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Infiltration Data from the Alberta Home Heating Research Facility

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Preface

International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an International Energy Programme. A basic aim of the IEA is to foster co-operation among the twenty-one IEA Participating Countries to increase energy security through energy conservation, development of alternative energy sources and energy research development and demonstration (RD&D). This is achieved in part through a programme of collaborative RD&D consisting of forty-two Implementing Agreements, containing a total of over eighty separate energy RD&D projects. This publication forms one element of this programme.

Energy Conservation in Buildings and Community Systems

The IEA sponsors research and development in a number of areas related to energy. In one of these areas, energy conservation in buildings, the IEA is sponsoring various exercises to predict more accurately the energy use of buildings, including comparison of existing computer programs, building monitoring, comparison of calculation methods, as well as air quality and studies of occupancy. Seventeen countries have elected to participate in this area and have designated contracting parties to the Implementing Agreement covering collaborative research in this area. The designation by governments of a number of private organisations, as well as universities and government laboratories, as contracting parties, has provided a broader range of expertise to tackle the projects in the different technology areas than would have been the case if participation was restricted to governments. The importance of associating industry with government sponsored energy research and development is recognized in the IEA, and every effort is made to encourage this trend.

The Executive Committee

Overall control of the programme is maintained by an Executive Committee, which not only monitors existing projects but identifies new areas where collaborative effort may be beneficial. The Executive Committee ensures that all projects fit into a pre-determined strategy, without unnecessary overlap or duplication but with effective liaison and communication. The Executive Committee has initiated the following projects to date (completed projects are identified by *):

I Load Energy Determination of Buildings*
II Ekistics and Advanced Community Energy Systems*
III Energy Conservation in Residential Buildings*
IV Glasgow Commercial Building Monitoring*

V	Air Infiltration and Ventilation Centre
VI	Energy Systems and Design of Communities*
VII	Local Government Energy Planning*
VIII	Inhabitant Behaviour with Regard to Ventilation*
IX	Minimum Ventilation Rates*
X	Building HVAC Systems Simulation*
XI	Energy Auditing*
XII	Windows and Fenestration*
XIII	Energy Management in Hospitals*
XIV	Condensation*
XV	Energy Efficiency in Schools*
XVI	BEMS - 1: Energy Management Procedures*
XVII	BEMS - 2: Evaluation and Emulation Techniques
XVIII	Demand Controlled Ventilating Systems*
XIX	Low Slope Roof Systems
XX	Air Flow Patterns within Buildings*
XXI	Thermal Modelling
XXII	Energy Efficient Communities
XXIII	Multizone Air Flow Modelling (COMIS)
XXIV	Heat Air and Moisture Transfer in Envelopes
XXV	Real Time HEVAC Simulation
XXVI	Energy Efficient Ventilation of Large Enclosures
XXVII	Evaluation and Demonstration of Domestic Ventilation Systems

Annex V Air Infiltration and Ventilation Centre

The IEA Executive Committee (Building and Community Systems) has highlighted areas where the level of knowledge is unsatisfactory and there was unanimous aggreement that infiltration was the area about which least was known. An infiltration group was formed drawing experts from most progressive countries, their long term aim to encourage joint international research and increase the world pool of knowledge on infiltration and ventilation. Much valuable but sporadic and uncoordinated research was already taking place and after some initial groundwork the experts group recommended to their executive the formation of an Air Infiltration and Ventilation Centre. This recommendation was accepted and proposals for its establishment were invited internationally.

The aims of the Centre are the standardisation of techniques, the validation of models, the catalogue and transfer of information, and the encouragement of research. It is intended to be a review body for current world research, to ensure full dissemination of this research and based on a knowledge of work already done to give direction and firm basis for future research in the Participating Countries.

The Participants in this task are Belgium, Canada, Denmark, Germany, Finland, France, Italy, Netherlands, New Zealand, Norway, Sweden, Switzerland, United Kingdom and the United States of America.

Contents

Air Leakage and Ventilation Characteristics of the Test House

This infiltration data set covers December 1990 to October 1991 from Reference Unit #5 at the Alberta Home Heating Research Facility (AHHRF) with a total of 6063 hours of data. This facility is made up of six permanent test houses, five of which are built to residential wood frame construction standards with a sixth house of masonry construction. The six unoccupied test houses have been continuously monitored since 1980 for building envelope energy losses and ventilation rates. The houses are arranged side by side in a row with a 2.8m sidewall separation. This side by side testing reduces the effects of weather variability in conduction studies of various energy conservation and ventilation strategies. The facility is located 10 km south of Edmonton, Alberta, at approximately 53.5° North latitude and 670 m (2200 feet) above sea level. The climate is dry with warm summers and cold winters. The range of temperatures and windspeeds measured at the site is given in a later section. The mean windspeed is 3.2 m/s (11.5 km/hour or 7.2 mph) and the yearly mean temperature is close to zero degrees Celsius.

The AHHRF was begun in 1979 to provide a site for fundamental research on residential heating strategies suitable for a northern climate. Initial funding for the test site construction was provided by the Alberta/Canada Energy Resources Research Fund. Studies performed at AHHRF include: testing various types and levels of insulation, heating by solar panels (including heat pumps and thermal mass storage), testing furnaces of different efficiencies, mechanical and passive ventilation strategies, radiant floor heating, low emissivity windows, turbine attic ventilators, radiant barriers, and attic ventilation, in addition to continuously monitoring ventilation rates.

The units are shown in the photographs of Figure 1 and 2, with the Masonry Unit #1 on the right in Figure 1, and on the left in Figure 2. Construction dimensions relevant to infiltration and ventilation are listed in Table 1. Reference Unit #5 has three windows, one in each of the North, East and West walls. The windows in the West and East walls are double glazed and slide to open. The window in the North wall is a sealed double glazed unit.

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.

As shown in Figure 1 and 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 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 #6) to provide wind shelter and solar shading similar to that experienced by interior houses in the row.

Table 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 storey 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)

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 shows the door in Reference Unit #5. The house has wood frame construction with 38 x 89 mm studs on 406 mm centers (2x4 studs on 16" centers) with 1.3 cm painted drywall on the interior and 9.5 mm 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. The location of leakage sites and general building configuration are shown in the isometric view of Reference Unit #5 in Figure 4.

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. 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 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 5. To avoid basement air stratification, a fan intake is located near the basement floor, and another intake is close to the ceiling.

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.

Distributed Envelope Leakage

Each house has 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. 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 and CGSB 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.

The pressure-flow characteristic of each house is fitted to the power law

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

where C is a flow coefficient dependent on leakage flow area and n is an exponent that characterizes the type of leak. For Reference Unit #5 the following values of C and n have been determined. For pressurization the results are shown in Figure 6a (Test number 11022) where:

$$C=0.0098\frac{m^3}{sPa^n} \tag{2}$$

$$n=0.58 \tag{3}$$

For depressurization the results are shown in figure 6b (Test number 11001) where

$$C=0.0089\frac{m^3}{sPa^n} \tag{4}$$

$$n=0.62 \tag{5}$$

The individual data points for pressure and flowrate and the test conditions of windspeed and indoor and outdoor temperature are given in the appendix to this documentation. These tests were performed in the summer and are thus representative of summer leakage area. Because this test house is humidified the leakage may be reduced in winter months as ice formation in cracks will block ventilation flows. The humidity is maintained at approximately 40% all year round.

The combined wind and stack effect pressures across a leakage site usually lie in the range from 1 Pa to 10 Pa. Leakage can 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 (1) to the orifice flow equation at a specified reference pressure ΔP_{ref}, and an air density ρ kg/m^3,

$$Q = C\Delta P_{ref}^{n} = A_L\left(\frac{2\Delta P_{ref}}{\rho}\right)^{0.5} \tag{6}$$

from which

$$A_L = C\left(\frac{\rho}{2}\right)^{0.5}\Delta P_{ref}^{n-0.5} \tag{7}$$

The equivalent leakage area for Reference Unit #5 for pressurization is

$$A_L=85.5cm^2 \tag{8}$$

and for depressurization is

$$A_L=81.4cm^2 \tag{9}$$

The above values of C, n, and A_L represent the total leakage in Reference Unit #5 because it has no additional leakage paths such as furnace flues or open windows in its tested configuration. Separate pressurization tests to find ceiling leakage show that 12.5 cm^2 of this leakage is in the ceiling. Most of this leakage is concentrated in a 7.5 cm diameter orifice flow meter that is used to measure exchange rates between the house and the attic. Above this orifice is a 7.5 cm thick blanket of fibreglass insulation that covers the whole attic floor. The insulation reduces the effective leakage area of the orifice. There is also a small contribution to ceiling leakage from the holes around the light fixtures in the ceiling.

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. Because the ceiling leakage has been measured directly it does not need to be estimated.

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 2 gives the distributed background leakage distribution for Unit #5 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.

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 hexafluoride, SF_6, to maintain a constant concentration in the test house. 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 Reference Unit #5 and Retrofit Unit #2.

The requirement for continuous unattended operation of the gas analyzer over periods of several months required special operation and calibration techniques to obtain

Table 2

Assumed Background Leakage Distribution for AHHRF Unit #5

Background Leakage Location	Reference Unit #5
North Wall #1	10%
South Wall #2	10%
East Wall #3	25%
West Wall #4	20%
Floor Level	20%
Ceiling	15%

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 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 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 $\pm$ 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.

Wind Measurement

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. The mean 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.

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.

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 walls must be estimated.

Infiltration Data File Configuration

All the data files are for Unit #5 at AHHRF. For each hour of operation the infiltration rate, Q [m^3/hour], indoor temperature, Tin [°C], outdoor temperature, Tout [°C], windspeed, U [m/s], and wind direction, Dir [degrees], are recorded. They are saved as ASCII characters so that most programmes can read the data. In the data files each hour of information is written to a record with the parameters separated by commas as shown in the data file printouts. Each record has the following format where each # represents a digit:

Q Tin Tout U Dir

###.#,##.#,###.#,##.###,###C_RL_F

Thus each record is always 29 characters long including the carriage return and linefeed (C_RL_F). The data is stored in a format such that each parameter occupies the same number of digits every hour. Unfilled digits or missing data are filled with blanks. This includes hours when the infiltration system was not operating. The infiltration system does not record data for the noon hour each day as this is when the zero samples are taken. The commas remain in the same positions and are not replaced with blanks when there is no data.

There are 6063 hours of data in total. Apart from the zeroing hours the additional blanks in the data files (a total of approximately 30 days spread over the 10 months) are from periods when the infiltration system was not operating. This occurs when the system is shut down for other experiments to be performed e.g. fan pressurization testing.

Each file contains a month of data. The file names are from the year, YY (e.g. 91) and month, MM (e.g. 06 for June) that the data was taken in the format YY-MM.INF. The extension .INF is used to represent INFiltration data. Each month is forced to have 31 days (744) hours even if it is shorter, and the extra hours are filled with blanks. This is done so that simple algorithms may be used to convert dates into a position within the files. Tables in the appendix of this documentation can be used as a reference to convert a date to an hour position within a file or to convert an hour to a date.

The accompanying program AIVCREAD.BAS is an example of how to read the data files. There are data files from December 1990 (90-12.INF) to October 1991 (91-10.INF) excluding April 1991 when the infiltration system was not operating. A printout of all the data is included on the appendix. This printout was obtained using AIVCPRT.BAS which is also included with this documentation.

Fan pressurization data file configuration

The data from the fan pressurization tests shown in figures 6a and 6b for pressurization and depressurization respectively are given in the data files named 11022.DAT and 11001.DAT. The data files are saved in ASCII code to be readable by most computer systems. In each data file are two columns for pressure difference (Pascals) and flowrate (m^3/s) as given in the table of results. There are 26 data pairs in each file.

Sample Data from AHHRF data set

The following figures illustrate the large range of data available from this data set covering windspeeds from 0 to 10 m/s (0 to 36 km/hour or 0 to 23 mph), Indoor-outdoor temperature differences from -4 to +60°C, 97% of possible wind directions, and extremes of shelter from completely unsheltered for South winds to heavily sheltered for East and West winds. The gaps that appear in timelines of data (Figures 16 and 17) are hours when the infiltration system is taking zero sample data that occurs at noon each day.

Figure 7 : Windspeed dependence of Infiltration rate. This data has been sorted for Temperature differences (ΔT) < 10°C and windspeed (U) > 3m/s (leaving 866 hours in this

figure from the 6063 total hours) to look at wind dominated ventilation only. The expected trend of increasing ventilation rate with increasing windspeed is clearly shown in this figure. The spread of data is due to wind shelter effects as both sheltered and unsheltered conditions are included.

Figure 8 : Wind Direction dependence of Infiltration Rate. As above, this data has been sorted for $\Delta T < 10°C$ and $U > 3m/s$ resulting in the same number of hours (866). To remove windspeed effects the infiltration rate for each point has been divided by U_{2n} where n is from the power law leakage function shown in figure 6 (n=0.582). The remaining spread of data is due to the effects of averaging wind direction over an hour. The variation of approximately a factor of three in infiltration rates is due to the house being sheltered from East and West winds (90° and 270°) by neighbouring houses, and exposed to North and South winds (0° and 180°).

Figure 9 : Indoor-Outdoor Temperature Difference dependence of Infiltration Rate. The data has been sorted for ΔT dominance with $U < 2m/s$ and $\Delta T > 5°C$ resulting in 1510 hours of data in this figure. The trend of increasing ventilation rate with increasing ΔT is clearly seen, as is the measurement system resolution at lower infiltration rates.

Figure 10 : Frequency of Occurrence for Infiltration Rates for the whole data set (6063 hours). The infiltration data has been binned every 0.01 ACH (Air Changes per Hour) for this figure that shows the number of data points in each bin. The mean infiltration rate for the whole data set is 0.0734 ACH in this skewed distribution with a mode of 0.055 ACH.

Figure 11 : Frequency of Occurrence for Windspeeds. The windspeed data has been binned every 0.25m/s and the number of data points in each bin are shown as the frequency of occurrence. the mean wind speed is 3.2m/s and the mode is 2.1m/s. This distribution is skewed in a similar fashion to the infiltration rates in Figure 10. These windspeeds were measured at the top of a 10m high meteorological tower at the test facility.

Figures 12,13 and 14 : Frequency of Occurrence for Indoor-Outdoor Temperature Difference. The data has been binned every 2.5°C and the number of points per bin are shown as frequency in this figure. The mean temperature difference is 19.1°C for the complete data set. This implies a mean outdoor temperature near 3°C given an indoor temperature maintained at 22°C. There are 85 points where the indoor temperature is lower than the outdoor temperature i.e. ΔT is negative in this figure. This occurs on summer days when the outside temperature is above 20°C and due to the thermal mass of the house it is then cooler than the ambient air temperature. The bi-modal temperature distribution can be separated into 2 distributions : one for summer and one for winter as shown in figures 13 and 14 respectively.

Figure 15 : Distribution of Wind Directions. The data has been binned every 5 degrees and the number of points in each direction bin is shown as the frequency of occurrence. This figure shows that the main weather systems at the test site tend to produce South-East (155°) and North-West (295°) winds. The main effect of wind direction at the test facility is to change the shelter effect from unsheltered for North and South winds to heavily sheltered for winds along the row of houses (East and West winds). The data set has many point for both these conditions and any points between with a complete range of wind directions covered by the 6063 hours of data in this figure. The only anomaly is the lack of data within a few degrees of North.

Figure 16 : A Complete Month of data from December 1990. The four figures show timelines of Infiltration rate, Windspeed, Wind Direction, and Indoor-Outdoor temperature difference in figures A through D respectively. These figures show the range of these parameters over a winter month, and the rate at which they change, with temperatures changing more slowly than wind direction and windspeed. Over the month the data covered the following ranges:

- Infiltration Rate. Mean = 0.10 ACH, Minimum = 0.04 ACH, Maximum = 0.25 ACH

- Wind Speed. Mean = 3.54 m/s, Minimum = 0.36 m/s, Maximum = 10.25 m/s

- Temperature Difference. Mean = 35.3°C, Minimum = 13.8°C , Maximum = 58.7°C

Figure 17 : Diurnal Variation of Temperature and Infiltration Rate. This figure shows a week of winter data from 14th March 1991 to 21st March 1991. The mean windspeed of 2.0 m/s is relatively low and the diurnal change of infiltration rate due to the diurnal variation in indoor-outdoor temperature difference can be observed.

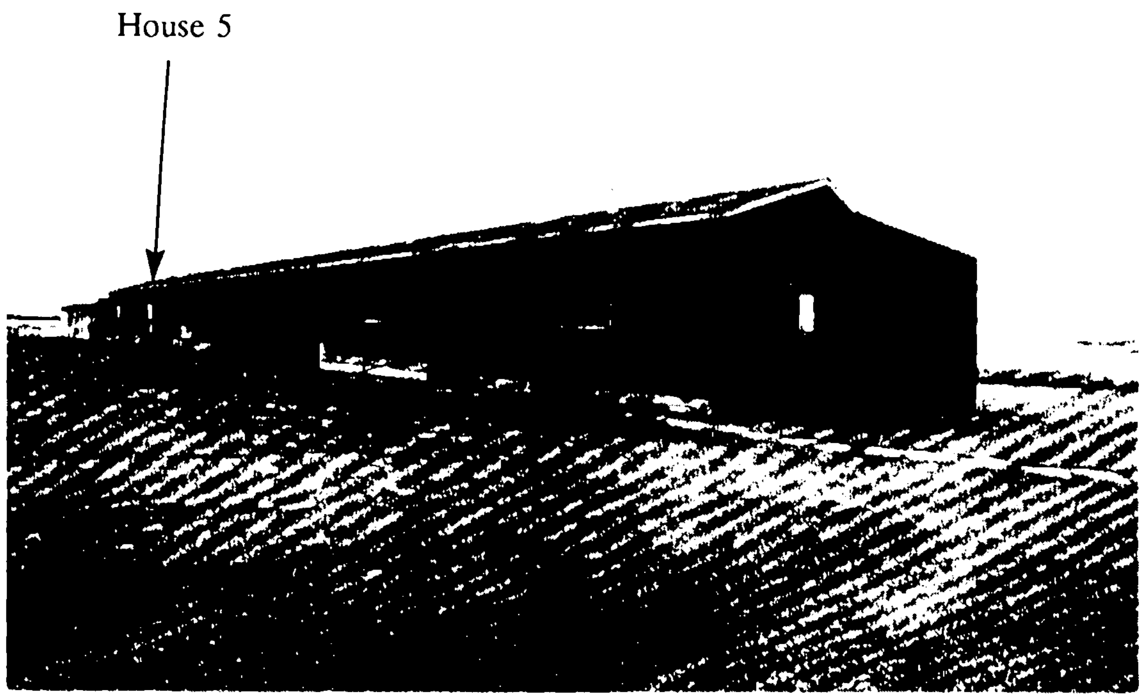


Figure 1 North side of test houses looking east along row from Masonry Unit 1 showing rain-capped flues and end wall wind shielding barrier.

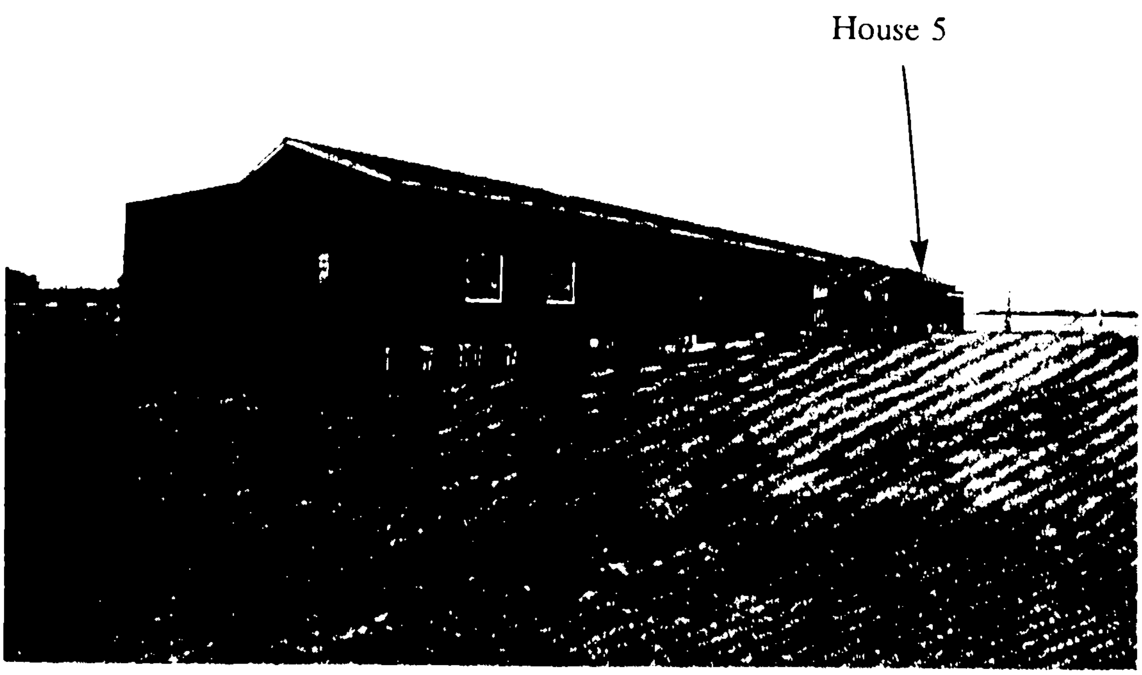


Figure 2 South side of test houses looking east along row from Masonry Unit 1.

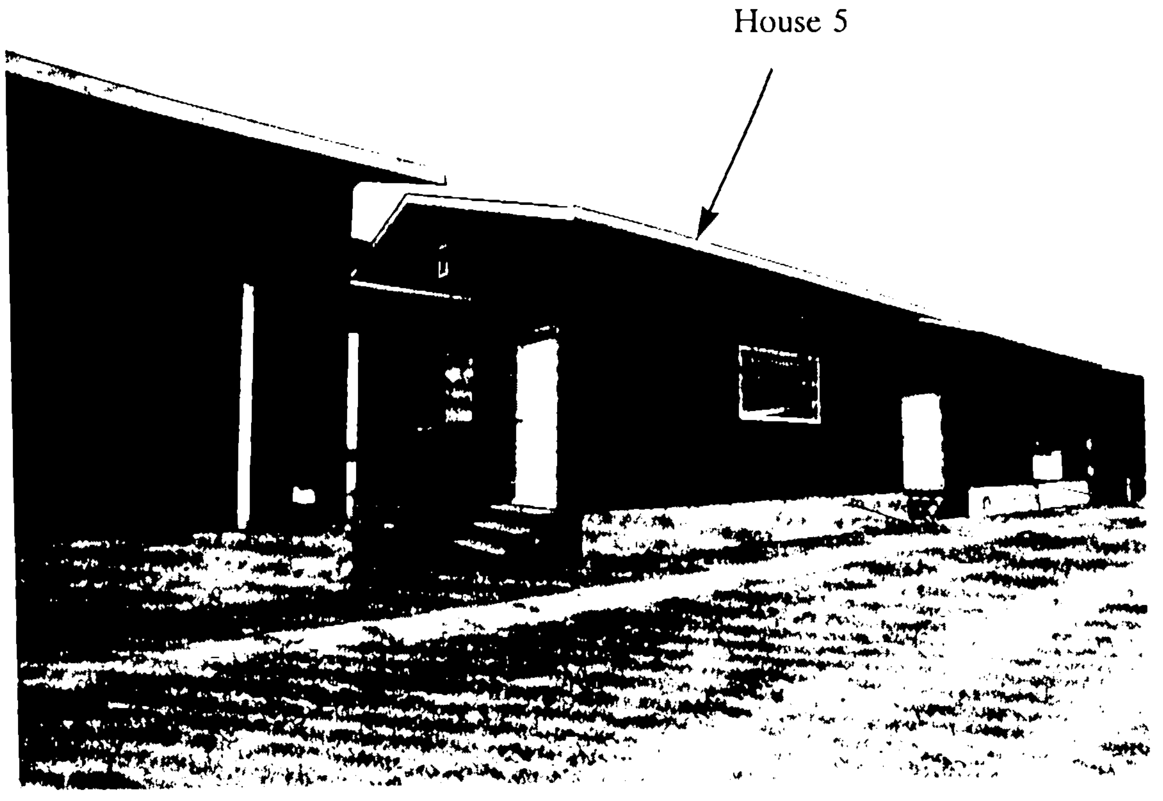


Figure 3 Reference Unit 5 from north-east showing plywood sheathing over vapour barrier on concrete basement.

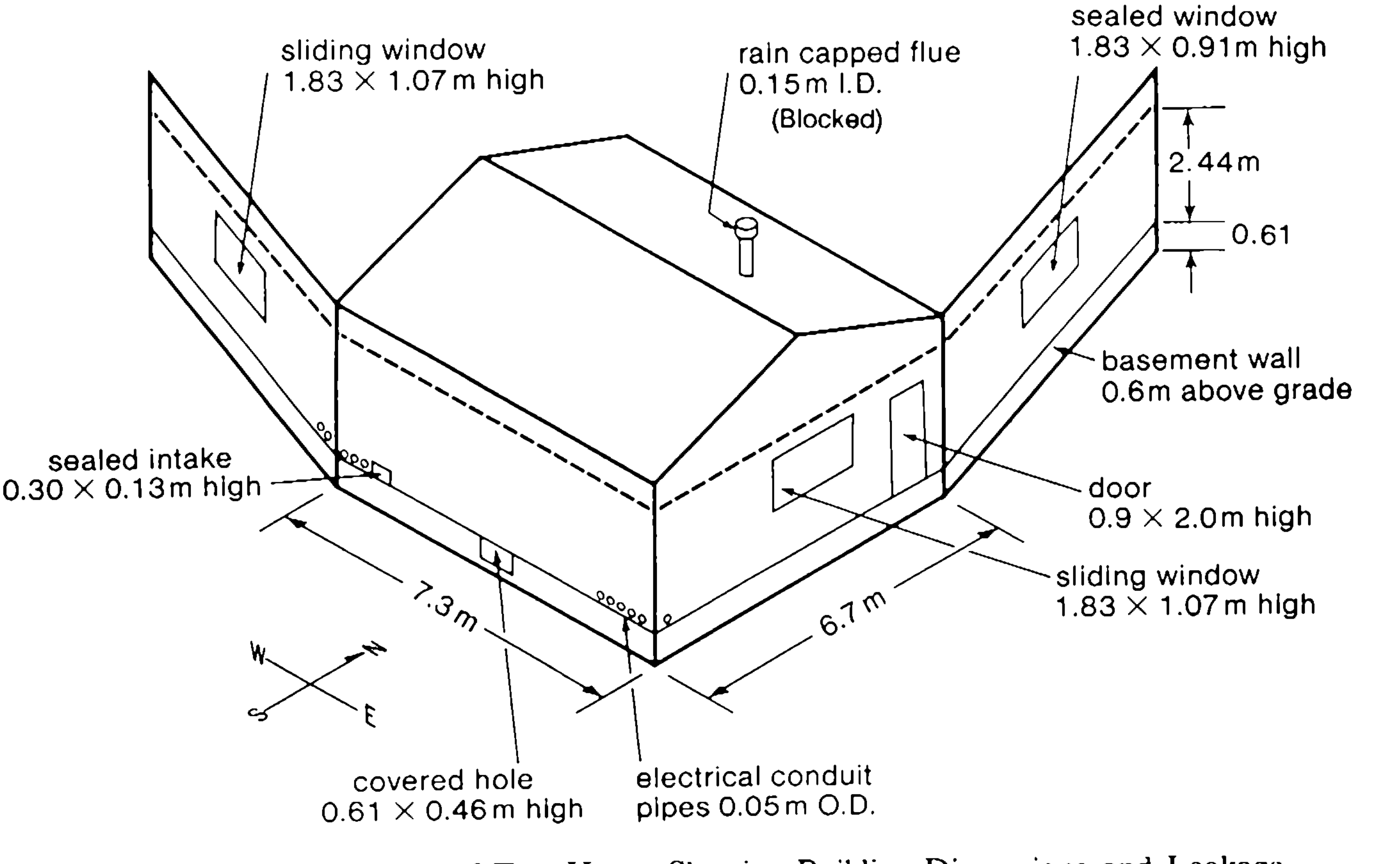


Figure 4 Isometric View of Test House Showing Building Dimensions and Leakage Sites

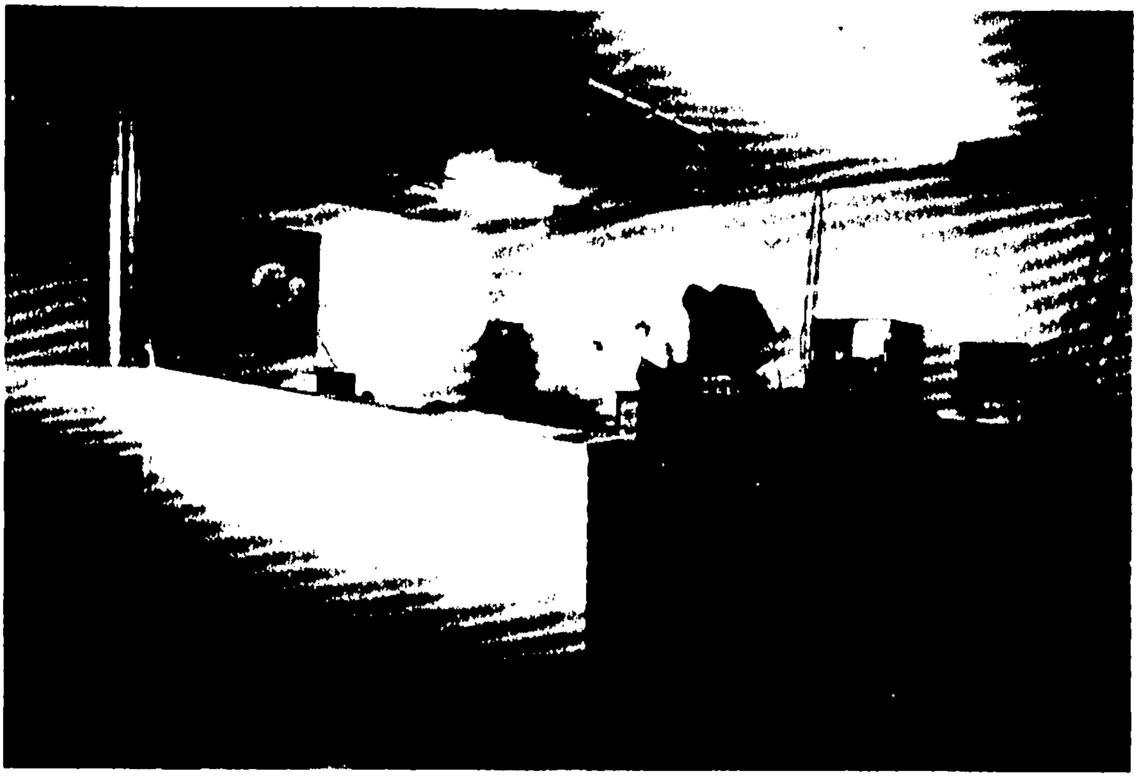


Figure 5 Main level of Reference Unit 5 with tracer gas concentration measurement and control system, flow meter on panel over east window, and open stairwell to basement.

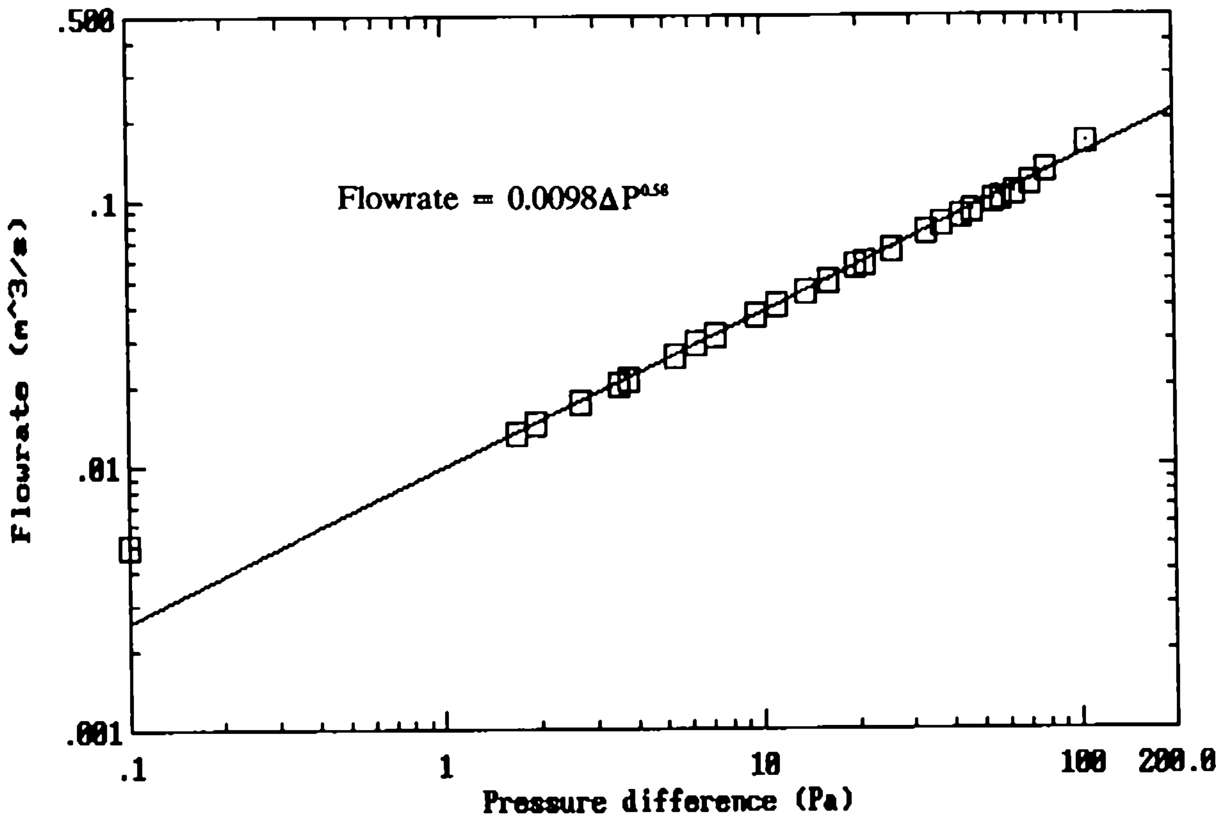


Figure 6a. Fan Pressurization Results for Reference Unit 5

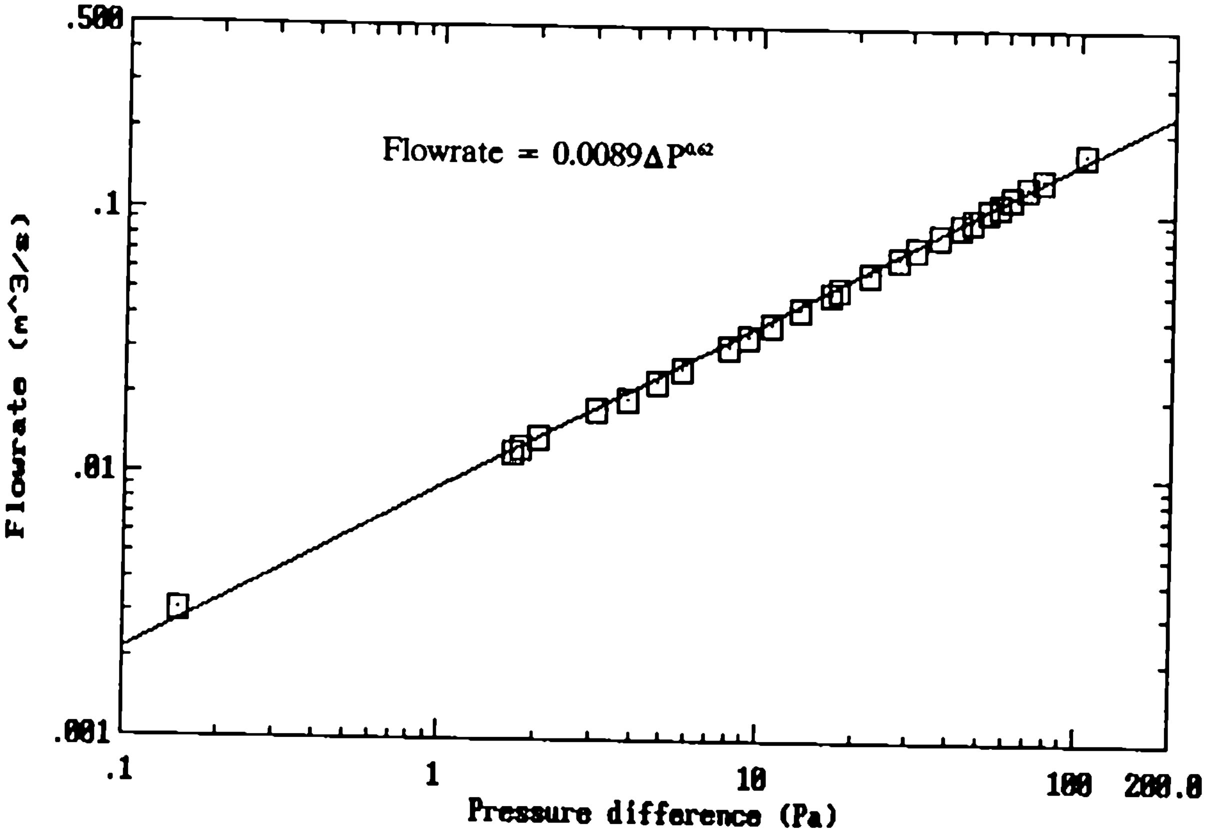


Figure 6b. Fan Depressurization Results for Reference Unit 5

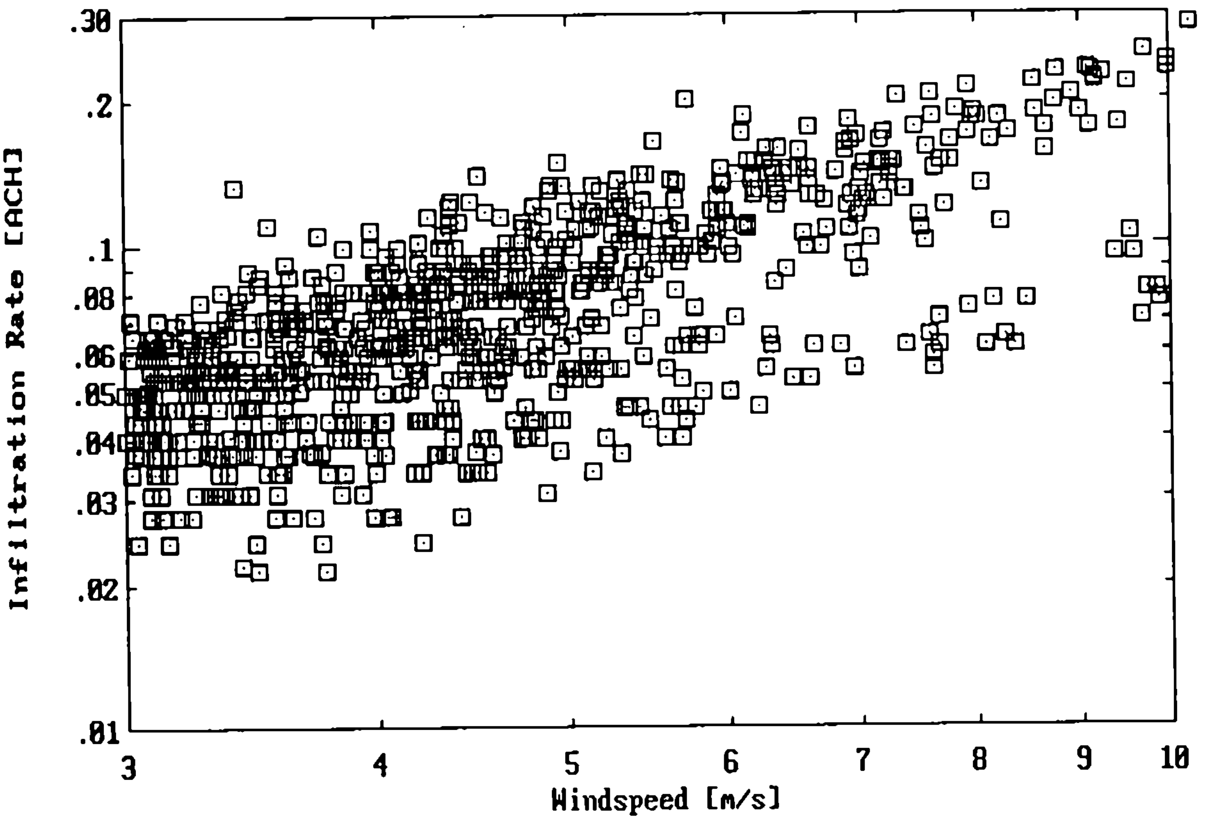


Figure 7. Windspeed Dependence of Infiltration Rate with $\Delta T < 10°C$ and $U > 3m/s$ (866 Hours).

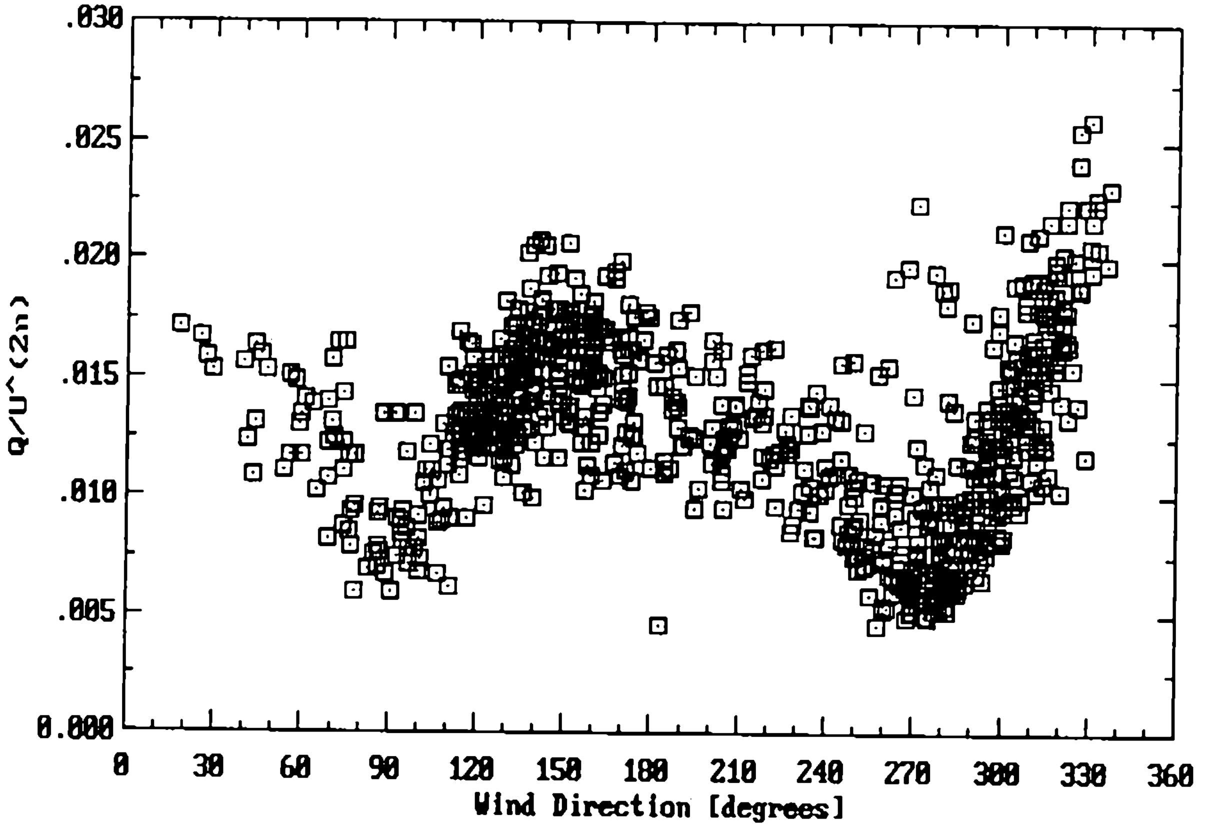


Figure 8. Wind Direction Dependence of Infiltration Rate due to Sheltering Effects of Neighbouring Buildings (Normalised to remove windspeed dependence). $\Delta T < 10°C$ and $U > 3m/s$ (866 Hours).

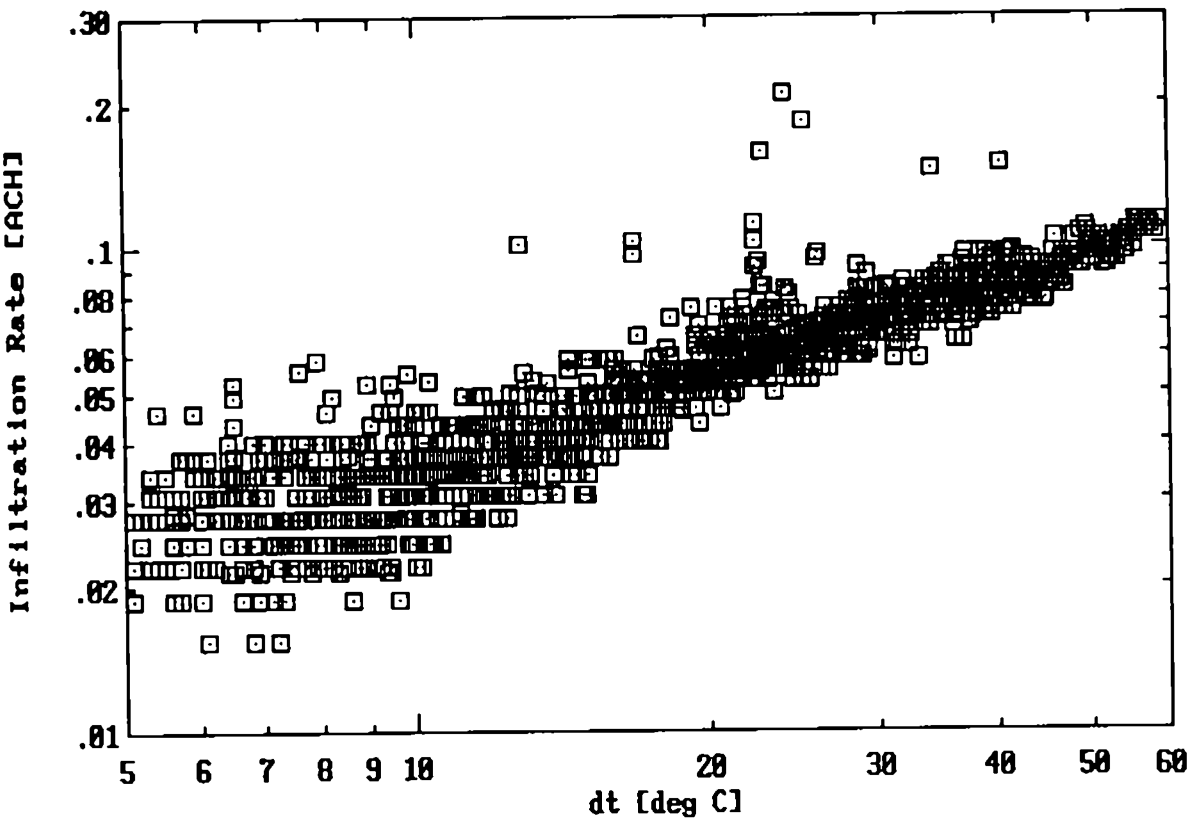


Figure 9. Indoor-Outdoor Temperature Difference Dependence of Infiltration Rate with $U < 2m/s$ and $\Delta T > 5°C$ (1648 Hours).

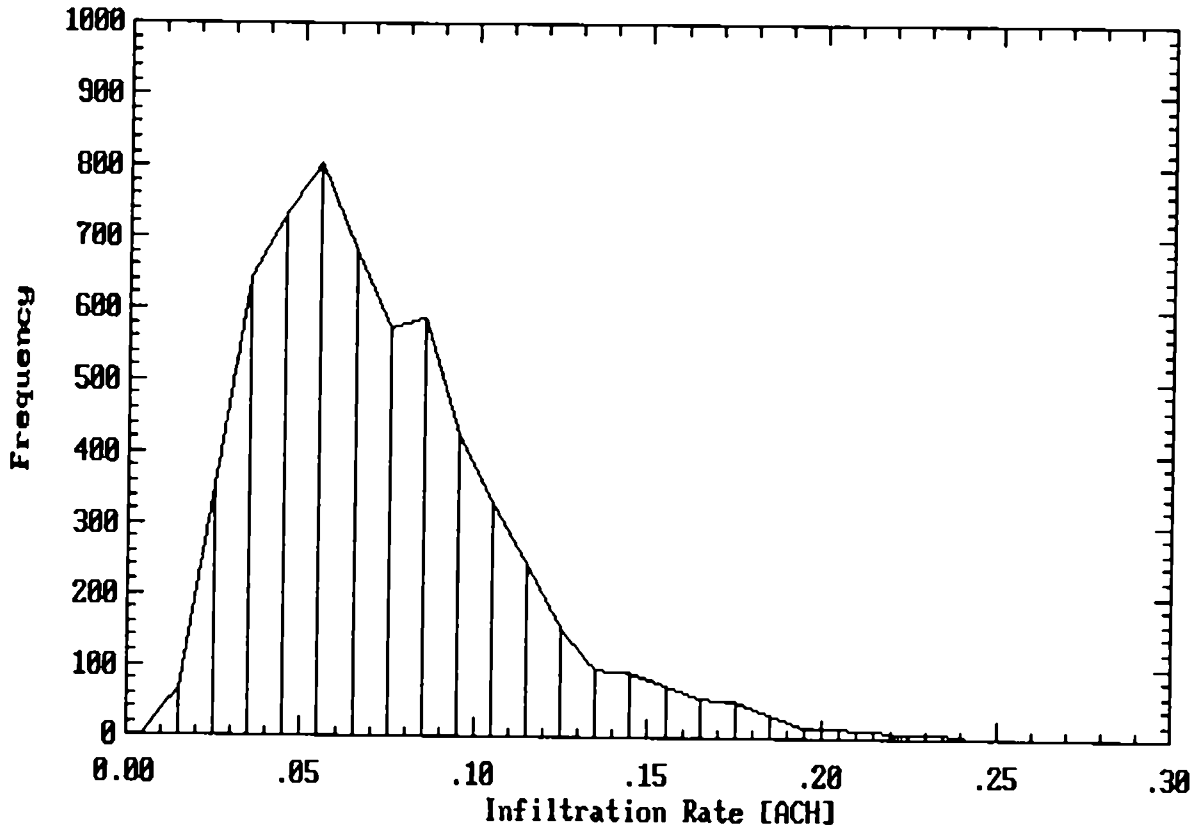


Figure 10. Frequency of Occurrence for Infiltration Rates for Whole Data Set (6063 Hours).

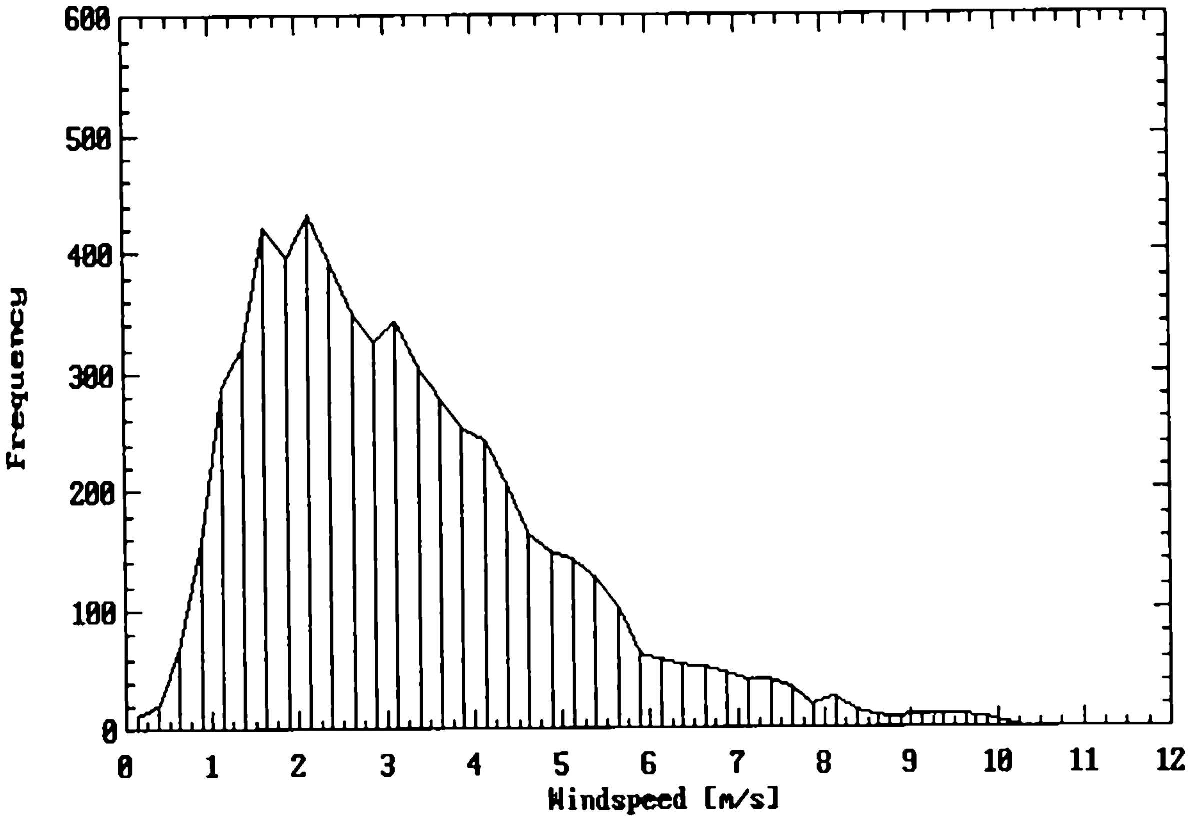


Figure 11. Frequency of Occurrence for Windspeeds (6063 Hours)

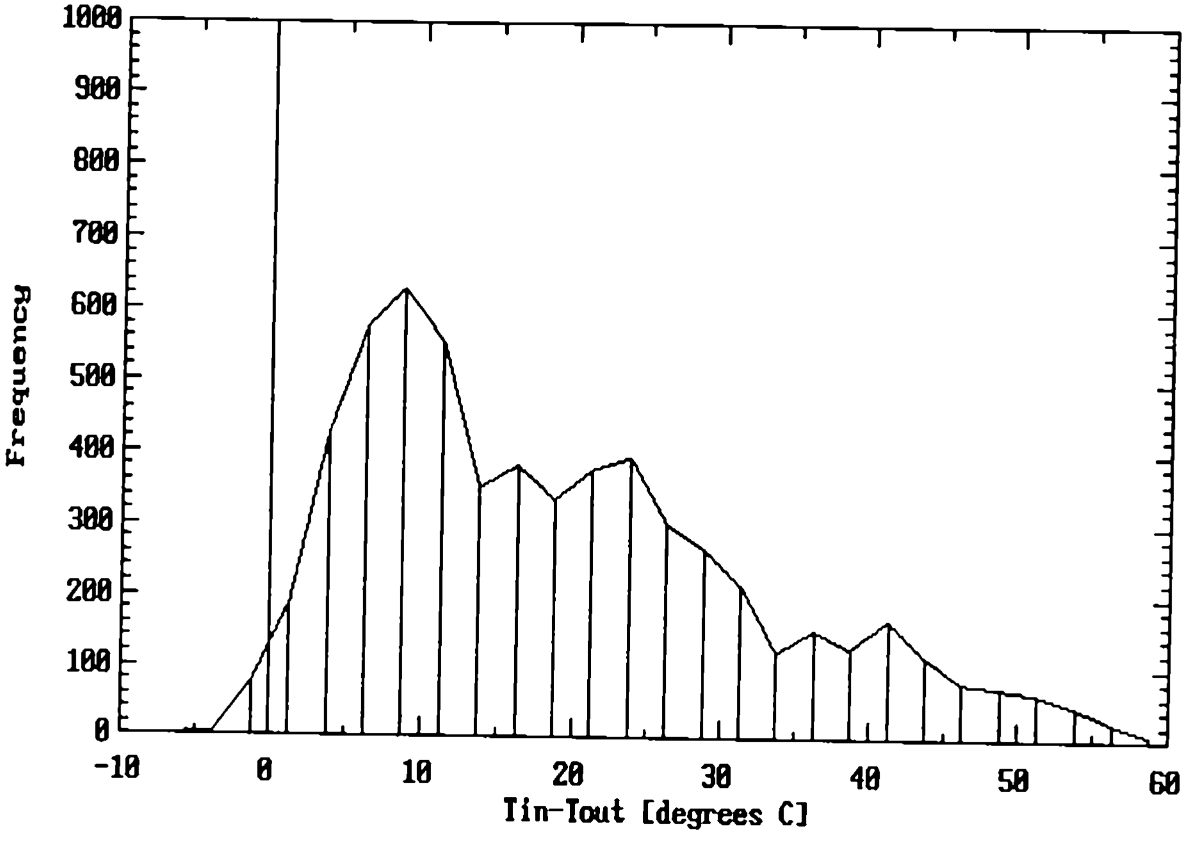


Figure 12. Frequency of Occurrence for Indoor-Outdoor Temperature Differences (6063 Hours).

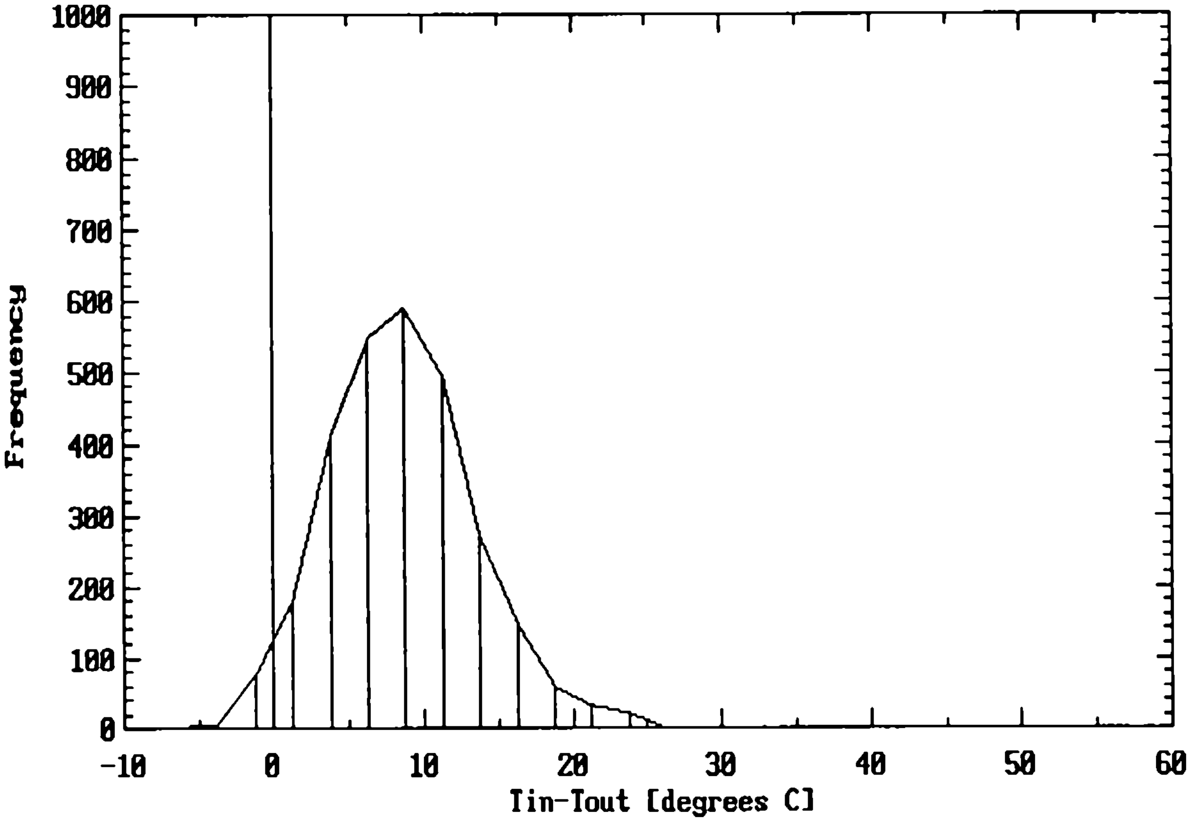


Figure 13. Summer Indoor-Outdoor Temperature Difference Distribution (2841 Hours).

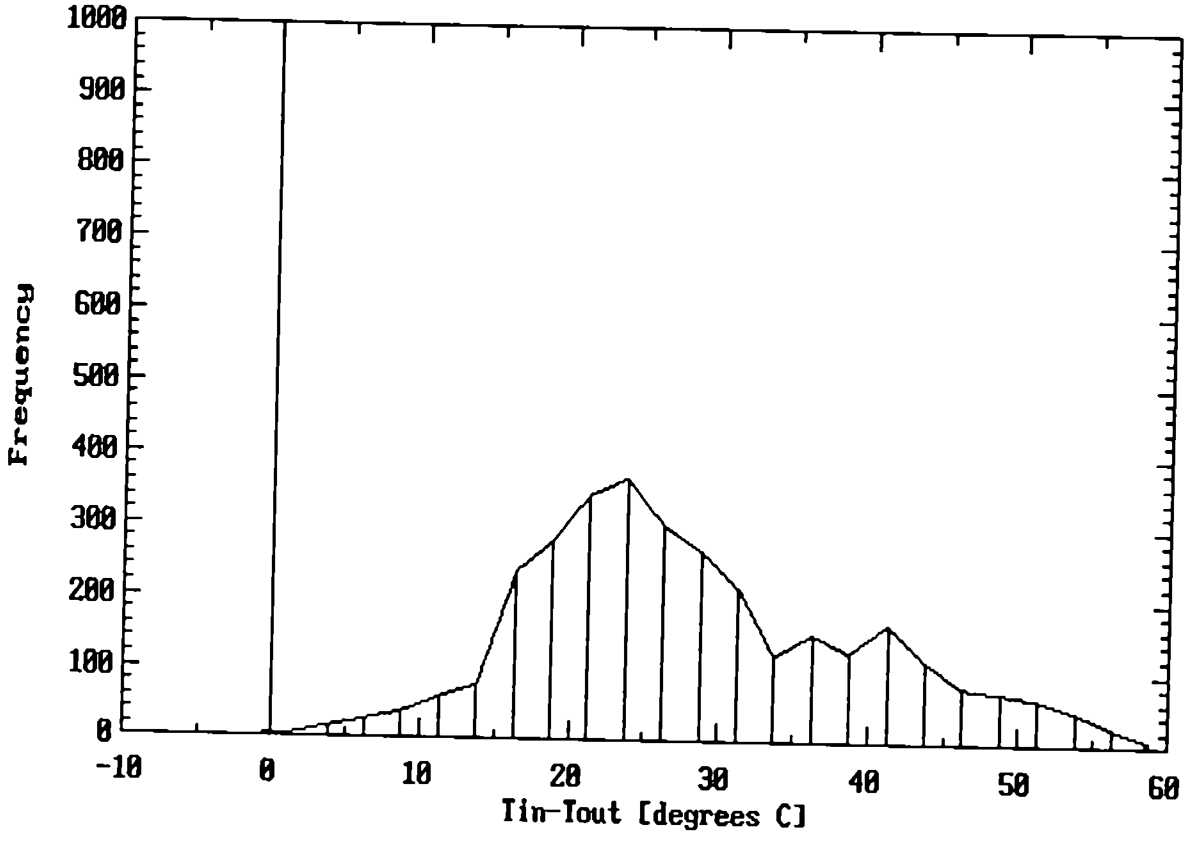


Figure 14. Winter Indoor-Outdoor Temperature Difference Distribution (3222 Hours).

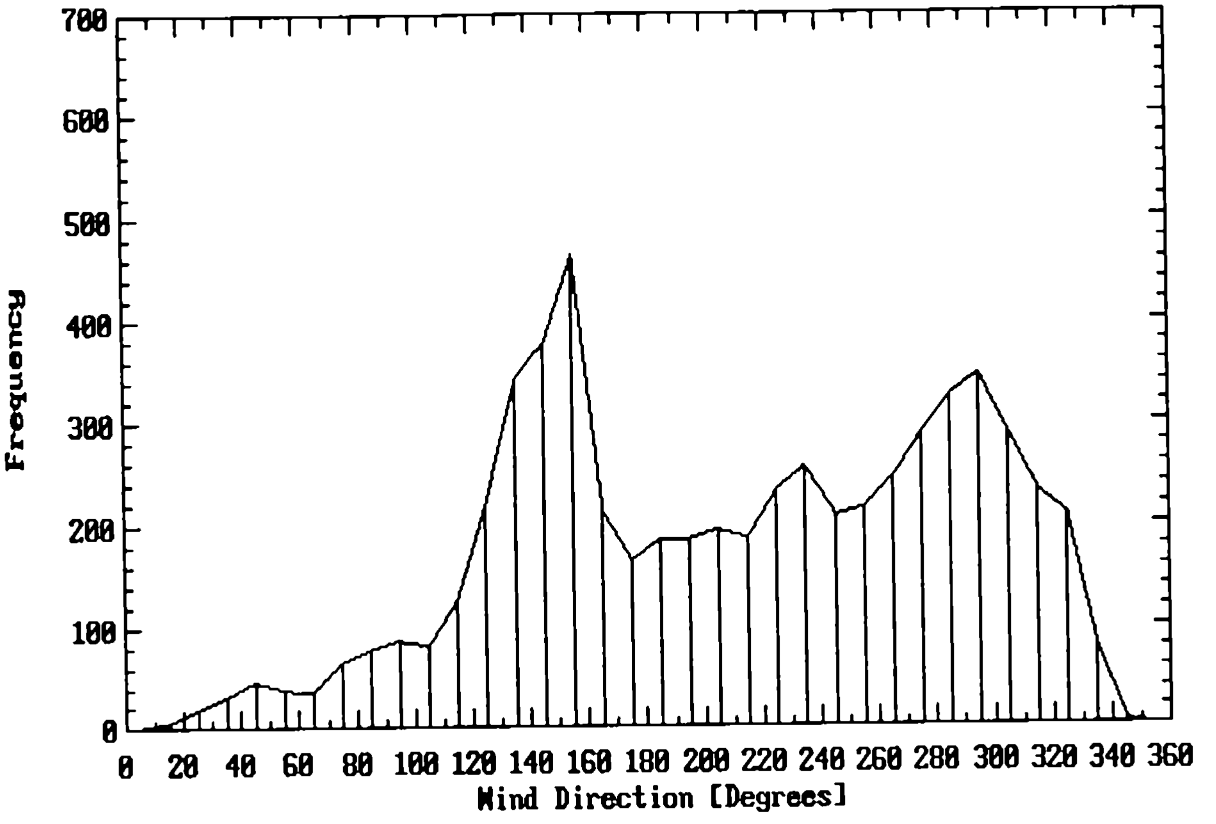
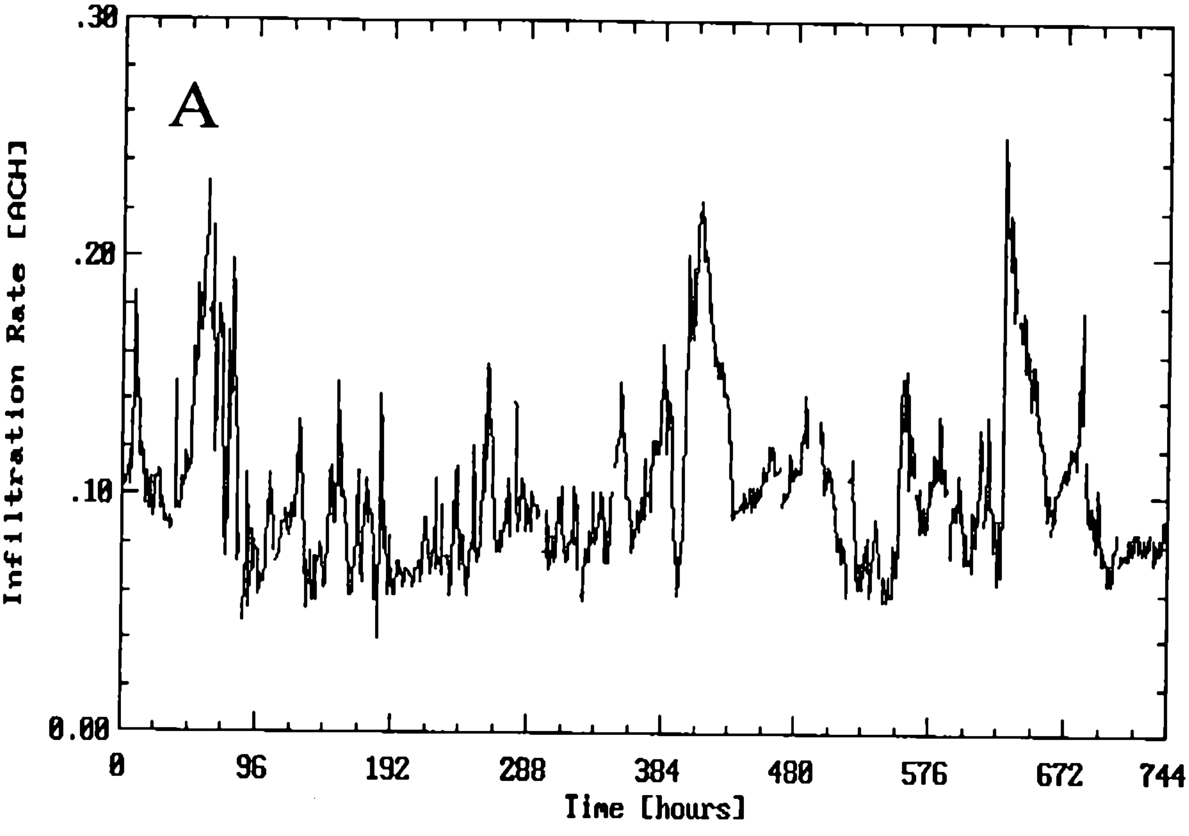


Figure 15. Distribution of Measured Wind Directions (6063 Hours).



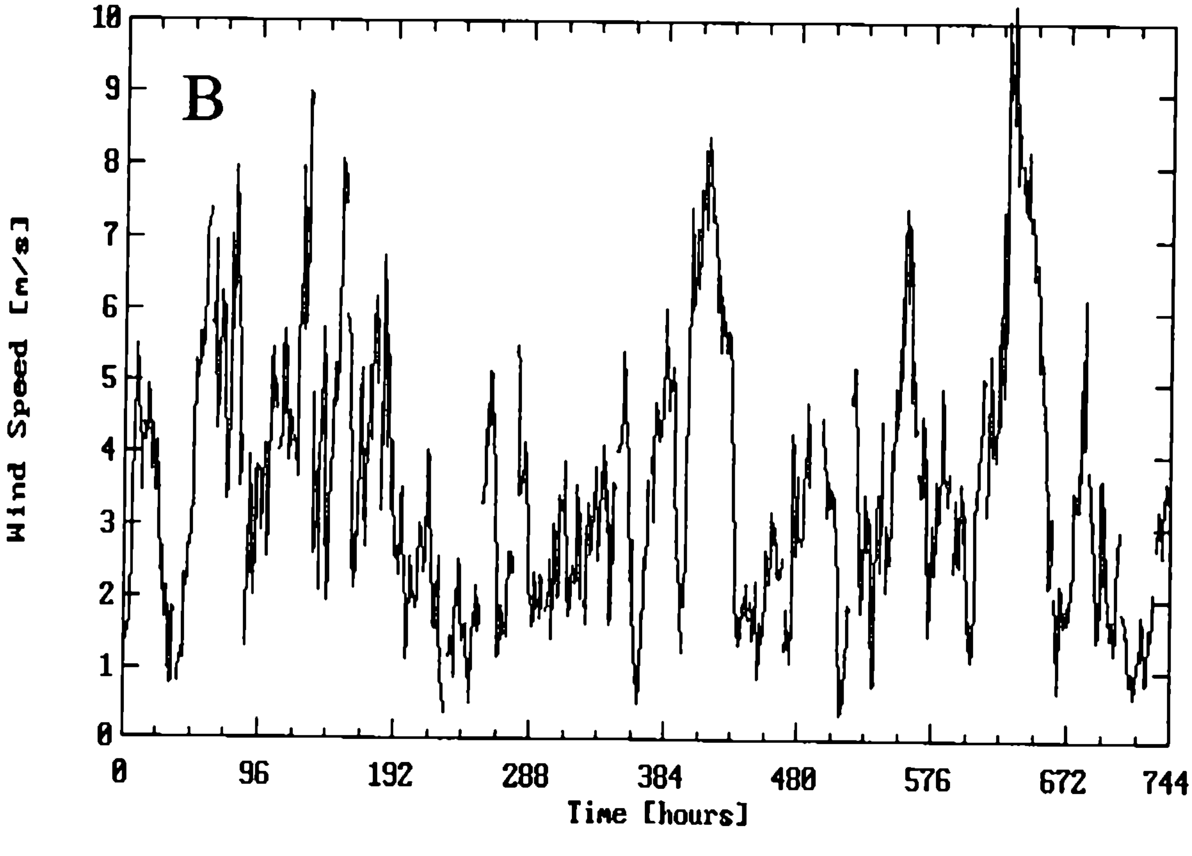
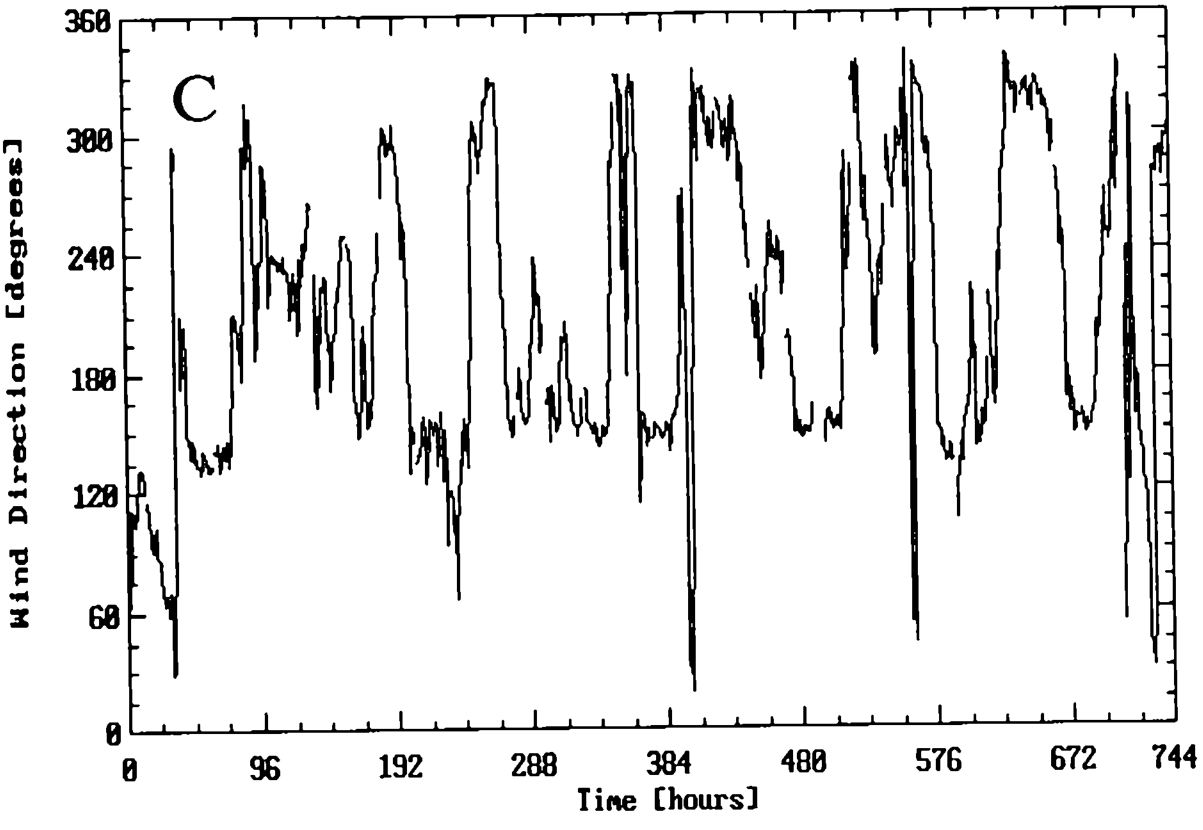
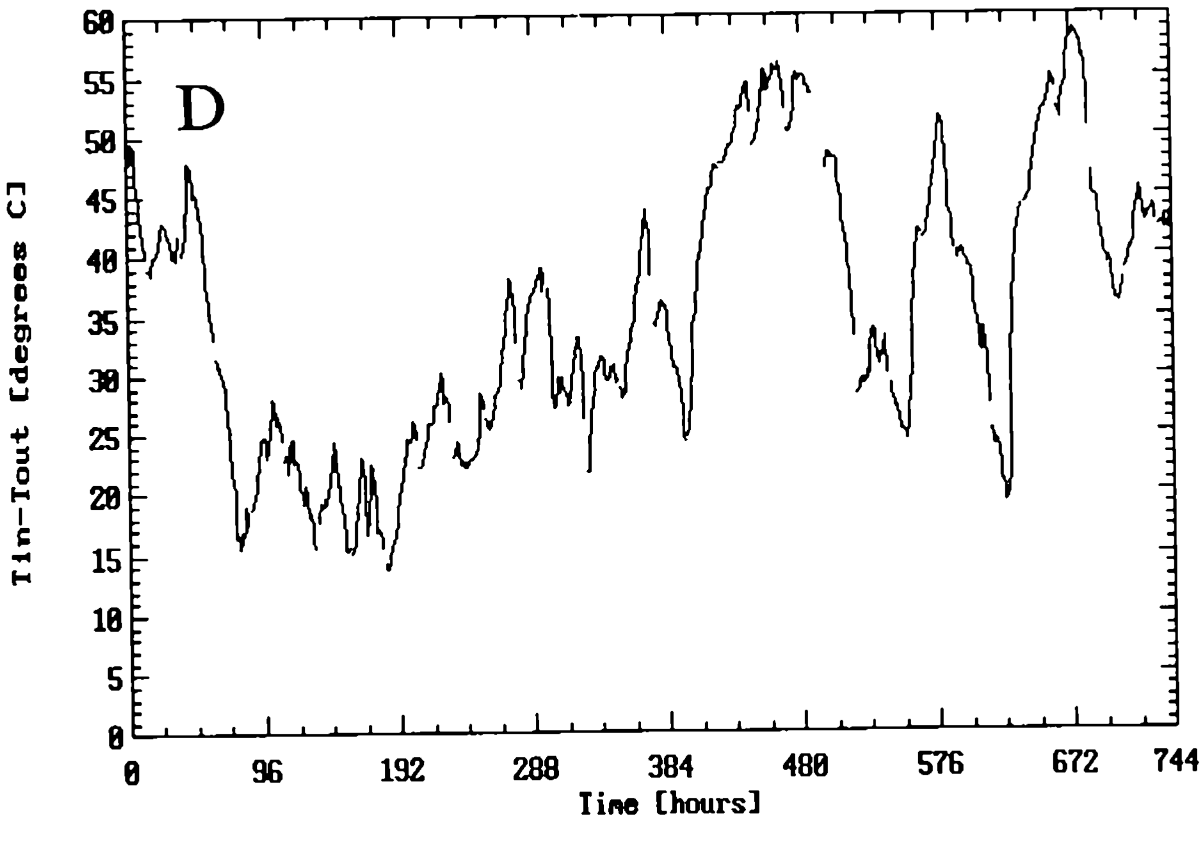


Figure 16. A Complete Month of Data from December 1990.


C
Wind Direction [degrees]
360
300
240
180
120
60
0
0
96
192
288
384
480
576
672
744
Time [hours]


D
Tin-Tout [degrees C]
60
55
50
45
40
35
30
25
20
15
10
5
0
0
96
192
288
384
480
576
672
744
Time [hours]

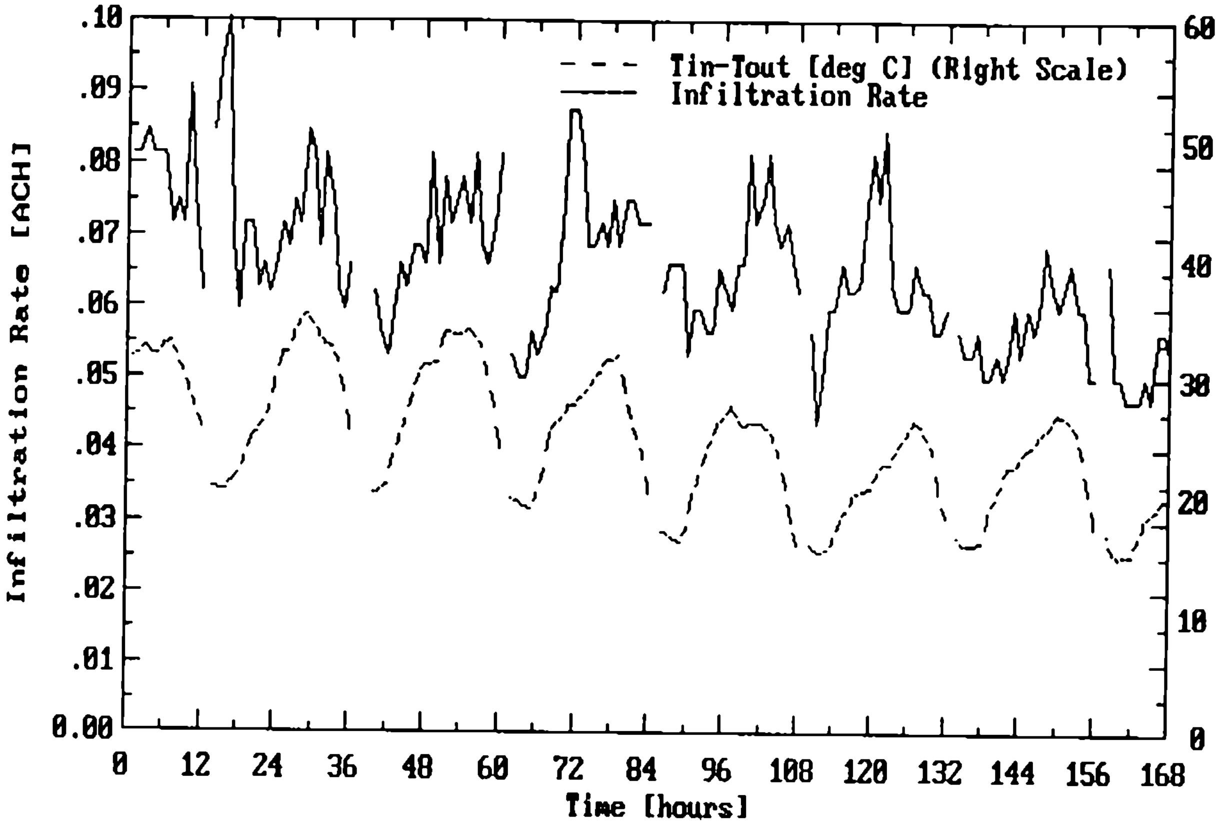


Figure 17. Diurnal Variation of Temperature Differences and Infiltration Rates. March 14th to 20th 1991.

APPENDIX

Table of Fan Pressurization Results

Pressure Difference is in Pascals and Flowrate in m^3/s.

Pressurization

Average Windspeed - 0.8 m/s
Average Tin - 22.8 degrees C
Average Tout - 9.8 degrees C

Pressure Difference	Flowrate
0.10	0.005
1.68	0.014
1.95	0.015
2.69	0.018
3.57	0.020
3.80	0.021
5.33	0.026
6.21	0.029
7.14	0.031
9.60	0.037
11.26	0.041
13.77	0.045
16.33	0.050
19.98	0.057
21.33	0.058
25.76	0.065
33.19	0.075
37.28	0.080
42.67	0.087
46.63	0.091
54.55	0.099
57.63	0.100
63.07	0.106
70.64	0.116
79.29	0.129
106.82	0.164

Depressurization

Average Windspeed - 1.1 m/s
Average Tin - 26.0 degrees C
Average Tout - 21.1 degrees C

Pressure Difference	Flowrate
0.15	0.003
1.79	0.013
1.70	0.012
2.03	0.014
3.10	0.018
3.86	0.020
4.76	0.023
5.72	0.025
8.05	0.031
9.24	0.034
10.87	0.038
13.44	0.043
16.70	0.049
17.82	0.052
22.18	0.060
27.38	0.069
30.99	0.074
36.74	0.082
43.02	0.091
46.31	0.095
52.01	0.103
56.51	0.108
61.29	0.115
68.76	0.125
77.60	0.137
105.11	0.171

90-12

DD:HH	Q	Tin	Tout	Wspd	Dir
01:01	23.5	20.9	-27.6	1.366	76
01:02	22.9	21.2	-26.7	1.525	64
01:03	23.5	21.2	-28.4	1.472	112
01:04	24.2	21.3	-28.0	1.981	109
01:05	25.9	21.2	-27.1	3.067	105
01:06	22.9	21.1	-25.0	3.637	104
01:07	27.7	21.3	-24.3	4.493	117
01:08	35.5	21.3	-22.5	5.315	130
01:09	40.8	21.3	-22.0	5.506	131
01:10	31.9	21.1	-21.1	4.622	132
01:11	32.5	21.3	-19.9	4.459	129
01:12	25.3	21.3	-18.7	3.457	121
01:13					
01:14	26.5	21.3	-17.8	4.371	115
01:15	24.1	21.0	-17.9	4.138	104
01:16	22.4	21.0	-17.6	4.698	99
01:17	21.2	21.2	-18.2	4.925	93
01:18	24.1	21.0	-19.1	4.590	91
01:19	20.6	21.0	-19.1	3.729	100
01:20	23.6	21.2	-19.2	4.006	103
01:21	22.4	20.9	-19.7	4.341	88
01:22	20.0	21.1	-20.2	3.462	87
01:23	22.9	21.2	-20.6	3.780	83
01:24	23.5	20.9	-21.5	4.137	76
02:01	23.5	21.1	-21.8	2.877	70
02:02	24.2	21.2	-21.4	2.349	64
02:03	23.5	20.9	-21.2	2.667	65
02:04	20.6	21.3	-20.7	2.157	69
02:05	21.7	21.0	-20.5	1.712	59
02:06	19.4	21.1	-19.9	2.142	70
02:07	20.0	21.2	-19.4	1.040	50
02:08	19.4	20.9	-19.2	1.020	29
02:09	19.4	21.2	-19.0	0.754	31
02:10	20.0	21.1	-18.7	0.908	182
02:11	18.8	21.0	-19.6	1.851	294
02:12	19.4	21.4	-20.4	1.778	284
02:13					
02:14	32.5	21.0	-19.2	0.810	210
02:15	20.6	21.3	-19.3	0.968	173
02:16	21.2	20.9	-20.1	1.148	198
02:17	20.6	21.0	-22.4	1.269	204
02:18	22.9	21.2	-24.7	1.123	164
02:19	23.5	20.9	-26.9	2.314	149
02:20	22.9	21.1	-26.4	2.141	146
02:21	24.7	21.1	-26.3	2.516	137
02:22	25.9	20.9	-25.9	2.705	146
02:23	24.1	21.1	-24.0	2.718	146
02:24	24.2	21.3	-23.9	3.161	136
03:01	25.9	21.1	-23.4	3.363	137
03:02	28.3	21.1	-23.5	4.408	134
03:03	35.5	21.2	-22.3	5.292	134
03:04	33.0	21.0	-21.2	5.028	130
03:05	38.4	21.2	-20.6	5.666	140
03:06	41.5	21.3	-19.0	5.687	141
03:07	38.4	21.0	-16.8	5.310	139
03:08	37.2	21.1	-15.5	5.951	135
03:09	42.0	21.1	-14.7	6.224	135
03:10	43.9	20.9	-14.0	7.059	131
03:11	44.4	21.2	-13.0	7.268	131
03:12	51.0	21.1	-12.2	7.408	133
03:13					
03:14	39.0	21.2	-10.3	5.806	141
03:15	37.3	20.9	-10.0	5.769	140
03:16	46.8	21.0	-9.9	6.970	145
03:17	39.6	20.9	-9.6	5.267	144
03:18	25.9	20.8	-9.2	4.320	131
03:19	36.6	21.0	-8.6	5.554	141
03:20	37.8	20.7	-7.5	5.722	144
03:21	39.6	21.0	-6.6	6.231	144
03:22	36.6	20.8	-5.3	5.550	137
03:23	37.8	20.8	-4.1	6.032	146
03:24	28.9	21.0	-2.3	4.788	141

DD:HH	Q	Tin	Tout	Wspd	Dir
04:01	18.2	20.8	-0.8	3.353	134
04:02	16.4	20.8	-0.6	3.736	155
04:03	28.9	21.1	2.6	5.877	192
04:04	37.2	20.9	4.5	7.040	210
04:05	27.1	20.9	4.2	5.699	211
04:06	43.8	20.8	5.2	7.967	204
04:07	36.0	20.8	4.1	6.490	196
04:08	34.2	20.8	3.9	6.654	195
04:09	28.9	20.8	4.2	5.766	189
04:10	25.9	20.9	3.2	5.567	177
04:11	15.9	21.0	2.0	3.528	177
04:12	18.2	21.1	3.5	4.208	294
04:13					
04:14	10.6	20.8	2.0	1.295	316
04:15	12.3	21.0	2.1	1.872	284
04:16	12.9	21.0	1.6	2.661	299
04:17	24.1	20.8	1.0	3.940	309
04:18	11.7	21.0	0.1	2.294	257
04:19	14.1	21.0	-0.5	2.508	252
04:20	13.5	20.9	-2.3	2.030	188
04:21	18.8	20.8	-3.7	3.746	213
04:22	15.3	20.8	-3.7	3.046	215
04:23	17.1	21.0	-3.8	3.829	237
04:24	17.1	20.9	-4.0	3.726	235
05:01	16.4	20.8	-2.8	3.756	246
05:02	12.9	20.8	-2.2	2.914	286
05:03	14.7	21.1	-3.1	3.662	283
05:04	14.1	20.9	-5.2	4.112	265
05:05	14.1	20.7	-6.8	2.799	243
05:06	14.1	21.1	-7.0	2.551	215
05:07	18.2	21.0	-6.3	3.721	237
05:08	20.6	20.8	-5.0	5.314	240
05:09	24.1	21.1	-5.1	5.452	239
05:10	22.9	20.9	-5.6	4.616	236
05:11	21.2	20.9	-4.6	5.018	238
05:12	17.0	21.1	-3.4	4.593	233
05:13					
05:14	15.9	21.0	-1.9	4.013	237
05:15	16.4	21.1	-2.3	4.173	233
05:16	17.0	21.0	-0.9	4.307	239
05:17	17.6	21.0	-1.3	5.448	232
05:18	19.4	21.1	-3.1	5.701	233
05:19	19.4	21.0	-3.6	4.721	231
05:20	19.4	20.8	-3.8	3.973	211
05:21	20.6	20.9	-1.8	3.895	208
05:22	18.8	21.1	-1.7	4.563	226
05:23	18.2	20.9	-1.6	4.238	231
05:24	21.2	20.8	-0.4	4.121	214
06:01	21.2	20.9	0.4	4.222	216
06:02	21.2	21.1	0.7	3.935	200
06:03	20.0	20.9	0.8	3.680	211
06:04	21.2	20.8	1.6	5.755	238
06:05	24.7	20.8	0.0	5.835	225
06:06	28.9	20.9	1.8	7.985	245
06:07	25.3	21.0	2.9	5.713	245
06:08	24.7	21.0	2.7	6.399	239
06:09	21.2	21.0	2.6	5.816	251
06:10	14.7	21.1	5.0	9.015	266
06:11	15.9	20.9	5.3	8.831	263
06:12	11.7	20.9	5.4	8.986	264
06:13					
06:14	17.0	20.8	3.1	4.817	230
06:15	14.1	21.1	2.5	2.580	174
06:16	12.3	21.1	1.8	2.789	163
06:17	16.4	21.0	2.0	3.739	210
06:18	12.3	20.9	1.3	2.092	197
06:19	16.4	20.9	1.9	3.968	224
06:20	15.9	20.8	1.4	4.580	223
06:21	17.6	20.9	0.4	5.748	229
06:22	15.9	21.1	0.1	4.204	224
06:23	15.9	21.0	-0.6	2.924	202
06:24	13.5	20.8	-2.5	1.948	197

DD:HH	Q	Tin	Tout	Wspd	Dir
07:01	14.1	20.7	-2.7	2.869	178
07:02	15.9	21.0	-3.4	3.356	172
07:03	18.8	20.9	-1.4	3.678	197
07:04	24.2	20.8	0.1	4.552	201
07:05	24.7	20.8	0.1	5.234	204
07:06	24.2	21.0	1.5	4.622	214
07:07	19.4	20.9	2.2	4.873	221
07:08	19.4	20.9	3.1	5.705	234
07:09	32.5	20.9	5.4	8.062	248
07:10	30.1	20.9	5.5	7.629	249
07:11	28.3	21.1	5.7	8.015	248
07:12	21.8	21.0	5.4	7.477	250
07:13					
07:14	22.4	21.1	5.9	5.918	246
07:15	20.0	21.1	5.5	5.671	239
07:16	17.6	21.0	4.6	5.556	231
07:17	17.0	20.9	3.4	4.909	223
07:18	12.9	20.9	2.2	2.450	167
07:19	12.9	20.9	-0.2	2.147	163
07:20	13.5	20.8	-1.5	2.872	149
07:21	15.3	21.0	-2.1	2.686	147
07:22	15.9	21.0	-1.6	3.200	149
07:23	21.2	20.9	2.0	4.837	196
07:24	24.2	20.8	4.2	5.157	204
08:01	18.2	20.8	3.9	4.348	204
08:02	14.7	20.9	2.1	3.117	170
08:03	14.1	21.0	-0.8	2.697	156
08:04	18.8	20.9	-1.5	3.741	153
08:05	20.6	20.8	-0.7	4.122	155
08:06	23.5	20.8	0.5	5.205	163
08:07	19.4	21.0	2.4	4.186	183
08:08	20.6	21.0	4.1	5.023	205
08:09	20.6	20.9	3.8	5.837	226
08:10	19.4	20.9	4.3	6.182	230
08:11	15.3	21.0	4.5	4.952	235
08:12	12.3	20.9	5.3	5.294	251
08:13					
08:14	8.8	21.1	6.8	4.656	269
08:15	10.6	21.3	7.4	3.207	292
08:16	31.2	21.1	7.3	6.734	303
08:17	22.9	21.1	5.9	5.307	300
08:18	17.1	20.9	5.2	4.048	300
08:19	19.4	20.9	5.2	5.655	289
08:20	17.6	20.9	4.8	4.527	292
08:21	12.9	20.9	3.8	3.207	293
08:22	18.2	20.9	3.0	4.125	305
08:23	15.9	20.8	1.9	3.325	295
08:24	13.5	20.8	0.7	2.557	294
09:01	12.9	20.9	0.0	2.536	281
09:02	12.9	21.0	-0.5	2.705	275
09:03	14.1	20.9	-1.1	2.318	275
09:04	15.9	20.8	-2.4	3.407	238
09:05	15.9	20.9	-2.6	3.528	251
09:06	14.7	21.0	-3.6	2.678	256
09:07	15.3	20.8	-3.6	2.349	241
09:08	13.5	20.8	-3.6	1.144	190
09:09	14.7	21.1	-4.5	1.791	130
09:10	15.3	20.9	-5.1	1.693	148
09:11	15.3	20.9	-4.8	2.558	153
09:12	14.7	21.1	-3.4	1.985	145
09:13					
09:14	14.7	21.0	-1.2	2.060	135
09:15	13.5	21.0	-1.3	1.831	139
09:16	14.7	20.9	-1.5	2.288	138
09:17	15.3	20.8	-2.1	2.584	139
09:18	15.3	21.0	-2.7	3.012	155
09:19	15.9	21.0	-3.3	2.775	158
09:20	15.9	20.8	-4.1	2.461	138
09:21	14.1	20.9	-5.0	2.360	124
09:22	17.0	21.1	-4.8	2.819	136
09:23	20.0	20.8	-5.1	4.022	156
09:24	20.0	20.8	-5.5	3.757	153

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The Air Infiltration and Ventilation Centre provides technical support to those engaged in the study and prediction of air leakage and the consequential losses of energy in buildings. The aim is to promote the understanding of the complex air infiltration processes and to advance the effective application of energy saving measures in both the design of new buildings and the improvement of existing building stock.

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