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The validation and comparison of mathematical models of air infiltration

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Annex V Air Infiltration Centre

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PREFACE

International Energy Agency

In order to strengthen cooperation in the vital area of energy policy, an Agreement on an International Energy Program was formulated among a number of Industrialised countries in November 1974. The International Energy Agency (IEA) was established as an autonomous body within the Organisation for Economic Cooperation and Development (OECD) to administer that agreement. Twenty-one countries are currently members of the IEA, with the Commission of the European Communities participating under a special arrangement.

As one element of the International Energy Program, the Participants undertake cooperative activities in energy research, development, and demonstration. A number of new and improved energy technologies which have the potential of making significant contributions to our energy needs were identified for collaborative efforts. The IEA Committee on Energy Research and Development (CRD), assisted by a small Secretariat staff, coordinates the energy research, development, and demonstration programme.

Energy Conservation in Buildings and Community Systems

The International Energy Agency 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, etc. The difference and similarities among these comparisons have told us much about the state of the art in building analysis and have led to further IEA sponsored research.

Annex V Air Infiltration Centre

The IEA Executive Committee (Building and Community Systems) has highlighted areas where the level of knowledge is unsatisfactory and there was unanimous agreement 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 to 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 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 a firm basis for future research in the Participating Countries.

Current participants in this task are Belgium, Canada, Denmark, Netherlands, New Zealand, Norway, Sweden, Switzerland, United Kingdom and United States of America. Italy also participated during the course of the model validation programme.

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Canada	Dr John Shaw National Research Council, Ottawa, Canada *(NRC Model)*
Netherlands	Mr Willem de Gids Institute for Environmental Hygiene-TNO, Delft, Netherlands *(TNO Model)*
Norway	Dr Sivert Uvsløkk Norwegian Building Research Institute, Trondheim, Norway *(NBRI Model)*
United Kingdom	Dr David Etheridge British Gas Corporation, London, UK *British Gas Model*
	Dr Peter Warren Building Research Establishment, Watford, UK *(BRE Model)*
	Mr Anthony Wilson The Oscar Faber Partnership, St. Albans, UK *(Oscar Faber Model)*

In addition, advice and assistance regarding specific models was gratefully received from:

United States of America	Mr James T. Cole Institute of Gas Technology, Chicago, USA *(IGT Model)*
	Dr Max Sherman Lawrence Berkeley Laboratory, California, USA *(LBL Model)*

Finally, numerical data for inclusion in this exercise were received from:

Canada	Dr John Shaw National Research Council, Ottawa, Canada
Netherlands	Mr Willem de Gids Institute for Environmental Hygiene-TNO, Delft, Netherlands
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	Dr David Etheridge British Gas Corporation, London, UK
United States of America	Dr Max Sherman Lawrence Berkeley Laboratory, California, USA
	Mr M.B. Stewart Owens-Corning Fiberglas Corporation, Granville, Ohio, USA

SUMMARY

This report describes the results of the Air Infiltration Centre's programme of model validation. The task involved the selection, performance assessment and comparison of mathematical models used to calculate hourly mean rates of air infiltration and fresh air exchange in buildings. It also involved the identification of the fundamental parameters necessary to achieve reliable results. This work was carried out under Annex V of the International Energy Agency implementing agreement on Energy Conservation in Buildings and Community Systems.

A total of ten models were selected for analysis; these ranged in complexity from single cell approaches, in which the interior of the building is assumed to be at a uniform pressure, to multi cell methods in which the interior of the building may be divided into regions of differing pressure interconnected by leakage paths. Empirical models developed for specific buildings, or having limited applications, were not included in this study.

To enable the performance of each model to be assessed, a number of key data sets were prepared. Each related to a specific building and contained sufficient experimentally measured data to satisfy the input needs of the selected models. They also contained corresponding direct measurements of air infiltration rates against which the calculated rates of air infiltration could be compared. The data sets were based on measurements made in dwellings and were selected to represent as wide a range of construction methods and climatic conditions as possible.

Model performance was judged on the consistency with which computations were within ±25% of the measured air infiltration rate. This level of accuracy was derived on the basis of possible errors resulting from measurement inaccuracies in both the input data and the air infiltration rate measurements.

Generally, excellent agreement between calculated and measured air infiltration rates was obtained, with a significant proportion of the results being well within the specified tolerance bands. The results were therefore extremely encouraging and illustrated the wide potential of air infiltration models. Important parameters included the external pressure distribution (inferred from wind and temperature data) and the air leakage characteristics of the building. The most difficult parameter to quantify was found to be the wind pressure distribution and it is thought that much improved results would be possible if a series of wind tunnel tests was performed to determine appropriate pressure coefficients for fixed degrees of shielding and a small range of building shapes.

1. INTRODUCTION

One of the main tasks of the Air Infiltration Centre has been to undertake an extensive programme of air infiltration model validation. The pressing need for this study became apparent following earlier investigations within the IEA's energy conservation in building and community systems programme, which showed a wide scatter in the results of building energy consumption predictions.[1] A subsequent analysis of these results revealed that, although air infiltration and ventilation can account for between 25 and 50% of the space heating demand of a building, they had not been given the same attention in energy calculations as other heat loss mechanisms. This model validation project is one specifically listed in the Annex V text.

The principal objectives of this study were to use experimental data to assess the reliability and full range of applicability of mathematical models used in the calculation of hourly mean rates of air infiltration, and to identify the key parameters which must be accurately specified in order to achieve reliable results.

This programme has progressed in five stages; these being to

- select appropriate models of air infiltration.
- establish the data needs of each model.
- prepare high quality data sets based on the results of as wide a range of experimental measurements as are available.
- use the available data to verify and assess the performance of the selected models.
- identify the key parameters of each model by means of a sensitivity analysis.

The results of this validation exercise are described in this report.

A total of ten models developed in five of the participating countries were selected for analysis. These range in complexity from 'single-cell' approaches in which the interior of the building is assumed to be at a single uniform pressure, to 'multi-cell' techniques in which the interior is subdivided into zones of differing pressure interconnected by leakage paths. Numerical data, based on air infiltration measurements and associated climatic data for fourteen dwellings, were also compiled for this study. From these data, three key data sets for use in each of the selected models were prepared and the remaining data were used for additional investigations as necessary.

The selected models are briefly described in Section 2 of this report. This is followed by a description of the numerical data sets in Section 3. The results are presented in full in Section 4 and a comparison between the performances of individual models, including an outline of their principal strengths and weaknesses is given in Section 5. Finally, an analysis of model parameters is presented in Section 6.

REFERENCES

1. International Energy Agency (IEA)
Air infiltration in buildings – draft program plan
US Department of Energy, October, 1979.

2. SELECTION AND DESCRIPTION OF MODELS

A wide variety of modelling techniques has been developed to cope with the problems of estimating the hourly mean rate of air infiltration in buildings. In general, these can be divided into two categories. The first comprises empirical approaches in which the physics of air flow is treated in very restricted terms. The second is based on a more fundamental approach involving the solution of the equation of flow for air movement through openings in the fabric of a building. While empirical approaches are normally fairly straightforward to apply, they either tend to be unreliable or to have a very limited field of application. On the otherhand, theoretical models have a potentially unrestricted range of applicability but can be very demanding on data. Because they have a more general application, this validation programme has concentrated on the latter variety of models.

A total of ten models were identified and selected for this study; these are listed in Table 2.1 and are described in further detail below. Typically, they take the form of a flow network in which nodes representing regions of differing pressure are interconnected by flow paths. Models 1–5 (Table 2.1) are of the 'multi-cell' variety in which the interior of the building may be divided into individual rooms or sections of differing pressures. The remaining models are 'single cell' approximations in which the interior of the building is assumed to be at a single uniform pressure. Models 3 and 5 include parameters to account for the non-steady contribution to flow arising from turbulence-induced pressure fluctuations.

Table 2.1: List of selected models

Ref No.	Name	Country
1	Building Services Research and Information Association (LEAKS)	United Kingdom
2	National Research Council	Canada
3	IG-TNO Institut voor milieuhygiene en gezondheidstechniek (ELA 4)	Netherlands
4	Oscar Faber Partnership (SWIFIB)	United Kingdom
5	British Gas model (VENT)	United Kingdom
6	Norwegian Building Research Institute (ENCORE)	Norway
7	Gas Research Institute/Institute of Gas Technology	United States of America
8	Lawrence Berkeley Laboratory	United States of America
9	Building Research Establishment	United Kingdom
10	Reeves, McBride, Sepsy model	United States of America

2.1 Building Services Research and Information Association model – LEAKS[1]

This is a 'multi-cell' model developed by the Building Services Research and Information Association to predict ventilation rates and air movement in buildings for a given set of conditions.

The building under consideration is divided into a set of nodes interconnected by flow paths. Each node represents a space inside or outside the building where substantially uniform pressure conditions prevail and the interconnections correspond to impedences to air flow. The model is written in FORTRAN and operates on a PRIME 300 computer. The maximum permissible number of nodes is 135 and the maximum number of interconnections to any node is 20.

The model is used to calculate the total air change rate for each internal node, the fresh air change rate for each internal node connected to an external node, and the overall fresh air change rate for the building.

The equation relating air flow through each component, with a pressure difference, $\triangle P$, across it is given by

$$Q = K(\triangle P)^{1/N} \quad (m^3 s^{-1})$$

where Q = flow rate ($m^3 s^{-1}$)
$\triangle P$ = pressure difference across leakage component (Pa)
K = flow coefficient ($m^3 s^{-1}$ at 1 Pa)
$^1/N$ = flow exponent

The input requirements for the model are

(i) flow coefficient and flow exponent for each flow path.

(ii) room volumes (m^3)

(iii) mechanical ventilation for each internal node ($\pm\ m^3 s^{-1}$)

(iv) surface pressures associated with each external node (Pa)

(v) building height (m)

(vi) level of openings (m)

(vii) external/internal air temperatures (° C)

(viii) wind speed and direction ($m\ s^{-1}$)

(vi)–(viii): to calculate surface pressures

The K and N values may be determined directly from leakage tests made on each leakage path or from published values such as those given in Chapter 22 of the 'ASHRAE Fundamentals'. Alternatively, it is possible to make use of the leakage characteristics determined by pressure testing the entire building. In this instance, the total leakage is distributed according to the leakage area or crack length represented by each leakage path.

The surface pressures are derived using an input program which combines predetermined wind pressures with a stack pressure. In general, direct measurements of surface pressure are not available and therefore have to be inferred from other data. In these circumstances, the pressure resulting from wind impingeing on the surface of the building (relative to the static pressure of the free wind) is given by

$$P_w = \frac{\rho}{2} C_p V^2 \quad (Pa)$$

where P_w = pressure due to wind (Pa)
ρ = air density ($Kg\ m^{-3}$)
C_p = pressure coefficient
V = wind speed at building height ($m\ s^{-1}$)

The pressure coefficient is assumed to be independent of wind speed but is a function of both wind direction and position on building surface. Most information on pressure coefficients comes from the results of wind loading tests made in wind tunnels on scale models of isolated buildings. Typical values are published by the British Standards Institute (BS 5925: 1980).

The pressure difference resulting from stack action between two vertically displaced openings is given by

$$P_s = \rho_o g\, 273h \left[\frac{1}{T_E} - \frac{1}{T_I}\right] \quad \text{(Pa)}$$

where P_s = stack pressure (Pa)
ρ_o = air density at 273K (Kg m^{-3})
h = vertical displacement between openings (m)
T_E = external temperature (K)
T_I = internal temperature (K)

Mechanical ventilation is accommodated by specifying the flow rate at each internal node.

2.2 National Research Council of Canada model[2a,b]

The purpose of this model is to calculate air flows and pressure differentials that occur in a building as a result of a combination of wind effect, stack action and the operation of air handling systems.

The computer program is written in FORTRAN IV and is currently available in Imperial units only. This program also forms the basis of the air infiltration sub-program 'INFIL' contained in the US National Bureau of Standards computer program for calculating heating and cooling loads in buildings.[2b]

The building is represented by a series of vertically stacked compartments interconnected by vertical shafts. Each shaft is terminated by two vents which may be located at any desired floor level. Leakage openings are specified for each external wall and for all floors and shaft walls, thus enabling air to pass from every compartment or cell to adjacent cells and to each of the vertical shafts. In order to reduce computing time, each cell may represent a number of building storeys.

The equation defining flow through each opening is given by

$$F = EA(\Delta P)^x \quad \text{(cfm)}$$

where F = air flow rate (cfm)
EA = flow coefficient (cfm.in^x at 1" wg)
ΔP = internal pressure difference (in wg)
x = flow exponent ($0.5 \leq x \leq 1.0$)

The model assumptions and limitations are

(i) friction resistance of vertical shafts is neglected.

(ii) net air supplied by the air handling system is assumed to be constant and independent of building pressures.

(iii) each component has an open floor plan with no provision for separate rooms or vestibules.

(iv) pressures, flows and leakage openings are assumed to occur at the mid-height of each level.

(v) temperatures inside each compartment and shaft are assumed to be constant at 75°F (24°C). (Other temperatures may be accommodated, however, simply by making an appropriate adjustment to the outside temperature.)

Input requirements include

(i) flow coefficient and flow exponent for each flow path.

(ii) number of floors.

(iii) distance between floors.

(iv) number of shafts.

(v) location of openings.

(vi) wind pressure (inferred from wind speed data).

(vii) external temperature.

2.3 IG-TNO Institut voor Milieuhygiene en Gezondheidstechniek – ELA 4[3]

This program, developed at IMG-TNO, Delft, was devised to replace an electrical analogue model used for air movement studies. This is a multi-cell model used to predict room pressures, air flows between the rooms and flows across the outside walls.

The building is characterised by a network in which each connection is described uniquely by two pairs of integers representing the 'from' and 'to' nodes for each connection respectively. The first number of each pair is the node number and the second the level number (set to zero for external nodes). The model, with a declared memory space of 52K, can accommodate up to 500 connections, i.e. 20 rooms with a maximum of 25 connections and 9 levels per room, up to 99 external nodes (wind pressure values) and 1 mechanical exhaust (+) or supply (–) per room.

The flow equation used is

$$Q = C(\Delta P)^{1/N} \quad (m^3 s^{-1})$$

where C = flow coefficient
ΔP = internal/external pressure difference (Pa)
$^1/N$ = flow exponent

Input requirements include

(i) number of rooms.

(ii) node connection descriptions.

(iii) C and N values for each connection.

(iv) temperature gradient (optional).

(v) facade/roof pressures for external nodes.

(vi) extract/supply flow rate, if any, for each room.

The program uses an iterative technique to arrive at room pressures and performs satisfactorily for flow coefficient ratios up to 1:1000. The effects of window opening and natural wind pressure fluctuations are included in the calculation method.

The practice of numbering internal and external nodes separately makes it relatively easy to modify the network. Furthermore, by specifying individual node levels, it is possible for more than one connection to be made between a room and the outside.

2.4 Oscar Faber model – 'SWIFIB'[4]

This program calculates air flows through a building envelope and may be used for predicting ventilation rates or as a pre-processor for smoke movement calculations. It considers the building as a 'multi-cell' network in which individual rooms are represented as nodes, and cracks and ventilation ducts are represented by connecting paths. The model caters for effects due to

– stack pressures.
– wind pressures.
– mechanical ventilation.

Output from the program includes

– room pressures (relative to a specified datum).
– mass flow rates (or air change rates) for each node.

Data requirements are

(i) *Flow description*

- – number of rooms.
- – volume of each room (m^3).
- – height of room above specified datum level (m).
- – room temperature (°C).
- – flow path interconnections.

(ii) *External data*

- – wind velocity reference height (m above datum).
- – wind velocity at reference height ($m\ s^{-1}$).
- – terrain index (defining roughness characteristics of surrounding area – used to calculate wind velocity profile).
- – atmospheric pressure (Pa).
- – external temperature (°C).

(iii) *Wind pressure data*

- – calculated from

$$\triangle P = C_p \frac{\rho}{2} V^2 \quad \text{(Pa)}$$

where C_p = pressure coefficient
ρ = air density ($Kg\ m^{-3}$)
V = wind speed ($m\ s^{-1}$)

The flow equations used are

$$Q = K\rho\ (\triangle P)^n \quad (m^3 s^{-1}) \qquad \text{(for leakage components) and}$$
$$Q = K_1 + K_2 \triangle P + K_3 \triangle P^2 \quad (m^3 s^{-1}) \qquad \text{(for mechanical ventilation components)}$$

where K = flow coefficient
n = flow exponent
K_1 =
K_2 = } coefficients describing the fan characteristics of the mechanical ventilation system.
K_3 =

2.5 British Gas model – VENT[6a,b]

This is a ventilation program devised by British Gas to predict individual room and whole house flow rates. It is used for estimating heat losses, water vapour removal, radiator sizing and ventilation studies, etc. VENT is a 'multi-cell' model written in FORTRAN and run on both a Univac 3600 mainframe and a CAI Alpha minicomputer.

The flow equations used in VENT depend on the type of opening and are given by

$$\overline{Q} = C_z A \left[\frac{2\overline{\Delta P}}{\rho}\right]^{1/2} \quad (m^3 s^{-1}) \qquad \textit{for purpose provided openings}$$

$$CAQ^{-2} + \frac{B_z L^2 \mu \overline{Q}}{\rho} - \frac{2A^3 \overline{P}}{\rho} = 0 \qquad \textit{for component and 'background' leakages}$$

where
- A = physical area of crack (m)
- B = } constants dependent
- C = } on crack geometry
- C_z = discharge coefficient
- L = length of crack (m)
- $\overline{\Delta P}$ = mean pressure difference across opening (Pa)
- $\overline{Q}$ = mean flow through crack ($m^3 s^{-1}$)
- z = depth of crack (m)
- ρ = density of air ($Kg\ m^{-3}$)
- μ = viscosity of air ($N.s.m^{-2}$)

A contribution arising from flow reversal due to turbulence is included, described by

$$\overline{Q}_T = F.0.4\left[\frac{2}{\pi}\right]^{1/2} . \frac{\Delta P_{RMS}.\overline{Q}}{\overline{\Delta P}} \quad (m^3 s^{-1})$$

where
- $\overline{Q}_T$ = mean turbulent flow contribution ($m^3 s^{-1}$)
- F = function of mean pressure difference (see text)
- ΔP_{RMS} = RMS pressure difference across crack (Pa)

A Gaussian distribution of ΔP is assumed. ΔP_{RMS} is estimated from P_{RMS} based on an RMS pressure coefficient of 0.3. The factor F allows this term to be suppressed for mean pressure gradients large enough to prevent flow reversal. F is interpolated linearly between

1 for $\overline{\Delta P} = 0$ and
0 for $\overline{\Delta P} > 3\Delta P_{RMS}$

The stack pressure is estimated using

$$P_s = 3462\left[\frac{1}{T_E} - \frac{1}{T_I}\right](H - N) \quad (Pa)$$

where
- T_E = external temperature (°C)
- T_I = internal temperature (°C)
- N = height of neutral plane of the cell in which the opening appears (m)
- H = height of opening above reference level (m)

The input requirements for the model are

(i) external pressure distribution.

(ii) internal and external temperatures.

(iii) leakage distribution.

The internal pressures for flow continuity are found by an interactive procedure.

In addition to the main model, a single cell version, known as VENT 2, has been developed.[6b] VENT 2 can be run on HP 87 and Tektronix 4051 desk-top computers. It retains the main features of VENT but the data input is significantly reduced.

2.6 Norwegian Building Research Institute model – ENCORE[6]

ENCORE is a complete energy analysis program for residential buildings, which contains a 'single-cell' model for calculating air infiltration based on a flow balance approach. The model is used to calculate mean hourly rates of ventilation throughout the heating season.

The overall air leakage is first found by means of a pressurization test and the results are apportioned according to the distribution of leakage components over the building envelope. The air flow through each component is then computed using an exponential form of the flow equation given by

$$q_l = \left(\frac{\Delta P_l}{R_l}\right)^{B_l} \quad (m^3s^{-1})$$

where
q_l = flow rate through opening (m^3s^{-1})
ΔP_l = pressure difference across opening (K Pa/m^2)
R_l = flow resistance
B_l = flow exponent ($0.5 \leq B_l \leq 1.0$)

The flow resistance, R_l, is calculated by means of the formula

$$R_l = \frac{50.0.1}{(Q_i\, n_{50}\, V/3600)^{1/7}}$$

where
R_l = flow resistance for i'th opening
n_{50} = building leakage factor (h^{-1} at 50 Pa)
Q_i = relative share of total leakage that passes through i'th opening (m^3s^{-1})
V = volume of building (m^3)

An iterative technique is used to calculate an internal pressure such that a flow balance between incoming and outgoing air is achieved.

The following data are necessary for computation:

(i) *Outdoor data*

- external air temperature (°C)
- wind speed (at 10m above ground) (m s^{-1})
- wind direction
- terrain category

(ii) *Constructional data*

- leakage factor
- leakage distribution
- shape of building (height/width, length/width)
- roof angle (°)
- height (m)
- volume (m^3)

(iii) *Ventilation conditions*

- type of ventilation system

- number of exhaust ducts
- diameter, length, type and fan capacity of each exhaust duct
- type and number of air inlets

Pressure data is inferred from measurements of wind and temperature. The wind induced pressure at each leakage location is given by

$$P_{Vi} = C_i \rho \frac{V^2}{\rho} \quad \text{(Pa)}$$

where P_{Vi} = wind pressure across i'th opening (Pa)
C_i = wind pressure coefficient across i'th opening
ρ = external air density (Kg m^{-3})
V = computed wind speed at a reference level equal to the mid-height of the building (m s^{-1})

The pressure coefficient data for eight building shapes are contained within the model and the appropriate shape, based on the external dimensions of the building, is automatically selected.

2.7 Gas Research Institute/Institute of Gas Technology model – INFIL

Program INFIL is a 'single-cell' simulation model for residential buildings. It is written in FORTRAN IV occupying < 13K bytes and requiring approximately 200 storage locations. A simplified version of the program has been generated for an HP-41-C programmable calculator.

INFIL was developed at the Institute of Gas Technology in Chicago, USA as an aid to calculating heating and cooling loads and assessing air quality. The model uses the characteristics of the structure, its heating system and the weather conditions to calculate the position of a 'neutral' plane on the leeward side of the house and thence the infiltration, exfiltration and chimney flow rates.

The flow equation used is

$$F = K \triangle P^n \quad \text{(cfm)}$$

where F = flow rate (cfm)
K = flow coefficient
$\triangle P$ = internal/external pressure difference (in wg)
n = flow exponent

A combined 'neutral' plane is defined, taking into account the effects of both wind and stack pressures. Envelope pressures below this plane are positive with respect to the interior, while above this plane envelope pressures are negative.

Air infiltration is given by

$$\text{Infiltration} = \int_0^{Y} K_x (C\rho_o gh - C\rho_i gh)^n dh + \int_0^{Y+z} K_l (C\rho_o gh - C\rho_i gh)^n dh \quad \text{(cfm)}$$

where C = unit conversion factor
g = acceleration due to gravity (ft s^{-2})
h = level of opening (ft)
K_x = leakage coefficient for leeward side
K_l = leakage coefficient for windward side
Y = level of leeward side 'neutral' plane (ft)
z = height difference between windward and leeward 'neutral' planes (ft)
ρ_o = external air density (lbs ft^3)
ρ_i = internal air density (lbs ft^3)

By continuity, air infiltration is balanced by exfiltration above the 'neutral' plane and air flow through the chimney (if present). These are given by

$$\text{Exfiltration} = \int_o^{H-Y-z} K_l \, (C\rho_o gh - C\rho_l gh)^n \, dh$$

$$+ \int_o^{H-Y} K_x \, (C\rho_o gh - C\rho_l gh)^n \, dh \quad \text{(cfm)}$$

and

$$\text{Chimney flow} = F_c = \frac{K_c}{T_c} \, ½ \left[\triangle P_x + 0.26 \, Bhc \left[\frac{1}{T_o} - \frac{1}{T_c} \right] \right]^n \text{(cfm)}$$

respectively, where

- B = barometric pressure (in.wg)
- F_c = chimney flow (cfm)
- H = height of building (ft)
- $\triangle P_x$ = internal/external pressure difference (in.wg)
- T_o = internal air temperature (°F)
- T_c = chimney temperature (°F)
- K_c = chimney characteristics

It is assumed that

(i) the pattern of crackage across a wall is uniform.

(ii) permeability of each wall is uniform but may differ between walls.

(iii) $n = 0.5$.

(iv) the wind pressure force on the windward walls is positive and does not cause pressure disturbance on the other walls.

(v) for wind directions that are not perpendicular to a wall of the house, the wind pressure effect is proportional to the cosine of the wind angle (relative to the windward face) x windspeed.

The input requirements of the model are grouped into fixed parameters, which are entered only once and variable parameters, which are entered for each set of conditions to which the house is exposed. The fixed parameters are

(i) The height of the house to the eaves from the reference level. If there is no basement, the floor level of the lowest storey is used.

(ii) The volume of the house (ft^3).

(iii) The wind shielding factor. This is the multiplier for the 10 metre 'open country' windspeed and is used to calculate the windspeed at eaves height. The conversion formula is

$$\frac{V}{V_{10}} = ah^b$$

a and b are parameters that vary with terrain and V_{10} is the standard 33ft (10m) wind speed measurement height.

(iv) The crack inventory. This relates door, window and cill leakages to crack length.

(v) Permeability of the house. This can be estimated by calculation from field measurements of air change rate.

(vi) The heating system parameters, i.e. chimney height above the reference level and the chimney flow characteristics. The latter is zero for an electric furnace.

The variable parameters are:

(i) Wind speed (at 33ft) in mph.

(ii) Wind direction. This takes the value 1 to 8 by 45° sectors with 8 representing a wind normal to the 'front' facade.

(iii) Internal temperature (°F).

(iv) External temperature (°F).

(v) Chimney temperature (°F).

The computer output includes the calculated total infiltration rate and chimney flow for each set of weather conditions. An important feature of this model is its ability to include explicitly the effects of a fossil fuel fired heating system.

2.8 Lawrence Berkeley Laboratory model[8]

This model was developed to predict the impact on air infiltration rates of retrofit and other changes in the building envelope using the minimum number of model parameters. The model was specifically designed for simplicity and therefore precise detail was sacrificed for ease of application.

Model parameters include

(i) leakage of structure.

(ii) ratio of floor/ceiling leakage to wall leakage.

(iii) height of building.

(iv) internal/external air temperature difference.

(v) wind speed.

(vi) terrain class.

(vii) shielding class.

The building is approximated by a single rectangular structure of 'single-cell' construction, through which air flow is described by the equation

$$Q = A\left[\frac{2}{\rho}\Delta P\right]^{1/2} \quad (m^3s^{-1})$$

where A = effective leakage area (m^2)
ρ = air density ($Kg\,m^{-3}$)
ΔP = internal/external pressure difference (Pa)

The effective leakage area, A, is determined by means of a building pressurization test.

The rates of air infiltration due to wind and stack driven pressure differences are calculated independently and are combined by summing the results in quadrature. The influence of mechanical ventilation systems is similarly included in the quadrature equation to yield a total ventilation rate of

$$Q\,total = (Q^2_{stack} + Q^2_{wind} + Q^2_{vent})^{1/2} \quad (m^3s^{-1})$$

where Q_{stack} = $A\,f_s\,\Delta T^{1/2}$ = stack infiltration (m^3s^{-1})
Q_{wind} = $f_w\,V$ = wind infiltration (m^3s^{-1})
Q_{vent} = flow rate of mechanical ventilation system (m^3s^{-1})
ΔT = internal/external temperature difference (K)
V = wind speed at roof ridge height ($m\,s^{-1}$)

and f_s and f_w are stack and wind parameters respectively.

The wind and stack parameters convert the wind speed and the internal/external temperature differences into equivalent pressures across the leakage area of the building. Terrain and shielding coefficients are used to calculate wind induced pressures from either 'on-site' or 'remote' wind speed data.

2.9 Building Research Establishment model[9]

The purpose of this model is to provide a method for relating air infiltration rate for any given set of conditions to the leakage characteristics of the building as determined by a pressurization test. Air movement under ambient conditions is described by the power law equation

$$Q_v = Q_T \left[\frac{\rho_o V^2}{\Delta P_T}\right]^n F_V(A_r, \varnothing) \quad (m^3 s^{-1})$$

where
Q_V = ambient flow rate ($m^3 s^{-1}$)
Q_T = flow rate at an arbitrarily chosen reference pressure ($m^3 s^{-1}$)
ρ_o = air density ($Kg\ m^{-3}$)
V = wind speed at roof ridge height ($m\ s^{-1}$)
ΔP_T = internal/external pressure difference (Pa)
F_V = infiltration rate function (see text)
A_r = Archimedes number
$\varnothing$ = surface pressure function

For wind action alone, this equation reduces to

$$Q_w = Q_T \left[\frac{\rho_o V^2}{\Delta P_T}\right]^n F_w(\varnothing) \quad (m^3 s^{-1})$$

where F_w = wind infiltration function

while for stack effect only, the flow equation becomes

$$Q_B = Q_T \left[\frac{\Delta T \rho g h}{T_i \Delta P_T}\right]^n F_B \quad (m^3 s^{-1})$$

where
F_B = stack infiltration function
ΔT = internal/external temperature difference (K)
T_i = internal temperature difference (K)
g = acceleration due to gravity ($m\ s^{-2}$)
h = height of building (m)
ΔP = reference pressure difference (50 Pa)

The infiltration function F_B is determined by the building shape and the distribution of leakage; F_w in addition depends upon the surface pressure coefficients, while F_v includes the effects of the major weather dependent parameters V and ΔT.

Assumptions and limitations

(i) The heated volume of the building is approximated by a single rectangular parallelipiped of height, h.

(ii) The pressure generated by the wind is assumed to be uniform across each face of the building and is inferred directly from wind data using the equation

$$P_i - P_o = \frac{C_{p_i} \rho_o}{2} V^2 \quad (Pa)$$

where
P_i = wind pressure (Pa)
P_o = pressure of free stream (Pa)
C_{p_i} = pressure coefficient for i'th face

(iii) The appropriate value of wind speed is given by

$$U = U_r \left[\frac{H}{H_r}\right]^{\alpha} \quad (m\,s^{-1})$$

where U_r = wind speed at reference level (m s[1])
H = overall height of building (m)
H_r = reference level at which wind speed is measured (m)
α = exponent dependent on the nature of local terrain

(iv) The reference pressure leakage, Q_T, and flow exponent, n, are determined by pressurizing the building over ranges of pressure between ±10 to 60 Pa.

(v) Air leakage is assumed to be uniformly distributed across each face but the total leakage Q_T may be distributed in any chosen proportion among the surfaces.

(vi) The exponent n is applied to all leakage paths.

(vii) Party walls and solid floors are assumed to be impermeable.

(viii) If the underfloor space is ventilated, the assumed surface pressure is obtained by determining the area weighted mean of the pressures of the exposed vertical walls.

2.10 Reeves, McBride, Sepsy model[10]

This is a single cell model which is used to calculate air flow through the building envelope. The model is based on a flow equation of the form

$$\text{Infiltration} = \beta_o C_T (A\triangle P_T + B\triangle P_W)^{1/2} - \text{(cfm or l/s)}$$

where $$\triangle P_T = 0.52\,P\,h\left[\frac{1}{T_o} - \frac{1}{T_i}\right] \quad \text{(Pa)}$$

and $$\triangle P_w = \frac{0.2549\,V^2}{T_o}$$

$\triangle P_T$ = Theoretical pressure difference across the enclosure due to stack effect (in wg or Pa)

$\triangle P_w$ = Pressure difference across enclosure due to wind effect (in wg or Pa)

P = Absolute pressure (psi or Pa)

h = Effective stack height. If leakage is evenly distributed, this is ~½ x height of ventilated space (H or m)

V = Wind velocity (mph or m s^{-1})

T_o & T_i = External and internal air temperatures (°R or K)

C_T = Total equivalent crack length

β = Constant determined by statistical regression, or from air infiltration measurements

A & B = Constants determined by experiment to have values of 4 and $\sqrt{2}$ respectively

An appropriate value for the effective stack height is supplied for three types of house. These are given as

Two storey	8ft	(2.4m)
Split level	6ft	(1.8m)
Ranch	4ft	(1.2m)

The input requirements for the model are

(i) an estimate for h (ft or m)

(ii) an estimate for $ß_oC_T$ (ft or m)

(iii) inside temperature (°F or °C)

(iv) outside temperature (°F or °C)

(v) wind speed (mph or m s^{-1})

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3. NUMERICAL DATA

An essential prerequisite of the validation exercise was to compile a comprehensive database of air infiltration measurements and associated climatic and building data. These data were selected on the basis of accuracy and completeness; in particular it was important that the information contained in them would be sufficient to meet the demands of each of the selected models. It was also essential that the data should represent as wide a range of building construction techniques, terrain and local shielding conditions, and climatic variations as possible so that the full range of applicability of the model could be assessed.

To assist in this task, the Centre prepared a standardised reporting format for the measurement of air infiltration in buildings[1]. The aim of this format was to provide a common method to set out experimental data, so making the information easy to extract for subsequent analysis. As a minimum requirement, it was necessary for each data set to contain the following details:

- building description.
- building environment.
- details of flow paths.
- results of pressurization tests.
- air infiltration measurement data.
- internal/external temperature data.
- local wind data.

The task of selecting appropriate data was shared by the participants and suitable data were received from five countries. These data comprised in excess of 300 air infiltration rate measurements and associated climatic details for 14 buildings (see Table 3.1). The data primarily related to dwellings with the exception of the information received from the Lawrence Berkeley Laboratory, which was based on measurements of air infiltration made in their Mobile Infiltration Test Unit. Unfortunately there were no data for commmercial or industrial buildings.

From the received data, three key data sets were prepared. The first was based on measurements made in an isolated, detached dwelling in Switzerland (see Appendix 1). The house lies on an exposed, south-facing slope and, for the prevailing wind directions, was not subject to interference by local shielding. The dwelling is of timber frame construction and naturally ventilated. Climatic measurements were made 'on site' and air infiltration rates were measured using an automatic tracer gas 'decay' technique. Direct measurements of wind pressure were also made on each face of the building. The data sets represented an almost continuous period of observation between 10–12 December 1979 and consisted of 18 hourly measurements. During this period, the building was subjected to an essentially wind dominated regime, with the wind speed varying between 3.7 and 10.2 ms^{-1}. Internal/external temperature differences ranged from between 7.2 and 16K and the measured air infiltration rates between 0.2 and 0.41 ach.

The second data set was based on measurements made in a detached dwelling in Ottawa, Canada (see Appendix 2). It is one of a number of adjacent houses constructed by the Housing and Urban Development Association of Canada as part of a building energy study. This particular dwelling is constructed to an 'up-graded' standard of thermal insulation and air tightness. It is electrically heated and naturally ventilated. The building is shielded to the rear by a 2.5m earth berm and to the sides by adjacent dwellings; the front of the building is relatively unobstructed. A total of 37 measurements using tracer gas decay were made during the Winter of 1978–79. During the measurement periods, wind speed ranged from between 1.0 and 10.6 ms^{-1}, temperature difference between 6.3 and 40.6K and measured infiltration rates between 0.08 and 0.32 ach.

The final data set was based on measurements made in a naturally ventilated, mid-terrace, three-storey dwelling in Runcorn, UK (see Appendix 3). The dwelling was constructed of pre-fabricated panels and was situated in a heavily shielded urban environment. A total of 15 air infiltration rate tracer gas measurements were made during May 1977. During this period, wind speed varied between 1.2 and 6.5 ms^{-1}, temperature difference between 5.8 and 14.4K and measured air infiltration rates betwen 0.37 and 0.68 ach.

Data sets for the remaining 11 buildings were also prepared to enable additional investigations to be undertaken as necessary.

While every effort was made to verify the accuracy of the data, there must inevitably be some error of measurement. For this reason, the isolated failure of a calculation to correspond with measurement was not regarded as significant. It was important, however, to investigate systematic departures of calculation from measurement.

Table 3.1: List of validation data

No.	Ref. No.	
1.	CA1	HUDAC Mk.XI Test House (detached standard), Ottawa, Canada
2.	CA2	*HUDAC Mk.XI Test House (detached upgraded), Ottawa, Canada
3.	NL1	Apartment Dwelling, Delft, Netherlands
4.	NL2	Mid-terrace House, Maasland, Netherlands
5.	NL3	Mid-terrace House, Schipluiden, Netherlands
6.	UK1	End-terrace House, Wales, UK
7.	UK2	*Mid-terrace House, Runcorn, UK
8.	UK3	Detached Dwelling (Electricity Council Research Centre), Scotland, UK
9.	UK4	Detached Dwelling (British Gas), London, UK
10.	CH1	*Detached Dwelling, Maugwil, Switzerland
11.	US1	Mobile Infiltration Test Unit, USA
12.	US2	Owens-Corning Test House (detached), USA
13.	US3	Owens-Corning Test House (detached), USA
14.	US4	Owens-Corning Test House (detached), USA

**Key data set*

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4. ANALYSIS OF RESULTS

Model performance was assessed by using the key data sets as input to the selected models and by comparing the corresponding calculated rates of air infiltration with measurement. Apart from the Reeves model (see Section 4.10), the measured rates of air infiltration were used solely for comparison purposes and therefore provided an independent datum against which the accuracy of a model could be assessed. In the case of the Reeves model, the first infiltration measurement of each data set was used as part of the input data. Calculations within 25% of measurement were regarded as satisfactory, this level of tolerance being based on allowances for measurement errors in both the input data and in the air infiltration rate measurements themselves. The performance of each model was judged on the proportion of calculations falling within this specified error band.

For a number of reasons, it was not possible to perform the entire validation exercise at the Air Infiltration Centre. In those instances where simulations could not be performed 'in-house', model users were invited to apply the data sets to their models and forward the results to the Centre for analysis. This enabled a much wider range of models to be included than could otherwise have been achieved.

4.1 BSRIA Model

The BSRIA model was the first to be studied; all three of the key data sets were used and the results are discussed below for each set of data.

Swiss test data (Maugwil house)

The flow network considered to most closely resemble the situation during the tracer gas tests is illustrated in Figure 4.1.1. The effective volume of the building was assumed to be represented by the gross volumes of the five rooms into which tracer gas was injected and the connecting space up to the stairwell door (see Appendix 1, Figure 1). The flow characteristics of each path are defined in Table 4.1.1. The given leakage characteristics of windows and doors were used directly, while the deficit between component leakage and total building leakage was evenly distributed along the roof/wall junction, the gable/roof junction and around the beam/wall penetrations. The sole plate for this dwelling is underground for most of its perimeter and was therefore ignored as a source of air leakage.

Wind pressures were inferred from published pressure coefficient data similar to those given in BS5925[1] and the Swedish Building Code[2] for isolated buildings (Table 4.1.2). The 10m 'on-site' measurements of wind speed were reduced to a roof ridge height of 7.5m using the following three wind profile equations

(i) BS5925 Power Law $\frac{U_{7.5}}{U_{10}} = kz^a \quad (ms^{-1})$

where, for open country and scattered windbreaks, k = 0.52 and a = 0.21.

(ii) LBL Power Law $U_{7.5} = U_{10}\,\alpha \left[\frac{7.5}{10}\right]^{\gamma} \; (ms^{-1})$ (Ref. 3)

where, for rural areas with low buildings (trees, etc.), $\alpha = 0.85$ and $\gamma = 0.20$.

(iii) Logarithmic Wind Profile $\frac{U_{7.5}}{U_{10}} = \frac{\ell_n(7.5-d_o)/z_o}{\ell_n(10-d_o)/z_o} \quad (ms^{-1})$

where d_o and z_o are constants dependent on roughness (for grass $d_o \simeq$ 10cm and $z_o \sim 1.73$).

Stack pressures were calculated directly from measurements of internal and external air temperature.

Comparisons between calculated and measured rates of air infiltration are illustrated in Figure 4.1.2. Excellent agreement was obtained, with all the calculated values being well within 25% of measurement. Very similar results (not illustrated) were achieved using each of the wind profile equations.

Table 4.1.1: Leakage data – Maugwil house *(BSRIA model)*

External Node Numbers	Leakage Site	k $\times 10^{-3} m^3/s$	1/N	†Height (m)
	Boiler room window	0.060	1.5	1.7
1	Boiler room vent	7.790	2.0	1.7
2	Front door	1.5	1.500	0.0
3	WC	0.024	1.5	2.0
4	Stairwell window	0.664	1.5	4.2
5	Studio patio doors	0.151	1.5	3.5
6	Living room patio doors	0.083	1.5	3.5
7	Dining room window	0.043	1.5	4.0
	Kitchen – window alone	0.098	1.5	4.1
8	*Kitchen – with ventilator –	0.251	1.5	4.1
	+	2.042	1.5	
9	Child's bedroom W	0.069	1.5	6.1
10	Master bedroom	0.069	1.5	6.1
11	Child's bedroom E	0.083	1.5	6.6
12	Bathroom window	0.083	1.5	6.6
13, 15	Eaves N and S	2.145	1.5	5.0
14, 16	Gable/Roof E and W	2.577	1.5	7.5
17	Bombshelter	4.032	1.5	2.5
18	Chimney	50.900	1.5	2.5
19, 20 internal nodes	Stairwell door	1.524	1.5	

**Kitchen ventilator: – represents internal underpressure; + represents internal overpressure*
†Node heights were taken at the centre of each component

Figure 4.1.1: Node network (Maugwil house) *(BSRIA model)*

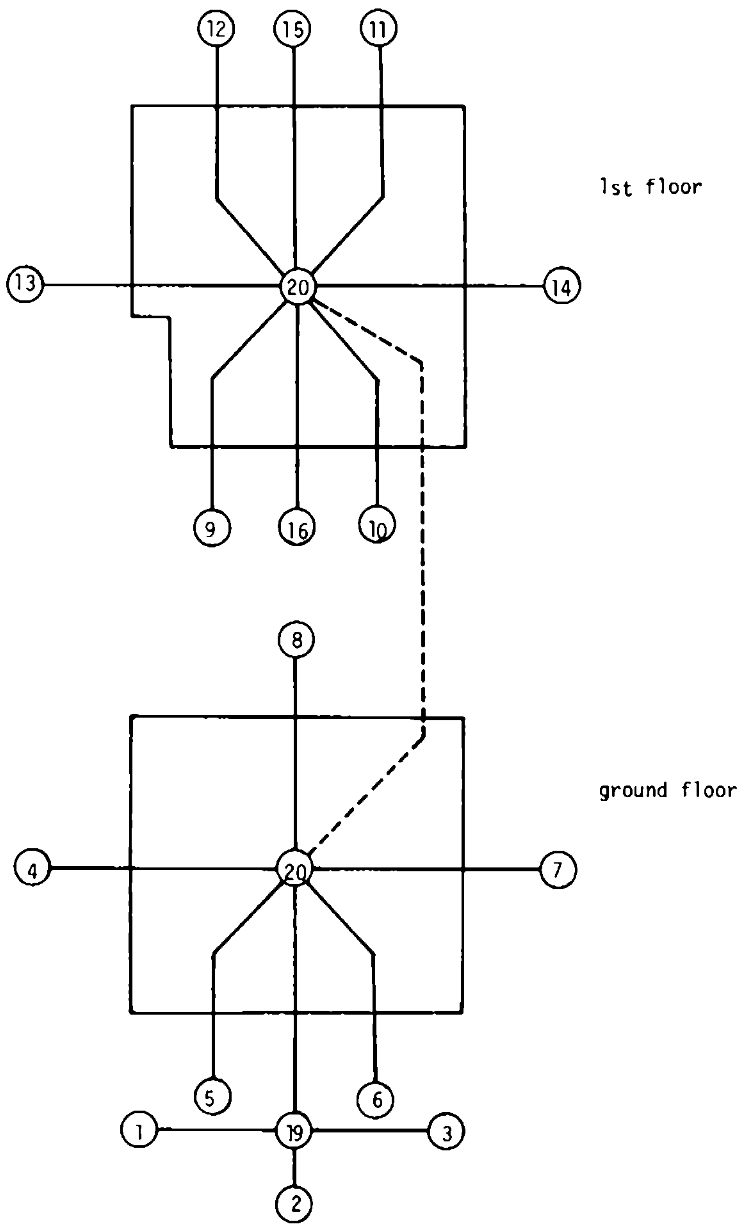
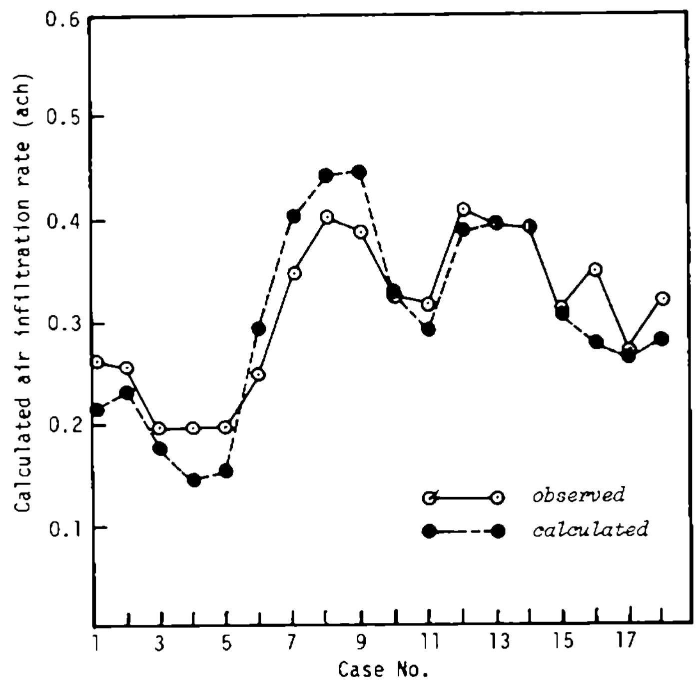
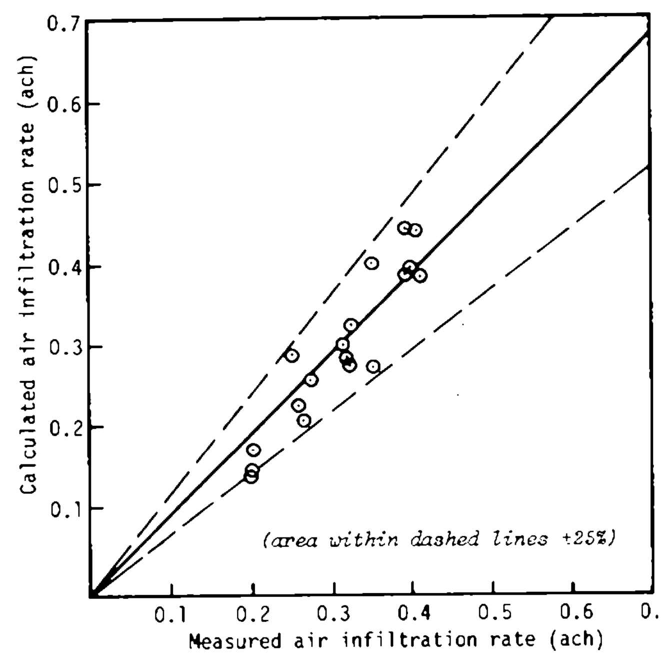


Table 4.1.2: Pressure coefficient data – Maugwil dwelling *(BSRIA model)*

	Pressure Coefficients			
Nodes	5, 6, 9, 14	1, 2, 7, 10, 15	3, 8, 11, 16	4, 12, 13
Wind direction: NW	0.7	−0.5	−0.2	−0.5
W	0.7	−0.3	−0.3	0.7

Figure 4.1.2: Comparison between calculated and measured air infiltration rates using published pressure coefficient data and wind profile equations (Maugwil house) *(BSRIA model)*





Canadian test data (HUDAC MK XI 'upgraded' test house)

The forced air heating system was used to mix the tracer gas and thus the internal volume was assumed to act as a 'single cell'. The resultant flow network is illustrated in Figure 4.1.3. Flow paths 2 and 3 are from the garage space to the ground floor and were assumed to be influenced by stack pressure only, with the garage preventing wind pressure acting directly on these surfaces. In the absence of further information, a uniform distribution of cracks was assumed with the total coefficient of leakage, K, equal to the value, C, determined from the pressurization tests (see Appendix 2). Complete flow path data is given in Table 4.1.3. Surface pressures were calculated as for the previous data set; the corresponding 'wind tunnel' pressure coefficients are given in Table 4.1.4.

Comparisons between calculated and measured air infiltration were found to fall into two distinct regimes (Figure 4.1.4). For wind coming from the North, North West and West directions, air flow was relatively undisturbed by obstructions and the modelled results were satisfactory with 63% of the calculations being within 25% of measurement. The results for the remaining wind directions showed little correlation and in general the computed air infiltration rates were much greater than measurements. Winds in these directions were substantially influenced by the earth berm to the rear of the building and by obstructions caused by adjacent properties on the other side. The mis-match for these wind directions was thought to be almost certainly due to the choice of pressure coefficients, which are only strictly applicable to buildings in isolation.

Figure 4.1.3: Node network (HUDAC Mk XI test house) *(BSRIA model)*

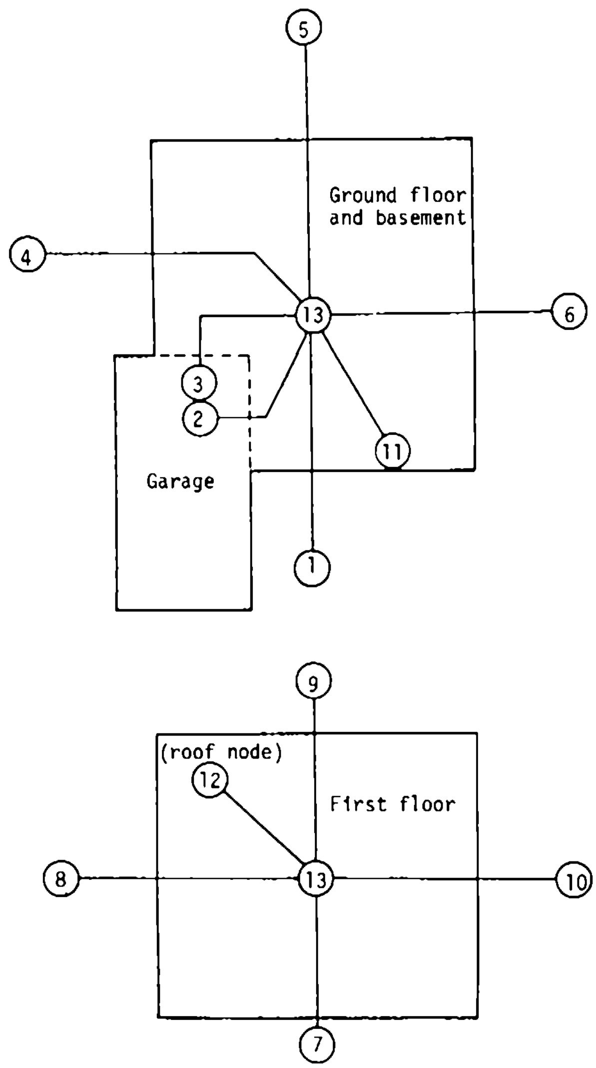


Table 4.1.3: Leakage data – HUDAC 'upgraded' dwelling *(BSRIA model)*

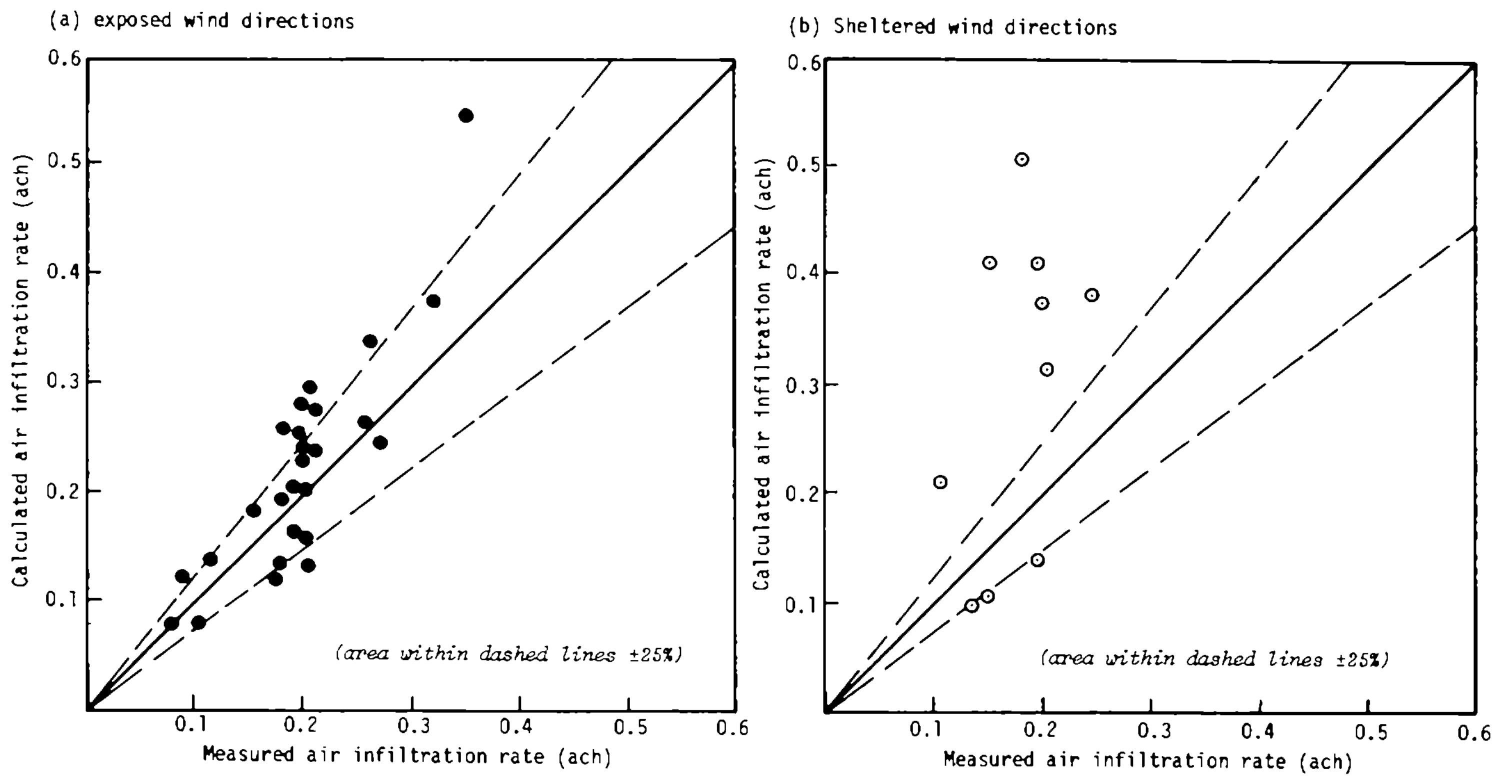
Node Number	Leakage Site	k $\times 10^{-3} m^3 s^{-1}$	1/N	*Height (m)
1	Front ground floor facade	1.1	1.41	0.0
2	Garage – NE facade	0.6	1.41	0.0
3	Garage – NW facade	0.5	1.41	0.0
4	NW ground floor facade	1.1	1.41	0.0
5	Rear ground floor facade	1.6	1.41	0.0
6	SE ground floor facade	1.5	1.41	0.0
7	Front first floor facade	1.6	1.41	2.6
8	NW first floor facade	1.4	1.41	2.6
9	Rear first floor facade	1.6	1.41	2.6
10	SE first floor facade	1.4	1.41	2.6
11	Ground floor 'roof'	0.4	1.41	1.4
12	First floor roof	4.0	1.41	3.0

**Level given with respect to lowest opening.*

Table 4.1.4: Pressure coefficient data – HUDAC 'upgraded' dwelling *(BSRIA model)*

	Pressure Coefficients			
Nodes	1, 7	5, 9	4, 8	6, 10
Wind direction:				
N	0.7	–0.3	0.7	–0.3
NE	–0.6	–0.6	0.7	–0.25
E	–0.3	0.7	0.7	–0.3
SE	–0.25	0.7	–0.6	–0.6
S	–0.3	0.7	–0.3	0.7
SW	–0.6	–0.6	–0.25	0.7
W	0.7	–0.3	–0.3	0.7
NW	0.7	–0.25	–0.6	–0.6

Figure 4.1.4: Comparison between calculated and measured air infiltration rates (HUDAC 'upgraded' house) *(BSRIA model)*



United Kingdom test data (Runcorn house)

The interior of the building was again treated as a single-cell with the leakage to the outside being evenly distributed according to the exposed surface area of the front, rear and roof of the house. The resultant node network is depicted in Figure 4.1.5. and the corresponding leakage parameters are given in Table 4.1.5. The dwelling was situated in a heavily shielded environment with the result that exposed wind pressure data would be inappropriate to use. On the otherhand, a comparison between measured air infiltration rates and internal/external temperature differences (Figure 4.1.6.) revealed a linear relationship for all but three of the data points, thus implying that air infiltration was dominated by stack action. The surface pressure distribution was therefore based on stack pressure calculations alone. The resultant comparison between calculated and measured rates of air infiltration is illustrated in Figure 4.1.7. and shows good agreement for the twelve air infiltration measurements that were proportional to temperature difference.

In general, the results using this model, were very encouraging. The importance of specifying an appropriate wind pressure distribution was very evident and therefore in an effort to determine the significance of this parameter, alternative strategies were attempted with subsequent models.

Figure 4.1.5: Node network (Runcorn dwelling) *(BSRIA model)*

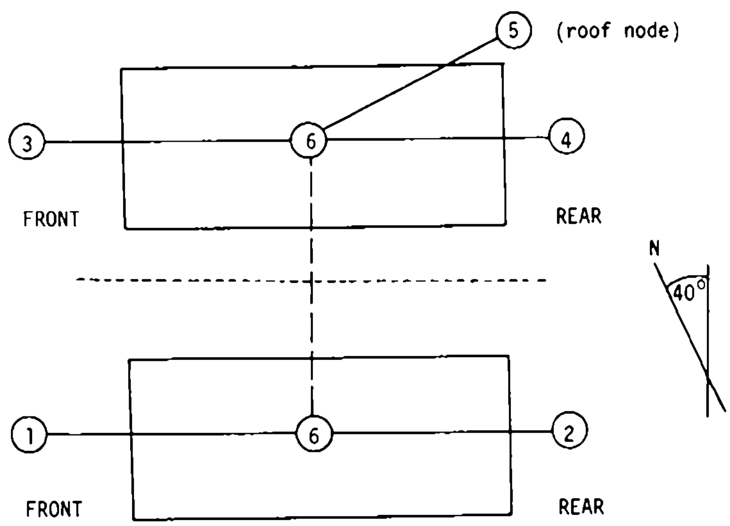


Table 4.1.5: Leakage data – Runcorn dwelling *(BSRIA model)*

Node Number	Leakage Site	k $x10^{-1}m^3s^{-1}$	1/N	*Height (m)
1	Front facade – lower	1.26	1.52	0.00
2	Rear facade – lower	1.26	1.52	0.00
3	Front facade – upper	0.52	1.52	3.75
4	Rear facade – upper	0.52	1.52	3.75
5	Roof	2.07	1.52	4.85

**Height given with respect to lowest opening.*

Figure 4.1.6: Measured infiltration vs internal/external temperature difference (Runcorn dwelling)

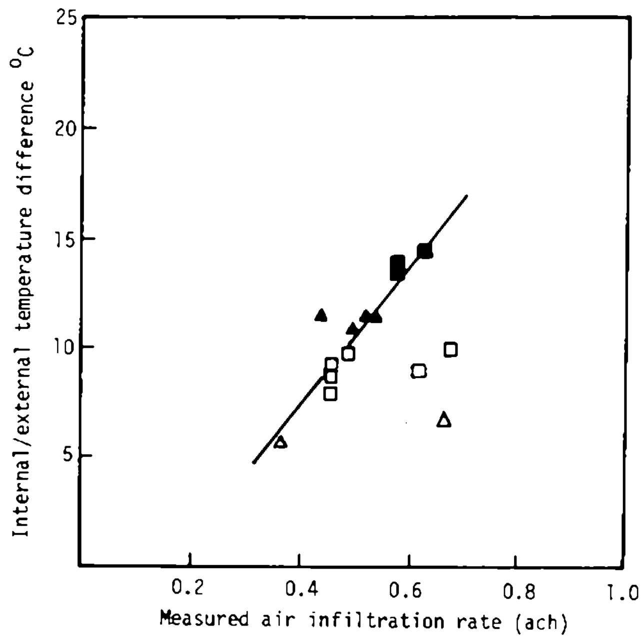
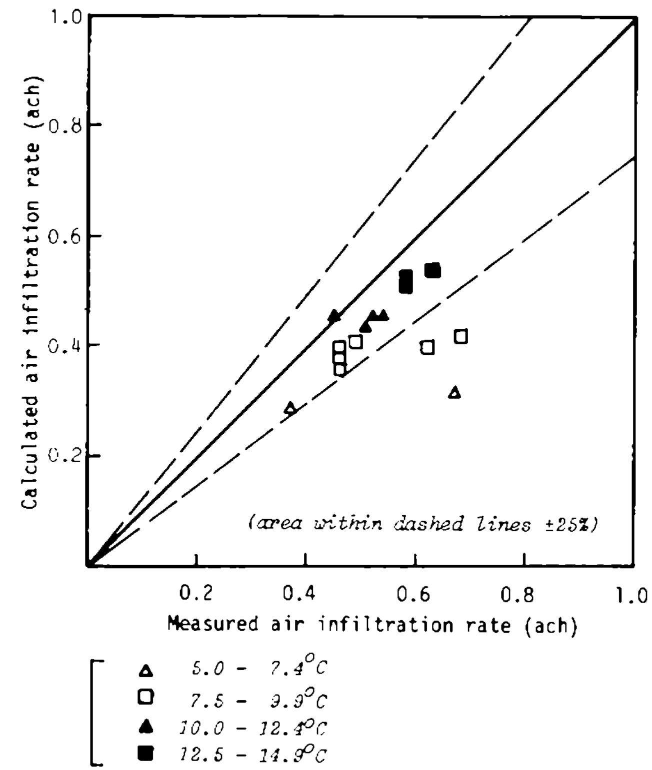


Figure 4.1.7: Comparison between calculated and measured air infiltration rates: stack effect only (Runcorn dwelling) *(BSRIA model)*



4.2 NRC Model

The NRC model was the second to be investigated and all three of the key data sets were again used. In addition to using similar pressure coefficient data and node networks to those used in the previous model, pressure coefficient data based on wind tunnel measurements made by the National Research Council of Canada for buildings subjected to varying degrees of local shielding were also applied.[4]

The NRC pressure coefficient data is illustrated in diagramatic form in Figure 4.2.1. It is intended for use where a building is surrounded by obstructions of differing sizes, ranging from one sixth to the total height of the building and for 15° sectors in wind direction, as a continuous function of the normalised building height. The pressure coefficients were determined at levels corresponding to the floor/ceiling heights and the mid-level of each floor. The value of each coefficient was determined directly from the figure, taking into account the surrounding terrain conditions only. The basic flow network used for all the data sets is given in Figure 4.2.2. Leakage openings were assumed to be uniformly distributed about the exposed surface of the building. A large vertical leakage between all internal cells was assumed, while the leakage to the roof space was based on the surface area of the top floor ceiling.

Swiss test data (Maugwil house)

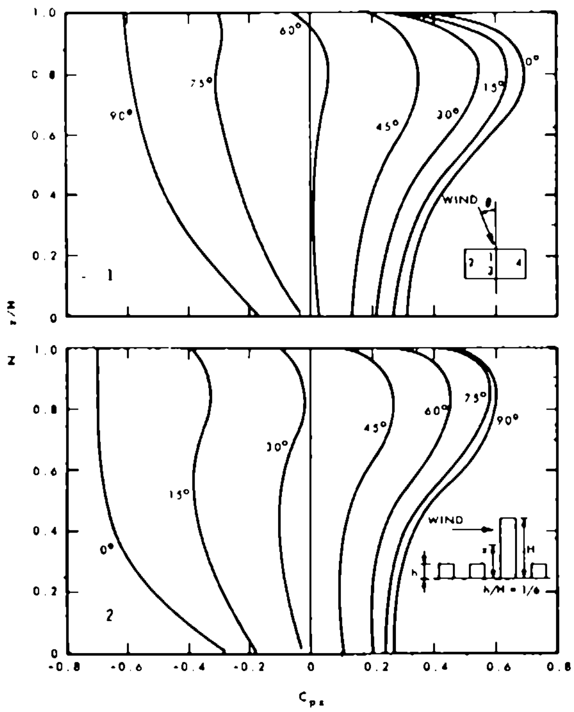
Direct comparisons between calculated and measured air infiltration rates, using the pressure conditions devised for the previous model (Table 4.1.2.) are illustrated in Figure 4.2.3. These showed the same excellent agreement as was achieved using the BSRIA model, with all calculations being well within 25% of measurement. The close similarity between the performance of the two models is also illustrated by direct comparison in Figure 4.2.4.

The calculations were repeated using the NRC pressure coefficient data, where it was assumed that the level of surrounding obstructions was equal to one sixth of the height of the building. The node network illustrated in Figure 4.2.2. was used and the corresponding leakage values are given in Table 4.2.1. Comparisons between calculation and measurement revealed a systematic under-estimate of the measured value with only ten of the eighteen calculations being within 25% of measurement (Figure 4.2.5). This result highlighted the significance of selecting the correct pressure data. In this instance, the dwelling was situated in an exposed location and the 'isolated' pressure coefficient data used in the first simulation was the most appropriate to apply.

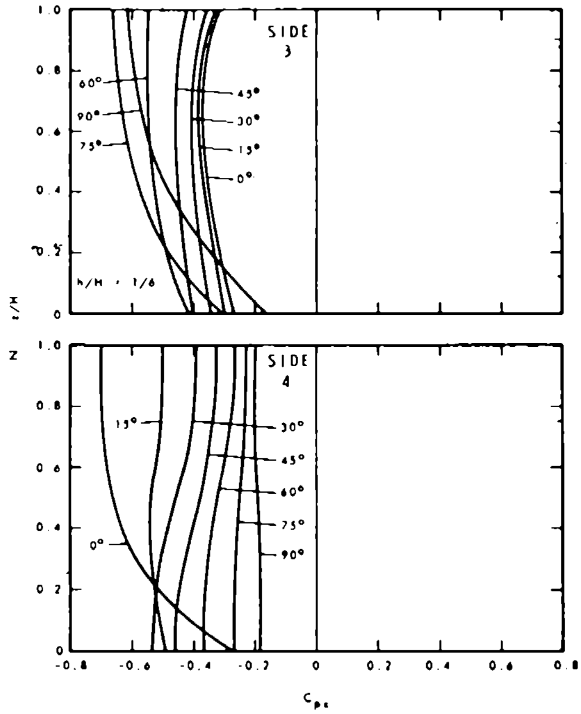
Table 4.2.1: Leakage data (Maugwil house) *(NRC model)*

Level	Distance between levels (ft)	Leakage (cfm in wg^{-1}/1000)					
		Face 1	Face 2	Face 3	Face 4	Floor	Stack
1. Basement		0.053	0.000	0.000	0.070	10.0	10.0
2. Basement/ ground floor perimeter	5.90	0.099	0.089	0.099	0.089	10.0	10.0
3. Ground floor/ 1st floor perimeter	8.86	0.099	0.089	0.099	0.089	10.0	10.0
4. Ceiling/attic	8.86	0.129	0.089	0.129	0.089	10.0	10.0

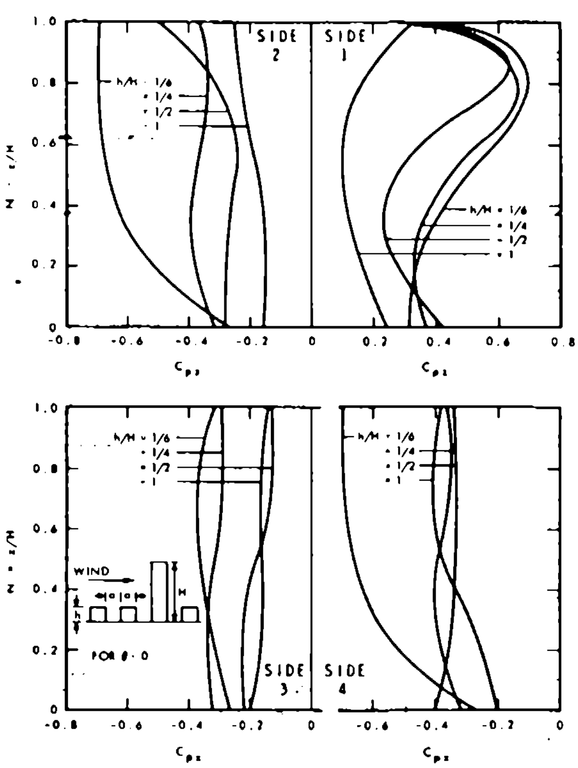
Figure 4.2.1: NRC pressure coefficient data



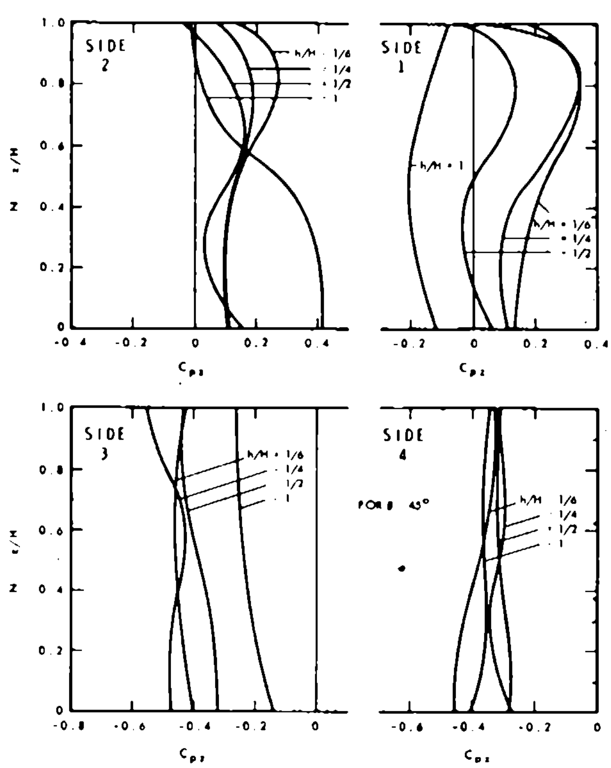
Vertical distribution of mean wind pressure coefficients of sides 1 and 2 for h/H = 1/6



Vertical distribution of mean wind pressure coefficients of sides 3 and 4 for h/H = 1/6



Vertical distribution of mean wind pressure coefficients for θ = 0° and various values of h/H



Vertical distribution of mean wind pressure coefficients for θ = 45° and various values of h/H

Figure 4.2.2: Node network for NRC model

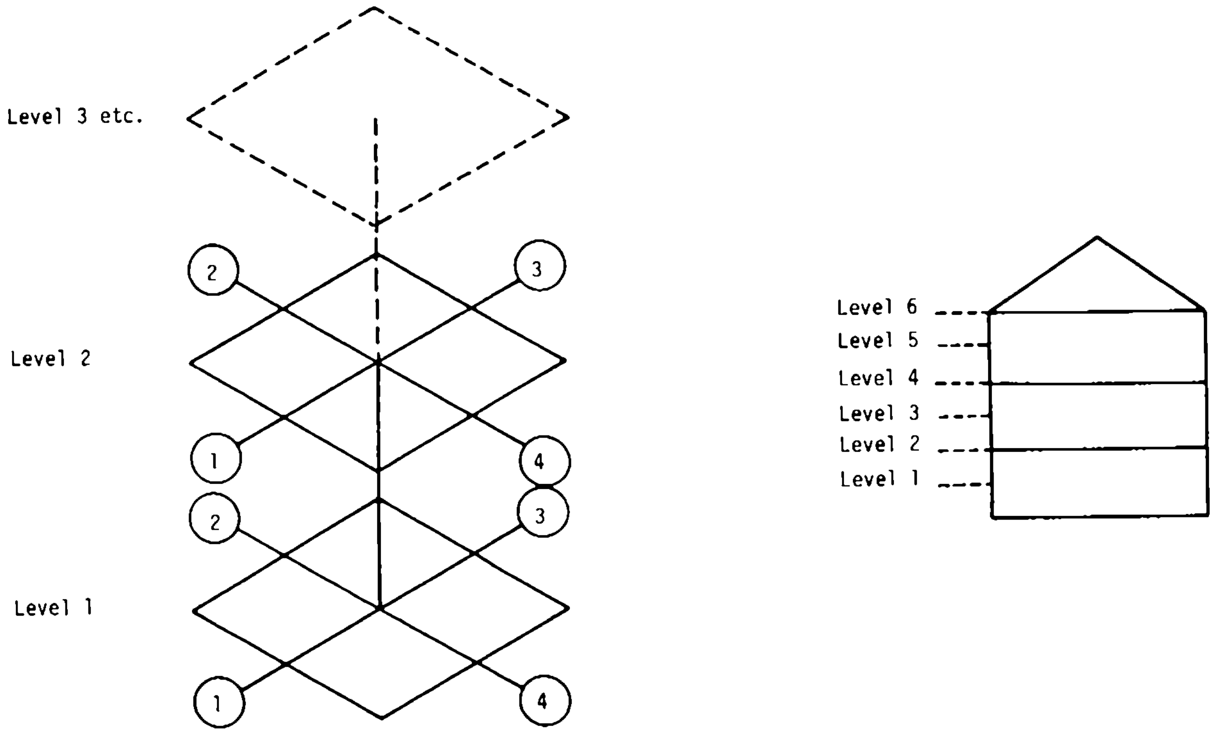


Figure 4.2.3: Comparison between calculated and measured air infiltration rates using 'isolated building' pressure coefficients (Maugwil house) *(NRC model)*

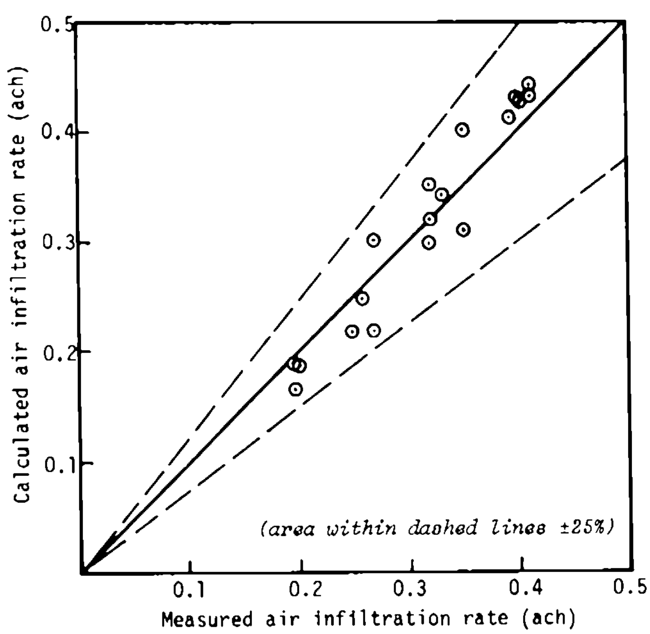


Figure 4.2.4: Comparison between NRC and BSRIA calculated results (Maugwil house)

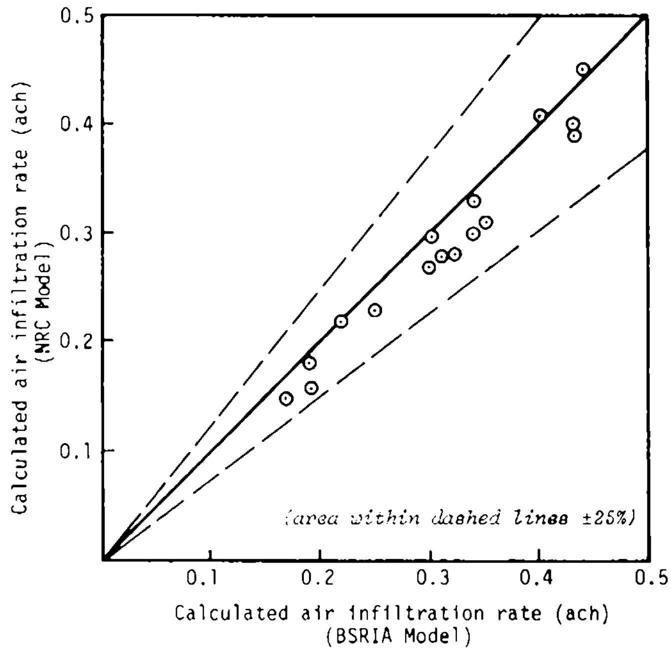
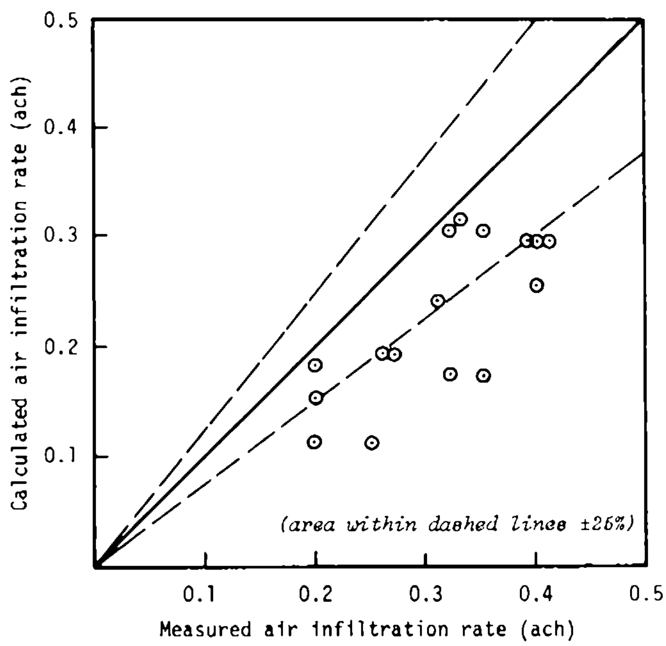


Figure 4.2.5: Comparison between calculated and measured air infiltration rates using NRC pressure coefficients (Maugwil house) *(NRC model)*

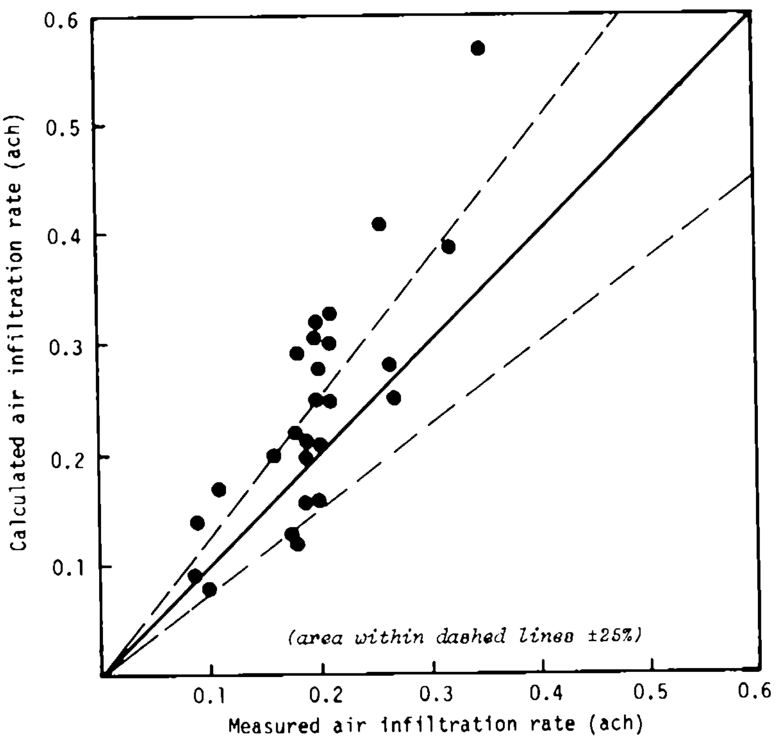


Canadian test data (HUDAC 'upgraded' house)

Both sets of pressure coefficient data were again used to calculate air infiltration in the heated space of this dwelling. Calculations based on the 'isolated' building pressure coefficient data, as given in Table 4.1.4, revealed similar results to those obtained with the BSRIA model, with the two distinct regimes being clearly apparent as before (Figure 4.2.6).

Figure 4.2.6: Comparison between calculated and measured air infiltration rates using 'isolated building' pressure coefficients (HUDAC 'upgraded' house) *(NRC model)*

(a) exposed wind directions



(b) sheltered wind directions

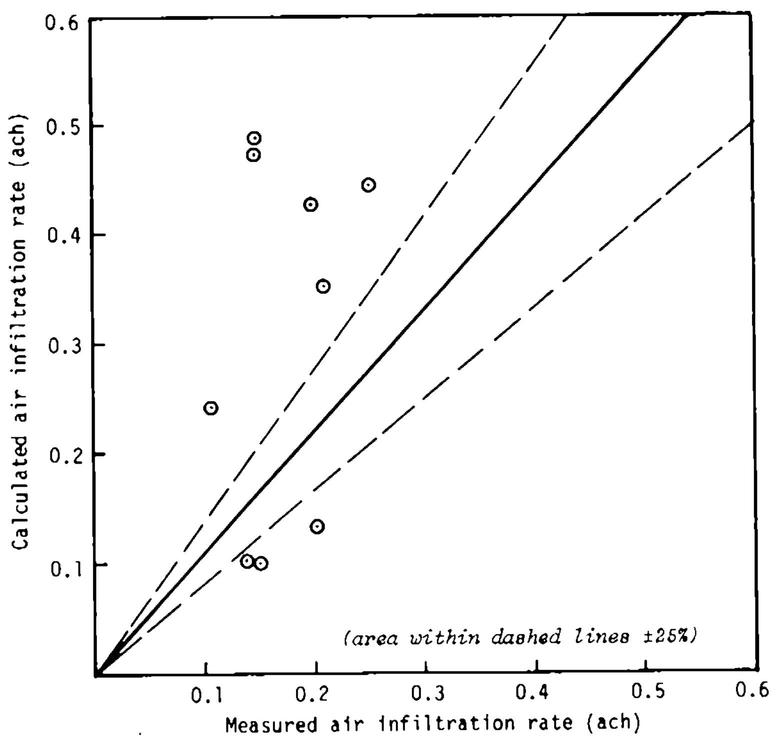
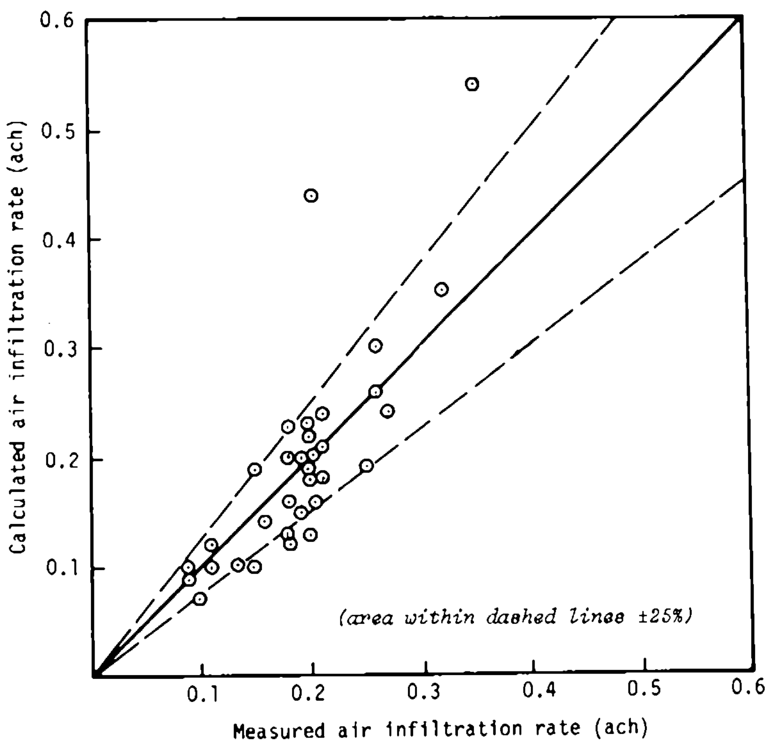


Table 4.2.2: Leakage data (HUDAC 'upgraded' house) *(NRC model)*

Level	Distance between levels (ft)	Leakage (cfm in wg^{-1}/1000)					
		Face 1	Face 2	Face 3	Face 4	Floor	Stack
1. Basement above grade		0.0316	0.0210	0.0218	0.0282	0.0	10.0
2. Ground floor lower half	4.0	0.0814	0.0548	0.0572	0.0734	10.0	10.0
3. Ground floor upper half	4.0	0.0814	0.0548	0.0572	0.0734	10.0	10.0
4. First floor lower half	4.0	0.0814	0.0734	0.0814	0.0734	10.0	10.0
5. First floor upper half	4.0	0.0814	0.0734	0.0814	0.0734	10.0	10.0
6. Roof space	2.0	10.0000	10.0000	10.0000	10.0000	0.71	0.0

Figure 4.2.7: Comparison between calculated and measured air infiltration rates using NRC pressure coefficient data (HUDAC 'upgraded' house) *(NRC model)*



The NRC pressure data enabled some allowance to be made for the varying degrees of upwind obstructions surrounding the building. For the moderately exposed North, North West and Westerly wind directions, an obstruction height equivalent to one sixth of the building height was assumed. For winds to the rear of the building, an obstruction height of one half was assumed (reflecting the influence of the earth berm) and for wind normal to the sides of the dwelling, the obstruction height was assumed to be equal to the height of the building. The leakage parameters are given in Table 4.2.2. The results revealed a substantial improvement over the previous simulation, with all but five of the calculations falling within 25% of measurement (Figure 4.2.7). There were two significant over-estimates of air infiltration rate which were found to coincide with high wind speeds. However, it was not possible to associate these over-estimates with an underlying wind speed problem, as equally high wind speeds at the Maugwil site produced consistently good results.

United Kingdom test data (Runcorn house)

The Runcorn house is subjected to extensive local shielding, therefore the influence of wind effect was investigated in terms of the most shielded pressure coefficients given by the NRC pressure data. The leakage parameters are given in Table 4.2.3.

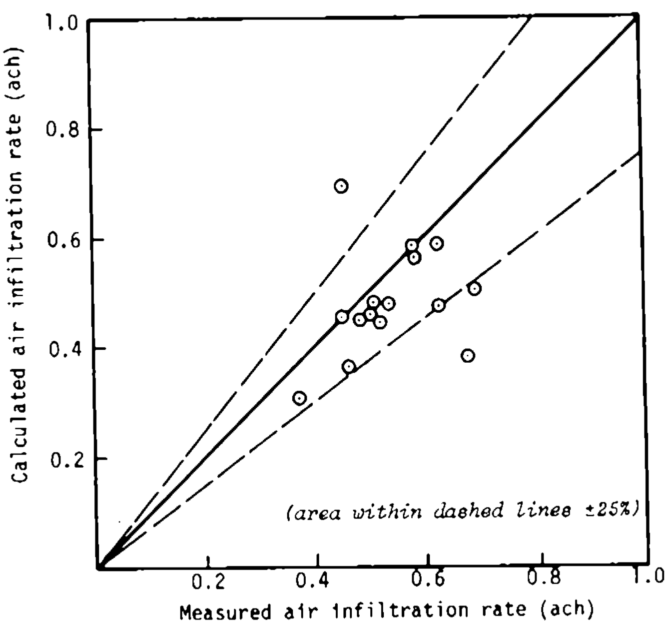
Consistent agreement between calculated and measured rates of air infiltration was obtained, with just two of the calculated values falling outside the 25% band (Figure 4.2.8).

Overall, the NRC model performed well, with consistent agreement between calculation and measurement being possible for all three data sets. When identical input data to the previous model were used, near identical results were achieved. Results were very dependent on the selection of wind pressure coefficients; the importance of selecting the most appropriate value was clearly indicated.

Table 4.2.3: Leakage data (Runcorn house) *(NRC model)*

Level	Distance between levels (ft)	Leakage (cfm in wg^{-1}/1000)					
		Face 1	Face 2	Face 3	Face 4	Floor	Stack
1. Ground floor		0.62	0.0	0.62	0.0	10.0	10.0
2. First floor	8.5	0.62	0.0	0.62	0.0	10.0	10.0
3. Second floor	8.5	0.62	0.0	0.62	0.0	10.0	10.0
4. Ceiling	8.5	0.62	0.0	0.62	0.0	0.0	10.0

Figure 4.2.8: Comparison between calculated and measured air infiltration rates using NRC pressure coefficient data (Runcorn house) *(NRC model)*



4.3 IG-TNO Model

(Results of model simulations were received from Willem de Gids, TNO, Delft, Netherlands.)

An assessment of this model was made using the Maugwil test data only. The dwelling was represented by a complete 'multi-cell' network (Figure 4.3.1.) which was used to calculate total air change rate for the entire heated space. The volume of the heated space was taken as the gross volume of the building minus the volume of the bomb-shelter and boiler room.

Wind-induced pressures were based on the direct measurements of pressure made on each face of the building. This was the only model investigated which incorporated these measurements. The measured pressures were assumed to have been made with respect to a common internal datum and were converted to pressure coefficients using the equation

$$C_p = \frac{2}{\rho V^2} P_m$$

where
C_p = pressure coefficient
ρ = air density ($Kg.m^{-3}$)
V = wind speed ($m\,s^{-1}$)
P_m = measured pressure (Pa)

Comparisons between calculated and measured air change rates are illustrated in Figure 4.3.2. Generally, good agreement was achieved with all but three of the calculations being within 25% of measurement. A problem was noted with some of the calculations in that, during the course of a measurement period, it was possible for the measured surface pressures to oscillate between negative and positive values. The net effect was to produce a 'mean' pressure of nearly zero, thus resulting in an under-prediction of the measured infiltration rate. It was also suggested by TNO that this problem might have arisen through inadvertent window or door opening.

Unfortunately, results using the remaining data sets were unavailable.

Figure 4.3.1: Node network (Maugwil dwelling) *(TNO model)*

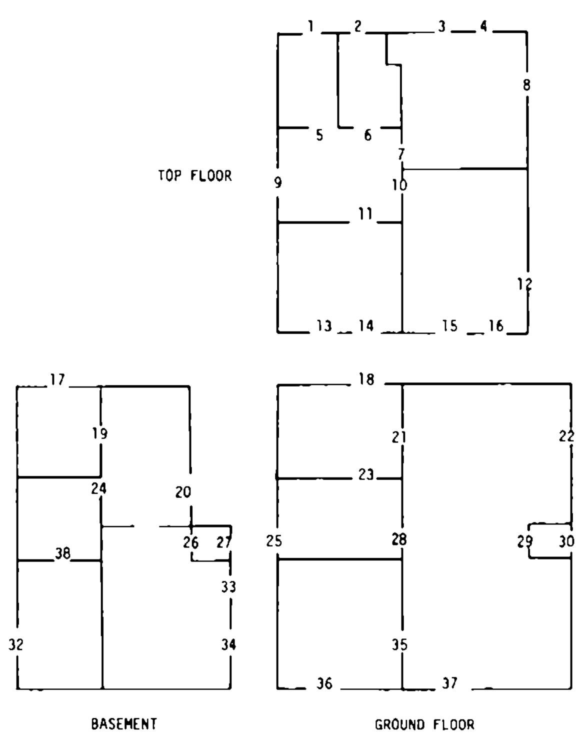
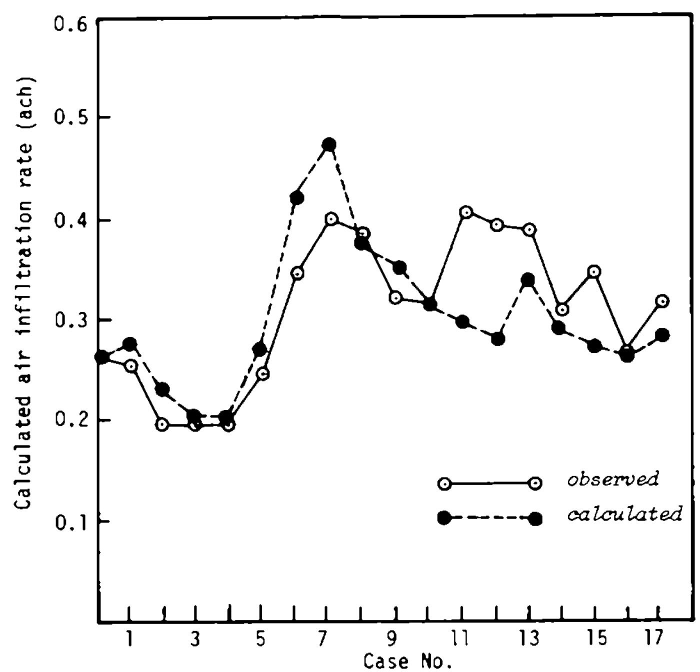
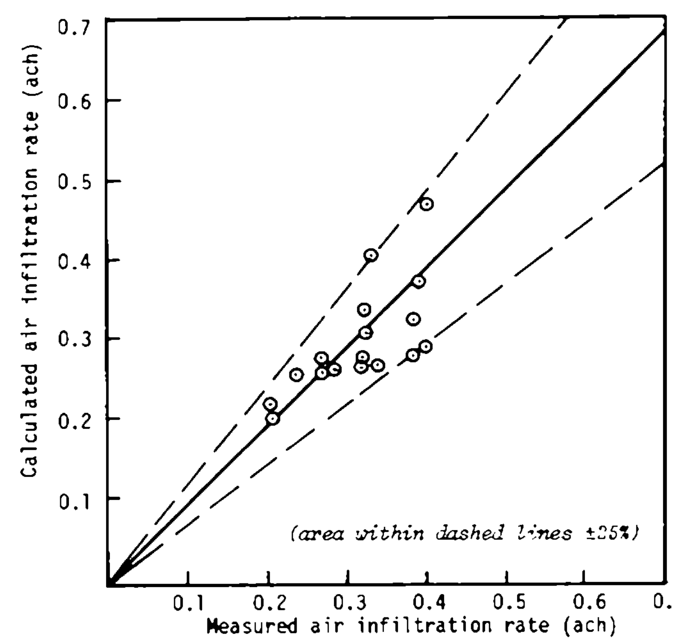


Figure 4.3.2: Comparison between calculated and measured air infiltration rates using direct wind pressure measurements (Maugwil house) *(TNO model)*





4.4 Oscar Faber Model

(Summary of results received from Mr A.P. Wilson, Oscar Faber and Partners.)

Data taken from the Swiss data set and from the LBL Mobile Infiltration Test Unit were used in the assessment of this model.

Swiss test data (Maugwil house)

The Maugwil dwelling was modelled using two internal nodes; one representing the 'unconditioned' ground floor area of approximate volume 70m^3 and the other representing the remaining heated volume of approximately 356m^3. The average elevation of the first node was taken as 1.2m and the elevation of the second node was taken as 4.2m. The model was run with data obtained at 19.30 on 10 December 1979.

The relevant input data was:

- Inside temperature in each node taken as 20.0°C.
- Outside temperature was 8.9°C.
- Main wind direction West.
- Wind velocity of 10 metres 5.96 ms^{-1}.
- Terrain index of 11 on the Davenport scale.

The model only allowed for window and door crackage components for which the area of crackage was given.

The wind pressure coefficients were based on data given in BS5925 assuming a Westerly wind.

The calculated results were 0.046 ach for the smaller volume node and 0.051 for the larger volume node. The corresponding measured infiltration rate in the Maugwil house was 0.266 ach. The predicted results are of the correct order bearing in mind that the air leakage characteristic curves for the building envelope show that leakage through windows and doors only acocunts for about 15% of the total air leakage. The SWIFIB predicted values given above represent 17% for the smaller volume node and 19% for the larger volume node.

To allow for the extra air infiltration due to eaves, side and roof gable ends, the area of these crackage components would need to be worked back from the actual infiltration notes obtained during experimentation. This seemed to be a time-consuming exercise, when the prediction based on measured window and door crackage gives flow rates in the correct order. Therefore, this has not been carried out.

United States data (LBL Mobile Infiltration Test Unit)

Two sets of simulations were performed; the first was based on measured wind pressures and the second on pressures inferred using the wind pressure coefficients published in BS5925.[1]

The input data and results for the first set of calculations are given in Table 4.4.1. The wind pressure values were considered to be dubious and, when used in the model, made the overall air infiltration rates too low. The results for the second set of simulations are summarized in Table 4.4.2. and were much improved, with all five of the data points analysed giving calculations within 25% of measurement.

Table 4.4.1: Data and results – (US1) LBL Mobile Infiltration Test Unit *(Oscar Faber model)*

At 2:17 on 26 February 1981:

Wind direction WRTN = 167°
Wind speed at 10 m = 1.9 ms^{-1}
Outside temperature = –1.8°C

(a) Results with four slits in each wall to allow for background air infiltration. Wind pressure coefficients based on data in BS5925[1].

	LBL measured infiltration m^3h^{-1}	LBL predicted infiltration m^3h^{-1}	SWIFIB predicted infiltration m^3h^{-1}
Wind effect only		25.5	16.80
Stack effect only		23.8	23.97
Total	27.42	34.9	25.32

(b) Results with two slits in each wall which assumes background air infiltration as the door. Wind pressure coefficients based on data in BS5925[1].

LBL measured infiltration m^3h^1	LBL predicted infiltration m^3h^1	SWIFIB predicted infiltration m^3h^1	SWIFIB percentage difference
27.43	34.9	25.6	10.5%

Table 4.4.2: Data and results – (US1) LBL Mobile Infiltration Test Unit *(Oscar Faber model)*

Time on 26.2.82	Outside tempera-ture °C	Wind speed at 10 m m/s	Wind direction WRTN	LBL measured infiltration m^3/h	LBL predicted infiltration m^3/h	SWIFIB predicted infiltration m^3/h	SWIFIB percentage difference m^3/h
1:17	–1.21	1.86	150	28.64	34.3	24.87	13.0%
2:17	–1.82	1.90	167	27.43	34.9	25.32	7.6%
3:17	–2.48	0.51	70–30	28.99	25.0	24.39	15.9%
4:17	–2.46	1.17	130	31.19	28.7	24.27	22.0%
5:17	–2.92	1.12	120	29.44	28.6	24.51	16.7%

Background air leakages taken as small infiltration on all sides.
Wind pressure coefficients based on data in BS5925[1].

4.5 British Gas Model 'VENT'

(Model simulations were performed by Dr David Etheridge, British Gas, UK.

Model simulations concentrated on the 'single-cell' version of this model, VENT 2, although the 'multi-cell' version had previously been used in a comparison exercise using the UK4 data set.[5] Three sets of data were analysed; these were

(i) CA1 HUDAC 'standard' house } Canada
(ii) CA2 HUDAC 'upgraded' house } Canada
(iii) UK2 Runcorn house United Kingdom

In each instance, simulations were performed both with and without the influence of turbulence correction.

Table 4.5.1. lists the values of the major parameters used in each simulation. The values of A/B^2 (shape parameter of the leakage curve $\triangle P = AQ^2 + BQ$) were chosen to correspond as closely as possible to the quoted value of the power 'n'.

The leakage distribution for the HUDAC houses was based on the numbers of windows and doors in each wall. For the Runcorn house, the total leakage was distributed in accordance with the distribution of component leakage. For both dwellings it was also necessary to specify the percentage of 'background' leakage. For the HUDAC houses this was taken as 60% of the total leakage, and for the Runcorn house a value is given in the data set.

The pressure distribution for all simulations was estimated, where possible, from the NRC data given in Figure 4.2.1. The reference wind speeds (wind speed at roof ridge height) were evaluated in the same way as for the BSRIA and NRC models.

The turbulence correction term requires that the root-means-square of the external pressure coefficients be specified. The values shown in Table 4.5.1. were chosen rather arbitrarily to be of similar magnitude to the C_p values.

Canadian test data (HUDAC houses)

Comparisons between calculation and measurement for both the 'standard' and 'upgraded' dwellings are illustrated in Figures 4.5.1. and 4.5.2. respectively. These results also illustrate the influence of the turbulence correction term and include additional summertime data for the 'upgraded' dwelling, based on measurements made outside the heating season (see Appendix 2). The winter measurements correspond to those applied to the BSRIA and NRC models and, for comparison purposes, are considered first. For the 'upgraded' dwelling 29 of the 37 calculations were within 25% of measurement, with no turbulence correction, and 28 of the calculations were within 25% with the inclusion of turbulence correction. The corresponding results for the 'standard' dwelling were 27 out of 32 data points and 24 calculations respectively.

The net effect of including the turbulence term was to increase the calculated rate of air infiltration. No conclusive evidence regarding the benefit of this term was obtained using the Canadian test data.

The very low summer measurements tended to be under-estimated by the model, both with and without the inclusion of the turbulence correction term. Not too much significance was attached to this result, primarily because measurements of extremely low rates of air infiltration are particularly difficult to make and can be significantly influenced by the choice of tracer gas.[6] Furthermore, these conditions fall well outside the necessary range of air infiltration models.

United Kingdom test data (Runcorn house)

Comparisons for both sets of conditions are illustrated in Figure 4.5.3. With no turbulence correction, ten of the fifteen calculations were within 25% of measurement. With turbulence correction, twelve of the calculations fell within the 25% band. Thus a small improvement in the result was achieved by including the turbulence term.

In general, agreement between calculation and measurement for all the data sets was felt to be reasonable, especially considering the uncertainties in interpreting the data. The largest differences between prediction and measurement tended to occur at high wind speeds, where the predicted values are sensitive to the values chosen for the reference wind speed and the pressure distribution.

Table 4.5.1: Values of major parameters used in British Gas model

House	Leakage Q50 m^3h^1	A/B^2	Leakage distribution %	Cp distribution on walls							Background leakage % and Cp_{RMS}
				Dir.	W1	W2	W3	W4	Roof	Roof	
HUDAC	988.9	0.03	Wall 1 – 25%	N	0.40	–0.40	–0.4	–0.1	0.0	–0.3	60%
Upgraded			Wall 2 – 25%	NW	0.50	–0.30	–0.5	–0.3	–0.3	–0.3	0.3
			Wall 3 – 20%	W	0.00	0.50	–0.3	–0.3	–0.3	–0.3	
			Wall 4 – 10%	S	0.40	0.00	–0.3	0.1	0.0	–0.3	
			Ceiling – 20%	E	–0.20	–0.2	0.20	–0.3	–0.3	–0.3	
				NE	0.50	–0.30	–0.4	0.1	–0.3	–0.3	
HUDAC Standard	1450.3	0.03	As above	As above							As above
Runcorn	3000.0	0.15	Wall 1 – 36%	0	0.15	–0.15	–	–	–0.15	–	56%
			Wall 2 – 48%	10–20	0.05	–0.20	–	–	–0.15	–	0.15
			Ceiling – 16%	40	–0.15	–0.20	–	–	–0.15	–	
				60–80	–0.15	–0.20	–	–	–0.20	–	

N.B. Runcorn wind directions are relative to building axis.

Figure 4.5.1: Comparison between calculated and measured air infiltration rates (HUDAC 'standard' house) *(British Gas model)*

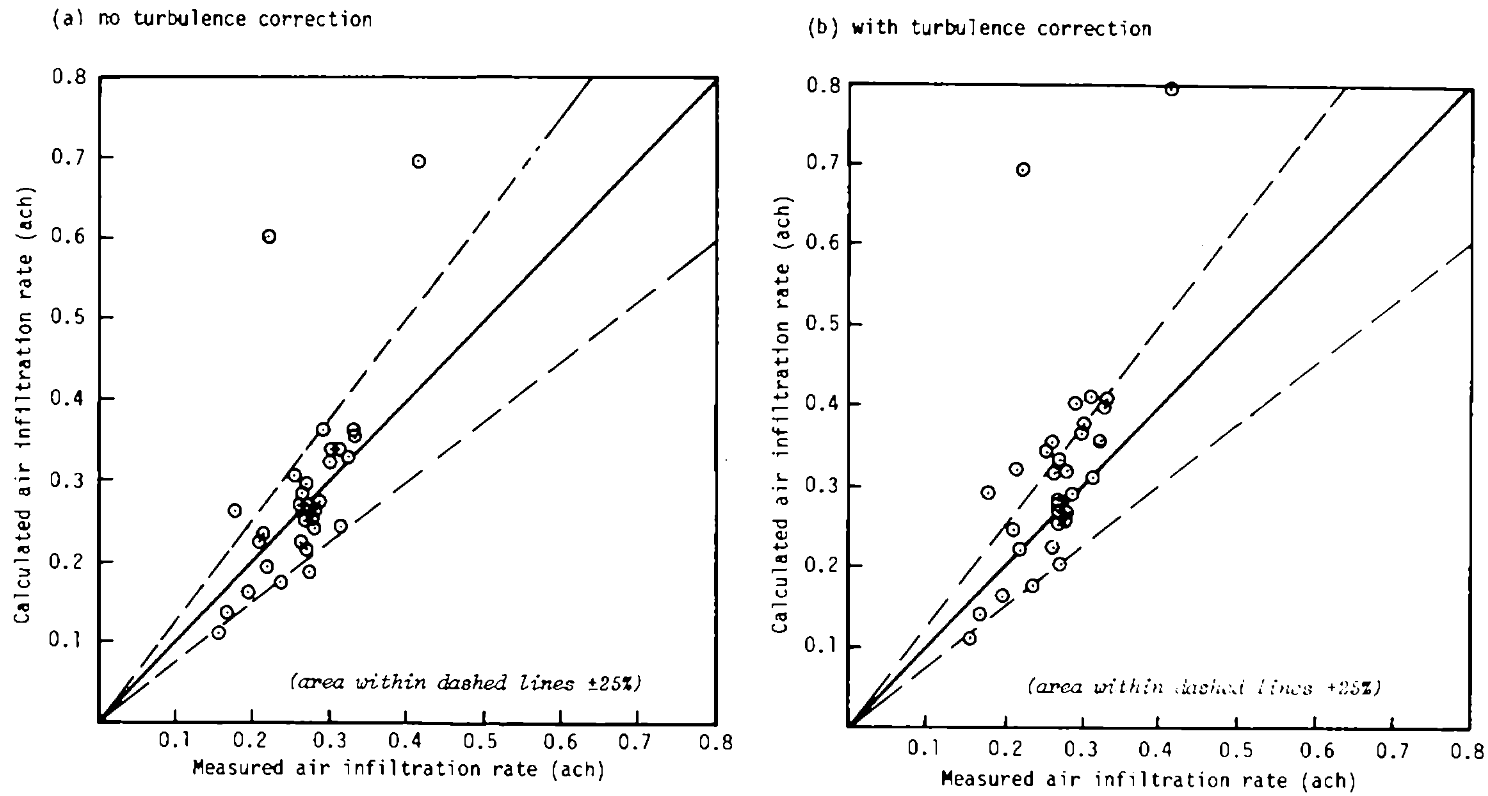


Figure 4.5.2: Comparison between calculated and measured air infiltration rates (HUDAC 'upgraded' house) *(British Gas model)*

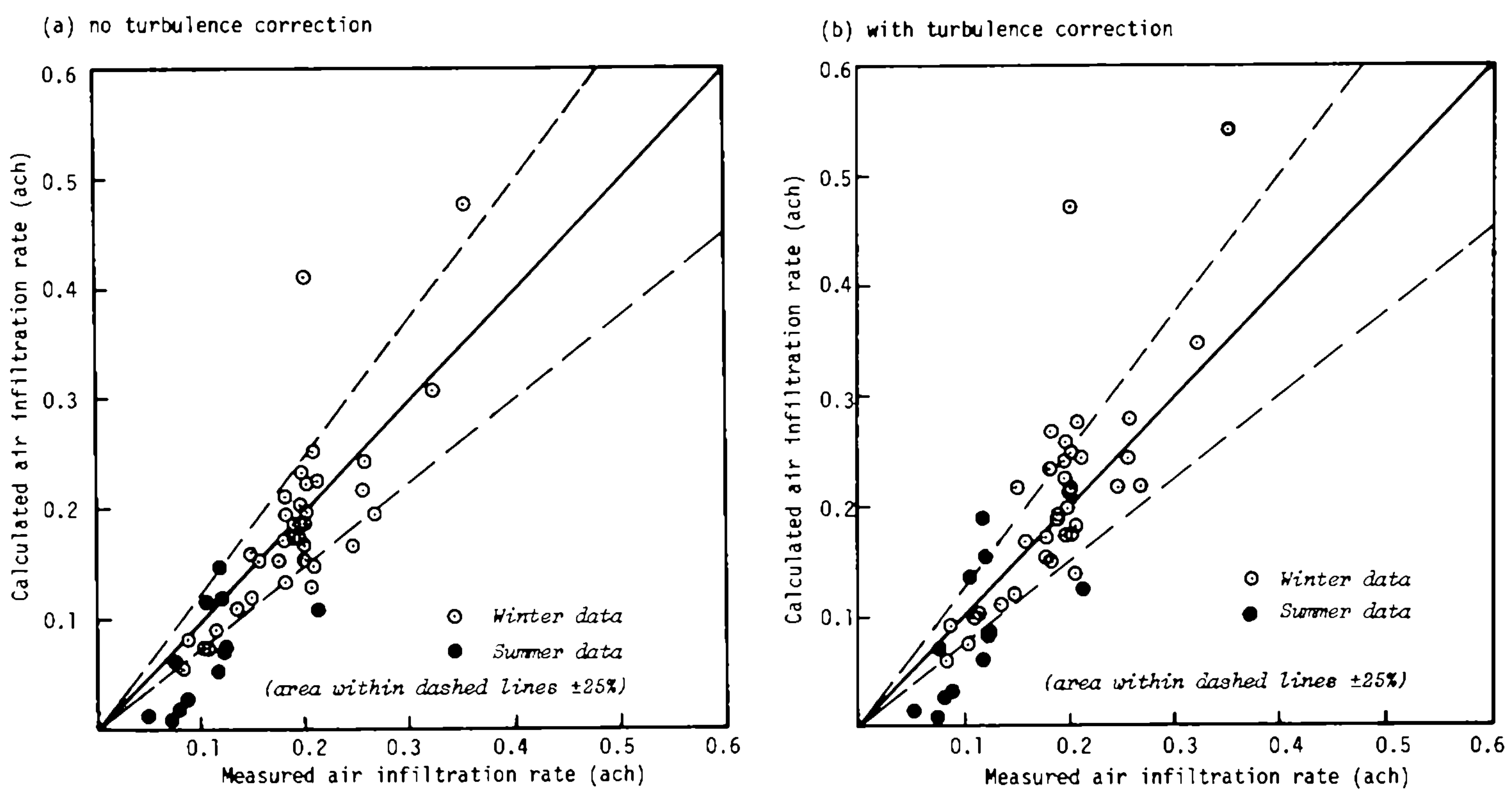
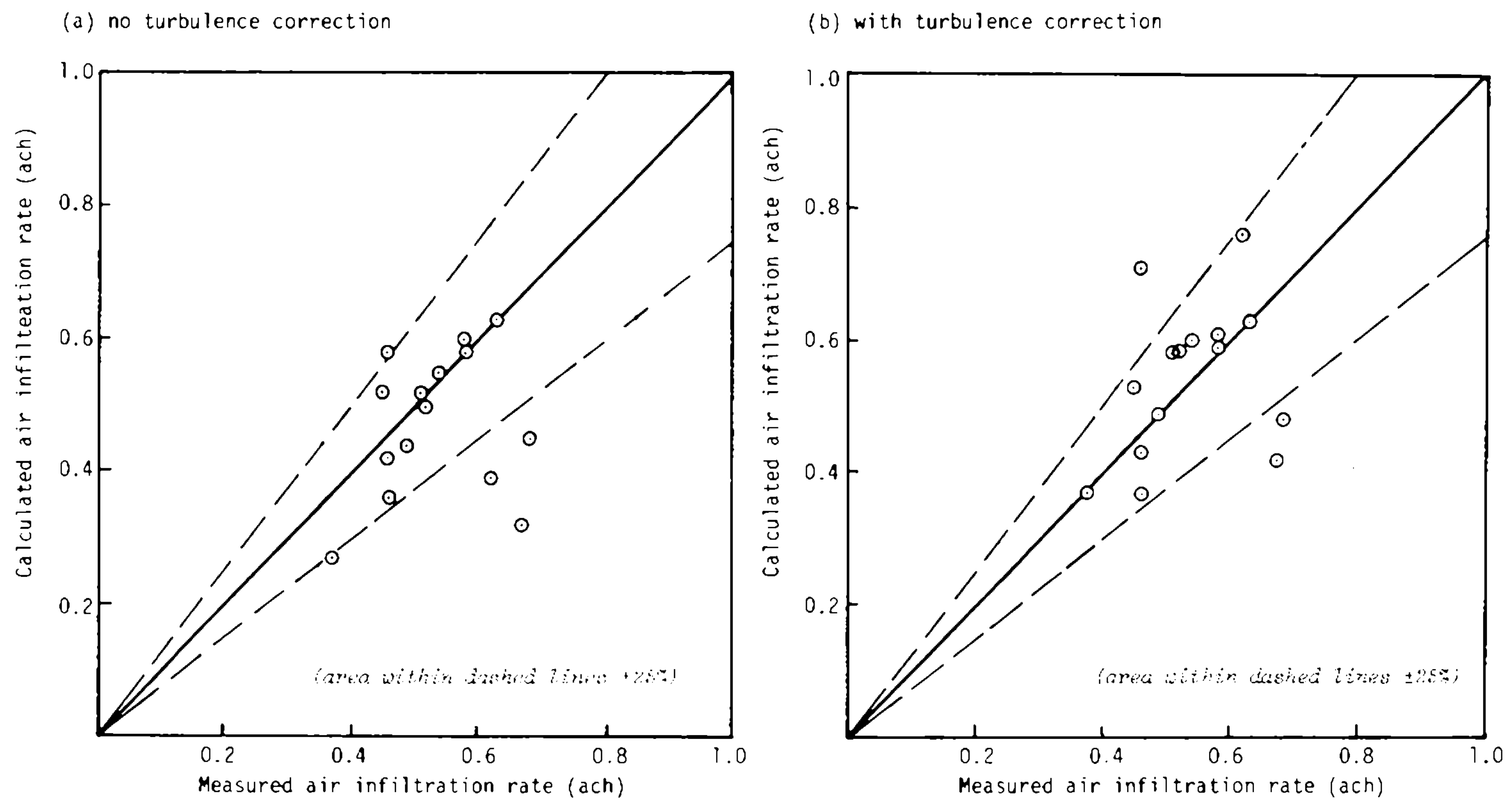


Figure 4.5.3: Comparison between calculated and measured air infiltration rates (Runcorn house) *(British Gas model)*



4.6 Norwegian model ENCORE

(Summary of results received from Sivert Uvsløkk, Norwegian Building Research Institute)

Six data sets including those for the Swiss and Canadian dwellings were used in the assessment of this model. The remaining data comprised the Canadian 'standard' dwelling (CA1), the 'KEMNAY' house (UK3), the SEGAS house (UK4) and measurements made in 25 identical Swedish detached houses[7].

The house volumes, leakage data and other important parameters used in the computations are given in Table 4.6.1. For all but the Swedish dwellings, it was assumed that no ventilation fans were in operation during the measurement periods. In the case of the Swedish dwellings, exhaust ventilation rates of 50 and 310 m^3h^{-1} were applied as compared with measured volumes which ranged from 40–60 m^3h^{-1} and 295–325 m^3h^{-1} respectively. Pressure coefficients were based on the values given in Table 4.6.2. and relate to wind tunnel measurements made on scale models of single buildings. Wind directions were taken into account except for the Swedish dwellings for which these data were not available.

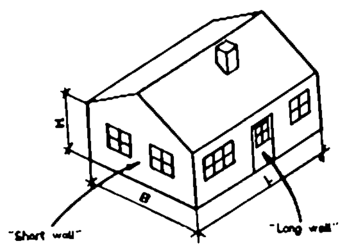
Table 4.6.1: Some of the parameters used during computation

House (AIC Dataset)	Mean leakage at 50 Pa pressure difference (m^3h^{-1})	Air volume (m^3)	Leakage factor n_{50} (h^{-1} at 50 Pa)	Leakage distribution with height: Height above ground	Leakage distribution with height: % of total	House shape	Wind pressure reference height (m)	Terrain type
HUDAC 1 (CA 1)	1450	386	3.8	Roof 5.4 Walls 5.4 " 4.2 " 2.9 " 1.7 " 0.4	22 18 10 20 10 20	1	3.0	2 suburban
HUDAC 2 (CA 2)	990	386	2.6	Roof 5.4 Walls 5.4 " 4.2 " 2.9 " 1.7 " 0.4	22 18 10 20 10 20	1	3.0	2 suburban
MAUGWIL (CH 1)	840	346	2.4	Roof 7.5 Walls 7.5 Roof 6.5 Walls 6.5 " 5.0 " 3.8 " 2.5 " 1.3 " 0.0	11 7 9 9 25 9 18 6 6	1	2.5	1 flat
KEMNAY (UK 3)	1955	260	7.5	Roof 5.3 Walls 5.3 " 4.1 " 2.8 " 1.6 " 0.3	7 21 10 24 10 28	1	2.7	2 suburban
SEGAS (UK 4)	5645	240	23.5	Roof 5.3 Walls 5.3 " 4.1 " 2.8 " 1.6 " 0.3	7 21 10 24 10 28	1	2.7	3 centre of city
25 Swedish houses (AIRBASE ref # No.4)	955-2055	367	2.6-5.6	Roof 5.3 Walls 5.3 Roof 4.0 Walls 4.0 " 2.8 " 1.5 " 0.3	11 2 18 7 25 26 12	4	2.8	2 suburban

The comparisons between computed and measured infiltration for each of the data sets are illustrated in Figures 4.6.1. (a) to (g) respectively. These diagrams also indicate temperature difference and wind conditions and show that calculations correspond satisfactorily with measurement for wind speeds below 2 ms^{-1} in all cases.

With the exception of the SEGAS house (UK4) which is of brick construction, computed infiltration was found to increase far more with higher wind speeds than did the measured values. This was found to apply particularly to the Canadian 'standard' dwelling (CA1) and the Swedish houses. A possible reason for this mis-match at higher wind speeds, suggested by the Norwegian Building Research Institute, is that the wind pressure coefficients used in the ENCORE computations do not fit satisfactorily for multilayer constructions containing ventilated air spaces. The coefficients used are based on wind tunnel measurements of external wind pressure, while it is the wind pressure on the air barriers that influences leakage. When there is a ventilated airspace between the outer skin and the air barriers, one may expect the wind pressure on the air barriers to be considerably lower than on the exposed skin. This applies in particular to roofs with ventilated attics.

Table 4.6.2: Pressure coefficient data *(Norwegian model ENCORE)*



Definition of building shape

Shape no.	1	2	3	4	5	6	7	8
H/B	1	1	½	½	½	3/2	3/2	3/2
L/B	1	2	1	2	4	1	2	4

Building shapes

Build. shape	Angle of attack				
	0°	45°	90°	135°	180°
1	0.8	0.4	-0.8	-0.6	-0.6
2	0.8	0.4	-0.7	-0.8	-0.6
3	0.7	0.4	-0.7	-0.6	-0.4
4	0.7	0.4	-0.5	-0.7	-0.5
5	0.7	0.4	-0.3	-0.7	-0.6
6	0.7	0.4	-0.8	-0.7	-0.7
7	0.8	0.4	-0.7	-0.8	-0.6
8	0.8	0.5	-0.5	-0.8	-0.7

Pressure coefficients for long walls

Build. shape	Angle of attack				
	0°	45°	90°	135°	180°
1	0.7	0.4	-0.8	-0.6	-0.6
2	0.8	0.4	-0.7	-0.6	-0.2
3	0.8	0.4	-0.8	-0.5	-0.4
4	0.7	0.3	-0.9	-0.6	-0.2
5	0.8	0.3	-0.9	-0.5	-0.2
6	0.7	0.4	-0.8	-0.6	-0.7
7	0.7	0.3	-0.7	-0.7	-0.4
8	0.8	0.2	-0.8	-0.7	-0.3

Pressure coefficients for short walls

Roof angle	Angle of attack				
	0°	45°	90°	135°	180°
0°	-0,8	-0,8	-0,6	-0,8	-0,8
15°	-0,9	-0,9	-0,6	-0,8	-0,7
30°	-0,8	-0,5	-0,6	-0,8	-0,6
45°	0.	-0,1	-0,7	-0,8	-0,7

Pressure coefficients for roofs.

Figure 4.6.1: Comparison between calculated and measured air infiltration rates *(NBRI model)*

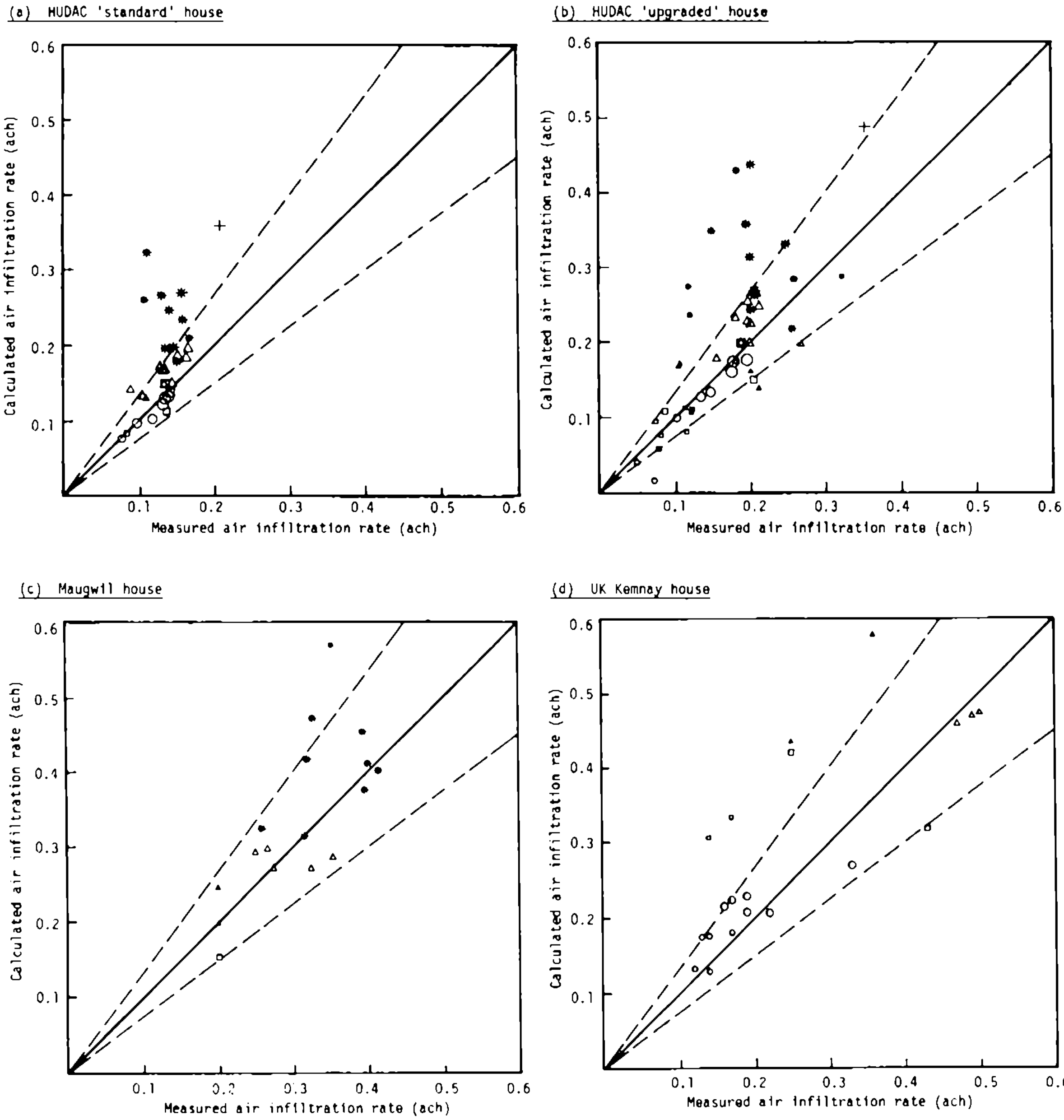
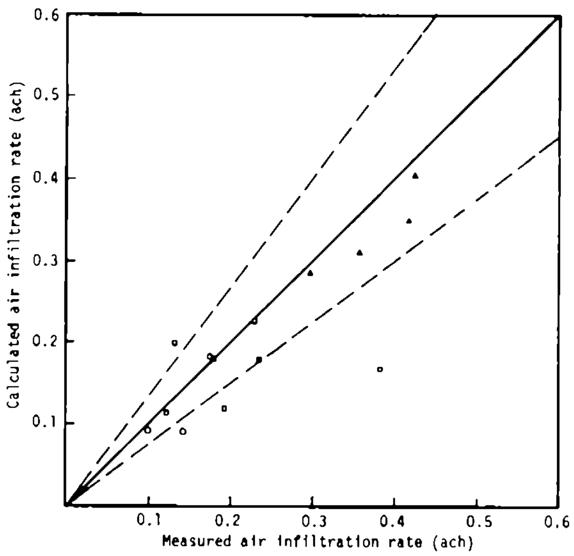
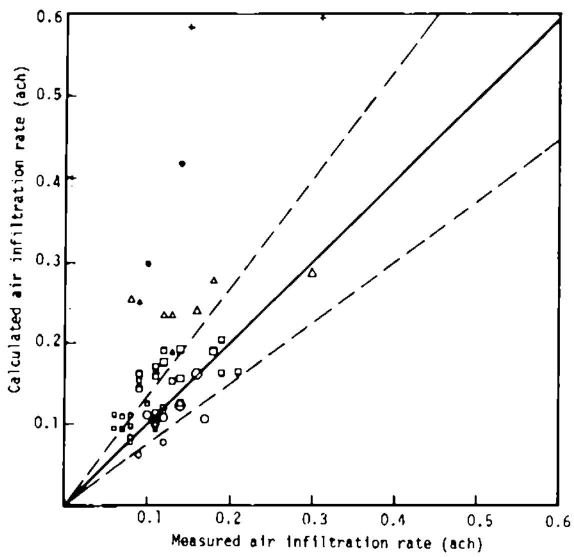


Figure 4.6.1: Comparison between calculated and measured air infiltration rates *(NBRI model)* – continued

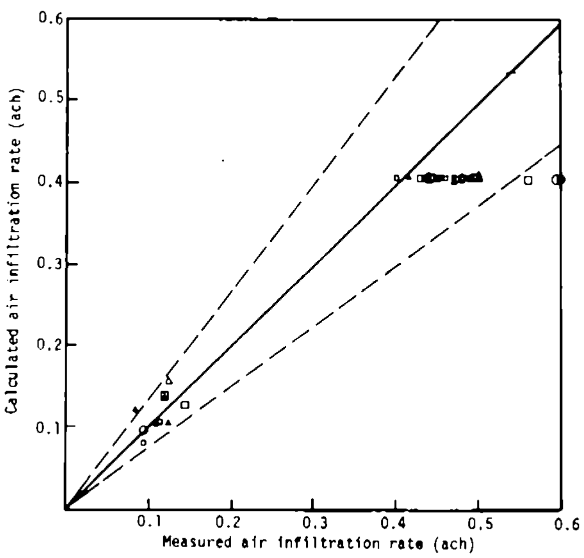
(e) UK SEGAS house



(f) 25 Swedish houses - no extract ventilation



(g) 25 Swedish houses - with extract ventilation (see text)



KEY

WINDSPEED (m/s) / TEMP. DIF. (°C)	0- 2	2- 4	4- 6	6-10	10 <
0-10	○	□	△	●	+
10-20	○	□	△	●	+
20-30	○	□	△	●	+
30 <	○	□	△	✱	+

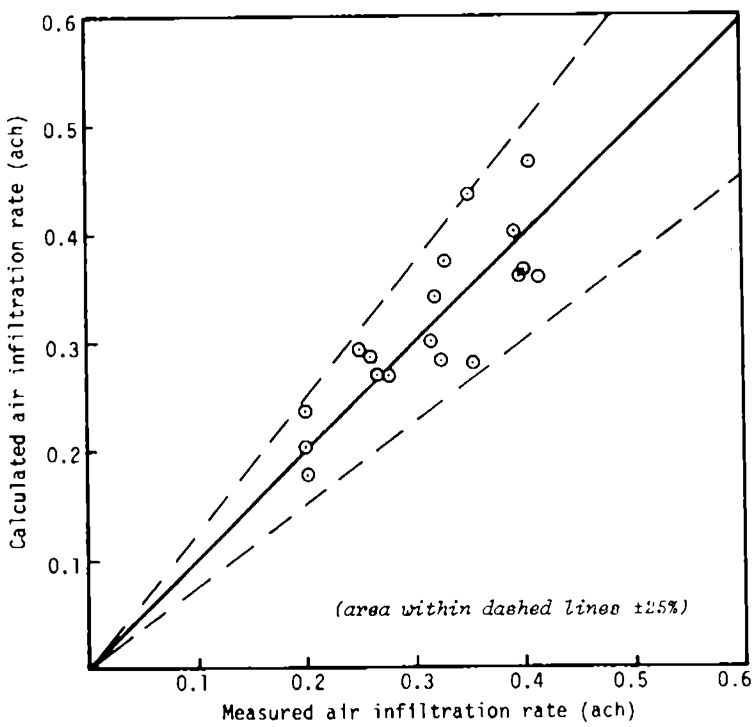
4.7 IGT Model

The input data for all the dwellings are summarized in Table 4.7.1. For each house, the walls were numbered 1 to 4, with wall 4 representing the front of the building. This model differed from the previously investigated models in that direct measurements of total building or component leakage were not used. Instead, a permeability factor was assigned based on an assessment of the leakiness of the building. Furthermore, an overall crack length was specified, based on the total perimeter length surrounding doors, windows, sashes and building foundations. There was no direct provision for dealing with the influence of local shielding.

Swiss data set (Maugwil house)

A permeability factor of 0.40 was assumed; this was based on the assumption of a fairly tight construction with a sealed basement. Comparisons between calculations and measurements are illustrated in Figure 4.7.1. Good results were achieved, with all the calculations being within 25% of measurement.

Figure 4.7.1: Comparison between calculated and measured air infiltration rates (Maugwil house) *(IGT model)*



Canadian data set (HUDAC house)

A permeability factor of 0.35 was selected for the HUDAC house. This was based on an extremely tight construction, incorporating an air/vapour barrier and triple-glazed windows. Calculations for both summertime and wintertime data were performed, as with the British Gas model, and the results are illustrated in Figure 4.7.2. Out of a total of 37 winter data points, 28 calculations were within 25% of measurement. The general trend of these results was a fairly wide scatter with a tendency to over-estimate the measured values. Some of the scatter was thought to be due to the influence of spatial differences in local shielding, which could not be readily included as part of the input data. Nevertheless, a significant proportion of the results were within the 25% sector.

Figure 4.7.2: Comparison between calculated and measured air infiltration rates (HUDAC 'upgraded' house) *(IGT model)*

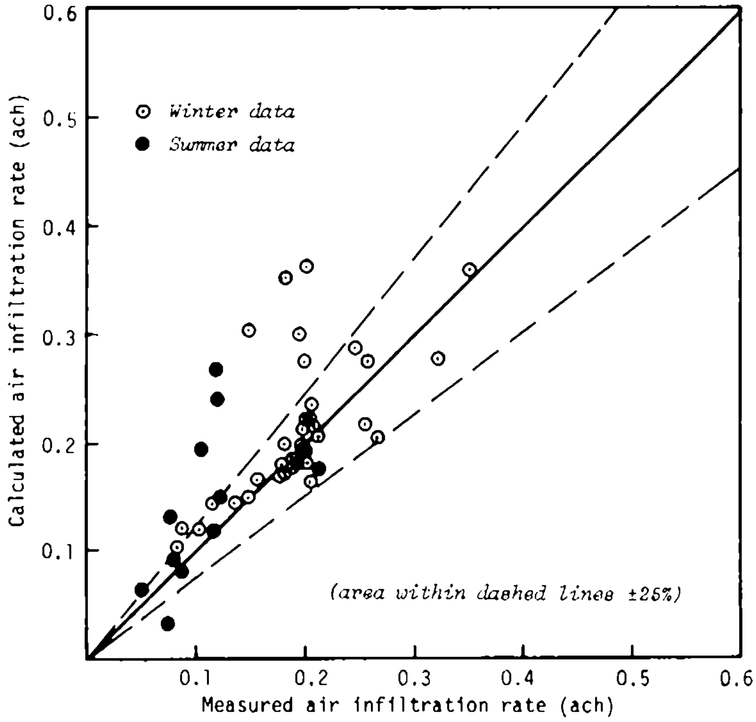
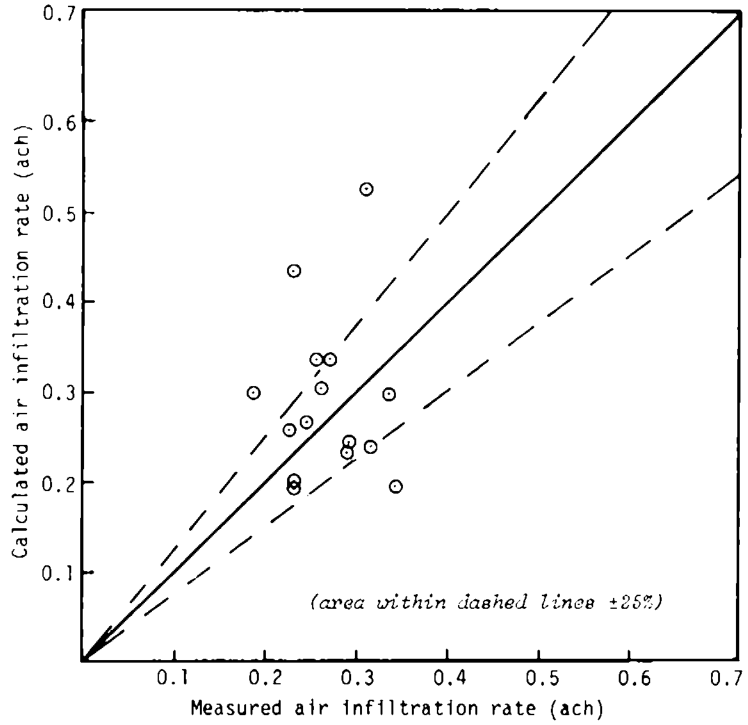


Figure 4.7.3: Comparison between calculated and measured air infiltration rates (Runcorn house) *(IGT model)*



UK data set (Runcorn house)

This dwelling was regarded as structurally fairly airtight with leaky windows. Both the skylight in the bathroom and the toilet extract duct were treated as a chimney with a flue temperature equal to that of the internal air temperature and a height equivalent to that of the house. A permeability factor of 1.75 was assumed. The results are illustrated in Figure 4.7.3. Again, there was a fairly wide scatter in results. Out of a total of 15 calculations, 10 were within the 25% 'acceptable error' band.

Overall, fairly good agreement was achieved using this model, especially considering that it did not make specific use of available air leakage data. The main problem seemed to be related to quantifying the surrounding shielding conditions.

Table 4.7.1: Summary of input data *(IGT model)*

	HUDAC Mk XI	MAUGWIL	RUNCORN
Title	HUDAC Mk.XI house (upgraded)	Maugwil test building	Runcorn house
Description	2-storey timber frame house, basement electric heating	Concrete basement and 2 floors, timber frame, oil fired burner and radiators	3-storey mid-terrace, glass-fibre reinforced plastic, district heating
House type	4	3 (eaves level≡upper storey floor)	4
Height of infiltrated space	5.4 m	7.30 m	7.08 m
Volume	386.0	342.0	220.23
Terrain classification	5 (on site)	5 (on site)	5 (on site)
Chimney: Height	–	–	7.08 m (building height)
Flow coefficient	–	–	5000
Total crack lengths:			
Building face 1:			
doors	530.0	0.0	0.0
windows	720.0	2669.0	0.0
foundation	800.0	911.0	0.0
Building face 2:			
doors	0.0	0.0	558.0
windows	2330.0	482.0	2582.0
foundation	800.0	822.0	360.0
Building face 3:			
doors	0.0	0.0	0.0
windows	0.0	2423.0	0.0
foundation	840.0	911.0	0.0
Building face 4:			
doors	800.0	590.0	558.0
windows	2140.0	1426.0	1608.0
foundation	800.0	822.0	360.0
Permeability factor	0.35 (very tight)	0.40 (tight – part sealed off)	1.75 (loose)

4.8 LBL model

Swiss data set (Maugwil house)

The surface area of the building was based as far as possible on the area enclosing the volume in which the tracer gas test was performed. The estimated surface area was 233m^2 of which 38m^2 was represented by the ceiling. The effective leakage area was calculated from the pressurization test data and found to be 0.0081m^2. Owing to the exceptionally exposed location of this dwelling, a Class 1 shielding coefficient was assumed (Table 4.8.1). Wind speed reduction to ceiling height was based on a Class II terrain value (see also Table 4.8.1). The stack parameter, f_s, and wind parameter, f_w, were calculated to be 0.321 and 0.356 respectively.

Comparisons between calculated and measured air change rates are illustrated in Figure 4.8.1. Excellent agreement was achieved with all the calculations being within 25% of measurement.

Table 4.8.1: Terrain and shielding definitions *(LBL model)*

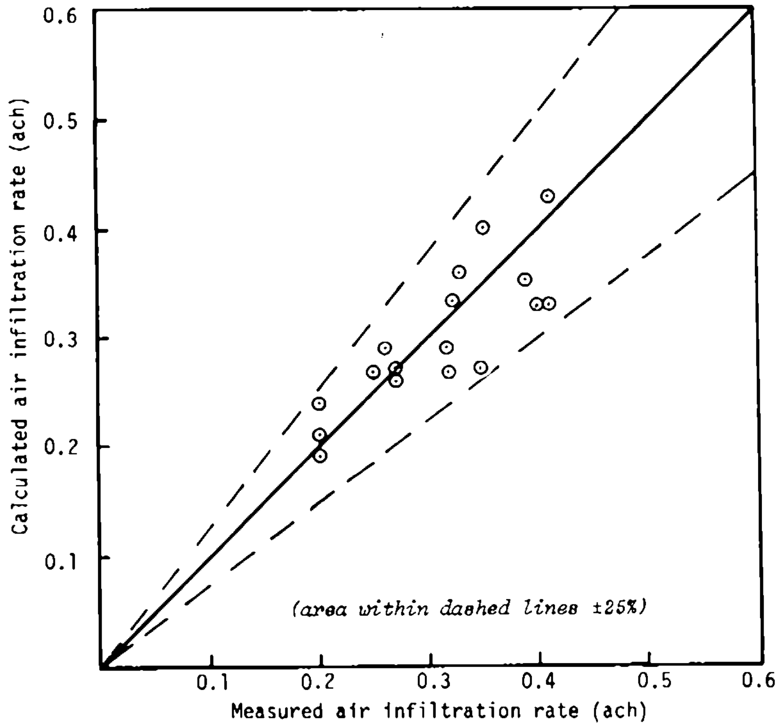
(i) Terrain parameters for standard terrain classes

Class	γ	α	Description
I	0.10	1.30	Ocean or other body of water with at least 5km of unrestricted expanse
II	0.15	1.00	Flat terrain with some isolated obstacles, e.g. buildings or trees well separated from each other
III	0.20	0.85	Rural areas with low buildings, trees, etc.
IV	0.25	0.67	Urban, industrial or forest areas
V	0.35	0.47	Centre of large city, e.g. Manhattan

(ii) Generalised shielding coefficients

Shielding Class	C'	Description
I	0.34	No obstructions or local shielding whatsoever
II	0.30	Light local shielding with few obstructions
III	0.25	Moderate local shielding, some obstructions within two house heights
IV	0.19	Heavy shielding, obstructions around most of perimeter
V	0.11	Very heavy shielding, large obstruction surrounding perimeter within two house heights

Figure 4.8.1: Comparison between calculated and measured air infiltration rates (Maugwil house) *(LBL model)*



Canadian data set (HUDAC 'upgraded' house)

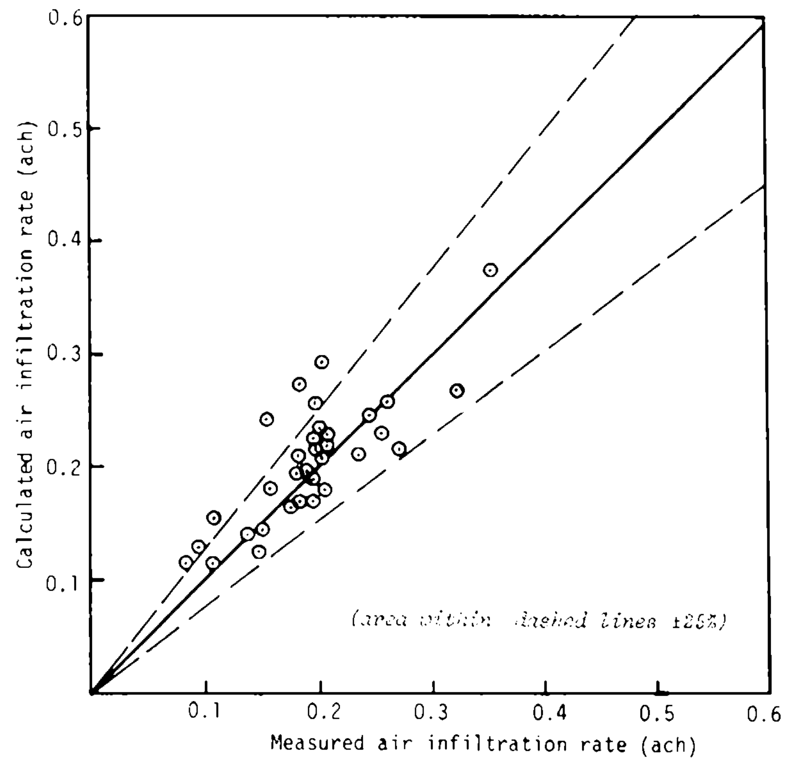
A wall surface area of 156m^2 and a ceiling area of 64m^2 was assumed. To account for spatial variations in local shelter, shielding coefficients were specified according to wind direction; the shielding classes selected are given in Table 4.8.2. Wind speeds at ceiling height (~ 5.6m) were determined using 'on-site' wind data measured at a level of 16m, where terrain class II conditions were assumed to apply (Table 4.8.1). The effective leakage area of the house was found to be 0.177m^2.

Table 4.8.2: Shielding for HUDAC 'upgraded' house *(LBL model)*

Wind direction	Shielding class	Shielding coefficient
N	II	0.30
NW	II	0.30
W	III	0.25
SW	IV	0.19
S	III	0.25
SE	III	0.25
E	III	0.25
NE	IV	0.25

The results are illustrated in Figure 4.8.2. and were again very good with 30 of the 37 measurements being within 25% of measurement.

Figure 4.8.2: Comparison between calculated and measured air infiltration rates (HUDAC 'upgraded' house) *(LBL model)*

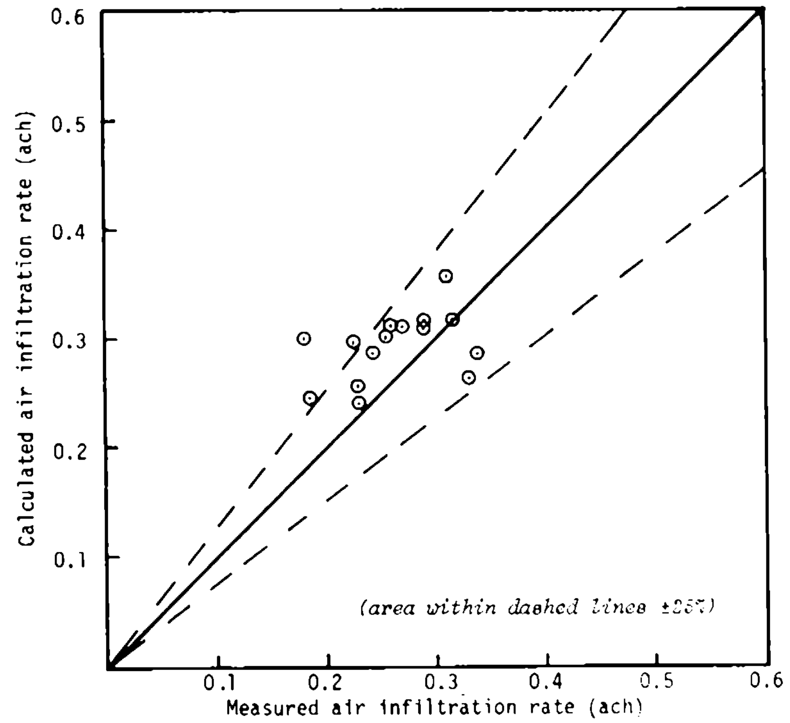


UK data set (Runcorn house)

Air infiltration paths in this dwelling were assumed to be through the front and rear facades and the ceiling. The net surface area of the walls was approximately $51m^2$ and the ceiling area was $31m^2$. The corresponding leakage area was $0.57m^2$. Class V terrain conditions were assumed, reflecting the heavily shielded location of this dwelling. The results are illustrated in Figure 4.8.3. Good agreement between calculation and measurement was achieved with all but three of the calculations being within 25% of measurement.

Despite the simplifications incorporated in the LBL model, the model performed extremely well. Furthermore, it was relatively straightforward to use and required the minimum of computational effort.

Figure 4.8.3: Comparison between calculated and measured air infiltration rates (Runcorn house) *(LBL model)*



4.9 Building Research Establishment Model

The BRE model was used in the analysis of four sets of data; these were the three key data sets and the data for the HUDAC standard dwelling. In each instance wind pressure coefficients were taken from the best available data appropriate to the shape of the building and the nature of its surroundings. Where the leakage characteristics of individual components were given in the data sets, these were used to estimate the distribution of the envelope leakage between external surfaces. Where available, the component leakage at 50 Pa was subtracted from the total leakage determined from the pressurisation tests. The remaining leakage was distributed between the surfaces on an area-weighted basis and the relevant component leakages added to obtain the total for each surface. The exponent obtained from the pressurisation test was assumed to apply to all individual surfaces.

Swiss test data (Maugwil house)

The wind data taken from the main table of results were used (see Table 7, Appendix 1). Wind pressure coefficients were obtained from BRE wind tunnel measurements on an isolated building of similar shape to the Maugwil House with a boundary layer appropriate to open country. The major difference between the full-scale and model building was the roof pitch which in the latter case was 30°.

The pressure coefficients were obtained for wind directions at 30° intervals and specific values at 15° intervals were obtained by interpolation. The values appropriate to the full-scale data sets are given in Table 4.9.1.

The results are illustrated in Figure 4.9.1. and show remarkably good agreement, with 16 of the 18 calculations being with ±25% of measurement.

Figure 4.9.1: Comparison between calculated and measured air infiltration rates (Maugwil house) *(BRE model)*

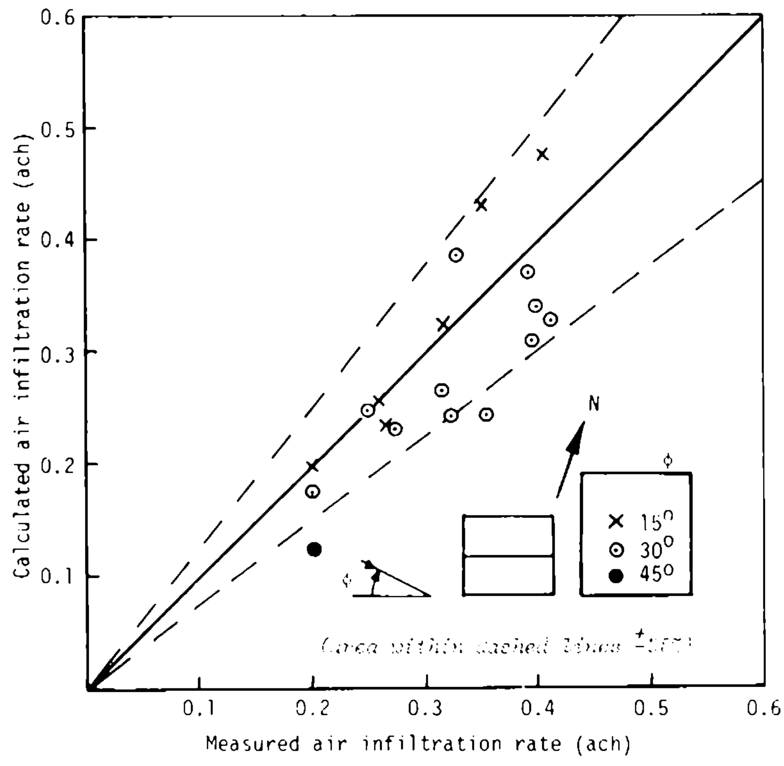


Table 4.9.1: Pressure coefficient data – Maugwil house *(BRE Model)*

			Walls			
0	0	Roof	West	North	East	South
260	15	–0.6	0.7	–0.2	–0.5	–0.5
275	30	–0.5	0.6	0.2	–0.4	–0.6
290	45	–0.3	0.4	0.4	–0.4	–0.5

(Note: Values rounded to first decimal place)

Canadian test data (HUDAC Mk.IX 'standard' and 'upgraded' test houses)

In the absence of specific data, wind pressure coefficients were obtained from BS5925. According to the notes accompanying the data sets there is moderate shielding of the test houses by other houses within two house heights and an earth berm. In accordance with the wall and roof pressures obtained by Lee et al[8] from wind tunnel measurements on housing arrangements of different densities, the BS5925 values have been halved. The resultant pressure coefficients are listed in Table 4.9.2.

Comparisons between calculation and measurement are illustrated for the 'standard' and 'upgraded' homes in Figures 4.9.2. and 4.9.3. respectively. As with the previous models, there is a fairly wide results scatter, possibly reflecting the difficulty in dealing with local shelter. Nevertheless, the results are again encouraging with a substantial proportion of the calculations being within 25% of measurement.

Figure 4.9.2: Comparison between calculated and measured air infiltration rates (HUDAC 'standard' house) *(BRE model)*

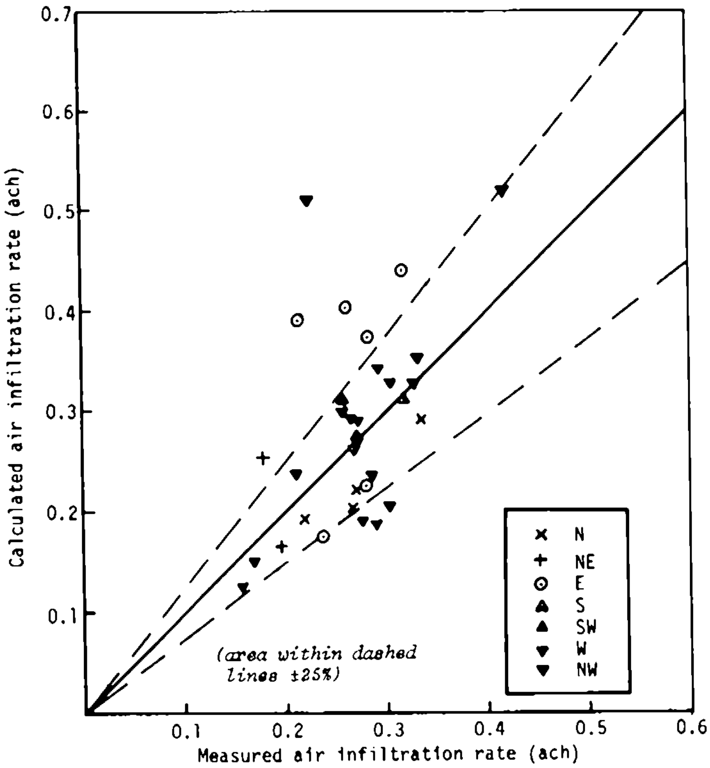


Figure 4.9.3: Comparison between calculated and measured air infiltration rates (HUDAC 'upgraded' house) *(BRE model)*

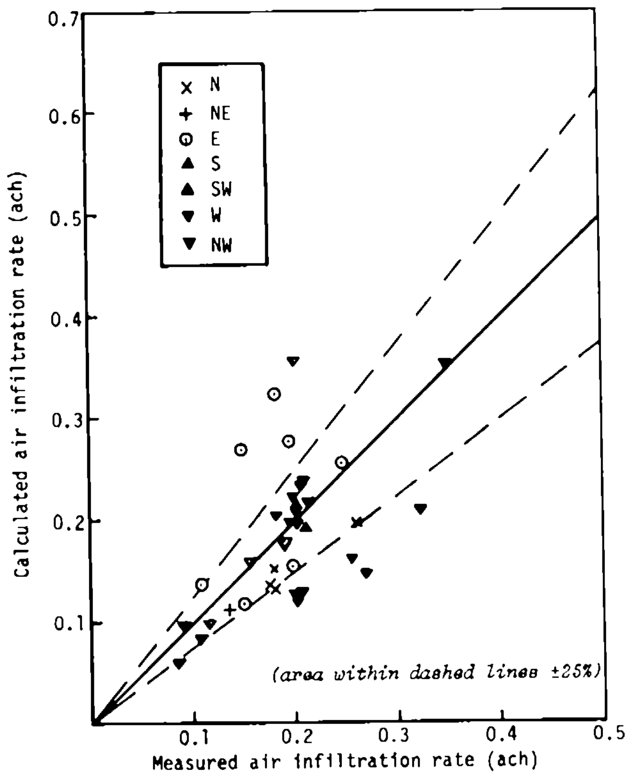


Table 4.9.2: Pressure coefficient data – HUDAC house *(BRE Model)*

Wind direction	Roof	Walls			
		North	East	South	West
N and NW	–0.17	0.35	–0.30	–0.12	–0.30
E and NE	–0.40	–0.30	0.35	–0.30	–0.12
S & SE	–0.17	–0.12	–0.30	0.35	–0.30
W and SW	–0.40	–0.30	–0.12	–0.30	0.35

United Kingdom test data (Runcorn dwelling)

In the absence of specific data, wind pressure coefficients were obtained from BS5925 for winds approximately parallel to the surface. For winds in the quadrant 270 to 360 the house is shielded by a parallel terrace of similar houses. For this range of wind directions the pressure coefficients were obtained from Hussain and Lee.[9] The pressure coefficients used are in Table 4.9.3.

Again, generally good agreement between calculation and measurement was achieved (Figure 4.9.4.) with only two points falling outside the 25% 'error' band.

Figure 4.9.4: Comparison between calculated and measured air infiltration rates (Runcorn house) *(BRE model)*

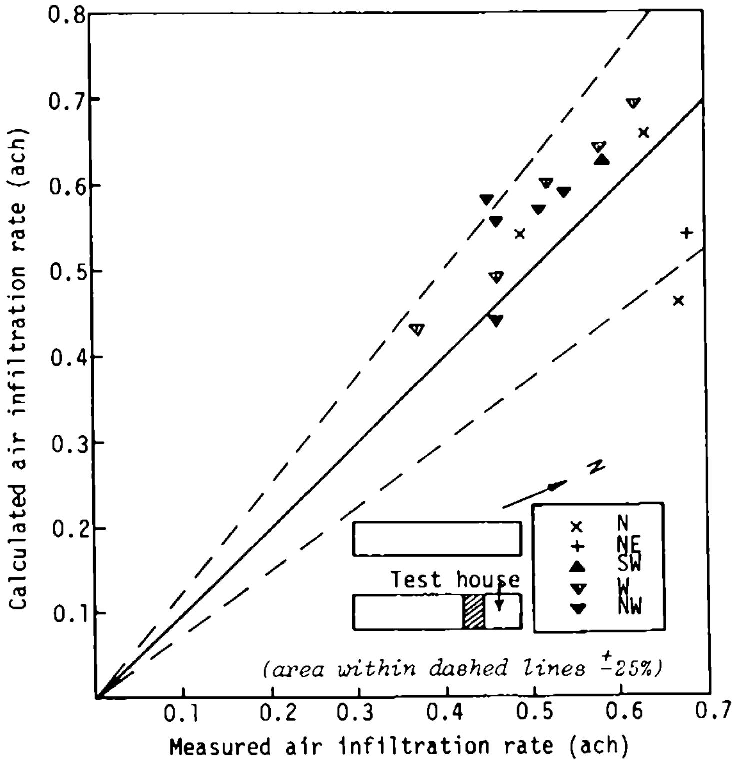


Table 4.9.3: Pressure coefficient data – Runcorn house *(BRE Model)*

Wind direction	Roof	Walls	
		East	West
270° to 360°	–0.10	–0.07	0.02
0° to 90° 180° to 270°	–0.60	–0.50	–0.50

4.10 Reeves McBride Sepsy Model

A summary of the input data for each of the houses is given in Table 4.10.1. In each case the product βC_T (see section 2.10) was determined using the first air infiltration measurement of each data set. The value of this constant was set such that the calculated rate of air infiltration was equal to measurement; thereafter this value was applied to the remainder of the data set.

Table 4.10.1: Summary of data used in Reeves model

	HUDAC Mk.XI 'upgraded'	MAUGWIL	RUNCORN
Effective stack height	2.44m	2.44m	2.44m
System state	No chimney (electric furnace)	No chimney (chimney sealed)	No chimney (outside heat source)
Volume (m^3)	386	413 overall 342 above stairwell door	220.23
Normalized crack length (m)	247.38	194.50	732
Initial conditions:			
internal temperature (°C)	22.20	20.90	20.30
external temperature (°C)	25.40	8.90	6.60
10m windspeed (ms^{-1})	2.32	5.96	2.00
measured infiltration rate (ach)	0.116	0.266	0.58
calculated βC_T	41.71	33.66	125.50

This technique worked well for the Maugwil house, with all of the calculations being within 25% of measurement (Figure 4.10.1). Results for the HUDAC 'upgraded' house were fairly widely scattered, with a general tendancy for the calculated rates of air infiltration to over-estimate the measured values; 21 of the 37 calculations were within 25% of measurement (Figure 4.10.2). This model did not perform satisfactorily for the Runcorn house, with only 5 of the 15 calculations being within 25% of measurement (Figure 4.10.3). For this dwelling virtually all the calculations systematically over-estimated measurement. This was thought to be due to the influence of wind being exaggerated by the model.

For the heavily shielded orientations of the Runcorn or HUDAC sites, it would probably have been better to calculate the constant βC_T for each wind direction. However this would require a substantial number of air infiltration measurements to be made and would therefore further limit the value of the model.

Figure 4.10.1: Comparison between calculated and measured air infiltration rates (Runcorn house) *(Reeves model)*

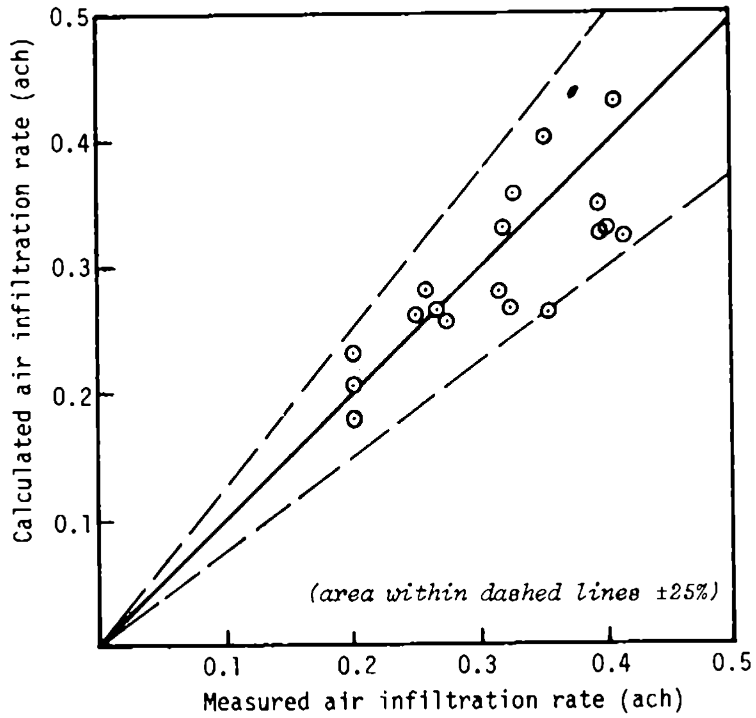


Figure 4.10.2: Comparison between calculated and measured air infiltration rates (HUDAC 'upgraded' house) *(Reeves model)*

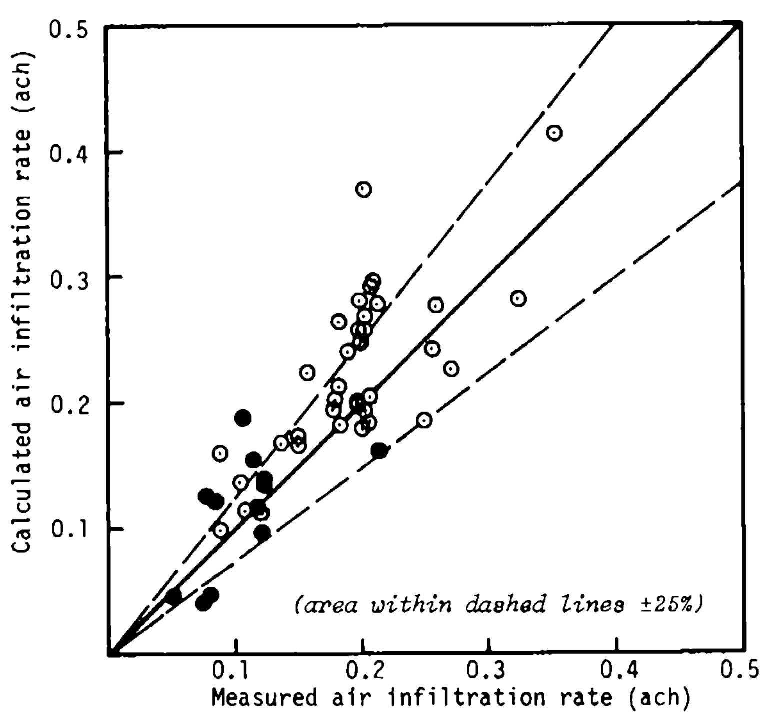
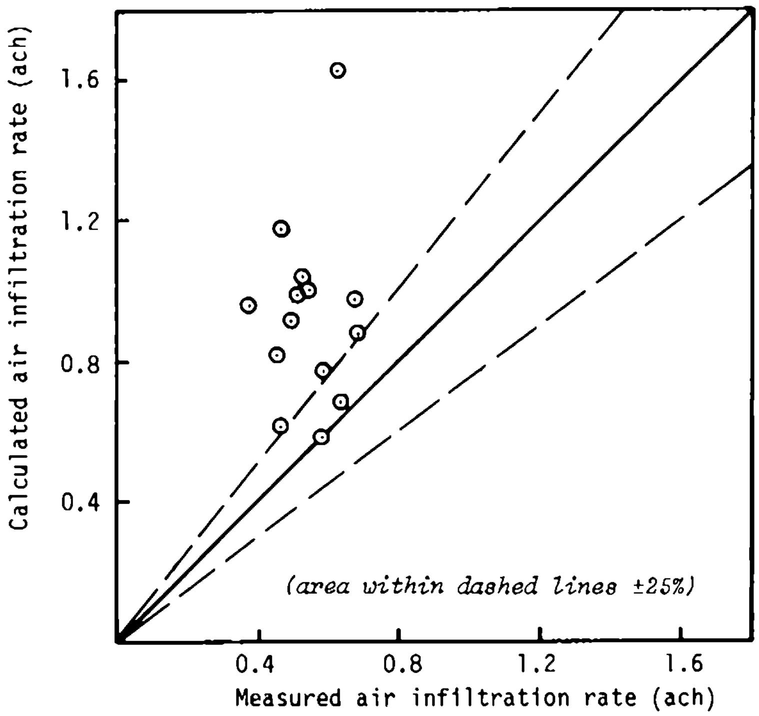


Figure 4.10.3: Comparison between calculated and measured air infiltration rates (Runcorn house) *(Reeves model)*



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5. Model Performance – Principal Strengths and Weaknesses

The three key data sets represented a wide range of terrain, wind and temperature conditions and therefore provided a comprehensive test to evaluate model performance.

The performance of each model is summarised in Table 5.1. The best results were achieved using the relatively exposed Swiss data set, with all calculations being within 25% of measurement for the BSRIA, NRC, IGT, LBL and Reeves models. The more sheltered Canadian and UK dwellings provided a much more severe test for the models. For the Canadian data set, the most consistent results were achieved using the NRC model, with 86% of the calculations being within 25% of measurement. For the UK dwelling, the NRC and BRE models performed best, with 87% of the calculations satisfying the 'error criterion'. Taking into account all the data sets, the NRC model gave the best overall performance, closely followed by the LBL model. However, it should be noted that all the models performed well and that good results mainly depended on the accurate specification of appropriate input conditions. Thus, when selecting a model, the choice depends primarily on model availability and the purpose for which it is required.

Table 5.1: Summary of results – % number of calculations within 25% of measurement

Model	Swiss data set	Canadian data set	UK data set
1. BSRIA	100	49	–
		63[1]	80[2]
2. NRC[3]	100	49	–
NRC[4]	56	86	87
3. IMG-TNO	83	–	–
4. Oscar Faber[5]	–	–	–
5. British Gas[6]	–	78	67
British Gas[7]	–	76	80
6. NBRI	83	78	–
7. IGT	100	76	67
8. LBL	100	81	80
9. BRE	89	73	87
10. Reeves et al[8]	100	57	33

1. *'Exposed' wind directions only. Calculation restricted.*
2. *Stack effect only.*
3. *BS5925 pressure coefficients.*
4. *NRC pressure coefficients.*
5. *Component leakages only modelled.*
6. *Without turbulent correction.*
7. *With turbulent correction.*
8. *First infiltration measurement of data set used as input data.*

The performances of the multi-cell models (models 1–5) were very similar to each other; they also showed similar strengths and weaknesses. The principal advantages of this type of model are that they can accommodate detailed flow networks and can be used to analyse air movement. Therefore, in addition to air infiltration studies, they also have applications in indoor air quality investigations. This advantage is particularly important when designing for minimum air change rates. Of the multi-cell models investigated, the most readily accessible was the version developed by the National Research Council of Canada (model 2) for which a complete computer coding and sample simulations are published in the literature[1]. A disadvantage of this model, however, is that each floor is treated in open plan, i.e. as a single-cell. Thus horizontal internal air movement cannot be simulated. Unfortunately, the remaining multi-cell models are only available commercially.

The main disadvantages of multi-cell models are, that they normally require 'main frame' computing facilities and also demand extensive data input, particularly in relation to the flow network and surface pressure distribution.

The performances of the single-cell models (models 6–10) were somewhat more variable, reflecting a wider range of modelling techniques. The common weakness of all single-cell approaches is that this technique can only be used to calculate air change rates in structures that can be assumed to have a uniform internal pressure. Results may be inaccurate if air movement is significantly restricted by internal partitioning. A further disadvantage of this method is that they cannot be used to determine air movement.

Of the single-cell models investigated, the LBL model gave the best overall result and is readily accessible. It is also one of the first models to be developed specifically to use the results of building pressurization tests. In addition to reliability the model offered many advantages. In particular, it could be operated on a small programmable calculator and could accommodate spatial variations in shielding by selecting the most appropriate shielding class for each wind direction.

The BRE model was also developed to use pressurization test data and offers similar advantages to the LBL model. Furthermore its performance was found to be good and it is readily available.

The main advantage of the NBRI model is that it is part of a much larger building energy model, which may be used in a complete analysis of building heat loss. Its principal disadvantage is that it contains a fixed range of pressure coefficient data, which make no allowances for variations in local shielding.

The IGT model was valuable in that it did not make specific use of air leakage or component leakage data. Instead, the permeability of the building is estimated, taking into account the type of building construction. It therefore has important applications in design, where leakage data are unavailable. The model is fairly straightforward to use and is readily available; its main disadvantage is that it is difficult to account for variations in local shielding.

The Reeves model was straightforward to apply but its accuracy was variable; this was partly due to the way in which only the first air infiltration measurement of each data set was used to determine the coefficient, βC_T. Had all the measurements been used, then possibly an improved coefficient would have been determined. The fundamental disadvantage of this model is that it requires air infiltration data before it can be applied; thus its use is restricted to those buildings in which such measurements can be made. Its main use, therefore, is to extend the results made during a measurement period to times when measurements can no longer be made.

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6. KEY PARAMETERS

6.1 Flow Equations

The flow equations used in the models investigated in this study fall into three categories. These are:

(i) Square root (LBL and Reeves model)

(ii) Quadratic (British Gas model)

(iii) Exponential (remaining models)

In general, the various flow coefficients necessary to ensure that these equations follow the known leakage characteristics of the building are determined in the 10–100 Pa pressure range whereas, for low rise buildings, ambient pressures rarely exceed 10 Pa. Thus although identical test data may be used to evaluate the flow parameters, a wide variation in calculated air flow can result at naturally occurring pressures. This is demonstrated using typical test data in Figure 6.1.1. The data were applied to each of the three flow equations and the predicted flow rates between 1–15 Pa were plotted. The percentage deviations of the quadratic and square root equations from the more widely used power law form are also illustrated. The results show that for pressure differences below 10 Pa, the quadratic equation rapidly diverges from the exponential form, and at 1 Pa the deviation is –32%. On the otherhand, the square root flow equation used in the LBL model deviates by +32% at 1 Pa and –17% at 10 Pa. There is therefore a significant difference in computed flow in the low pressure regime. This result is also apparent in the final air infiltration calculation as illustrated in Figure 6.1.2. In this figure, the percentage deviations of the LBL air infiltration calculations (square root equation) from the NRC calculation (exponential equation) for the HUDAC dwelling are compared. These results correspond almost exactly with those illustrated in Figure 6.1.1.

The significance of these results is less clear. This is because, while the percentage difference in results can be quite large, these differences tend to apply to the low infiltration rates where measurement errors themselves can be of the same magnitude. Many more data need to be analysed before the significance of each flow approximation can be properly assessed.

6.2 Wind Pressures

The importance of wind pressure has been vividly demonstrated throughout this study and it has been shown that the magnitude of these pressures is significantly influenced by local obstructions. Fortunately, however, infiltration rate calculations are relatively insensitive to small errors in pressure estimate. This is because the pressure is raised to the power of the flow exponent, which is always less than unity. Typically for a flow exponent of between 0.5–0.7, an 'error' in the pressure calculation of 20% will yield a flow error of only 11–15%; this is well within the tolerances of existing calculations. It is for this reason that it is believed a well co-ordinated wind tunnel study will provide sufficient information to satisfy most modelling needs.

6.3 Stack Pressures

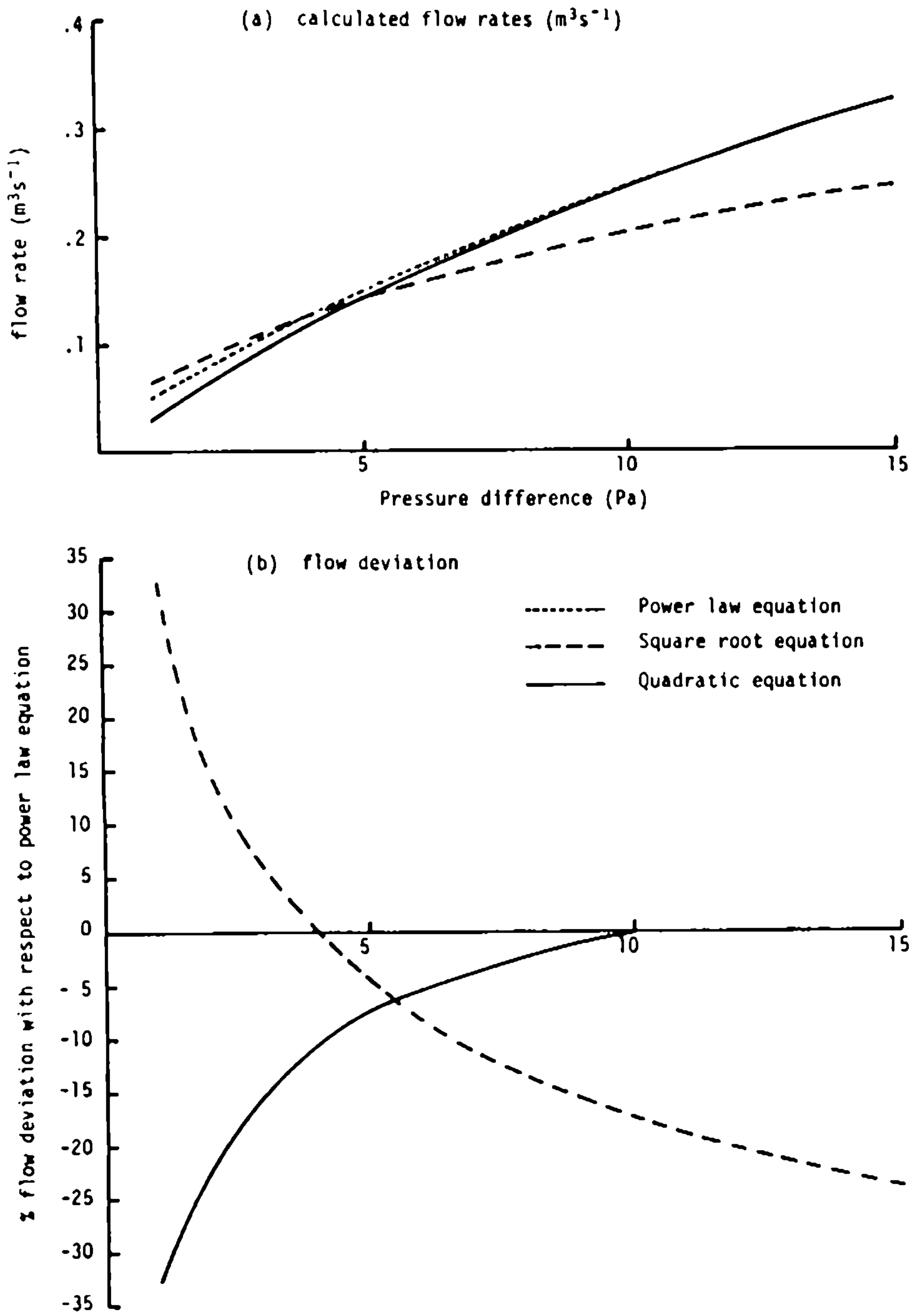
The sensitivity of infiltration to stack pressure is the same as that for wind pressures. Invariably the stack pressure is calculated from temperature data and the experience of this study is that such calculations may be performed without difficulty.

6.4 Building Leakage and Leakage Distribution

For a given set of climatic and shielding conditions, air infiltration rate is approximately proportional to a building's leakage. Therefore it is essential that all leakage components are included in the model. For existing buildings, it has been found that the easiest and most effective way to accomplish this is to use the results of a building pressurization test. However for projected buildings this is clearly not possible and, if models are to be effective, the building must be designed and constructed to a specified level of airtightness. The building should then be tested on completion to ensure that the design standard has been achieved.

Small variations in the assumptions concerning leakage distribution were found to have only a marginal effect on the calculation of air change rates. For example, the BSRIA treatment of the Swiss dwelling placed leakage openings according to specific components and roof/eave joints; on the otherhand, the NRC treatment distributed the leakage according to surface area represented by each node. Despite these different interpretations, the results were nearly identical. However where there are obviously large component leakages at specific locations, these should be treated individually in the flow network.

Figure 6.1.1: Comparison between flow equations



6.5 Climatic Variables

Wind speed

The wind induced pressure increases by the square of the wind speed and therefore extreme care in measurement is necessary if serious errors are to be avoided. In particular, it is important that nearby obstructions do not influence this measurement.

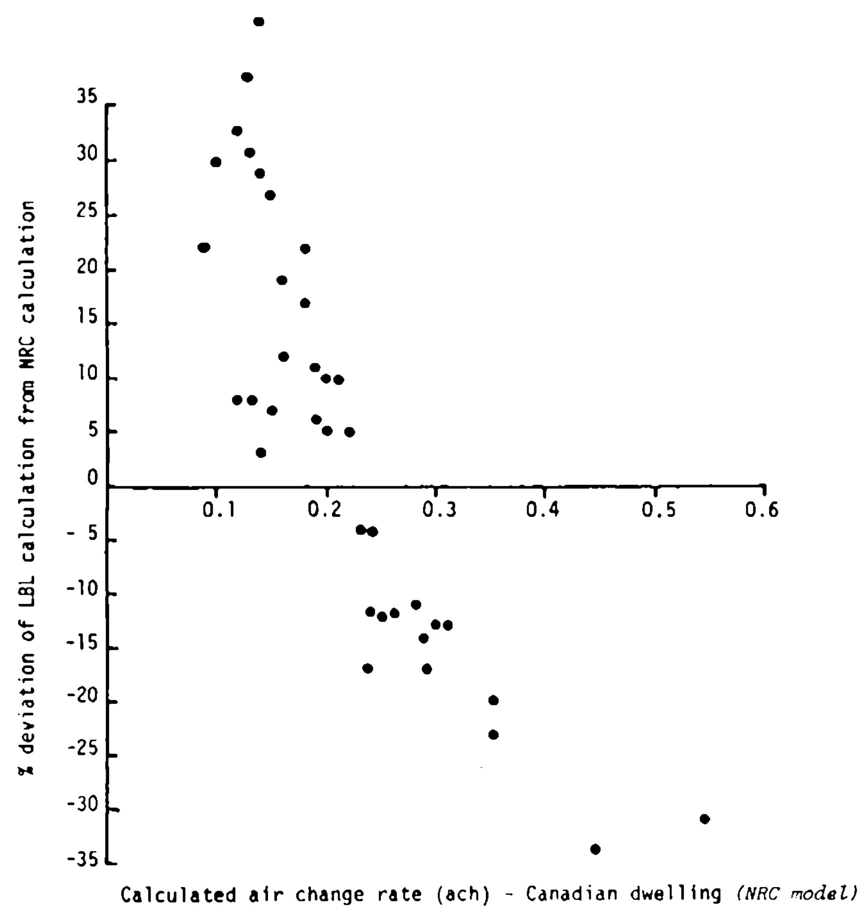
Wind direction

Wind direction is vital in the determination of wind pressure, especially when each face is exposed to different degrees of local shielding.

Temperature data

Stack pressure is directly proportional to internal/external temperature differences. In this study the use of average air temperature values proved to be adequate in the calculation of stack pressure.

Figure 6.1.2: Percentage deviation of LBL model results (square root flow equation) from NRC model results (exponential flow equation) *(HUDAC 'upgraded' house)*



7. CONCLUSIONS

7.1 Model Performance

The comparisons between calculated and measured infiltration rates were generally found to be excellent and provided much scope for optimism. Calculations based on the exposed Maugwil house were found to give the best overall fit.

The selected models encompass a wide variety of modelling techniques and the performance of each of them is briefly assessed below.

BSRIA model

The BSRIA model was tested against all three of the key data sets. It was found that provided the input conditions were adequately specified, calculations consistently within 25% of measurement were achieved. When using wind and temperature data to estimate surface pressure, excellent agreement between calculated and measured air infiltration rates was obtained for exposed wind directions. For sheltered directions, the calculations tended to over-estimate the air infiltration rate; this was not surprising since the pressure coefficients used to derive the pressure distributions were based on wind tunnel studies on isolated buildings. It is possible to use alternative pressure coefficient data.

NRC model

Good results were achieved using the Canadian model. When the same input data to the BSRIA model was used, the computed results of the two models were very similar. The NRC pressure coefficient data provided much improved results for the sheltered HUDAC and Runcorn houses.

IMG-TNO model

This model produced generally good results for the Maugwil house although pressure reversals, which occured during the measurement period, were thought to result in a number of under-estimates. Unfortunately, results using the other data sets were not available.

Oscar Faber model

This model was used to calculate air infiltration due to component leakage only and should therefore be analysed in this light. Air infiltration in the LBL test unit was almost entirely through component leakage paths and good agreement between calculated and measured air infiltration was observed. With the Swiss data, the component leakage amounted to only 15% of the total air leakage and therefore a correspondingly lower rate of air infiltration was calculated.

British Gas model

This model also produced good results. The inclusion of the turbulent correction parameter, contained within the British Gas model, resulted in a marginal increase in the calculated rate of air infiltration throughout the entire data range. It was not possible to illustrate conclusively the overall benefit of this correction term using these data sets.

Norwegian Building Research Institute model

This model was assessed against six sets of data. Good results were obtained for wind speeds of less than 2 ms^{-1}. For higher wind speeds, the calculated air infiltration rate tended to be greater than measurement; this was again thought to be due to the use of inappropriate pressure coefficients.

Institute of Gas Technology model

This model did not make direct use of air leakage test data. Instead, an assessment of air leakage was made, based on construction type. While this technique probably accounted for some of the scatter noted in the results, the model nevertheless performed moderately well, especially for the Maugwil house. This technique is of particular value in design applications or in other instances where detailed knowledge of the leakage characteristics of the building is unknown.

LBL model

Encouraging results were obtained and this model gave the best overall performance of the single-cell models. The ability to select shielding coefficients appropriate to the degree of shielding for each wind direction was extremely useful.

BRE model

In view of the simplicity of this model, the results were very good with consistently accurate predictions being achieved using each of the data sets. The best performance was achieved using the Runcorn data. It is thought that a greater understanding of wind pressure coefficients will result in improved accuracy.

Reeves model

This model differs from those previously investigated in that the first air infiltration measurement of each data set was used as part of the data input. Therefore, this technique is limited to buildings in which tracer gas measurements have already been made. The model worked well for the exposed Maugwil house but did not perform satisfactorily for the heavily sheltered Runcorn house. A reason for the poor performance with the latter data set was thought to be due to the influence of local shielding on the wind induced pressure distribution.

7.2 Model Parameters

Flow equations

Within the ±25% tolerance against which calculated and measured air infiltration rates were compared, each of the flow equations assessed gave acceptable results.

Wind pressure

The results were particularly sensitive to the wide difference in wind pressure corresponding to exposed and shielded environments. However, air infiltration calculations were fairly insensitive to variations in pressures of under 20%. For this reason, it is concluded that a systematic wind tunnel study incorporating fixed degrees of shielding and a small range of building shapes (including pitched roofs) would provide sufficient wind pressure data to satisfy most modelling requirements. Wind pressures could then be readily calculated from 'on-site' measurements of wind speed and wind direction.

The use of direct wind pressure measurements was partially successful. However, problems associated with pressure reversals were apparent and require further investigation. The development of a standard direct wind pressure measurement technique for air infiltration studies would be particularly useful.

Stack pressure

The well shielded site of the UK Runcorn house provided an opportunity to examine the use of stack pressure alone in calculating air infiltration. The generally good results indicated that the stack pressure calculations were satisfactory.

Building leakage

In all the dwellings, the total building leakage was considerably greater than the sum of the specified component leakages. The models were sensitive to leakage and it was found necessary to take full account of all sources of leakage.

7.3 Climatic Data

Wind speed

The reduction of 'on site' wind speed to roof height was satisfactory. All the wind profile equations used performed well.

Wind direction

This proved to be a key parameter both for analysing the infuence of local obstructions on pressure distribution and for calculating pressure coefficients. It was found that for good results, the angle of the wind with respect to the building had to be specified in no greater than 45° sectors.

Internal/external air temperature

An average measurement of internal and external air temperature was found to be sufficient to calculate stack pressure.

7.4 Numerical Data Sets

The data sets proved to be a most valuable asset. It is essential to use as wide a range of data as possible in any model validation exercise so that the full range of applicability of models can be properly evaluated.

Following the use of these data sets, there was much feedback regarding the need for additional material and the clarification of certain points. Where possible, this additional material has been obtained and hence the value of the data sets has been further enhanced.

APPENDIX 1

I. GENERAL INFORMATION

Country	Principal Researcher	Date
Switzerland	H. Muehlebach P. Hartmann	June, 1981

Address:

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Section 151
Ueberlandstrasse
8600 Duebendorf
Switzerland

Telephone/Telex:

Telephone: 01/823 4251
Telex: 53817

Title of Project:

Messgebäude Maugwil (Maugwil Test Building)

Principal Objectives:

Measurement of air infiltration data as a function of climatological data in an unoccupied, closed building and measurement of energy consumption for computer model verification.

References:

1. EMPA Report No. 39400/c
   Langzeit-Untersuchung betreffend Luftdurchlässigkeit und Luftwechsel eines Einfamilienhauses. April 1981
2. Hartmann, P., Muehlebach, H.
   Automatic measurements of air change rates (decay method) in a small residential building without any forced-air-heating system.
   1st AIC Conference, Windsor, UK, 6-8 October 1980.
3. Air Infiltration in Switzerland
   AIR, Volume 1 No.4, 1980.

Comments:

II. TEST SITE DESCRIPTION

A. Geographic Information

(1) Location.
Approximately 4 Km to the north of Wil SG in Maugwil.
47.5°N, 9.1°E
Site plan : (see Ref.1)

(2) Height above sea level.

(3) Terrain.

Please append map showing the surrounding area indicating location and size of obstacles such as trees, fences and other buildings, also relief.

The house is located on the upper part of a south-facing slope (see Plate 1).

The slope provides some shelter from the wind on the north side, otherwise the situation is exposed with few nearby structures or trees (see Fig 1).

(4) Orientation.
The facades of the house face approximately N65°E (East facade) N155°E (South facade) N245°E (West facade) N335°E (North facade) (see Fig.2).

(5) Location of Meteorological Station.

Meteorological measurements were made on site.

B. Climatic Information (where available)

Climatic data is supplied for Zurich (see Table 1)

(1) % frequency wind speed v direction *(by 22½° sector – attach table).*

(2) % frequency wind speed v temperature *(attach table).*

(3) Hours of daylight/insolation *(attach table).*

(4) Cloudiness.

(5) Precipitation, humidity.

(6) Other – anthropogenic factors.

C. The Building

(1) History.

The test building was erected in the early part of 1979. The measuring equipment was installed in July of the same year

(2) Construction material and technique.

The building has a solidly-constructed basement floor and 2 upper floors of wood construction

External walls and ceilings:

The outside wall and ceiling of the cellar were constructed of concrete cast in situ. Such of the cellar walls as lie below ground level are of concrete slabs on the outside. Outside walls not covered by earth in the heating space in the entrance hall and the ceiling over the tank room are insulated with a 5cm thick slab of wood-wool-polystyrene compound and plastered.

Both of the upper floors were built using a lightweight wood construction.

(continued overleaf)

(3) Dimensions *(Please append diagram to report for clarity.)*

(a) Plan: attach diagram (internal/external).	(see Fig. 2 and Ref. 1)
(b) Elevation.	Building height is 10m
(c) Total volume.	
(d) Effective volume.	*Heated volume is given as 500m³
(e) Floor area.	74.9m²
(f) Ceiling area.	
(g) Facade (wall) area.	160 m²
(h) Total area of windows.	27 m²
(i) Total area of external doors.	
(j) Number, volume and layout of rooms (refer to (a)).	(see Table 2)
(k) Shape: roof pitch, etc.	
(l) Attic, basement, crawlspace.	
(i) Insulation.	
(ii) Description.	

* *see overleaf*

(2) *(continued)*

The thermal insulation (5cm thick) is found between the wooden uprights.

The ground floor external walls have an additional 2cm thick layer of insulation on the outside.

The ceiling joists of the ground floor ceiling penetrate the external walls at the eaves and form the supports for the rafters.

The steep roof and top floor ceiling are insulated with a total of 8cm of polystyrene slabs.

Windows and doors:

Except for the stairwell window, the wood framed windows are fitted with laminated glass and sealed using soft PVC section in the grooves. The stairwell window is double glazed and has no caulking strip. For internal doors there is an air gap of approximately 5mm between the door leaf and the floor (no sill).

(3) (d) * *Excluding the bomb shelter, the tank room and the volume between the roof and the top floor ceiling (see Table 2 for room volumes).*

C. The Building

(4) Gaps in the envelope.

(a) Doors (external). — (see Table 3 and Ref. 1 for measured and estimated leakage values, type, etc.)

(i) Type.

(ii) Cracklength.

(iii) Comments.

(b) Windows. — (see Table 3 and Ref. 1 for measured and estimated leakage values, type, etc.)

(i) Type.

(ii) Cracklength.

(iii) Comments.

(c) Ventilation openings.

(i) Type. — The only major ventilation opening is one in the chimney supplying air directly to the fire.

(continued overleaf)

(ii) Cracklength.

(iii) Open area.

(iv) Degree of closure.

(v) Comments.

(4) (c) (i) *(continued)*

The chimney has a square cross-section 20cm x 20cm and is 6m in height. It is located in the living room (No. 6). (See Fig.2 for room numbers).

Volumes used in pressure tests are given in Tables 4a) and 4b)

(d) Chimneys, flues.

(i) Size, type.

(ii) Location.

(iii) Condition of dampers.

The damper supplying air to the fire is leaky when closed leaving a circular gap of area approximately 30 - 40cm^2. This supply air is also directed to the furnace room (see Ref. 1 for details).

also estimates of crack size for:

(e) Cavity walls and other communicating spaces, also electrical outlets.

(f) Soleplate, ceilings, corners, skirting boards.

(g) Plumbing outlets, drains, etc.

(h) Other major sources.

from the above and the measured leakage,

(j) Background leakage.

(k) Comments.

No numerical estimates are given for other sources of leakage, although leakage was detected where the joists supporting the floor penetrate the outside wall at the junction of the outside and the roof, the internal wall/roof junction on the upper floor, the hatchway on the attic staircase and the penetration of the connecting rods through the window frames. These were located using thermography with an underpressure of 20 Pa (see Ref. 1).

(5) HVAC system.

(a) Type of system.

The house is heated by an oil fired burner feeding hot water radiators and the domestic hot water supply. The storage tank for the latter is fed by a charge pump. This pump was disconnected and the boiler emptied for the duration of the tests.

Heating in the rooms is by panel radiators and convectors. The convectors are in the living room (6) and the studio (5). (See Fig.2 for room numbers)

(b) Blower fan capacity (where available).

(c) Duct tightness and location.

(d) Frequency of operation, duration of operating cycle.

(e) Operating temperature. (see overleaf)

(f) Location of air inlets. (see page 9, (c)(i))

(g) Comments.

(6) Pollution (non anthropogenic).

(a) Interior.

(b) Exterior.

(5) (e) *(continued)*

The flow temperature of the system has a maximum of 90°C with a return temperature of 70°C. The flow temperature is regulated by an outside air thermostat and the heat output to the rooms by radiator thermostats.

During the tests, the room temperatures were held constant as far as possible to 20°C throughout the tests, day and night.

III. FUNCTION OF BUILDING

A. Type (including use)

The house is designed as a single family house but was unoccupied at the time of tests.

B. Occupancy

(1) Times occupied and number of users.

(2) Behaviour of occupants.

(a) Window opening.

(b) Door opening.

(c) Other voluntary ventilation.

(d) Heating habits.

(e) Pollution (anthropogenic).

(i) Cooking.

(ii) Aerosols, solvents, etc.

(iii) Smoking.

(iv) Other

(f) Level of activity of occupants.

(g) Comments.

C. Special Requirements

D. Other

E. Comments

IV. MEASUREMENTS

Date and time measurements taken. October 1979-June 1980 (see Fig.5 Ref.1 Page 10 for details)

A. Pressurisation Measurements – internal

(1) Technique employed.

Pressurization method:

The determination of the air leakage of the building envelope was carried out by raising a pressure difference across the facade with an efficient fan. The volumetric flow rate was measured for the ranges of pressures ± 10 Pa to ± 50 Pa. From these the characteristic curve was found.

(continued overleaf)

(2) Equipment used.

(see Fig. 3). Further details not given.

(3) Description of procedures for calibrating equipment.

(4) Results (attach relevant tables, graphs etc.)

(a) Pressurisation.
The leakage curves are shown in Fig. 4 and Table 4 for unsealed and sealed condition and for two different dates.

(b) Depressurisation.

(c) Alternating pressurisation (infrasonic).

(5) Comments.

(1) Pressurization method: *(continued)*

The volumetric flow rate for 50 Pa was found and reduced to an air change number by

$$n_{L50} = \frac{\dot{V}_{L50}}{V} \quad [h^{-1}]$$

n_{L50} = air change number for a differential pressure of 50 Pa $[h^{-1}]$

$\dot{V}_{L50}$ = volume air flow for a differential pressure of 50 Pa $[m^3/h]$

V = air volume of the house $[m^3]$

B. Pressure Measurements – external (including wind tunnel studies)

(1) Technique used (including conditions)

(2) Equipment used.

Not described

(3) Calibration procedure.

(4) Location of surface pressure taps (see II.C (3)).

(see Fig. 1)

(5) Measurement results (attach as table).

The results are displayed in columns 14 to 17 of Table 7.

(6) Comments)

C. Interior Conditions

(1) Temperature (dry bulb).
(2) Relative humidity.
(3) Air flow.
(4) Other.
(5) Comments.

(See Tables 5 and 6 for measurement details and location of sensors. See Tables 7 and 8 for data).

D. Exterior Conditions

(1) Description of equipment used.
(2) Weather – off-site.
- (a) Wind speed.
- (b) Wind direction.
- (c) Dry bulb temperature.
- (d) Stability conditions.
- (e) Other (see A5. for location).
- (f) Comments.

(3) Weather on-site.
- (a) Wind speed.
- (b) Wind direction.
- (c) Dry bulb temperature.
- (d) Relative humidity.
- (e) Turbulence scale.
- (f) Turbulent intensity.
- (g) Stability conditions (where available).
- (h) Other.
- (i) Comments.

(See Tables 5 and 6 for measurement details and location of sensors. See Tables 7 and 8 for data)

E. Infiltration

(1) Measurement technique.

A schematic of the experimental arrangement is given in Fig. 5 and the apparatus is illustrated in Fig. 6. The tracer gas is nitrous oxide injected into the rooms when the gas concentration decays to a preset threshold. The six rooms are then sampled in turn, each for 10 minutes, such that each room is visited once per hour (Table 7). The tracer gas is mixed by two fans for 10 minutes after injection. The data is recorded continuously on a paper strip for monitoring purposes and on magnetic tape near the end of each 10 minute sampling period, together with all other data.

(2) Equipment used (include photographs).

(3) Calibration procedures.

(4) Measurement results (attach relevant table, graphs, etc).

(See Tables 7 and 8 for summary of results) Further details are available from AIC.

(5) Comments

(1) *(continued)*

The number of air changes is calculated for each room and the mean value determined. This is given in the final column of Table 8.

F. Other

(1) Qualitative.

(a) Smoke sticks.

(b) Acoustic techniques.

(c) IR. Thermography. Details given in Ref. 1

(2) Energy consumption.

(3) Other.

(4) Comments.

V. NUMERICAL/COMPUTER MODELS

A. Type of Model

B. Correlations

(1) Variables used.
Effect on air change rate of wind speed, temperature difference, sealing of chimney

(2) Sign and goodness of fit.

(3) Problems encountered in attempting to find a correlation.

(4) Comments.
(See Figs. 7(a) and (b))

C. Computer Models

Details of the Fortran program used for processing the raw data can be supplied by the AIC if required.

(1) Name and description of model, including assumptions.

(2) Input.

(3) Output.

(4) Agreement with observation.

(5) Comments.

D. Any Other Theoretical Work of Interest

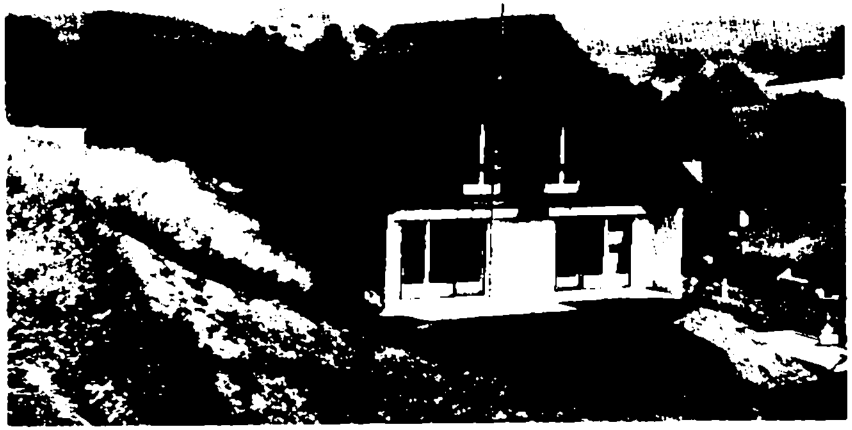

Plate 1: View of test building from the West

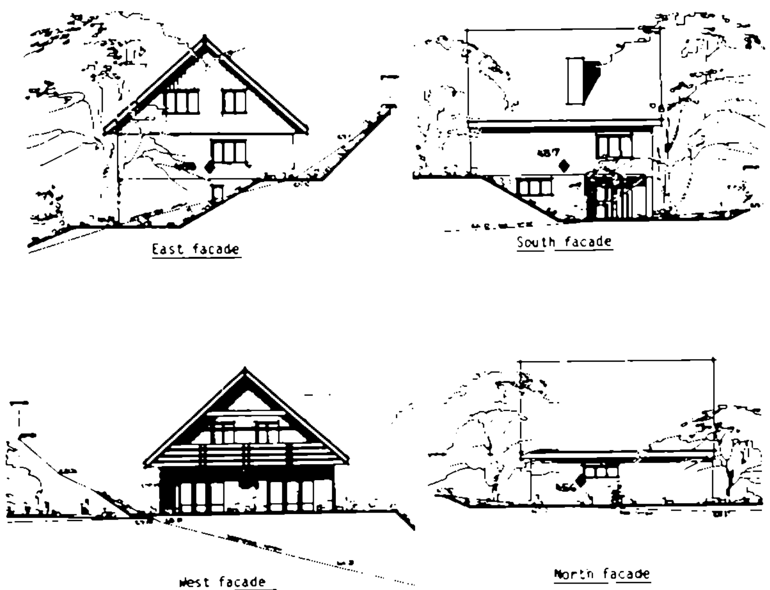

Fig. 1: Elevations of the test building

◆ Pressure measurement point   457 Measurement number

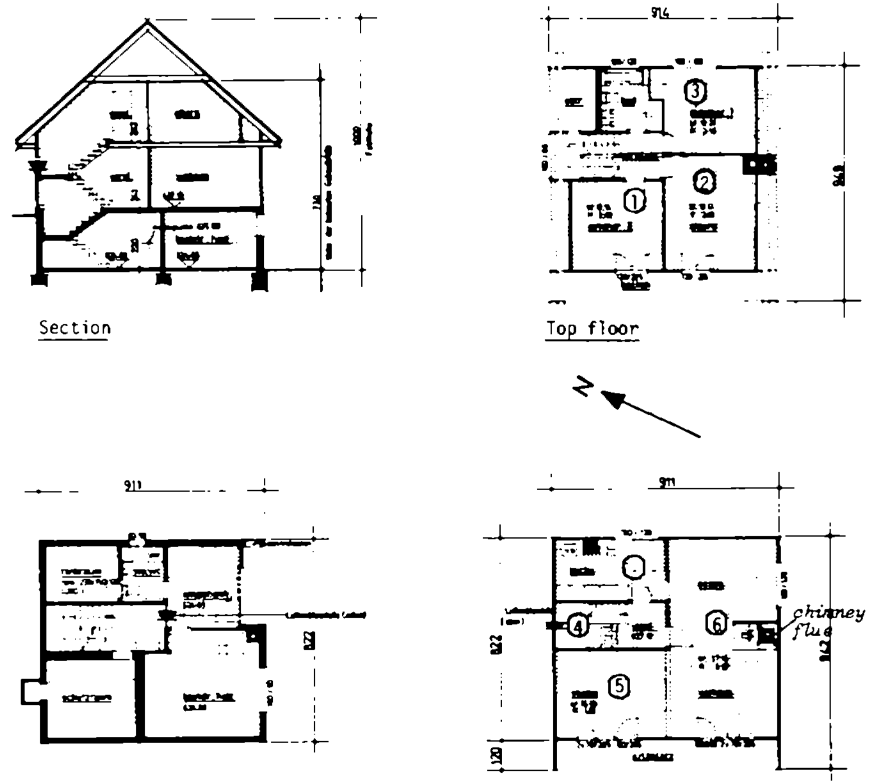

Fig. 2: Floor plans and building section

- Sites of fans for pressurization and depressurization for the measurement of the leakage of the building envelope.
- Heated part of the building.
- (2) Room number

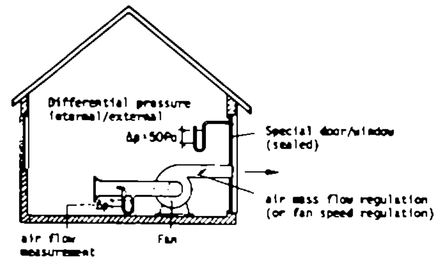

Fig. 3. Measurement arrangement for the determination of the air leakage of the building envelope.

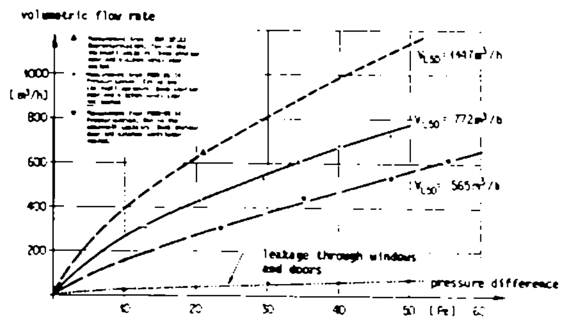

Fig. 4. Air leakage characteristic curves for the building envelope

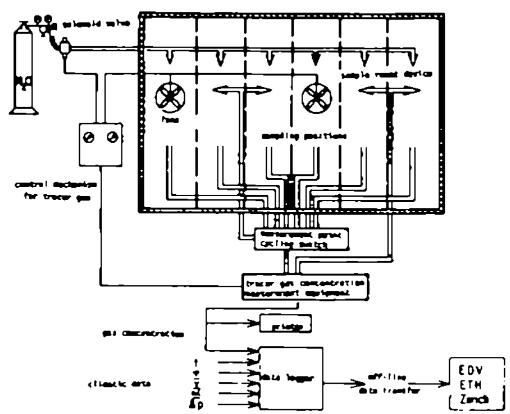

Fig. 5. Schematic diagram for the experimental arrangements for the determination of the air change rate.

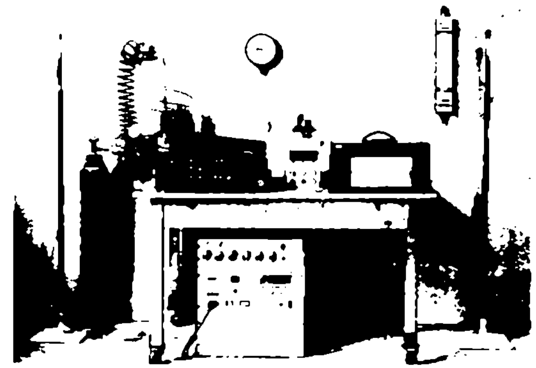

Fig. 6: Illustration of the equipment required for the measurement of air infiltration.

From left to right:

Tracer gas cylinder (N_2O) with pressure regulator valve, solenoid valve (above), fan for mixing the air, control equipment for the tracer gas supply (left foreground), air transfer pump, gas analyser, manometer for controlling the pressure in the gas analyser (above), chart-recorder and a flow meter for the determination of the volumetric flow rate of the sample.

A tracer gas injection point, with the closed end, is illustrated on the extreme left and a sampling point on the extreme right.

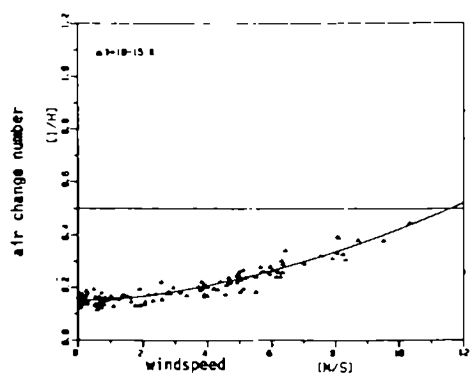

Fig. 7 (a) Air change measurement values depending on the windspeed for the temperature difference in the range 10 to 15°K with the chimney sealed.

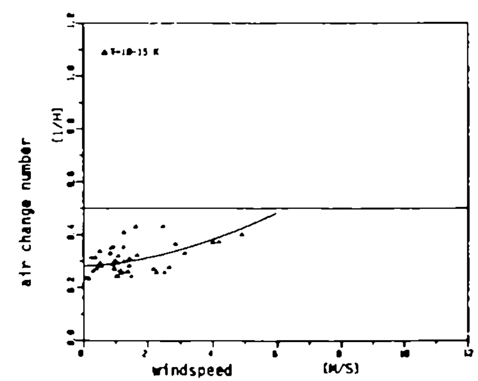

Fig. 7 (b) As above, but with the chimney unsealed.

TABLE 1 Climatic Information

Average monthly values (Period - 1901-60)

Zurich h - 563m, latitude - 47.2°N, longitude - 8.3°E

Ref: Swiss Meteorological Institute, Zurich

			Jan	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Temperature	daily mean	°C	-1.0	0.2	4.2	8.0	12.5	15.5	17.2	16.6	13.5	8.4	3.3	-0.2	8.2
	mean monthly max.	°C	10.5	13.1	19.1	23.6	28.3	30.4	32.3	31.4	27.6	21.7	15.2	11.6	33.1
	mean monthly min.	°C	-9.8	-9.4	-5.2	-1.5	1.9	6.7	8.7	6.1	4.5	-0.2	-3.9	-8.0	-12.5
Wind*	average speed	m/s	2.7	3.0	2.9	3.0	2.8	2.7	2.5	2.4	2.2	2.2	2.6	2.9	3.0
	directions > 15%		SW, W	SW,W, NE	W,SW, NE	SW,W, NE	NE,SW, NW,W	W,NW NE,SW	NW,W, SW,NE	W,NW, SW	W,SW, NE,NW	W,SW, NE,NW	SW,W NE,NW	SW,NE, W.	
Solar	mean sunshine duration	h	45.6	79.2	142.6	166.8	203.1	219.6	240.3	216.4	166.8	111.0	53.4	35.3	1680
	max possible sun duration	h	249	265	345	385	435	444	447	416	355	314	253	237	4145
	mean horizontal global radiation	MJ/m²	101.1	177.8	321.2	425.1	572.0	616.2	635.2	537.9	375.6	225.1	105.9	173.2	4166
	cloudiness	1/10	8.3	7.3	6.2	6.3	6.3	6.3	5.9	5.8	6.1	7.1	8.2	8.6	6.9
	humidity	%	83	77	71	63	69	69	68	72	77	82	84	84	75
Precipitation	mean monthly	mm	68	61	69	88	107	138	139	132	101	80	72	73	1128
	max. daily sum	mm	51	44	47	48	90	81	62	[illegible]	57	45	45	44	90
	mean no. of days with precipitation >0.3mm		14.2	12.8	11.7	13.3	14.3	14.7	14.3	14.1	12.4	11.9	12.0	13.0	158.7
	number of days with snowcover		16.7	12.3	6.4	2.3	0.1	-	-	-	-	0.2	4.1	12.1	54.2
	mean monthly max snow height	cm	17.0	13.6	8.8	6.0	-	-	-	-	-	0.4	6.4	9.1	24.4

* Zurich Airport

Table 2 Room Volumes

Room No.	Volume (m^3)	Room Name
1	25	(Children's bedroom - West)
2	38	(Master bedroom)
3	26	(Children's bedroom - East)
4	67	(Staircase)
5	33	Studio
6	117	(Living room)
Total	306	

Table 3 Measured leakage values for doors and windows

Window/door	Weatherstrip	Cracklength (m)	Crack leakage a - value ($m^3_n/mh\Delta p^{2/3}$)	Air leakage of the windows ($m^3_n/h\Delta p^{2/3}$)
Standard window measured in the laboratory	Yes	6.60	0.029	0.191
Staircase	No	4.82	0.496	2.4
Kitchen	Yes	8.10	0.0435	0.352
Dining room	Yes	8.10	0.0194	0.157
Living room	Yes	5.53	0.0539	0.296
Studio	Yes	5.53	0.0985	0.542
Bathroom	Yes	5.78	0.0516	0.298
Child's bedroom I	Yes	8.10	0.0369	0.299
Master bedroom	Yes	7.53	0.0327	0.246
Child's bedroom II	Yes	7.53	0.0331	0.249
W.C. (basement)	Yes	2.82	0.0314	0.089
Front door	At the side and above	-	>0.900	>5.500

Table 4a) Pressure Test

Measurement Building - Maugwil
Date of Measurement - 14.5.80

1. $Q = C.\Delta p^n$ — Power curve — Q [m^3/s], Δp [Pa]

2. $A_{50} = \frac{Q_{50}}{V_H}$

3. Q_{50}

4. $L_4 = \frac{Q_4}{\sqrt{\frac{2}{\delta}\Delta p_4} \cdot A_H}$

Q_{50} = Flow rate at 50 Pa

A_{50} = Air change rate at 50 Pa

V_H = Volume of conditioned space

A_H = Floor area of conditioned space

δ = Density of air 1.2 kg/m^3

L_4 = Spec. leakage area at 4 Pa

Notes:	V_H m^3	A_H m^2	C	n	A_{50} [h^{-1}]	Q_{50} [m^3/s]	L [$\frac{cm^2}{m^2}$]
Chimney sealed	435	190	0.0157	0.67	1.77	0.214	0.81
All vents and stack sealed	413	180	0.00663	0.81	1.37	0.157	0.438

Notes by default

a) Volume of conditioned space (and area)

b) Structure in normal condition (unsealed)

Table 4c) Proportion of air permeability of building envelope due to window and door cracks

	Values referring to the measurement dates May 1980 (m^3/h)	February 1981 (m^3/h)
Volume air flow with sealed bomb-shelter and ventilator	530	1075
Volume air flow through window and door cracks Σ a-value $\pounds_{50}$ Pa$^{2/3}$	64	64
Unidentified air flow	466	1011
Corresponding to:	88%	94%

Table 4b) Air permeability of the building envelope at 50 Pa pressure difference

Date of measurement	Air inflow and extract point	Pressure difference[1] Inside/Outside (Pa)	Sealing: Bomb shelter door	Sealing: Kitchen ventilator	Building volume under consideration (m^3)	Air permeability[2] (flow at 50Pa) (in m^3/h)	Building air changes[3] (at 50Pa) (at 50Pa)
May 1980	Staircase upper	+ 50	No	No	435	772	1.77
	"	+ 50	Yes	No	413	623	1.51
	"	+ 50	Yes	Yes	413	561	1.36
	"	- 50	No	Yes	435	772	1.77
	"	- 50	Yes	Yes	413	565	1.37
May 1980	Staircase bottom	+ 50	No	No	365	738	2.02
	"	+ 50	Yes	No	342	551	1.61
	"	+ 50	Yes	Yes	342	512	1.50
	"	- 50	Yes	No	342	540	1.58
	"	- 50	Yes	Yes	342	530	1.55
February 1981	Staircase upper	- 21	Yes	Yes	413	1147[4]	2.78

Notes: [1]*Flue pressure differences mean "overpressure in the building".*
[2]*These data are based on outside air conditions of 13°C/940 mb.*
[3]*The air change in the building was determined on the basis of the measured "air permeability" and the controlled volume.*
[4]*Calculated for the pressure difference of 50 Pa by the formula $\dot{V}_L = a\Delta p^{2/3}$*

Table 5. Measurement details for climatic data

Variable		Sampling Interval	Number of sample points	Locations of sample points
Air temperature	ϑ_L	10 min		
inside-			17	In the middle of the room at approx. 1.5m in height
outside-			2	On the north side of the building & 20m from it, 3m above ground
Relative humidity	φ_L	10 min		
inside-			1	Staircase - ground floor
outside-			1	North facade
Solar radiation				Situated
global radiation- (horizontal)	I_g	30 sec	1	On south side of the building, approximately
diffuse radiation- (horizontal)	I_d	30 sec	1	5m from it.
Wind velocity	V_w	continuous	2	4m above the roof ridge (10m above garden seat)
Wind direction	γ	30 sec	2	Also 40m from building and 10m high

TABLE 6 Measurement List - Maugwil (EMPA)

Key to computer printout of measurements (Table 8)

Measurement Number	Measurement Type	Unit	Room No.		Comments
7	Temp	°C	4	staircase - ground floor	
8	Temp	°C		kitchen	
9	Temp	°C	6(E)	dining room	
10	Temp	°C	6(W)	living room	
11	Temp	°C	5	studio	
12	Temp	°C	4	staircase	
15	Temp	°C	3	child's bedroom - East	
16	Temp	°C	2	master bedroom	
17	Temp	°C	1	child's bedroom - West	
19	Temp	°C	Outside Temperature		180°
61	Wind velocity	m/s	4m above top of roof		N
62	Wind velocity	m/s	- 40m beside the house - 10m above ground level		270° West 90° East
63	Wind direction		Average of No. 61 and 62 directions		0/360° South
456	Pressure	Pa	on North facade		10 Min. average
457	Pressure	Pa	on South facade		10 Min. average
458	Pressure	Pa	on East facade		10 Min. average
459	Pressure	Pa	on West facade		10 Min. average
460	N_2O Concentration	PPM	Measurement Time Hrs., Min	Room No.	
			10	1	
			20	2	
			30	3	
			40	4	
			50	5	
			0	6	

Table 7 Temperature, Wind, Pressure and Infiltration Data

(see Table 6 for key to measurement numbers)

Measurement Number		7	8	9	10	11	12	15	16	17	19	61	62	63	456	457	458	459	463
MESSTELLNAME		007	008	009	010	011	012	015	016	017	019	C1	C2	29+3172	455	457	458	459	462
EINHEIT		GRD C	GRD C	GRD C	GRD C	GRD C	GRD C	GRD C	GRD C	GRD C	GRD C	M/S	M/S	WINKEL	PA	PA	PA	PA	PPM
Date	Hr. Min																		
10/12/79	18.00	20.2	21.1	21.7	21.5	20.8	20.0	21.0	20.2	20.3	12.0	8.4	7.8	283.5	.7	-2.6	6.1	16.5	7.0
10/12/79	18.10	20.1	21.1	21.7	21.7	20.7	20.0	20.9	20.2	20.3	12.3	9.1	8.5	286.4	.7	-1.7	7.9	19.1	9.0
10/12/79	18.20	20.1	21.0	21.7	21.5	20.8	20.2	21.0	20.1	20.2	12.0	9.5	7.8	283.4	.0	-1.6	5.4	17.5	8.6
10/12/79	18.30	19.8	21.1	21.7	21.5	20.7	20.3	21.0	20.1	20.5	9.9	8.6	8.1	288.1	-.9	-1.6	4.6	16.6	9.6
10/12/79	18.40	19.9	21.1	21.4	21.5	20.9	20.0	21.1	20.2	20.2	9.9	7.7	7.0	287.2	-.8	-1.5	6.2	15.7	36.1
10/12/79	18.50	19.8	21.1	21.7	21.6	20.7	20.0	21.0	20.2	20.4	9.9	7.0	6.8	282.4	-.3	-2.3	3.7	12.9	24.4
10/12/79	19.00	19.3	21.1	21.7	21.6	20.7	20.2	21.0	20.2	20.4	9.9	8.1	7.5	287.6	.7	-2.3	4.6	13.9	23.6
10/12/79	19.10	19.3	21.2	21.6	21.6	20.8	20.1	21.0	20.2	20.4	9.5	8.0	7.3	284.3	.8	-1.5	5.0	12.9	28.5
10/12/79	19.20	19.3	21.1	21.6	21.6	20.9	20.1	21.0	20.2	20.4	9.2	7.7	7.8	286.3	.3	-2.4	4.6	13.9	24.5
10/12/79	19.30	19.8	21.1	21.7	21.6	20.8	20.0	21.0	20.2	20.4	9.1	6.7	6.1	288.7	.7	-1.5	4.6	11.4	21.4
10/12/79	19.40	19.7	21.1	21.6	21.5	20.9	20.0	21.0	20.2	20.4	9.3	7.5	6.7	288.1	.3	-1.5	3.7	12.9	21.2
10/12/79	19.50	19.9	21.1	21.7	21.6	20.9	20.2	21.2	20.2	20.4	8.6	6.1	5.7	287.3	.3	-1.5	3.7	13.5	19.9
10/12/79	20.00	19.3	21.3	21.7	21.6	20.8	20.0	21.1	20.2	20.4	8.8	6.0	5.7	282.3	.8	-1.5	2.9	7.0	17.9
10/12/79	20.10	19.7	21.1	21.7	21.6	20.8	20.1	21.1	20.2	20.5	9.3	6.3	5.9	284.7	-.9	-1.4	2.9	8.7	22.1
10/12/79	20.20	19.7	21.1	21.7	21.6	20.8	20.1	21.1	20.2	20.4	8.9	6.5	6.1	272.0	.7	-1.5	2.9	10.5	19.0
10/12/79	20.30	19.8	21.1	21.7	21.5	20.9	20.3	21.1	20.3	20.4	9.2	6.8	5.8	277.6	.1	-1.4	2.9	7.8	18.2
10/12/79	20.40	19.8	21.2	21.7	21.7	20.9	20.9	21.1	20.2	20.4	9.3	7.0	6.7	280.6	.3	-2.3	2.9	13.5	16.3
10/12/79	20.50	19.7	21.2	21.8	21.6	20.8	20.1	21.1	20.3	20.5	8.9	6.3	5.9	278.3	.8	-2.3	1.9	11.4	15.3
10/12/79	21.00	19.7	21.1	21.9	21.6	20.7	20.1	21.1	20.3	20.4	8.7	6.4	5.9	278.6	.8	-2.2	2.9	9.6	13.3
10/12/79	21.10	19.3	21.1	21.8	21.6	20.7	20.1	21.1	20.4	20.4	8.7	5.9	5.4	279.9	.0	-1.3	2.9	8.8	17.0
10/12/79	21.20	19.7	21.2	21.8	21.6	20.9	20.1	21.1	20.3	20.5	8.9	6.2	5.7	278.9	.1	-1.5	1.8	8.7	15.0
10/12/79	21.30	19.8	21.2	21.8	21.6	20.9	20.1	21.2	20.3	20.5	9.1	6.2	5.9	277.8	.0	-2.4	1.9	8.7	14.0
10/12/79	21.40	19.7	21.2	21.8	21.7	20.9	20.1	21.1	20.3	20.5	9.1	6.7	6.6	276.8	.8	-3.3	2.8	10.5	12.4
10/12/79	21.50	19.9	21.2	21.9	21.6	20.7	20.2	21.1	20.3	20.5	8.5	6.8	6.8	274.6	-.8	-3.2	1.0	10.5	11.5
10/12/79	22.00	19.7	21.2	22.0	21.7	20.4	20.1	21.1	20.3	20.4	9.2	6.7	6.2	279.5	.8	-1.5	2.0	8.7	10.4
10/12/79	22.10	19.3	21.2	21.8	21.7	20.9	20.2	21.5	20.3	20.5	9.1	7.5	7.0	277.7	-.8	-3.4	3.7	12.1	13.0
10/12/79	22.20	19.3	21.2	21.9	21.7	20.8	20.0	21.1	20.4	20.5	9.2	8.3	7.5	285.7	.8	-1.6	5.4	14.7	11.5
10/12/79	22.30	19.3	21.2	21.8	21.7	20.9	20.1	21.1	20.3	20.5	9.1	7.3	6.7	278.3	.8	-2.5	3.7	12.9	11.0
10/12/79	22.40	19.9	21.0	21.5	21.5	20.8	20.1	21.4	20.3	20.5	9.5	7.1	6.9	284.3	.8	-.6	2.9	9.6	9.1
10/12/79	22.50	19.3	21.0	21.7	21.3	20.6	20.0	20.9	20.2	20.3	9.3	7.5	6.9	282.6	.9	-.5	3.6	14.7	8.3
10/12/79	23.00	19.9	20.8	21.2	21.1	20.6	19.9	20.7	20.0	20.2	9.6	7.4	6.7	284.7	.8	-1.5	5.4	11.3	29.1
10/12/79	23.10	19.9	21.7	21.2	21.5	20.4	19.5	20.5	20.0	20.2	9.2	5.9	5.5	278.4	.9	-2.0	2.9	9.6	32.2
10/12/79	23.20	19.7	20.6	21.2	21.2	20.3	19.5	20.4	19.9	20.0	9.3	5.7	5.7	273.8	.2	-2.3	1.9	8.7	28.3
10/12/79	23.30	19.7	20.5	21.2	21.2	20.2	19.7	20.3	19.8	19.9	9.2	5.1	4.7	274.2	.8	-1.4	1.0	6.0	24.5
10/12/79	23.40	19.7	20.4	21.1	21.1	20.1	19.7	20.1	19.7	19.8	9.5	4.8	4.5	282.3	.8	-1.4	1.0	5.2	25.6
10/12/79	23.50	19.6	21.3	21.2	21.1	19.9	19.5	21.0	19.6	19.7	10.2	6.3	5.8	284.2	.3	-.5	1.8	7.0	23.0
11/12/79	0.00	19.6	20.3	20.9	21.3	19.8	19.5	19.9	19.5	19.6	10.6	7.0	6.5	286.6	-.9	.3	3.6	12.1	22.0
11/12/79	0.10	19.6	20.2	20.9	20.9	19.8	19.5	19.4	19.5	19.5	10.4	5.8	5.5	282.2	.0	-2.4	2.9	10.5	27.3
11/12/79	0.20	19.5	20.2	21.8	20.9	19.7	19.3	19.7	19.4	19.4	10.7	5.9	5.5	279.0	.9	-2.3	1.9	8.7	22.0
11/12/79	0.30	19.5	20.1	20.7	20.9	19.6	19.3	19.6	19.3	19.3	10.7	5.8	4.7	277.4	-.9	-1.4	1.0	6.9	21.3
11/12/79	0.40	19.3	20.1	20.7	20.8	19.6	19.5	19.5	19.2	19.3	10.3	3.6	3.2	274.8	.0	-1.4	.1	3.6	20.6
11/12/79	0.50	19.4	20.3	20.6	22.3	19.5	19.3	19.5	19.2	19.2	12.3	5.1	4.7	279.6	.8	-1.4	1.0	5.2	19.3
11/12/79	1.00	19.4	20.0	20.6	20.8	19.5	19.3	19.4	19.1	19.2	14.9	6.9	6.4	284.0	.8	-.4	2.9	8.7	18.1
11/12/79	1.10	19.3	19.0	21.6	20.7	19.5	19.2	19.4	19.1	19.1	14.7	5.9	5.5	277.5	.3	-2.2	2.9	8.0	21.3
11/12/79	1.20	19.3	19.0	21.5	20.8	19.5	19.2	19.3	19.1	19.1	11.3	4.9	4.7	274.3	.3	-1.3	1.0	6.0	18.6
11/12/79	1.30	19.3	19.0	21.5	20.7	19.6	19.1	19.2	19.0	19.2	10.5	4.5	5.8	257.0	.8	-2.2	-2.3	5.2	18.3
11/12/79	1.40	19.3	19.0	21.4	20.7	19.4	19.1	19.2	18.9	18.9	9.7	4.3	4.6	265.2	.8	-2.4	-1.5	4.5	16.6
11/12/79	1.50	19.3	19.5	20.4	20.6	19.3	19.1	19.1	18.9	18.9	9.6	4.7	4.2	284.0	.8	-.0	1.0	5.2	15.7
11/12/79	2.00	19.3	19.8	20.4	20.6	19.3	19.3	19.1	18.8	18.9	9.3	4.0	3.7	285.0	.8	.0	.1	5.2	15.0
11/12/79	2.10	19.2	19.8	20.4	20.6	19.3	19.2	19.1	18.8	19.0	9.2	4.5	4.3	258.6	.8	-2.4	-2.3	5.2	16.0

Table 8 Summary of Results

DATE	TIME	Injection Cycle Duration H	Temperature Inside TI C	Temperature Inside/Outside TI - TA K	Wind Velocity V M/S	Wind Direction R	Pressure Differences North (456) Pa	Pressure Differences South (458) Pa	Pressure Differences East (457) Pa	Pressure Differences West (459) Pa		Air Change Rate 1/H
10/12/79	19.30	1.0	20.9	12.0	5.96	N	.09	2.83	-1.67	9.75	12.67	.266
10/12/79	19.30	2.0	20.9	11.9	6.33	N	.08	2.72	-2.27	10.39	13.19	.258
10/12/79	23.40	1.0	19.9	9.3	5.21	W	-.06	1.61	-1.39	7.60	9.20	.200
10/12/79	23.40	2.0	19.6	9.8	4.40	W	.16	-.89	-1.47	5.15	5.31	.200
10/12/79	23.40	3.0	19.4	10.8	3.71	W	.16	-1.70	-1.27	3.65	3.81	.201
10/12/79	23.40	4.0	19.3	10.2	5.92	W	-.13	2.24	-.94	10.01	12.25	.250
11/12/79	5.40	1.0	19.2	7.2	9.54	W	.25	5.37	-6.46	24.92	30.54	.351
11/12/79	5.40	2.0	19.6	6.3	10.23	W	1.12	.91	-10.25	28.17	30.19	.405
11/12/79	9.20	1.0	20.2	11.5	8.46	W	.50	2.01	-7.16	16.73	19.31	.392
11/12/79	12.30	1.0	20.4	13.2	8.24	W	-.20	5.00	-2.02	17.54	22.55	.326
11/12/79	12.30	2.0	20.5	13.8	7.52	W	-.11	4.79	-.69	11.77	16.57	.319
11/12/79	16.20	1.0	20.5	15.4	7.29	W	.44	2.80	-3.13	7.21	10.45	.413
11/12/79	19.20	1.0	20.5	16.0	7.41	W	.40	1.94	-3.52	-.11	2.42	.399
11/12/79	22.20	1.0	19.9	15.5	7.32	NW	.75	1.40	-3.98	16.20	18.35	.395
12/12/79	1.20	1.0	18.9	15.4	6.13	W	.73	1.27	-2.64	11.77	13.76	.315
12/12/79	1.20	2.0	18.8	15.3	5.72	W	.43	1.66	-1.91	10.03	12.13	.353
12/12/79	5.20	1.0	18.6	15.3	5.50	W	.30	2.81	-1.68	8.53	11.64	.274
12/12/79	5.20	2.0	19.0	16.3	5.75	NW	.55	2.73	-2.14	9.72	13.08	.324
14/12/79	11.40	1.0	20.2	14.8	3.99	NW	.24	1.69	.32	5.08	7.34	.167
14/12/79	11.40	2.0	20.3	15.2	5.76	NW	.36	2.27	-1.79	10.07	12.70	.270
14/12/79	11.40	3.0	20.3	15.6	6.64	NW	.23	3.31	-2.29	12.83	16.36	.271
14/12/79	11.40	4.0	20.4	15.7	6.74	NW	.31	4.81	-1.64	13.03	17.36	.271
14/12/79	17.40	1.0	20.4	17.5	3.31	NW	.46	2.37	.37	4.76	7.95	.207
14/12/79	17.40	2.0	20.4	18.3	1.34	NW	.51	2.24	1.56	2.07	6.37	.182
14/12/79	17.40	3.0	20.4	17.7	1.59	W	.31	2.18	2.24	1.46	6.19	.168
14/12/79	17.40	4.0	20.4	16.6	2.70	NW	-.12	.76	2.10	2.48	5.34	.196
14/12/79	17.40	5.0	20.2	15.6	4.12	NW	-.03	1.53	.42	6.11	8.06	.264
15/12/79	0.40	1.0	19.0	17.2	2.29	NW	.58	2.52	1.04	2.96	7.10	.197
15/12/79	0.40	2.0	18.8	16.2	2.50	NW	.45	1.86	1.10	3.25	6.71	.195
15/12/79	0.40	3.0	18.6	14.7	3.16	NW	.39	1.29	.95	3.74	6.37	.181
15/12/79	0.40	4.0	18.4	13.5	4.32	NW	.46	1.93	.05	5.58	8.02	.190
15/12/79	0.40	5.0	18.3	13.3	4.22	NW	.35	2.05	-.14	5.47	7.87	.193
15/12/79	0.40	6.0	18.6	13.9	2.59	NW	.43	1.51	.62	3.03	5.59	.154
15/12/79	8.40	1.0	19.6	14.3	3.35	N	.61	1.25	.43	1.45	3.74	.169
15/12/79	8.40	2.0	19.7	14.1	4.56	N	.29	1.61	.79	4.31	7.00	.172
15/12/79	8.40	3.0	19.9	13.6	5.12	N	.25	2.77	.35	7.68	11.04	.194
15/12/79	8.40	4.0	20.2	12.9	6.12	N	.52	2.86	-1.27	10.57	13.96	.239
15/12/79	8.40	5.0	20.3	13.9	8.32	N	.31	-.43	-3.93	20.12	20.43	.304
15/12/79	15.20	1.0	20.2	15.8	8.43	NW	.31	5.35	-2.35	19.58	25.17	.340
15/12/79	15.20	2.0	20.1	15.5	9.17	NW	.38	5.33	-2.36	23.51	29.14	.341
15/12/79	19.40	1.0	20.0	16.5	10.24	NW	.31	6.02	-3.46	28.64	34.98	.367
15/12/79	19.40	2.0	20.0	18.4	8.69	NW	.59	6.35	-2.48	22.81	29.75	.371
15/12/79	23.40	1.0	18.9	18.2	4.18	NW	.58	3.55	.19	7.41	11.74	.223
15/12/79	23.40	2.0	18.7	17.7	5.70	NW	.52	3.40	-1.31	11.35	15.27	.266
15/12/79	23.40	3.0	18.4	17.5	6.33	N	.65	2.69	-2.65	13.19	16.53	.324
15/12/79	23.40	4.0	18.2	17.3	6.47	N	.65	2.82	-3.05	13.73	16.41	.326
16/12/79	5.20	1.0	18.1	17.4	6.06	NW	.63	2.83	-2.35	12.51	15.98	.287
16/12/79	5.20	2.0	18.6	17.7	6.44	NW	.64	3.02	-2.67	13.61	17.26	.320
16/12/79	5.20	3.0	18.8	17.7	6.37	NW	.61	3.85	-1.95	12.97	17.43	.323
16/12/79	10.20	1.0	19.7	18.2	6.42	NW	.59	4.92	-1.14	12.29	17.80	.298

APPENDIX 2

I. GENERAL INFORMATION

Country	Principal Researcher	Date
Canada	C.Y. Shaw	

Address:

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Title of Project:

The Mark XI Energy Research Project

Principal Objectives:

To measure energy consumption and factors which affect it, including infiltration.

References:

1. Quirouette, R.L.
   The Mark XI Energy Research Project: Design and Construction
   Building Res. Note No. 131

2. Shaw, C.Y. and Tamura, G.T.
   Mark XI Energy Research Project: Airtightness and Air Infiltration Measurements.
   Building Res. Note No. 162, June 1980.

Comments:

Tests were carried out on the standard(H1) and upgraded (H4) test houses. 1978/79.

II. TEST SITE DESCRIPTION

A. Geographic Information

(1) Location.
Fortune Drive, Orleans, Ontario, Canada
(5 km east of Ottawa)

(2) Height above sea level.

(3) Terrain. Flat with low buildings (houses)

Please append map showing the surrounding area indicating location and e of obstacles such as trees, fences and other buildings, also relief.

See Fig.1 for site plan

Shielding is moderate. Buildings within 2 house heights + 2.5m earth berm (see Fig.1)

(4) Orientation. Front facade points 24°W of North

(5) Location of Meteorological Station. On site

B. Climatic Information (where available)

Detailed measurements taken on site.

(1) % frequency wind speed v direction *(by 22½° sector – attach table).*

(2) % frequency wind speed v temperature *(attach table).*

(3) Hours of daylight/insolation *(attach table).*

(4) Cloudiness.

(5) Precipitation, humidity.

(6) Other – anthropogenic factors.

C. The Building

(1) History.

Single detached houses. 2 storey, 3 bedroom with basement and attached garage. Standard - built to Ontario Building Code 1975 by Talback Construction of Ottawa. Construction began 6th July 1977, essentially completed by end of December 1977.

(2) Construction material and technique.

Standard house

Wood frame construction. 2x4 stud walls, 2x8 wood joists, wood trusses 24" oc. Cast-in-place concrete foundations, 8" walls. Wall insulation: glass fibre, paper backed, R12. Ceiling insulation: glass fibre, paper backed, R20. Basement insulation: glass fibre, paper backed, R7 inside, extending 2ft below grade. Windows: double glazed, wood frame (sliding and double hung). Exterior doors: metal insulated, ~R6, no storm door. Roof: asphalt shingles 210 lb. Siding horizontal: alum. 8" ivory white. Brick on front of house only, one storey, garage. Soffits continually vented, A6. Facia: aluminium.

(for details of upgraded house - see continuation overleaf)

(3) Dimensions *(Please append diagram to report for clarity.)*

(a) Plan: attach diagram (internal/external).		(see Fig.2)
(b) Elevation.		(see Fig.2)
(c) Total volume.	(incl. basement)	386.0 m^3
(d) Effective volume.		
(e) Floor area.	(gross)	1249 ft^2 (118.0 m^2)
(f) Ceiling area.		673 ft^2 (63.7 m^2)
(g) Facade (wall) area.	(above grade)	1525 ft^2 (144.4 m^2)
	(foundation wall)	891 ft^2 (84.4 m^2)
(h) Total area of windows.		164 ft^2 (15.5 m^2)
(i) Total area of external doors.		44 ft^2 (4.2 m^2)
(j) Number, volume and layout of rooms (refer to (a)).		(see Fig.2)
(k) Shape: roof pitch, etc.		
(l) Attic, basement, crawlspace.	(gross basement enclosure area)	1437 ft^2 (136.0 m^2)
(i) Insulation.		
(ii) Description.		

(2) *continued*

Upgraded house

As standard, except:

6" walls, 2x4 studs + 2x2 horizontal strapping inside. Wall insulation: glass fibre, friction fit, R12 + R7, 4ml polyethylene vapour barrier throughout. Ceiling insulation: glass fibre, friction fit, R20 + R12, exterior sheathing 1" fibreboard, R3. Basement insulation: closed cell polystyrene 1½", R7.5, outside of wall extending to footing. Windows: triple glazed, wood frame, casement, awning, has storm door, R~7.5.

C. The Building

(4) Gaps in the envelope.

(a) Doors (external).

(i) Type.

(ii) Cracklength.

(iii) Comments.

(b) Windows.

(i) Type.

(ii) Cracklength.

Length of sash crack for windows	Standard 42.85m Upgraded 67.59m
Frame wall leakage	-Negligible
Window leakage	-See Fig.3

(iii) Comments.

(c) Ventilation openings.

(i) Type.

(ii) Cracklength.

(iii) Open area.

(iv) Degree of closure.

(v) Comments.

C. The Building (continued)

(d) Chimneys, flues.

(i) Size, type.

No chimney

(ii) Location.

(iii) Condition of dampers.

also estimates of crack size for:

(e) Cavity walls and other communicating spaces, also electrical outlets.

(f) Soleplate, ceilings, corners, skirting boards.

(g) Plumbing outlets, drains, etc.

(h) Other major sources.

from the above and the measured leakage,

(j) Background leakage.

(k) Comments.

Area of outside envelope: 227.7 m^2

C. The Building (continued)

(5) HVAC system.

(a) Type of system.
Forced air electric furnace 15 kW (st) 10 kW (ug)

Design heating load: Standard: 46,400 Btu/h (13,600 W)
Upgraded: 13,755 Btu/h (10,186 W)

Upgraded house also has heat pump

(b) Blower fan capacity (where available).

(c) Duct tightness and location.

(d) Frequency of operation, duration of operating cycle.

(e) Operating temperature.

(f) Location of air inlets.

(g) Comments.

(6) Pollution (non anthropogenic).

(a) Interior.

(b) Exterior.

III. FUNCTION OF BUILDING

A. Type (including use)

B. Occupancy

(1) Times occupied and number of users. Unoccupied during tests, but furnished. Will be let to families in future and monitoring will continue.

(2) Behaviour of occupants.

(a) Window opening. Windows instrumented to detect opening, but not used in this experiment.

(b) Door opening. Also to be instrumented, but no results given.

(c) Other voluntary ventilation.

(d) Heating habits.

(e) Pollution (anthropogenic).

(i) Cooking.

(ii) Aerosols, solvents, etc.

(iii) Smoking.

(iv) Other

(f) Level of activity of occupants.

(g) Comments.

C. Special Requirements

D. Other

E. Comments

IV. MEASUREMENTS

Date and time measurements taken.

A. Pressurisation Measurements – internal

(1) Technique employed.

A centrifugal fan with a capacity of 380 l/s was placed in the living room of each house. The discharge side of the fan was connected by a 10 cm diameter duct to an outside window, where the flow rate was measured with a laminar flow element accuracy ~5% of measured value.

(2) Equipment used.

MERIAM LFE Element

(3) Description of procedures for calibrating equipment.

(4) Results (attach relevant tables, graphs etc.)

Using $Q = CA(\Delta p)^n$

Q in l/s, C in $l/s\ m^2\ (Pa)^n$, Δp(Pa)

(A = 227.8 for both)

Standard → C = 0.11 n = 0.71) whole house

Upgraded → C = 0.075 n = 0.71)

(a) Pressurisation.

(b) Depressurisation.

(c) Alternating pressurisation (infrasonic).

(5) Comments.

(see Fig.4)

B. Pressure Measurements – external (including wind tunnel studies)

(1) Technique used (including conditions)

The exterior walls and ceilings are fitted with pressure taps, but no measurements were made in this series.

Pressure differences have been measured at four different levels in calm weather, wind speed < 1 m/s, to find the neutral plane - results not given.

(2) Equipment used.

(3) Calibration procedure.

(4) Location of surface pressure taps (see II.C (3)).

(5) Measurement results (attach as table).

(6) Comments)

C. Interior Conditions

(1) Temperature (dry bulb). - (see Tables 1 & 2). Measured by thermocouple.

(2) Relative humidity. - Monitored - results not given.

(3) Air flow. - Measured in forced air ducts by orifice plate - results not given.

(4) Other. - Electrical energy to each room, also to appliances - monitored, results not given.

(5) Comments. - Moisture in the building fabric was also monitored - no results given.

D. Exterior Conditions

(1) Description of equipment used.

(2) Weather – off-site.

(a) Wind speed. -Measured at 10m to rear of house at 18m above ground (see Tables 1 & 2)

(b) Wind direction. -By octant (see Tables 1 & 2)

(c) Dry bulb temperature. -(see Tables 1 & 2)

(d) Stability conditions.

(e) Other (see A5. for location).

(f) Comments.

(3) Weather on-site.

(a) Wind speed.

(b) Wind direction.

(c) Dry bulb temperature.

(d) Relative humidity.

(e) Turbulence scale.

(f) Turbulent intensity.

(g) Stability conditions (where available).

(h) Other.

(i) Comments.

E. Infiltration

(1) Measurement technique.

Used tracer gas decay method. Tracer gas was CO_2 produced by placing pieces of dry ice on a hot plate in the living room. After a pre-determined amount of CO_2 gas was generated, the remaining dry ice was taken out of the house. After allowing sufficient time for the tracer gas to mix with the air inside the house, using the forced-air circulation system, the CO_2 concentration was measured periodically by sampling from the return air duct of the forced-air system. CO_2 was measured using an infra red gas analyser.

(2) Equipment used (include photographs).

(3) Calibration procedures.

(4) Measurement results (attach relevant table, graphs, etc). (see Tables 1 & 2)

Autumn, Winter and Spring measurements were made on both houses. In Summer the standard house was occupied so only the results from the upgraded house were available.

(5) Comments

Heat Loss Analysis indicates ventilation heat loss of 4.415W (32.1%) for the standard house.

F. Other

(1) Qualitative.

(a) Smoke sticks.

(b) Acoustic techniques.

(c) IR. Thermography.

(2) Energy consumption.

Estimated annual heating consumption: Standard - 20212 kW.h
Upgraded - 15125 kW.h

(3) Other.

(4) Comments.

V. NUMERICAL/COMPUTER MODELS

A. Type of Model

B. Correlations

(1) Variables used.

(2) Sign and goodness of fit.

(3) Problems encountered in attempting to find a correlation.

(4) Comments.

C. Computer Models

(1) Name and description of model, including assumptions.

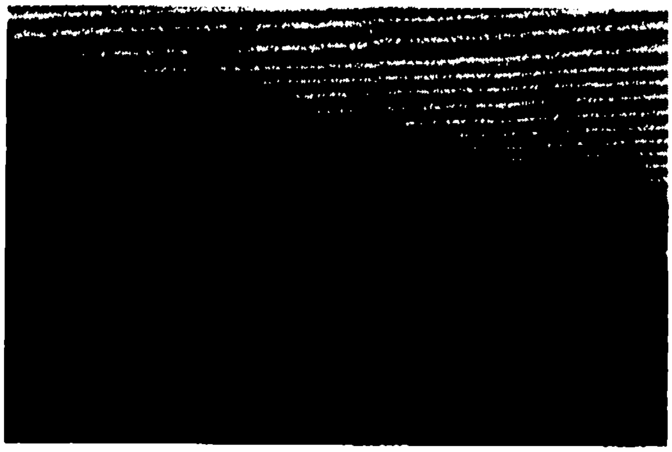
(2) Input.

(3) Output.

(4) Agreement with observation.

(5) Comments.

D. Any Other Theoretical Work of Interest



Canadian dwelling

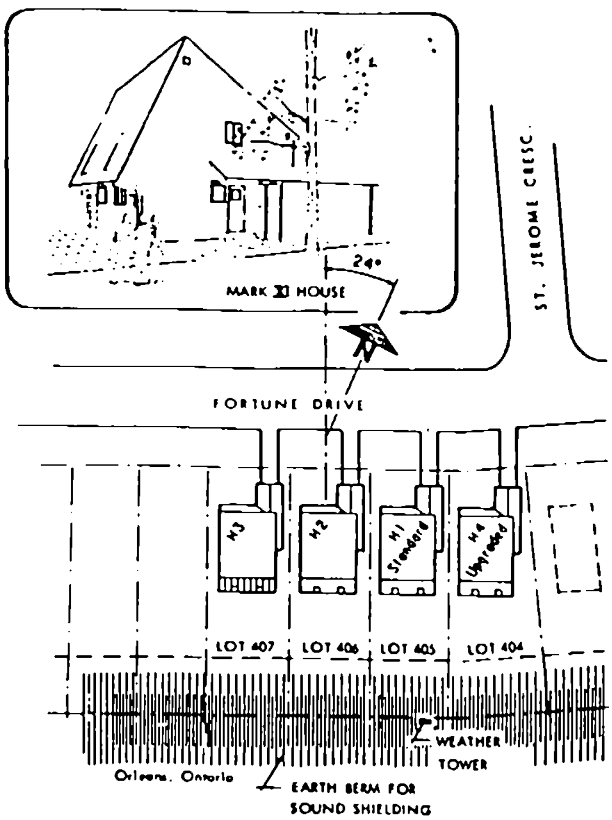


FIGURE 1

SITE PLAN - MARK XI PROJECT

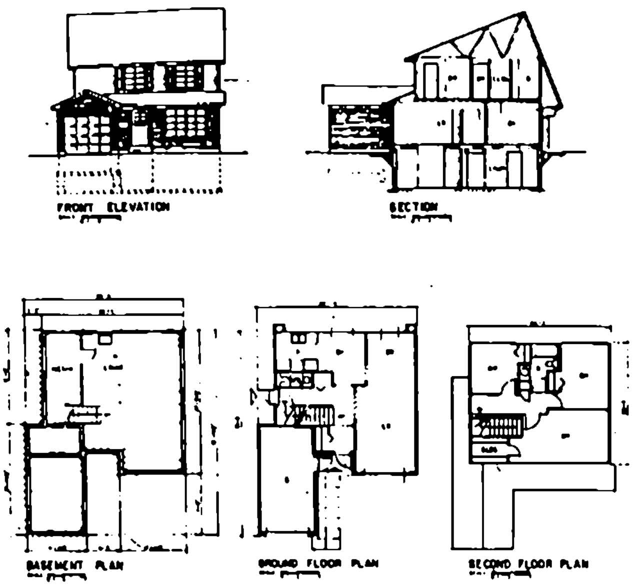


FIGURE 2

HOUSE NO. 1 - STANDARD CONSTRUCTION
(TYPICAL ARCHITECTURAL DESIGN OF ALL 4 HOUSES)

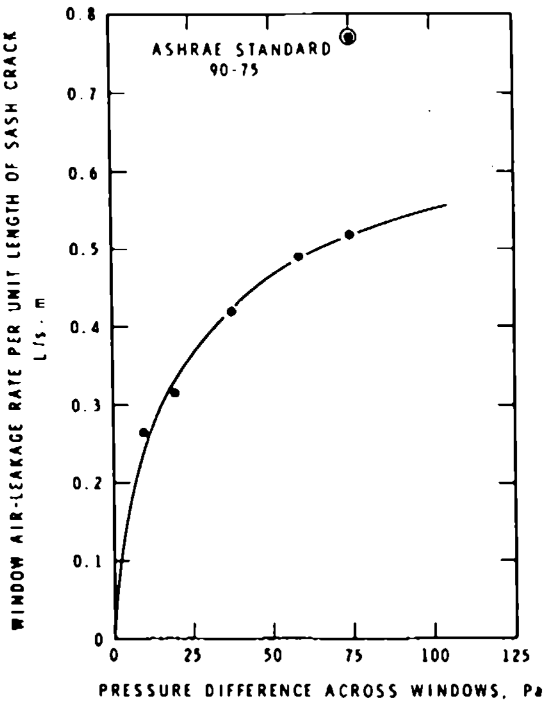


FIGURE 3

WINDOW AIR-LEAKAGE RATE OF THE UPGRADED HEAT-PUMP HOUSE

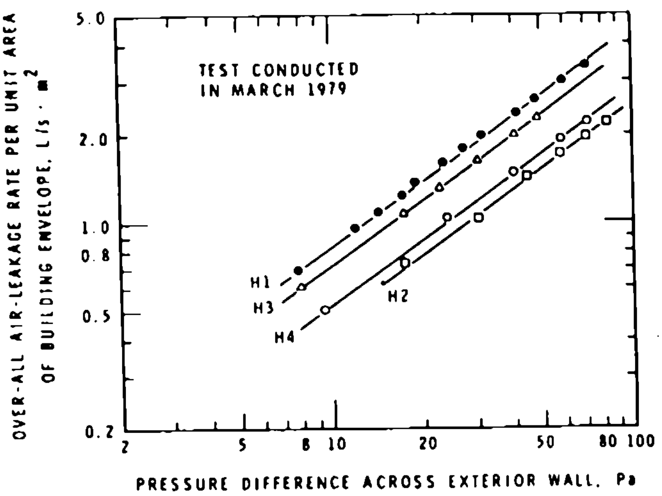


FIGURE 4

OVER-ALL AIR-LEAKAGE RATE FOR THE FOUR ENERGY-CONSERVATION RESEARCH HOUSES

TABLE 1
Air Infiltration Rates - Spring, Autumn and Winter Results
(Tracer Gas Decay)

DATE 1978-1979	Wind Speed, m/s	Wind Direction	Air Temperature, °C		Upgraded House**	Standard House**
			Inside	Outside	Air changes/hr.	Air Changes/hr.
April 10	7.33	N	22.	7.5	0.258	0.334
Jan. 26	4.83	N	22.4	4.0	0.181	0.219
Dec. 20	1.65	N	20.4	-12.7	0.176	0.264
Feb. 12	0.98	N	21.8	-15.6	0.178	0.269
April 20	2.82	NW	22.5	16.2	0.082	--
Aug. 15	5.27	NW	22.5	15.5	0.201	--
Aug. 15	8.05	NW	22.5	15	0.322	--
April 14	5.99	NW	22.5	11.3	0.268	--
April 18	6.39	NW	22.2	9.3	0.255	--
Feb. 13	3.93	NW	20.7	-2.6	0.205	0.274
Feb. 5	10.55	NW	22.	-10.6	0.352	0.415
Feb. 16	4.11	NW	22.1	-16.1	0.199	0.288
April 20	3.84	W	22.5	15	0.114	--
April 12	3.35	W	22.5	9.5	0.087	--
Feb. 27	2.19	W	20.2	0.5	--	0.168
Jan. 29	6.12	W	23.4	-3.4	0.201	0.301
Mar. 16	4.43	W	21.8	-4.4	0.158	0.21
Jan. 22	9.61	W	21.	-4.7	0.201	0.222
Jan. 30	5.63	W	22.6	-5.5	0.196	0.271
Jan. 31	4.69	W	22.5	-7.4	0.188	0.267
Jan. 4	5.68	W	19.8	-9.3	0.181	0.255
Feb. 1	5.23	W	22.6	-9.6	0.201	0.265
Feb. 2	5.99	W	23.1	-10.8	0.197	0.303
Mar. 15	6.30	W	21.3	-12.2	0.206	0.292
Feb. 15	3.84	W	22.1	-15.4	0.188	0.27
Jan. 19	2.32	W	19.	-18.2	--	0.284
Feb. 9	5.23	W	21.8	-18.7	0.212	0.326
Feb. 14	5.86	W	20.7	-19.9	0.208	0.331
Feb. 28	1.07	W	21.4	3.9	0.103	0.135
April 6	7.38	S	22.	-0.2	0.2	0.318
Feb. 20	6.48	S	22.4	-3.7	0.206	0.27
Jan. 5	5.95	SW	20.	-9.0	--	0.256
Aug. 10	5.01	E	21.1	12.5	0.107	--
April 9	9.34	E	22.5	4.6	0.182	--
April 2	8.05	E	22.2	3.8	0.149	0.214
Feb. 23	7.64	E	22.4	-1.0	0.247	0.281
Jan. 24	8.	E	22.	-4.7	0.195	0.260
Jan. 23	1.43	E	21.	-5.6	0.148	0.236
Feb. 19	1.16	E	22.	-15.9	0.196	0.279
Jan. 17	7.78	E	20.5	-19.5	--	0.314
Feb. 21	1.61	NE	22.8	-2.0	0.135	0.195
Feb. 26	5.14	NE	20.6	-2.6	--	0.178

**Air infiltration measurements were conducted simultaneously in the standard and upgraded houses.

TABLE 2
Air Infiltration Rates - Summer Results - Optional
(Tracer Gas Decay)

Date, 1979	Wind Speed* m/s	Wind Direction	Air Temperature, °C		Upgraded House
			Inside	Outside	Air Changes/hr.
July 17	3.13	N	22.2	25.4	0.116
July 17	3.49	N	22.2	25.1	0.075
July 17	3.93	N	22.2	25.1	0.123
Aug. 21	3.84	N	22.2	24.6	0.122
July 19	5.14	W	21.1	29	0.105
July 18	2.28	W	22.2	26.5	0.087
Aug. 16	4.60	W	21.7	19.0	0.212
July 31	7.09	S	22.2	26.8	0.118
July 31	6.39	S	21.9	24.5	0.12
Aug. 20	1.74	S	22.8	24.4	0.05
Aug. 13	2.41	S	22.5	23.6	0.08
Aug. 20	1.12	NE	21.7	21.5	0.073

*The cup anemometer was located approximately 18 m above ground and about 10 m to the rear of the houses.

APPENDIX 3

I. GENERAL INFORMATION

Country

United Kingdom

Principal Researcher

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Telephone/Telex:

09273 74040 / 923220

Title of Project:

Natural Ventilation in Modern Dwellings - Runcorn Development Corporation House

(Data set UK2)

Principal Objectives:

References:

Comments:

Test period: 23 March 1977 - 25 May 1977

II. TEST SITE DESCRIPTION

A. Geographic Information

(1) Location.
Rosmain Grove, Southgate, Runcorn, Cheshire

(2) Height above sea level.

(3) Terrain. Flat, urban, in the centre of housing estate.

Please append map showing the surrounding area indicating location and size of obstacles such as trees, fences and other buildings, also relief.

(no map given)

(4) Orientation.

(5) Location of Meteorological Station. On site.

B. Climatic Information (where available)

(1) % frequency wind speed v direction *(by 22½° sector – attach table).*

(2) % frequency wind speed v temperature *(attach table).*

(3) Hours of daylight/insolation *(attach table).*

(4) Cloudiness.

(5) Precipitation, humidity.

(6) Other – anthropogenic factors.

C. The Building

(1) History.

3 storey, 3 bedroom, mid-terrace house completed January 1977 (Fig.1)
Owned by Runcorn Development Corporation.

(2) Construction material and technique.

Glass fibre reinforced plastic with tongue and groove flooring on the first and second floors. Single glazed, metal framed windows fitted in the kitchen, lounge and bedrooms. The bathroom has a skylight with four vents fitted. Each window is fitted with a metal surround which is not sealed, hence there is a double gap around the perimeter.

(3) Dimensions *(Please append diagram to report for clarity.)*

(a) Plan: attach diagram (internal/external). (see Fig.2)

(b) Elevation.

(c) Total volume.

(d) Effective volume. 220 m^3

(e) Floor area.

(f) Ceiling area.

(g) Facade (wall) area.

(h) Total area of windows.

(i) Total area of external doors.

(j) Number, volume and layout of rooms (refer to (a)). Room volumes (see Table 1)

(k) Shape: roof pitch, etc. Flat roof, rectangular plan.

(l) Attic, basement, crawlspace.

(i) Insulation.

(ii) Description.

C. The Building

(4) Gaps in the envelope.

(a) Doors (external). (see Table 2 for cracklengths, C & n values)

(i) Type.

(ii) Cracklength.

(iii) Comments.

(b) Windows. (see Table 2)

(i) Type.

(ii) Cracklength.

(iii) Comments.

(c) Ventilation openings.

(i) Type.

(ii) Cracklength.

(iii) Open area.

(iv) Degree of closure.

(v) Comments.

(d) Chimneys, flues.

(i) Size, type.

(ii) Location.

(iii) Condition of dampers.

also estimates of crack size for:

(e) Cavity walls and other communicating spaces, also electrical outlets.

(f) Soleplate, ceilings, corners, skirting boards.

(g) Plumbing outlets, drains, etc.

(h) Other major sources.

from the above and the measured leakage,

(j) Background leakage. ~56%

(k) Comments.

(5) HVAC system.

(a) Type of system.

District heating scheme in operation served radiators in the kitchen, hallway, lounge and bathroom.

(b) Blower fan capacity (where available).

Extract fan in the bathroom operated by the light switch, remains in operation for 28 minutes after the light has been switched off (~10 air changes). Capacity = 24.7 l/s.

(c) Duct tightness and location.

(d) Frequency of operation, duration of operating cycle.

(e) Operating temperature.

(f) Location of air inlets.

(g) Comments.

(6) Pollution (non anthropogenic).

(a) Interior.

(b) Exterior.

III. FUNCTION OF BUILDING

A. Type (including use)

B. Occupancy

(1) Times occupied and number of users. The dwelling was unfurnished and unoccupied at the time of the test.

(2) Behaviour of occupants.

(a) Window opening.

(b) Door opening.

(c) Other voluntary ventilation.

(d) Heating habits.

(e) Pollution (anthropogenic).

(i) Cooking.

(ii) Aerosols, solvents, etc.

(iii) Smoking.

(iv) Other

(f) Level of activity of occupants.

(g) Comments.

C. Special Requirements

D. Other

E. Comments

IV. MEASUREMENTS

Date and time measurements taken. 23 March - 25 May 1977.

A. Pressurisation Measurements – internal

(1) Technique employed.

Whole house pressurisation tests performed by replacing the front door with a fan unit. Individual leakages were measured for windows and doors.

(2) Equipment used.

(3) Description of procedures for calibrating equipment.

(4) Results (attach relevant tables, graphs etc.) (see Table 3)

(a) Pressurisation.

(b) Depressurisation.

(c) Alternating pressurisation (infrasonic).

(5) Comments.

B. Pressure Measurements – external (including wind tunnel studies)

(1) Technique used (including conditions)

(none given)

(2) Equipment used.

(3) Calibration procedure.

(4) Location of surface pressure taps (see II.C (3)).

(5) Measurement results (attach as table).

(6) Comments)

C. Interior Conditions

(1) Temperature (dry bulb). (see Table 4)

(2) Relative humidity.

(3) Air flow.

(4) Other.

(5) Comments. Whole house and individual room temperatures are available (107 individual room + 27 whole house)

D. Exterior Conditions

(1) Description of equipment used.

(2) Weather – off-site.

(a) Wind speed.

(b) Wind direction.

(c) Dry bulb temperature.

(d) Stability conditions.

(e) Other (see A5. for location).

(f) Comments.

(3) Weather on-site.

(a) Wind speed. Measured at 10m (see Table 4)

(b) Wind direction. (see Table 4)

(c) Dry bulb temperature. (see Table 4)

(d) Relative humidity.

(e) Turbulence scale.

(f) Turbulent intensity.

(g) Stability conditions (where available).

(h) Other.

(i) Comments.

E. Infiltration

(1) Measurement technique.

Whole house air infiltration rates measured by tracer gas decay. Air change rates for individual rooms can be made available (for lounge, kitchen, toilet, bedroom 1, bedroom 2, bedroom 3, bathroom, stairwell)

(2) Equipment used (include photographs).

Nitrous oxide measured using a Grubb-Parsons infra-red gas analyser (now IRGA 120). Multi-point sampling was used for all tests. Twelve sample tubes, equally spaced, connected to a manifold. Two circulatory fans were operated at each (open) internal doorway for even mixing. Windows were kept closed.

(3) Calibration procedures.

(4) Measurement results (attach relevant table, graphs, etc).

(see Table 4)

(5) Comments

15 whole house data sets) given

Lounge	- 12 data sets	) available but not given
Kitchen	- 14 data sets	)
Toilet	- 16 data sets	)
Bedroom 1	- 8 data sets	)
Bedroom 2	- 10 data sets	)
Bedroom 3	- 9 data sets	)
Bathroom	- 12 data sets	)
Stairwell	- 17 data sets	)

F. Other

(1) Qualitative.

(a) Smoke sticks.

(b) Acoustic techniques.

(c) IR. Thermography.

(2) Energy consumption.

(3) Other.

(4) Comments.

Fig.1

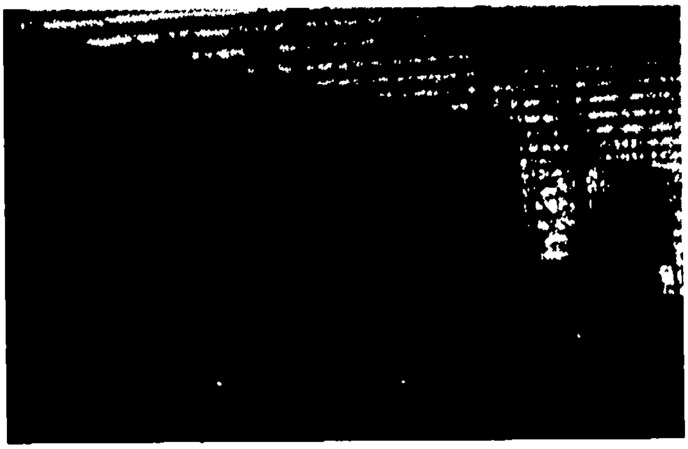

Fig. 2 Internal layout of building

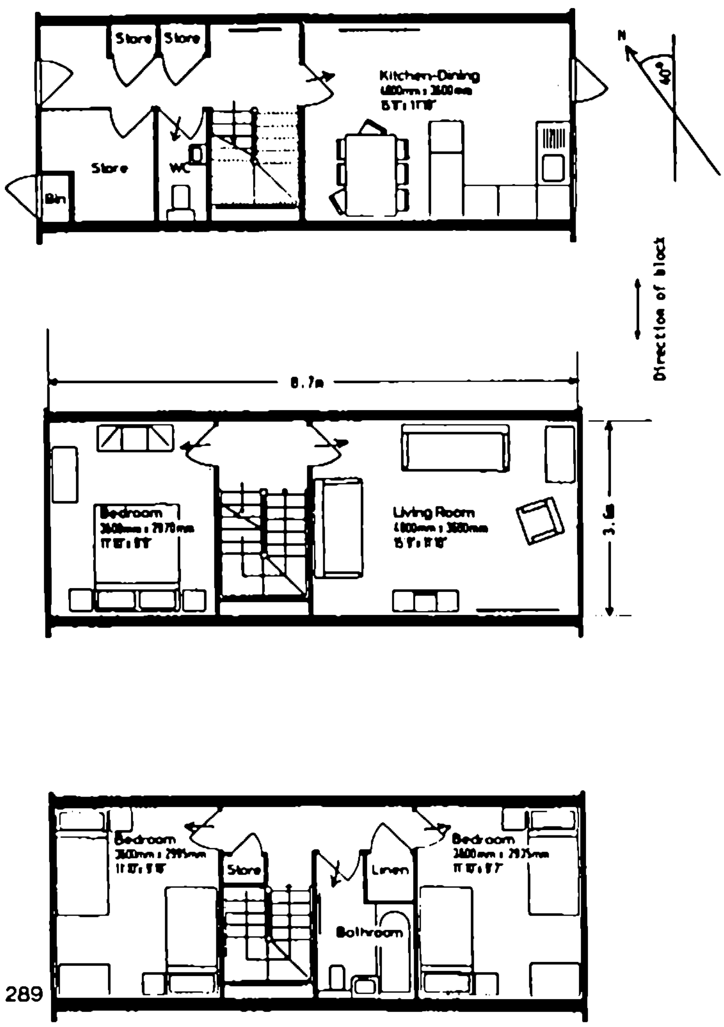

TABLE 1 ROOM VOLUMES

Room	Volume m^3
Lounge	48.68
Kitchen	36.89
Toilet	4.88
Bedroom 1	28.69
Bedroom 2	39.79
Bedroom 3	16.67
Bathroom	10.44
Stairwell	36.66

TABLE 2 AIR LEAKAGE CHARACTERISTICS OF WINDOWS

Window	$\frac{1}{n}$	n	k	Openable crack length m
Lounge	0.54	1.85	0.64	3.98
Kitchen	0.52	1.92	0.84	3.98
Bedroom 1	0.54	1.85	0.48	3.98
Bedroom 2	0.67	1.49	0.45	3.98
Bedroom 3	0.69	1.45	0.49	3.32
Bathroom	0.58	1.72	0.50	3.32

TABLE 2 (cont/.....)

AIR LEAKAGE CHARACTERISTICS OF DOOR				
Door	$\frac{1}{n}$	n	k	Crack length m
Lounge	0.53	1.89	6.23	5.52
Kitchen	0.55	1.82	5.17	5.50
Toilet and Toilet door	0.59	1.69	4.38	5.30
Bedroom 1	0.51	1.96	9.62	5.52
Bedroom 2	0.58	1.72	7.53	5.52
Bedroom 3	0.59	1.69	4.91	5.50
Bathroom	0.57	1.89	6.23	5.52
Rear (Lounge)	0.56	1.79	5.67	5.62
Front	0.54	1.85	7.56	5.62
Loft and loft hatch	0.50	2.00	3.43	3.08
WINDOW AND GAP ABOVE DOOR				Crack area m^2
Lounge	0.52	1.92	5.39	0.0070
Kitchen	0.50	2.00	6.13	0.0070
Toilet	0.52	1.92	4.51	0.0057
Bedroom 1	0.53	1.89	5.00	0.0078
Bedroom 2	0.54	1.85	5.38	0.0062
Bedroom 3	0.53	1.89	5.08	0.0078
Bathroom	0.53	1.89	6.34	0.0078

TABLE 3 WHOLE HOUSE PRESSURIZATION TEST RESULTS

Conditions: External doors and windows closed.
Toilet fan off, but not sealed.

SET 1(a)	Positive internal pressure	SET 1(b)	Negative internal pressure
P (Pa)	Q (m^3/h)	P (Pa)	Q (m^3/h)
10.0	1350	99.8	860
20.0	1840	19.6	1450
30.0	2600	29.4	1900
40.0	2870	39.2	2300
50.0	3150	49.0	2650
60.0	3710	58.8	3110
		62.8	3280

Conditions: External doors and windows closed.
Toilet fan off and sealed.

SET 2(a)		SET 2(b)	
P (Pa)	Q (m^3/h)	P (Pa)	Q (m^3/h)
10.0	1350	10.0	670
20.0	1850	20.0	1350
30.0	2580	30.0	1800
40.0	2850	40.0	2270
50.0	3140	50.0	2640
60.0	3700	60.0	3030
		63.5	3240

TABLE 4 TEST DATA FOR THE WHOLE HOUSE

Test No	Data	Air change rate	Flow from air change rate l/s	Wind speed m/s	Wind direction	Room temp. °C	External temp. °C
W1	28.6.77	0.30	18.56	2.7	-	20.1	17.5
W2	"	0.27	16.70	2.2	310	20.7	16.7
W3	"	0.34	21.03	1.0	160	20.1	12.2
W4	29.6.77	0.45	27.84	4.2	270	19.4	16.0
W5	"	0.45	27.84	4.0	290	20.5	18.4
W6	"	0.29	17.94	3.2	270	20.5	17.7
W7	"	0.28	17.32	2.7	270	21.1	17.2
W8	30.6.77	0.37	22.89	4.2	240	18.3	13.3
W10	"	0.50	30.93	6.2	260	20.6	17.3
W11	"	0.44	27.22	5.5	260	20.1	15.9
W12	4.7.77	0.21	12.99	2.5	130	26.0	26.8
W13	"	0.29	17.94	1.5	150	26.7	21.3
W14	5.7.77	0.41	25.36	3.2	60	23.0	19.4
W15	"	0.37	22.89	4.0	70	25.1	25.2
W16	"	0.44	27.22	3.7	70	25.7	25.3
W17	6.7.77	0.34	21.03	2.5	70	22.9	20.8
W18	"	0.26	16.08	2.5	60	23.9	27.5
W19	"	0.34	21.03	2.7	90	25.8	25.3
W21	7.7.77	0.25	15.47	1.7	90	25.2	25.9
W22	"	0.32	19.79	0.2	-	25.8	18.2

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The Air Infiltration 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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