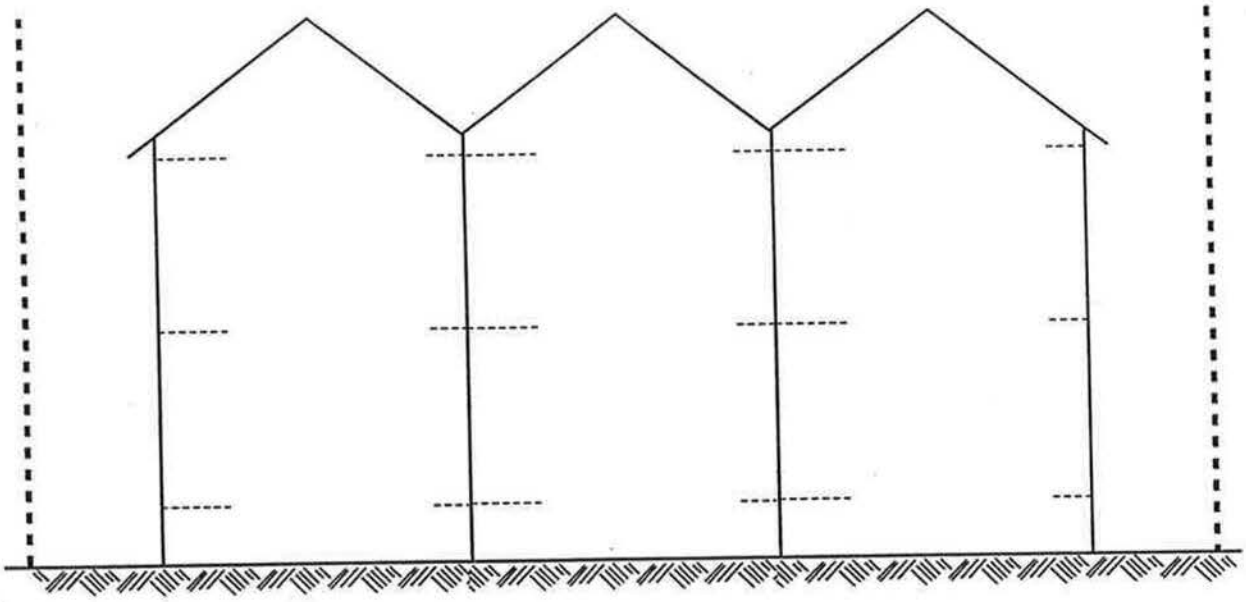
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.35 ACH
avg. 0.35 ACH
max. 0.36 ACH

2SF4LO.DAT

TABLE 5-16 and B-49

Townhouse Ventilation Rates With No Passive Vents, No Flue, Close Row Shelter



Background Leakage Area	100%
Flue Leakage Area	0%
Passive Vents Leakage Area	0%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.04	0.09	0.17	0.31
SPRING/FALL	10C	0.06	0.10	0.18	0.32
SHOULDER	0C	0.09	0.12	0.19	0.34
WINTER	-20C	0.15	0.17	0.22	0.37

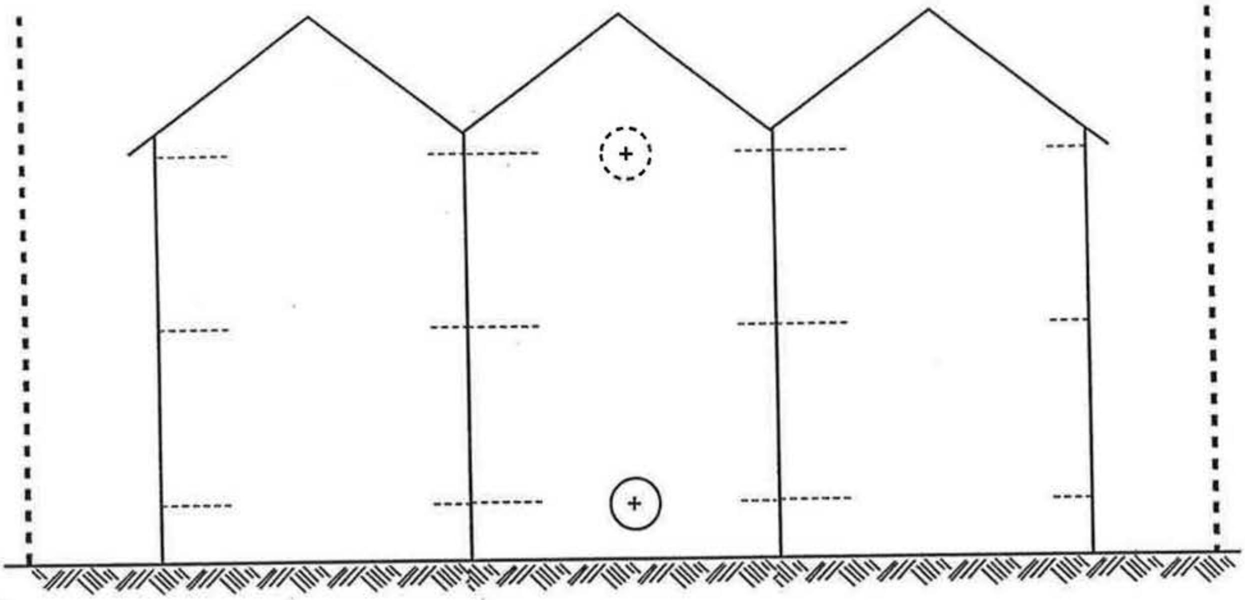
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.08 ACH
avg. 0.18 ACH
max. 0.26 ACH

THNOVENT.BDT
(BASEMENT)

TABLE B-50

Townhouse Ventilation Rates With Two Passive Vents, No Flue, Close Row Shelter



Background Leakage Area	76%
Flue Leakage Area	0%
Passive Vents Leakage Area	24%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.06	0.12	0.22	0.40
SPRING/FALL	10C	0.09	0.13	0.23	0.41
SHOULDER	0C	0.14	0.16	0.25	0.42
WINTER	-20C	0.22	0.23	0.29	0.46

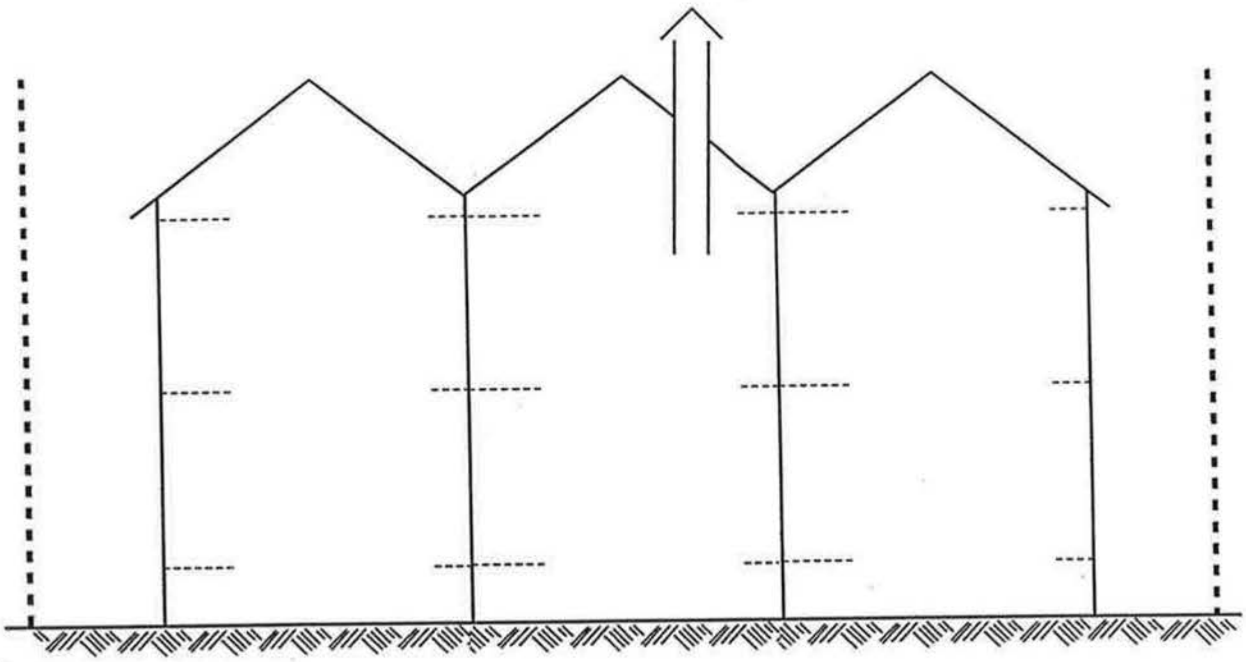
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.11 ACH
avg. 0.23 ACH
max. 0.35 ACH

THN2LOHI.BDT
(BASEMENT)

TABLE 5-17 and B-51

Townhouse Ventilation Rates With No Passive Vents, Flue, Close Row Shelter



Background Leakage Area	75%
Flue Leakage Area	25%
Passive Vents Leakage Area	0%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.08	0.15	0.25	0.44
SPRING/FALL	10C	0.12	0.18	0.27	0.45
SHOULDER	0C	0.17	0.22	0.31	0.48
WINTER	-20C	0.27	0.31	0.38	0.54

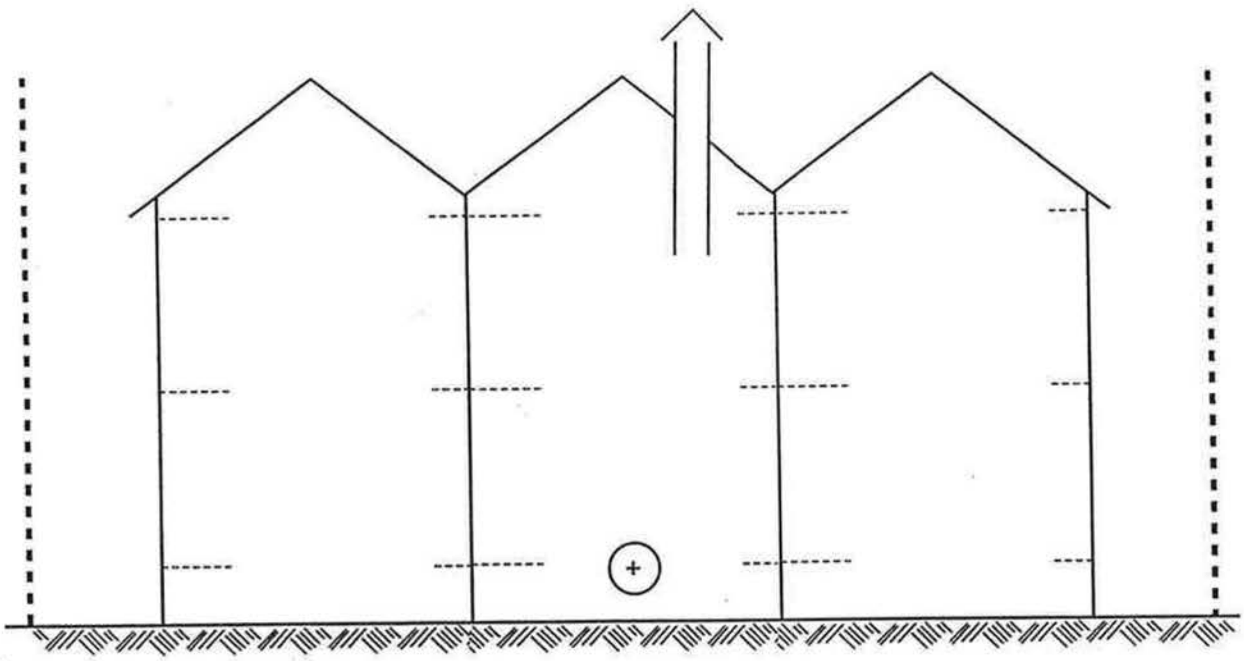
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.22 ACH
avg. 0.27 ACH
max. 0.33 ACH

THF0VENT.BDT
(BASEMENT)

TABLE B-52

Townhouse Ventilation Rates With One Passive Vent, Flue, Close Row Shelter



Background Leakage Area	67%
Flue Leakage Area	22%
Passive Vents Leakage Area	11%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.09	0.17	0.28	0.48
SPRING/FALL	10C	0.13	0.19	0.30	0.49
SHOULDER	0C	0.20	0.24	0.33	0.52
WINTER	-20C	0.30	0.34	0.41	0.59

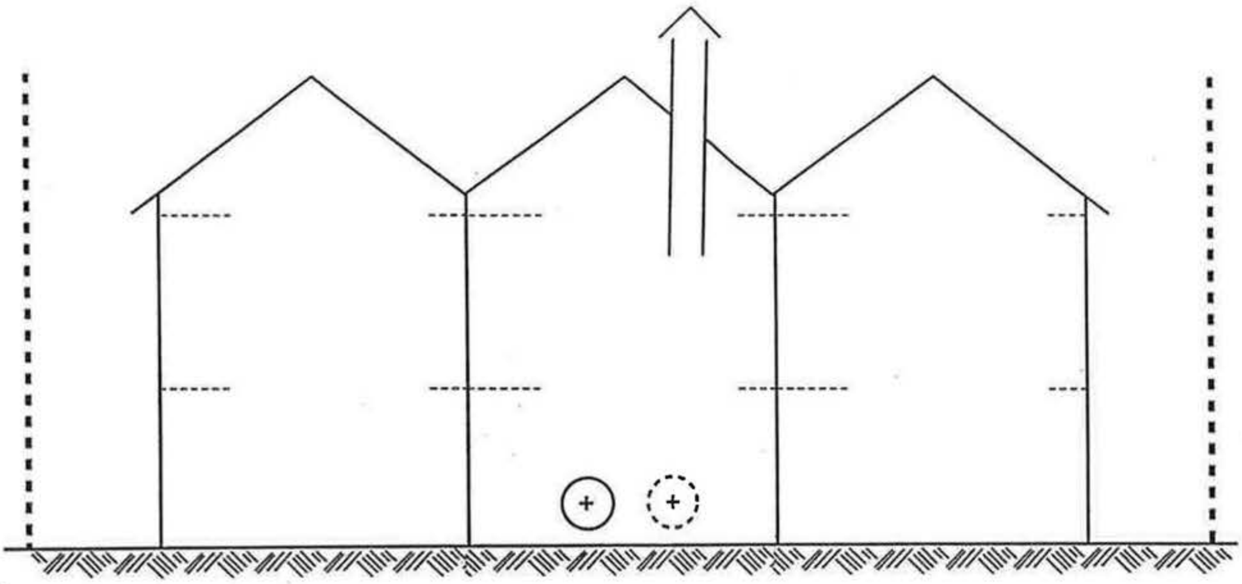
Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.23 ACH
avg. 0.30 ACH
max. 0.40 ACH

THF1LO.BDT
(BASEMENT)

TABLE 5-18 and B-53

Townhouse Ventilation Rates With Two Passive Vents, Flue, Close Row Shelter



Background Leakage Area	61%
Flue Leakage Area	20%
Passive Vents Leakage Area	19%

Natural Ventilation Rate ACH (360° average)

Season	Outdoor Temperature T_{out} For indoor temperature T_{in} = 20C	Unsheltered Site Wind Speed at Eaves Height U_H			
		LIGHT 1.0 m/s (3.6 km/h)	MODERATE 3.0 m/s (10.8 km/h)	STRONG 4.0 m/s (14.4 km/h)	HIGH 5.0 m/s (18.0 km/h)
SUMMER	15C	0.11	0.18	0.30	0.52
SPRING/FALL	10C	0.15	0.21	0.32	0.54
SHOULDER	0C	0.22	0.26	0.36	0.57
WINTER	-20C	0.33	0.36	0.44	0.63

Wind Direction Variability at U_H = 4 m/s, (14.4 km/h), T_{out} = 10C

min. 0.23 ACH
avg. 0.32 ACH
max. 0.41 ACH

THF2LO.BDT
(BASEMENT)