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Leakage distribution in buildings

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Summary

This document examines those factors which can influence the leakage distribution in a building. These include building style, construction quality, materials and ageing. The effect of pressure on leakage distribution is considered, as is the possible seasonal effect of variations in humidity. Methods of measuring leakage distribution are discussed. There is a discussion of the simulation of leakage distribution for modelling purposes in the light of the results of model validation studies. Information on leakage distributions measured in situ, taken from papers in the Air Infiltration Centre's bibliographic data base AIRBASE, is summarised in the Appendix. Surveys of the frequency of occurrence of different leakage sites are also to be found there.

PREFACE

International Energy Agency

In order to strengthen cooperation in the vital area of energy policy, an Agreement on an International Energy Programme 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 dissemmination 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.

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

1 Introduction

A major weakness in the input to models for air infiltration calculation is the lack of knowledge of the distribution of leaks in the building envelope. If one compares two buildings with different leakage distributions under the same conditions of wind and temperature, their leakage distributions determine the relative magnitudes of wind and stack driven infiltration and thus, the different air flow patterns in the buildings.

The leakage distribution in buildings is a function of the style of construction which, in turn, is a response to the climatic conditions at the site and the prevailing architectural fashion at the time. The latter is often the greater influence.

The leakage distribution of a building, being largely accidental, may admit a sufficient quantity of outside air for adequate ventilation, provided that wind and stack pressures are sufficient to drive it. Unfortunately this occurs rarely in the locations where it is most needed. This inadequacy is often exacerbated by the choice of location of moisture producing areas such as kitchens in traditional building design. Here it is not uncommon to find moist air being drawn into the rest of the house by buoyancy driven air flows. When buildings were very leaky this did not matter much but, with modern tighter construction methods, condensation problems can arise.

There have been attempts in recent years to achieve controlled natural ventilation by modifying the leakage distribution. For example, Etheridge and Gale (1) and O'Sullivan and Jones (2) report on a project on a four level hillside terrace house where trickle vents were introduced into windows along with weatherstripping other major leakages successfully changing the airflow pattern.
A slot vent controlled by the temperature of the outside air has been developed in Sweden (3) for the purpose of controlling the strong flows generated by stack effect during the Scandinavian winter.

The usefulness of this type of measure is, however, limited by the level of uncontrolled leakage - installing a trickle vent in a window will have little effect if there is a much larger leakage area elsewhere in the room.

An alternative approach involving the deliberate sealing of the structure coupled with mechanical ventilation is practised in Scandinavia. Here the level of uncontrolled leakage is also important, particularly in the case when mechanical ventilation is introduced into a building with a view to heat recovery. When uncontrolled leakage is large, it can render heat recovery economically unviable, even when conditions are otherwise favourable. (4)

2 The effect of building style on leakage

The amount of a building's leakage which cannot be attributed to components such as windows and doors (= "background leakage") depends to a degree on its architectural style. These differences reflect the proportion of the enclosing surface which is exposed, and the complexity of the building shell (5), which, in turn, reflects the length of joints between the internal structure and the external cladding.

The effect of the exposed area on the overall leakage is illustrated in Fig.1 in which the percentage of background leakage is given for different types of building. The detached house examples were calculated using the results of a retrofit exercise near Denver Colorado at 25 Pa, the remainder are quoted at 50 Pa and consist of a semi-detached house in Belgium (6) a survey by BRE (7) and two flats in Japan (8). (see Tables A.1 and A.2)

Sulatisky reported the results of a survey of the leakage characteristics of 200 new single family houses in Canada of which 195 yielded useable data. All but 16 of these were fitted with vapour barriers.

The presence or absence of a vapour barrier in the walls is a major factor in timber frame buildings, and can contribute significantly for other forms of construction. Where there is a vapour barrier, the perimeter of the building appears to be a more representative measurement, reflecting the dominance of the wall-roof and soleplate leakages. (9)
Analysis of the data in Sulatisky (9) showed that the best reduction of data took place when a characteristic length L was used in the equation:-

$$Q = C'.L.\Delta P^n = C.\Delta P^n \qquad (1)$$

where Q is the flow rate and ΔP the pressure difference across the walls of the house during a pressurisation test. where L is defined by:-

$$L = \frac{(\text{floor area})*(\text{shell area})}{(\text{volume})*(\text{fraction of volume above grade})} \qquad (2)$$

Excluding the roof from the shell area, this reduces to the perimeter for a simple single storey building of rectangular shape.

The largest variation in Sulatisky's data appeared to be between provinces, reflecting variations in local building form. (see Fig.2)

Sulatisky commented on the tightness of new Canadian housing. Comparing results for all the houses, single storey dwellings were, on average, 6% tighter than split level houses, which, in turn, were approximately 12% tighter than two storey houses.

3 The role of construction quality

Variations in the standards of site practice generate much of the variation in whole house leakage rates. It has been observed that even for houses of nominally identical construction, the total leakage and the leakage distribution can vary widely. (10, 11)

Figure 1: Proportion of background leakage by style of construction[6,7,8,17]

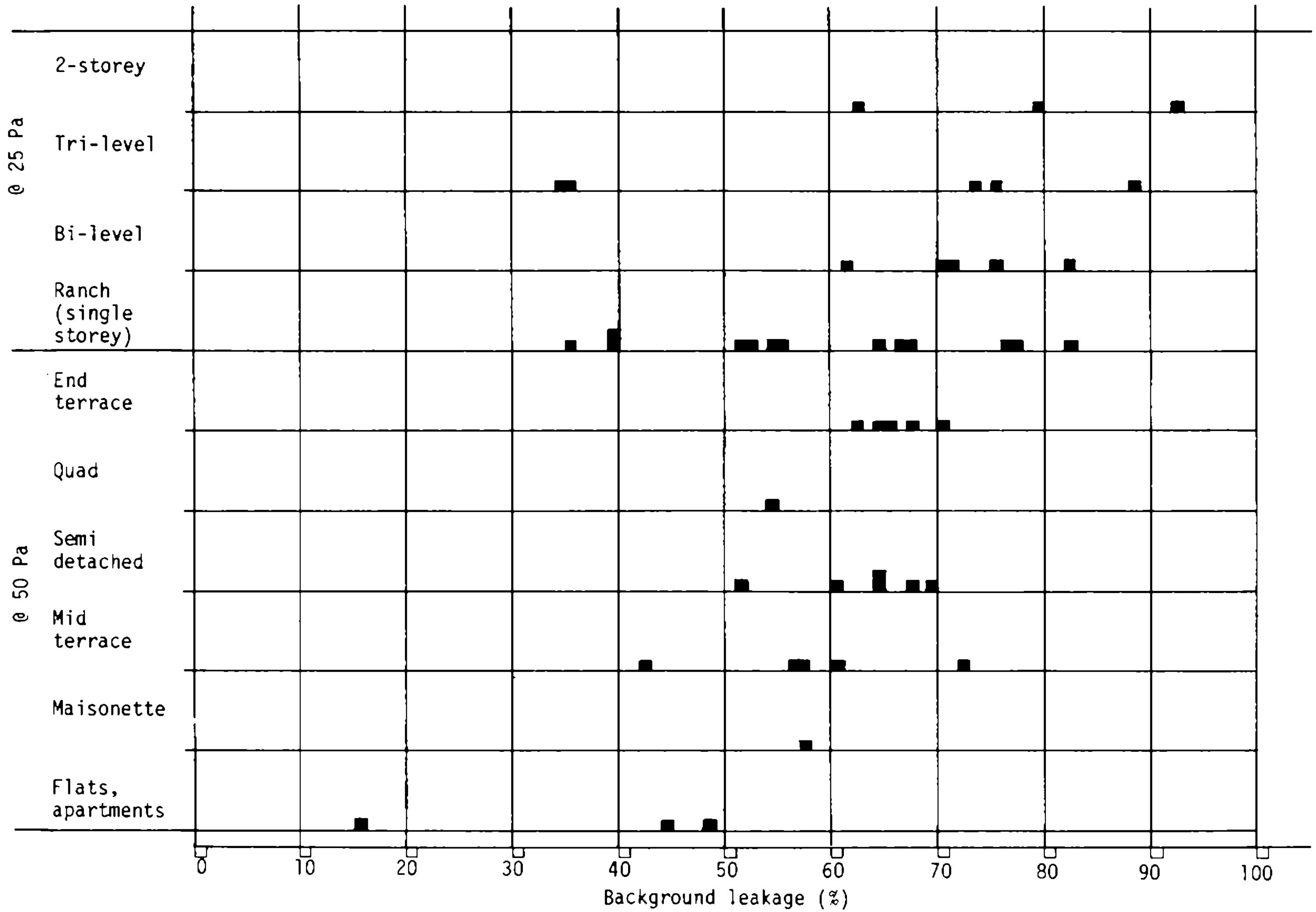
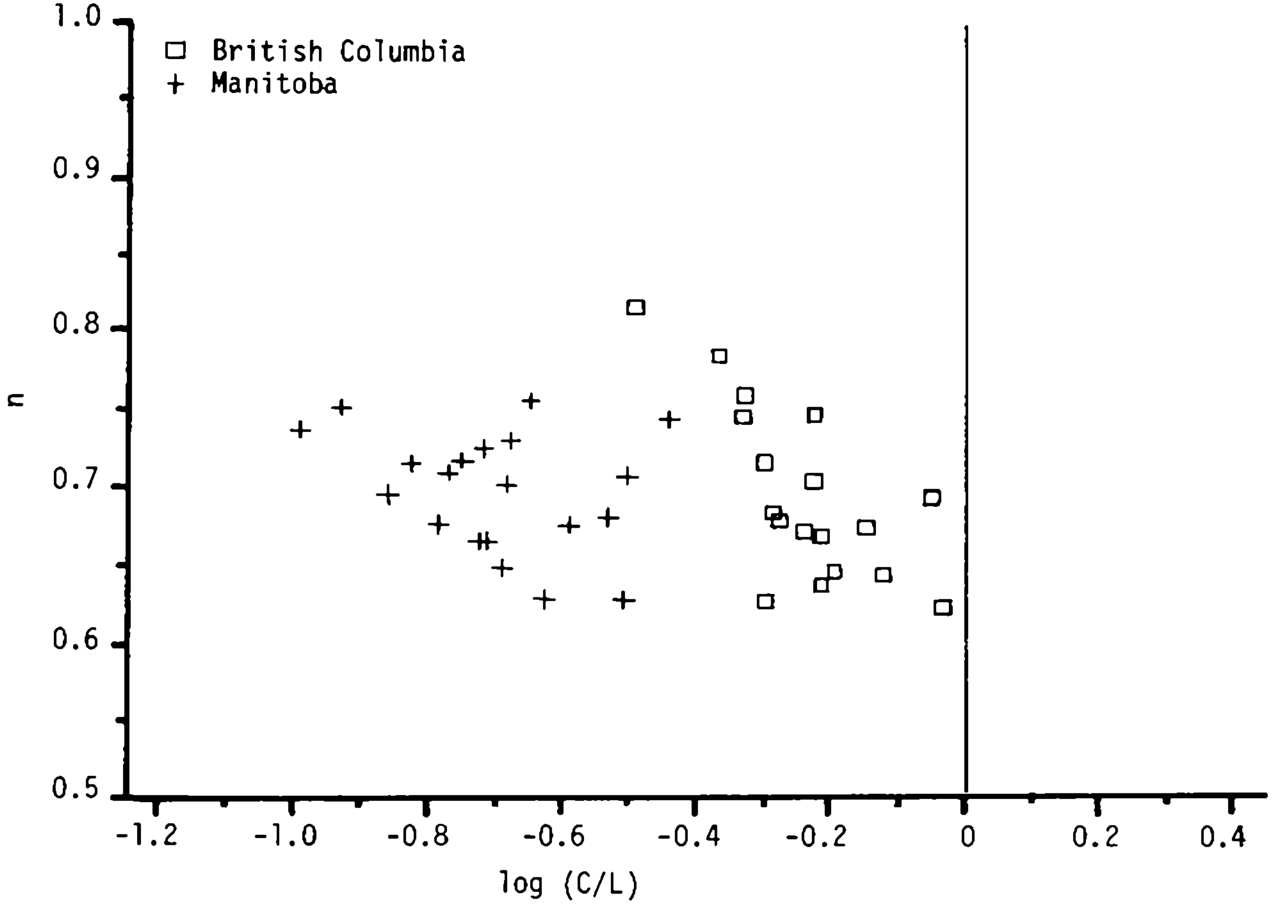


Figure 2: Comparison of leakage characteristics of single dwellings in two Canadian Provinces



4 The variation of leakage distribution with pressure

The variation of leakage distribution with pressure arises fron the fact that the flow rate (Q) through a leak is a non-linear function of the pressure difference (P) across it. This can be represented by an equation of the form:-

$$Q = C.\Delta P^{n} \qquad (3)$$

When considering the leakage distribution at any pressure, it is necessary to take into account the behaviour of the various component and background leakages as reflected in their values of the exponent n.

Large leakages, such as ventilation stacks and unweatherstripped front doors usually have values of n close to 0.5, reflecting the normally turbulent flow within them. Smaller leakages have larger n values, approaching 1.0, the classical value for steady laminar flow, for tight structures. Within a building, there will be a population of cracks, joints and openings with a variety of values of n. As pressure rises, this will bring about a substantial variation in leakage distribution. It is also possible that pressurisation may itself open up smaller leaks. This latter effect can be identified where there is a large difference between the results of pressurisation and depressurisation tests in the same building. The effect of varying pressure on leakage distribution is illustrated in Fig.3 (7). The effect is also notable for the Delft flat (Table A.2), where the proportion of flow through the facade and the ventilation shafts changes by about 6½% as the pressure is increased from 5 Pa to 50 Pa.

5 Other factors affecting leakage distribution

Many houses, particularly in Europe, are built with double thickness brick or brick and block walls with a cavity between the inner and outer leaves to inhibit moisture penetration. This cavity can supply an extra leakage path from the underfloor space to the attic space which can be an important route for moisture transport. (Trethowan (12))

A wall cavity can also supply long leakage paths whereby outside air can reach wall ceiling junctions, electrical fittings, etc. Retrofitting such a house usually involves the introduction of granular or foam insulation into the cavity which strongly inhibits such flows. A properly fitted vapour barrier can almost eliminate them.

Some modern timber frame houses have an open cavity behind exterior cladding, which can act as a capacitance, affecting the response of the wall leakages to transient wind pressures. (13) Here, though, the leakage distribution itself and stack pressures are not affected.

The area, type and installation method of doors and windows is an important factor. One of the most marked differences occurs between wood frame and metal frame windows and doors. Bassett (5) looked at the difference between wood moulding and aluminium extrusion joinery for 40 houses. The former had leakages in the range 3 to 5 $dm^3/s.m$ at 50 Pa and the latter 0 to 1 $dm^3/s.m$ at 50 Pa.

Figure 3: Variation of the proportion of whole house air leakage attributable to various components with applied test pressure (House 17)

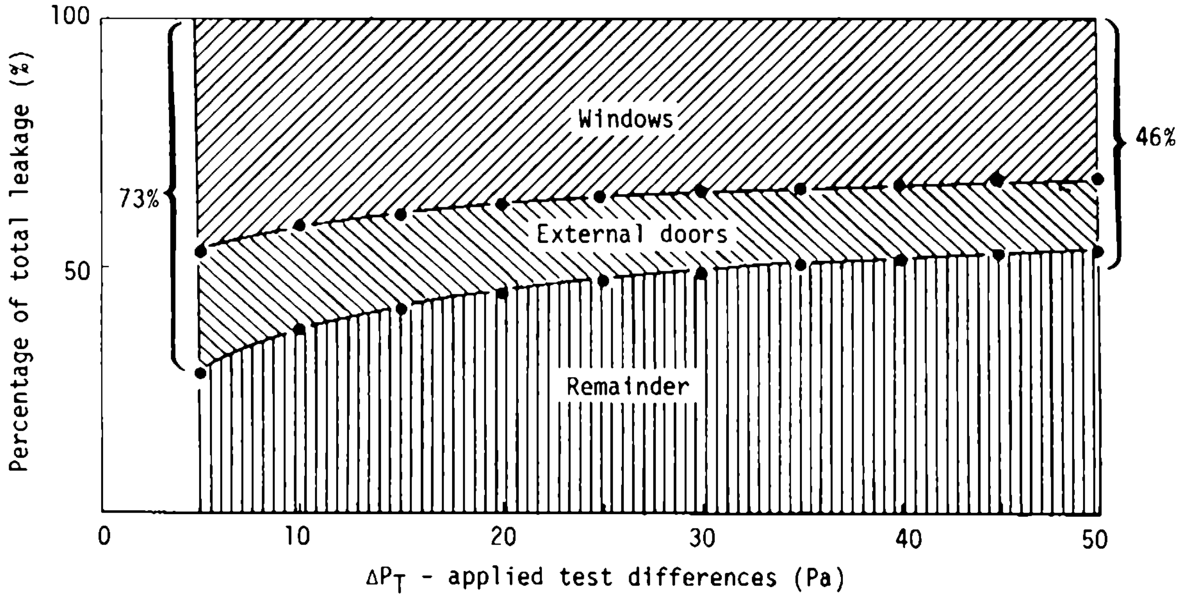
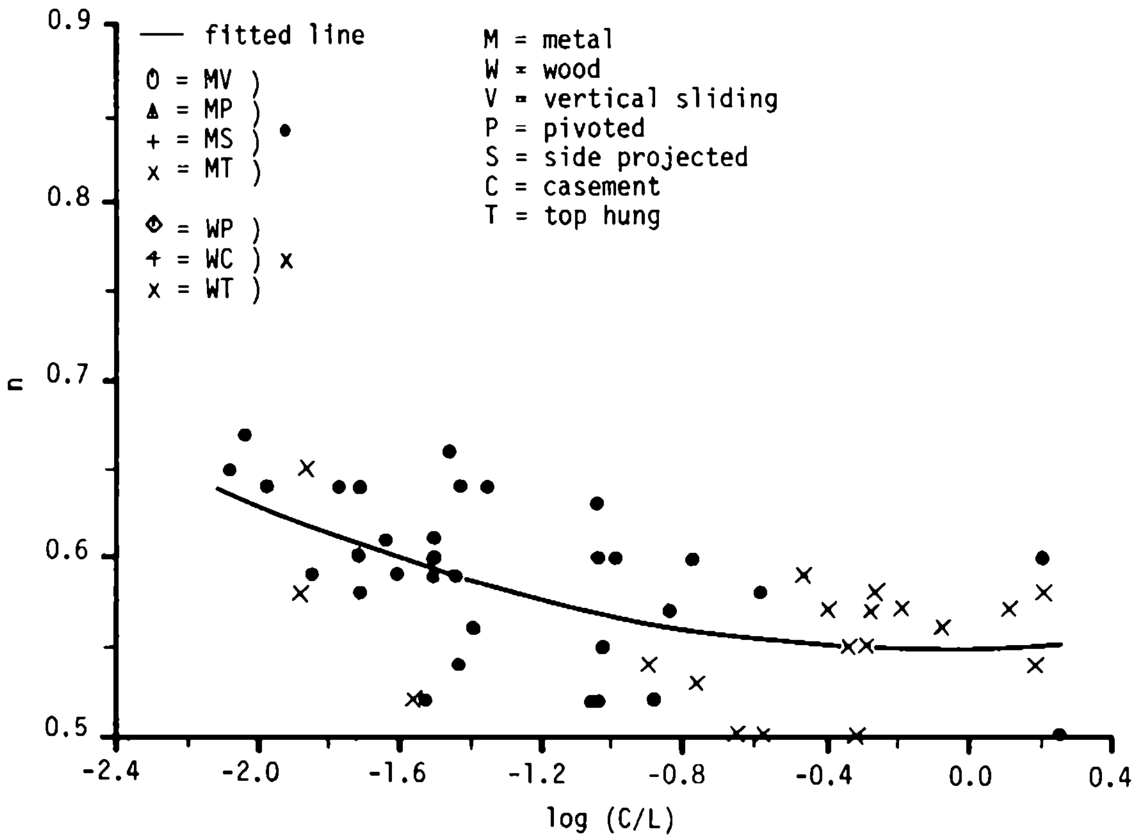


Figure 4: Leakage characteristics : components
Openable windows - no vents



The difference between wood and metal frame windows also appeared when n was plotted against log (C/L) for openable windows for a set of 8 houses in the U.K. collected for use in the AIC's model validation exercise. (14) (see Note, Table A.1)
(Here L is the crack length around the window) (see Fig.4)

The form and construction of the roof is also influential. Where there is a separate roof space with a loft hatch it can form a major leakage route. ((15) + AIC MVDS - NL2, and NL3 see Table A.1)
The pitch of the roof can critically affect the flow through ventilation stacks which penetrate it, depending on the location of the terminus of the stack. (16) The joint between the roof and the vent stack can also provide a significant leakage path where there is no ventilated roof space.

Other important routes include plumbing and soil pipe penetrations through walls. and, particularly where there are suspended timber floors, purpose provided air bricks.

Two surveys (from the USA and Finland) indicating the prevalence of major leakage sites are given in Table A.4 (17,18).

6 Variation of leakage distribution with time

The leakage of a house changes with time, mostly during the first year. Elmroth and Logdeberg (19) observed an increase of about 70% in the leakage at 50 Pa of five new Swedish houses during their first year of occupation. After a second year the leakages of the houses were remeasured and found not to have changed significantly. Measurements by Warren and Webb (7) on three British houses indicated an 83% increase in the first year.
Hedberg performed a similar exercise over a period of two years with 11 houses at Täby. These were built during the period 1977 to 1978 and tested each year from 1980 to 1982. The leakages of two of the houses were measured from the time they were built (1977). The leakage was seen to increase over the first two years for one house and three years for the other by over 50% and to remain essentially constant thereafter.(20)
It should be remarked, however, that the results quoted in the above examples are for data gathered at roughly annual intervals.

Measurements carried out at more frequent intervals on house 11 in the BRE survey (7) (Fig.5 and Table A.1) and on the BRAT test house (21) (Fig.6) show a variation of the order of 25% over the year. The leakage appears to be a maximum in the winter months and a minimum in the summer. The variation is possibly attributable to variations in the moisture content of the wood in structural timbers.(21) (see Fig.6)
An examination of Fig.5 would suggest that the frames of windows and doors are not much affected, possibly because they are usually painted or otherwise treated to exclude moisture.

Within the overall life of a building, other factors may contribute to increasing leakage area :-

1) The materials used in the construction of the building, particularly their resistance to weathering and corrosion. (22)

Figure 5: Seasonal variation of whole house air leakage at 50 Pa (House 11)[7]

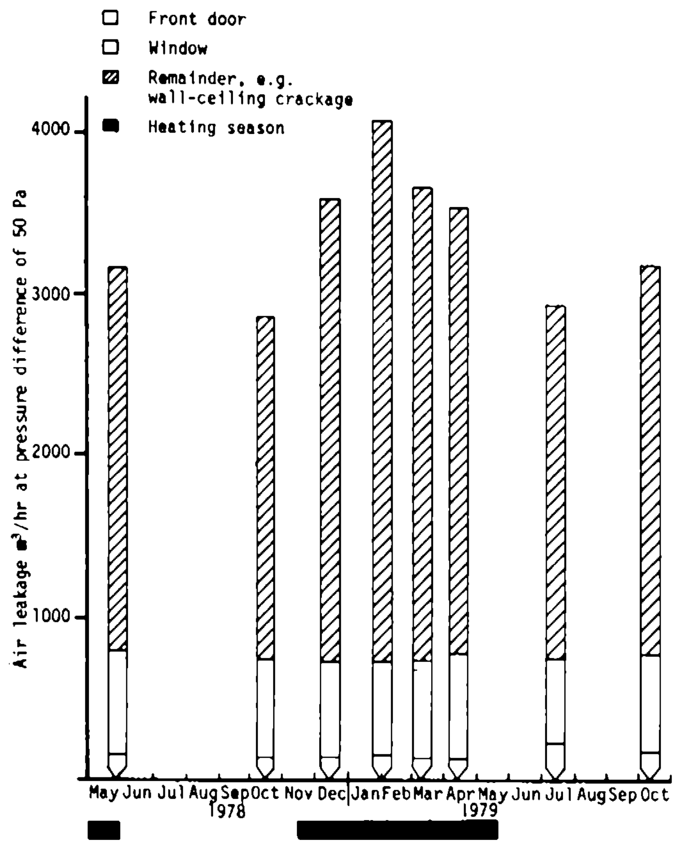
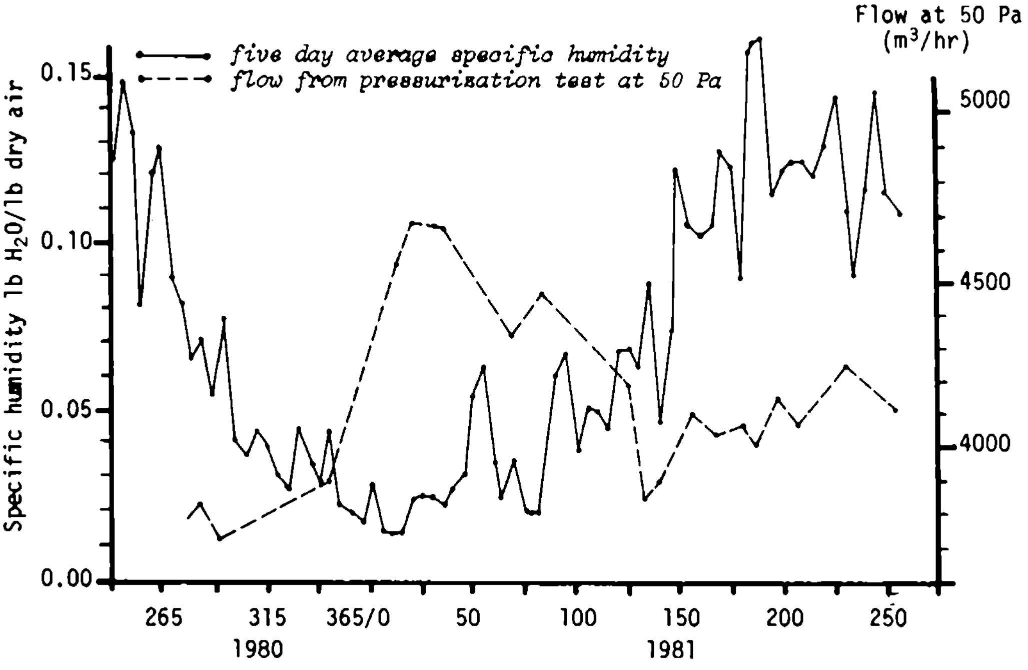


Figure 6: Comparison of leakage of the BRAT test house at 50 Pa with the five day average specific humidity
Data from Persily[21]



2) Environmental stresses including land slip, traffic vibrations, thermal stresses, wind and stack pressures, etc.,

3) Settlement of foundations, etc.

Although there are no published data, there are some documented cases of large leakages appearing due to failure of gaskets and reinforced concrete panels, particularly in high rise office and apartment buildings.

7 Methods of detection of air leakage

Leakage detection has two aspects, the location of the leakage paths and the quantification of the air flows passing through them. Thermography and acoustic methods lend themselves to the detection of large leaks in conjunction with a whole house pressurisation test. (23)
Hunt (24) used successive sealing of major leaks in conjunction with tracer gas tests, however, the changes in the observed air infiltration rate fell within the error band for the observations. Alternatively multiple tracer gas tests have been used to follow large scale air movements between spaces with considerably greater success, e.g. between the attic and upper floors of a house. (15) (see Table A.1)

Georgii (25) attempted to use a combined measurement using CO_2 to find the overall infiltration rate, and an aerosol to detect how much of it was flowing through larger joints and cracks. He tried both a wet aerosol formed from 0.002N $CaCl_2$ solution and a dry one formed by evaporating a fine spray of tap water. The measurements showed a pronounced difference between the values for the gas and the aerosol.

The most widely used method for measuring the leakage distribution has been the steady state pressurisation test. This has been employed in three ways.

1) Testing each component separately and comparing the relative magnitude of the leakages. (26, 27, 28, 29) This method is used when it is not practical to carry out a pressurisation test on the whole building. It also finds favour among the proponents of the "Equivalent Leakage Area" as a means of characterising leakage. (30, 31, 32, 5, 8, 33, 34, 35)

2) Pressurising the whole building, successively sealing each leakage site in turn and measuring the new leakage. (36, 37, 26, 38, 39, 40, 41, 42)

3) The "plenum method" where the building, or part building is pressurised and the leakage of each component within the pressurised space being measured using a pressure chamber. (43, 44)

All three methods suffer from the usual limitations of pressurisation tests. Persily (21) measured the leakage of a building 80 times during the course of a year. For windspeeds less than 2.2 m/s the standard deviation of the flow rate at 50 Pa was of the order of 1% to 2%. For higher windspeeds variations up to 15% were observed. Variations with

TABLE 1: Comparison of measurement methods

Method	Location of large leakages	Location of small leakages	Measurement of flow through		Overall	Advantages	Disadvantages
			large leakages	small leakages			
Thermography and pressurization	**	*	-	-	*	Gives a clear visual image of major crack locations	Difficult to calibrate. The level of pressurization needed to generate a good image is high, perhaps enough to give rise to induced leakage.
Acoustic detection and pressurization	**		*		*	Measures actual flow velocities in the larger cracks → equivalent area.	Velocities measured are not typical. Induced leakage may also be a problem.
Tracer gas (multiple)	*	*	*	*	*	Local residence time information can yield some specific data - generally useful for measuring the exchange of air between spaces. Pressures are in the natural range.	Highly sensitive to weather conditions ∴ not very repeatable. In a wind dominated regime - not very good. In a stack dominated regime - much more predictable.
Pressurization test and successive sealing and unsealing	**	*	**	**	*	Controlled conditions. Repeatable, quick, relatively easy.	Result is steady state - ability to predict behaviour under transient pressures doubtful. Induced leakage could be a problem
Alternating pressurization test			**	**	*	Pressures in the natural range	Limited to smaller structures

wind direction were also noted. Where the share of the leakage attributed to a component is of the order of 1% to 2%, therefore, the result must be used with caution.
It should also be noted that flow behaviour under a steady, uniform pressure does not necessarily reflect that under transient pressures produced by the natural wind.

The capabilities, advantages and disadvantages of the above methods are summarised in Table 1.

In order to overcome the disadvantages of low pressure measurements, some workers have resorted to an alternating pressure test using a piston, or more lately bellows, to displace a volume of air. This method is, however, limited to relatively small volume structures, such as single family houses, by the magnitude of the pressure signal which can be achieved and by the mechanical stability of the equipment. The method could be used together with the successive sealing technique for component leakage measurement but, so far, only the results of whole house measurements have been received. (45, 46)

8 Theoretical modelling of leakage distribution

Johnny Kronvall (47) has devised a program for modelling flow through complex building elements such as the floor- wall joints, or the interaction of joists with their supporting masonry. The model was used to simulate the effect of combining leakages of different sizes. He concluded that the larger leakages dominate, and that the shape of the flow/pressure curve can provide information on the leakage distribution. This type of model requires exact input information which is not readily available and so is more suitable for detailed academic studies rather than for general application.

9 Simulation of leakage distributions for modelling purposes

For modelling purposes, attempts have been made to simulate leakage distributions by summing the contribution from the various components in the form of their equivalent leakage areas. The equivalent leakage area is defined as the area of an orifice which would pass the same airflow as the leakage path at a given reference pressure. This reference pressure is 4Pa in the United States, and 10Pa in Canada. (48, 30, 49) The usefulness of this approach hinges on whether the leakages can be considered as simply additive. There is some doubt of the validity of this approach since it does not allow for the variation of leakage distribution with pressure that occurs when there are leakages with widely differing values of flow exponent. (e.g. AIC MVDS NL1 in Table A.2)(14)

10 Performance in practice

The principal question one must ask of a method of measuring or simulating leakage distributions is whether it is able to predict air

TABLE 2A: Key to assumed leakage distribution

Variation	Assumed leakage distribution
No.1	Leakage of each building element is distributed according to the measured result (Table 1). Other obscure leakages are uniformly distributed over the envelope
No.2	Same as No.1 but the flow component n at each building element is equal to that for a whole house.
No.3	Same as No.2 but other obscure leaks are uniformly distributed along ceiling/wall and wall/wall interfaces.
No.4	The total leakage is distributed over the envelope (House C has no leakage in the floor).
No.5	Total leakage is concentrated at the entrance and the windows.
No.6	As No.1 but residue distributed in proportion to measured component leakages

TABLE 2B: Comparison of calculated *vs* measured air infiltration for 3 test structures in Japan (#NO 1598)

Calculation	Variation of leakage distribution	The ratio of the standard deviation of error to the average of measured values		
		House A	House B	House C
LBL model	Uniform distribution	0.795	0.907	0.391
	Measurement	1.116	0.918	0.568
BRE model	Uniform distribution	0.223	0.416	0.167
	Measurement	0.581	0.470	0.243
JCV model	No.1	0.745	0.484	0.230
	No.2	0.622	0.467	0.215
	No.3	0.539	0.454	0.203
	No.4	0.223	0.418	0.165
	No.5	0.802	0.380	0.370

TABLE 2C: Comparison of calculated *vs* measured air infiltration. Summary of results of AIC model validation exercise (AIC Technical Note No.11)

		% number of calculations within 25% of measurement		
Model (C_p set)	Assumed leakage distribution	Swiss data set	Canadian data set	United Kingdom data set
1. BSRIA	2 (+ eaves)	100	49	-
	4	100	63[1]	80[2]
2. NRC[3] (BS 5925)	4	100	49	-
NRC[4] (NRC)	4	56	86	87
3. IMG-TNO (measured ΔP)	2	83	-	-
4. British Gas[6]	6	-	78	67
British Gas[7] (with turbulence)	6	-	76	80
5. NBRI	4	83	78	-
6. IGT	4	100	76	67
7. LBL	4	100	81	80
8. BRE	4	89	73	87
9. Reeves et al[8]	4	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.

flow rates which compare favourably with reality. The answer to this question will depend on the proportion which appears as background leakage. Yoshino et al (36) compared the performance of three single cell models, - the LBL model, the BRE model and the JCV model. They used different leakage distributions, with field infiltration measurements on three test structures. A summary of their findings is given in Table 2b. They draw attention to an interesting point that, for these single cell models, the assumption of a uniform leakage distribution appears to give the best results.
Some results of the Air Infiltration Centre's model validation exercise, which included multi cell models, are given in Table 2c.

While the results appear to be good for single cell models, and for whole house ventilation rates with multi cell models, the results of calculated air flow rates for individual rooms are less good (50, 51), probably arising from a failure to take proper account of transient wind pressures arising from the approaching wind and eddy shedding by the building itself.

11 Conclusion

The spread of leakage within any set of nominally identical houses, or components, is large. The best one can hope for, therefore, is to be able to supply a band of leakage values encompassing the range encountered in the field.
The most important features of the leakage distribution are the relative magnitude and location of the largest leakages, and the proportion of background leakage arising from the exposed wall area.
For the calculation of the ventilation rates of individual rooms there is some advantage to be gained by determining how the response to transient pressures differs from that in a steady state pressurisation test.

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Appendix

Key to tables:-

Building type:- Apt.= apartment, Mus = Museum, Sch.= School, Rnch.= Ranch.
House types :- 1S = 1 storey, 2S= 2 storey etc., Bi = Bilevel, Tri = Trilevel,
4L = 4 level.
Suffixes, A = built on grade, B = basement, C = crawlspace,
mt = mid terrace, et = end terrace, semi = semi detached, dt = detached
qd = quad, ms = maisonette, exptl = experimental, Fac. = facade.

Wall construction :- A = Asbestos, B = Brick, C = Concrete, F = Fibreboard,
I = Insulation, P = Plaster, S = Stone, ST = Stainless steel
M = Aluminium, W = wood.
Suffixes :- st = stucco, sh = shingles, si = siding, cl = cellular, bl=block
b = board, v = veneer.

Window construction :- W = Wood frame, etc (materials code as for walls)
Acst. = acoustic window
Suffixes:- sl = sliders, h = horizontal, v = vertical, c = casement,
dh = double hung, hp = horizontally pivoted.
1g = single glazed, 2g = double glazed, 3g = triple glazed.

Table A.1 Whole Buildings

Art.	Typ	Wall	Wndw	Af m2(ft2)	V m3(ft3)	A m2(ft2)	Cond	Total(unt) dm3/s	Component (%age)
(39)	1SB	Bvst	Whsl	77.1 (830)	379 (13400)	... (...)	75Pa	547.4	Ceiling (65), Outside Walls (15), Windows and Doors (20)
	1SB	Bvst	Whsl	77.1 (830)	379 (13400)	... (...)	75Pa	519.1	Ceiling (67), Outside Walls (21), Windows and Doors (22)
	1SB	Bv	Wdh	99.4 (1070)	487 (17200)	... (...)	75Pa	1137	Ceiling (16), Outside Walls (65), Windows and doors (19)
	1SB	Bv	Wdh	89.2(960)	436 (15400)	... (...)	75Pa	1236	Ceiling (34), Outside Walls (42), Windows and doors (24)
	2SB	BvAsh	Wdh	107.8(1160)	411 (14500)	... (...)	75Pa	1024	Ceiling (8), Outside Walls (77), Windows and doors (24)
	2SB	BvMsi	Whsl	128.2(1380)	471 (16640)	... (...)	75Pa	1104	Ceiling (11), Outside Walls (66), Windows and doors (22)
(38)	Sch.	CclP	Ms12g	2694(29000)	11495(406000)	1175(12651)	50Pa	7880	HVAC (42.9), Walls (44.2), Openable Windows (3.6), Doors (9.1)
	Sch.	BICbl	Ms12g	1858(20000)	7361(260000)	1136(12234)	50Pa	5340	HVAC (24.2), Walls-Openable Windows-Doors (75.8)
	Sch.	BICbl	Ms2g	2620(28200)	9980(352500)	1241(13357)	50Pa	10600	HVAC (29.2), Walls-Openable Windows-Doors (70.8)
	Sch.	CIcl	Ms2g	3003(32331)	11900(420303)	1365(14695)	50Pa	9150	HVAC (15.7), Walls (80.8), Openable windows (0), Doors (3.5)
(52)	= (39)	House No's 1 and 3							
(42)	50 homes of various designs			max 300(3220)			62.2Pa	3209	Soleplate (24.6), Electrical Outlets (20.3), Exterior Windows (11.8), Recessed Spotlights (5.2)
				avg 165(1780)			.25"st	1207	Bath Vent (1.3), Sliding Glass Door (1.7), Fireplace (5.5), Dryer vent (2.8), Range Vent (5.2), Duct System (13.5)
				min 100(1072)				377.5	Exterior Door (4.6) = 37% via weatherstrip, 9% via threshold, 54% wall-frame joint Other (3.5)(probably chimney-wall joint)
(see also (53))									

(6)	1SC CIC Wclg 92.0 6 identical houses	228.4	50Pa	722	Windows and Doors (27.3), Ventilation shafts (15.7), Plasterboard ceiling joints (10.0) Loft trap door (4.6), Crawlspace hatch (5.4), Other (37)
(37)	2S semi		50Pa	833	Windows and back door (40), Other (60) (blower door replaces front door)
	2SC exptl. dbl door		50Pa	1000	Windows and back door (1.4), Suspended floor (32), Stack pipe casing (9.4), Other (57.2) (blower door replaces front door)
(10)	see (37)				
(17)	Rnch	210(7410)	25 Pa	613	Background (55.4),Caulkable leakage (44.6) (see items marked with a * in Table (A.4))
	Rnch	342(12060)	25 Pa	665	Background (66.9),Caulkable leakage (33.1)
	Rnch	223(7888)	25 Pa	451	Background (52.5),Caulkable leakage (47.5)
	Rnch	217(7670)	25 Pa	481	Background (67.5),Caulkable leakage (32.5)
	Rnch	236(8327)	25 Pa	439	Background (<39),Caulkable leakage (>61)
	Rnch	429(15150)	25 Pa	453	Background (<52.1), Caulkable leakage (>47.9)
	Rnch	233(8235)	25 Pa	821	Background (82.2),Caulkable leakage (17.8)
	Rnch	212(7482)	25 Pa	613	Background (54.5),Caulkable leakage (45.5)
	Rnch	258(9108)	25 Pa	<163	Caulking increased the leakage.
	Rnch	357(12600)	25 Pa	341	No change after caulking leakage
	Rnch	318(11220)	25 Pa	609	Background (39.2),Caulkable leakage (60.8)
	Rnch	319(11270)	25 Pa	585	Background (77.3),Caulkable leakage (22.7)
	Rnch	317(11200)	25 Pa	594	Background (76.1),Caulkable leakage (23.9)
	Rnch	375(13230)	25 Pa	344	Background (<64.2), Caulkable leakage (>35.8)
	Rnch	509(17960)	25 Pa	<339	No change after caulking leakage
	Bi	227(8030)	25 Pa	1090	Background (95.2), Caulkable leakage (4.8) (Furnace vent open)
	Bi	303(10700)	25 Pa	642	Background (82.4),Caulkable leakage (17.6)
	Bi	371(13110)	25 Pa	<339	Background (70.0),Caulkable leakage (30.0)
	Bi	354(12480)	25 Pa	314	Background (75.2),Caulkable leakage (24.8)
	Tri	379(13400)	25 Pa	562	Background (61.8),Caulkable leakage (39.2)
	Tri	404(14250)	25 Pa	467	Background (71.6),Caulkable leakage (28.3)
	Tri	372(13150)	25 Pa	845	Background (73.7),Caulkable leakage (26.3)
	Tri	415(14640)	25 Pa	680	Background (<34.7), Caulkable leakage (>65.3)

(17)	Tri		382(13490)		25 Pa	680	Background (88.9),Caulkable leakages (11.1)
	Tri		445(15710)		25 Pa	887	Background (75.6),Caulkable leakages (24.4)
	Tri		295(10410)		25 Pa	680	Background (35.2),Caulkable leakages (>64.8)
	2S		257(9067)		25 Pa	736	Background (61.9),Caulkable leakages (39.1)
	2S		434(15310)		25 Pa	986	Background (79.4),Caulkable leakages (20.6)
	2S		304(10730)		25 Pa	779	Background (91.7),Caulkable leakages (8.3)
(40)	1SMH MI	51.3(552)	109.3(3860)	126.7(1364)	50 Pa	481	Bathroom ventilation fan (14), Between ceiling and flue vent (8), Lower hinge side of rear entrance door (<1) Two plumbing holes through floor (4), Wall heater (3), All exterior electrical outlets and switches (<2) Window/inside panel joints (18), Front base of furnace (1), Paneling side joints (8), Wall ceiling joints (14), Furnace room door (<1)
(15)	2S				tracer		40-80% through loft with wind normal to the roof ridge.
	4 bed detached house				gas		50-70% with the wind normal to the gable.
	2S				tracer		Leakage through loft 60% to 95%.
	mid terrace house				gas		With 2 upper windows open, loft leakage = 35%
(54)	2S				tracer)		Windows (8.9)
	2S				gas)		Windows (32.9)
(32)	2SC 8Pb Mhp		200		ELA	0.130m2	Kitchen dining room (27.4), Lounge (9.3), Hall and landing (13.1), W.C.(7.7), Bathroom (10.8), Bedroom 1 (8.5), Bedroom 2 (7.7), Bedroom 3 (7.7), Under stairs (3.8), Other windows (3.1)

(55)	2SA BFIPb Wdhlg gable MFIPb	113(1212)	275(9700)		tracer+presstests		
					.12"wg	757	Exterior Wall (27.9)
					.12"wg	781	Ceiling (12.3)
					.13"wg	769	Party wall (4.5)
					.110"wg	793	Windows and doors (4.5)
					.065"wg	756	Electrical outlets - exterior walls (3.1)
					.13"wg	852	Electrical outlets - party walls (1.3)
					.065"wg	878	Floor-wall interface (23.1)
							Other (incl. ceiling wall interface) (23.3) With furnace on 50% duty cycle:- Blower and burner of furnace (30), Walls and Ceilings (31), Windows, doors and electrical outlets (6).
(7)	2Semi		197	186	50 Pa	642	Background (64)
	2Semi		254	185	50 Pa	613	Background (52)
	2Semi		249	175	50 Pa	808	Background (64)
	2Set		196	133	50 Pa	858	Background (67)
	2Set		196	133	50 Pa	781	Background (69)
	2Smt		164	100	50 Pa	614	Background (42)
	2Smt		200	108	50 Pa	678	Background (57)
	2Smt		77	33	50 Pa	369	Background (60)
	2Smt		179	127	50 Pa	489	Background (72)
	2Set		196	131	50 Pa	1147	Background (72)

Seasonal variation of leakage for this house which was unoccupied. (* = heating season):-

	May '78 *				50 Pa	883	Front Door (4.5), Windows (20.0), Other (75.5)
	Oct '78				50 Pa	789	Front Door (4.2), Windows (21.8), Other (74.0)
	Dec '78 *				50 Pa	997	Front Door (3.3), Windows (16.7), Other (80.0)
	Feb '79 *				50 Pa	1133	Front Door (3.2), Windows (14.3), Other (82.5)
	Mar '79 *				50 Pa	1014	Front Door (3.3), Windows (17.2), Other (79.5)
	Apr '79 *				50 Pa	978	Front Door (3.4), Windows (18.7), Other (77.9)
	Jul '79				50 Pa	811	Front Door (7.5), Windows (18.2), Other (74.3)
	Oct '79				50 Pa	856	Front Door (5.2), Windows (20.4), Other (74.4)
	2Semi		261	170	50 Pa	1051	Background (69)
	2Semi		261	170	50 Pa	1108	Background (67)
	2Set		247	215	50 Pa	992	Background (76)
	2Sms		169	97	50 Pa	450	Background (57)
	2Sqd		179	87	50 Pa	944	Background (54), Doors and windows (46)
					5 Pa		Doors and windows (73)

(7)	2Smt		220	99	50 Pa	900	Background (56) Windows and W.C.fan (29), Back door (8.7), Service penetrations (2.6), Skirting boards (17.8), Other (41.9)
	2Set		221	134	50 Pa	642	Background (70)
(35)	2SC BP				1 Pa	125	Facades (10), Ducts (27), Roof-wall joint (42), Unidentified (21)
	2SC BP				1 Pa	140	Facades (25), Ducts (27), Roof-wall joint (43), Unidentified (5)
(56)	Survey						Soleplate (60), Window and door perimeters (20), Ceiling-attic penetrations (20)
(1)	4LAt BCIPb W		160		20 Pa	520	Before alteration:- Stairs and landing (36), Bedroom 2 (3), Bedroom 3 (4), Living room (5), Toilet (7), Kitchen (7), Bedroom 1 (10), Hall (12), Bathroom (16)
	4LAt BCIPb W		160		20 Pa	470	Strip vents fitted, joints taped, hall door weatherstripped:- Stairs and landing (36), Bedroom 2 (4), Bedroom 3 (5), Living room (7), Toilet (4), Kitchen (11), Bedroom 1 (14), Hall (9.5), Bathroom (9.5)
(see also (2))							
(57)	2SCmt B2P Wclg	85.4	315	Facd. 67	...	1000cm2	Vent. ducts (27.2), Roof (42.4), Facades (10.0), Other (20.4)
(2)	4LAt BCIPb W		160		50 Pa	440	Windows and back door (11), Skirting boards (24), Loft hatch and letterbox (5), Remainder (60)

(2) (see also (1))							(20 Pa) (50 Pa)		Increase in overall leakage when trickle vents are open. House 1 (+5.5)(+21.2) House 2 (+4.3)(+11.4) House 4 (+4.5)(+2.5) House 5 (+6.3)(+7.4) House 6 (+8.0)(+6.8) House 13 (+10.3)(+6.4) House 14 (+15.8)(+4.3) House 19 (+13.9)(+11.6) House 20 (5.4)(+9.9)
(58)	2SC 2SC 2SC 2SC	CPb CPb CPb CPb	Whplg Whplg Whplg Whplg	100 100 100 100	230.85 230.85 230.85 230.85	e.t.133.35 m.t. 79.65 dt1:163.22 dt2:194.62	50 Pa 50 Pa 50 Pa 50 Pa	1266 1242 1288 1408	Crawlspace ventilators + floorboards (25) Crawlspace ventilators + floorboards (25) Crawlspace ventilators + floorboards (40) Crawlspace ventilators + floorboards (40)
(31)	SB,SC	var	Wdh	var	var	var	SLA ELA 4Pa SLA	10-18cm2/m2 avge800 cm2 2.3-13 cm2/m2	8 Atlanta houses: Ducts (25) 10 San Francisco Bay, 16 Reno Nevada: with dampers:- a) Ductwork (13), Electric gaskets (1), Fireplace (without insert) (9), Kitchen vents (1), Bathroom vents (2), Other (74) b) Ductwork (13), Electric gaskets (1), Fireplace (24), Kitchen exhaust vents (6), Bathroom exhaust vents (3), Other (53)
(20)	2S 1.5S			17 21			50 Pa 50 Pa	83 194	Windows (14) Windows (7)
(59)	2S (15 yr old detached house)						20 Pa	930	By component:- Suspended floor (12.3), Walls (42.7), Loft (13.5), Other (31.4) By room:- Kitchen (16.6), Bedroom 1 (11.3), Bedroom 2 (10.8), Lounge (8.8), Bedroom 3 (8.7), Bedroom 4 (6), Bathroom (5.3), W.C.(<1), Hall, stairs and landing (31.4)

(5)	40hs var.	100		Aeq	0.11 m2	Brick chimney and open fireplace (19), Openable windows and doors (17), Electrical switchboard detail (1 case)(8), 100 mm flue and free standing fireplace with all dampers open (7), Bath toe space detail (avge of 3 cases)(6)
	Houses over 5 years old:-					Openable windows and doors (23)
(8)	2Set	93.0		10 Pa	485 cm2	Background (25.9), Electrical outlets (1.9), Ventilation inlet (2.4), Inspection hatch in closet ceiling (4.5), Windows (25.4), Entrance door (0), Vent in entrance door (39.9)
(30)	19 houses var. with fireplace			4 Pa	ELA	Sill plate and wall-ceiling joint (31), H.V.A.C. Systems (15), Fireplace (14), Vents (4), Pipes (13), Doors (11), Electrical outlets (2), Windows (10)
	11 houses without fireplace			4 Pa	ELA	Sill plate and wall ceiling joint (42), H.V.A.C. Systems, Vents (5), Pipes (12), Doors (10), Windows (14), Electrical outlets (4)
(33)	Bi		328 (11600)	4 Pa	712 cm2	Attic (15.7), Interior wall leaks to attic (3.8), Basement/Exterior (8.2), Basement/Garage (19.6), Other (52.7)
	Same house			50 Pa	10.1 ach	Attic (12.7) Interior wall leaks to attic (5), Basement/Exterior (8.6), Basement/Garage (12.9), Other (60.8)

(60)	1 house tested 3 times (for reproducibility)								Cracks + openable windows and doors (36.5 to 37) Shower vent and fireplace flue (6.6 to 8)
(34)							50 Pa	ELA	Walls (18 to 50) avg.(35) Ceilings (3 to 30) avg.(18) Heating System (3 to 28) avg. (15) Windows/ Doors (6 to 22) avg.(15) Fireplaces (0 to 30) avg.(12) Vents (2 to 12) avg.(5)
(61)	var. var.								12 facades, measures proportion of leakage due to gaps and joints.
(62)	Mus. S		W3g		10300				Wooden roof (70) (with exhaust fan in use) Windows (5 to 10)
(9)	var.								Surveys 200 houses across Canada. gives C, n, Q50 and ELA for houses with and without chimneys and ducts sealed.
(36)	1SC	W	W1g	23.7	60.0	...	1 Pa (5 Pa) {50 Pa}	73.0 228.6 1198.	Entrance (20.7){22.0}, Eastern window (5.56){9.9}, Western window (40.1){38.3}, Other (33.7){29.9} (inc.Ceiling-wall) S.window + floor-wall joint sealed
	1SC	W	W1g	23.7	60.0	...	1 Pa (5 Pa) {50 Pa}	77.8 232.4 1213.	Entrance (23.8){30.5}, Western window (17.5){25.8}, Floor-wall joint (25.5){16.1}, Other (33.2){27.6} (inc. Ceiling-wall) E. and S. windows sealed.

(36)	1SA	W	Wlg	23.7	60.0	...	1 Pa (5 Pa) (50 Pa)	140.4 460.3 2713.	Entrance (19.7){27.6}, Eastern window (6.54){9.35}, Southern window (15.6){15.8}, Western window (28.1){18.9}, Floor-wall joint (3.18){1.58}, Ceiling-wall joint (9.84){11.0}, Other (17.0){15.7} no sealed elements.
AIC MVDS	2SCmt	B2P	Wlg	122	310	Facd. 57.5	(1 Pa) (50Pa)	133 1235	NL2, Maasland, from C & n values. a) by component group:- Facades inc. Windows (28.2){29.8}, Vent shafts (20.6){21.4}, Crawlspace (2.3){2.5}, Attic window and roof (48.8){46.2} b) by room calc. from given C & n values Attic (48.8){46.2}, Living room and Kitchen including crawlspace (21.4){20.6}, Bedroom 1 (3.61){3.88}, Bedroom 2 (2.55){3.17}, Bedroom 3 (0.68){1.48}, Bathroom (16.2){18.0}, W.C. (2.18){2.34} , Hall inc. front door (4.51){4.27}
AIC MVDS	2SCmt	B2P	Wclg	85.4	315	Facd. 67	... (1 Pa) (50 Pa)	1000cm2 98.77 920.2	NL3, Schipluiden, see (57) NL3, Schipluiden, a) by component group, Facades inc. Windows (12.5){15.3}, Vent shafts (23.7){16.3}, Roof and boiler flue (63.8){68.4} b) by room calc. from given C & n values Loft (63.8){68.4}, Living room (1.65){3.46}, Bedroom 1 (2.02){1.91}, Bedroom 2 (1.82){2.65}, Bedroom 3 (2.63){3.83}, Bathroom (6.72){5.63}, Kitchen (10.9){8.3}, W.C. (8.91){4.57}, Front door (1.52){1.28}

Note:- AIC MVDS = Air Infiltration Centre Model Validation Data Set
This data was accumulated by the AIC for the model validation exercise.
Data from 14 houses was made available to participants. The remainder
of the data is largely unpublished for access to which requires the
owners' permission.

Table A.2 Apartments, flats and rooms

Art.	Typ	Wall	Wndw	Af m2(ft2)	V m3(ft3)	A m2(ft2)	Cond	Total(unt) dm3/s	Component (%age)
(25)	Cellar				30.03			5.8 =0.7 ach	Large openings (11.7)
								8.0 = 0.95 ach	Large openings (13.7)
								8.5 =1.01 ach	Large openings (17.6)
(41)	4S				252 (8900)		75Pa	720 per m2	3rd floor apartment: Windows+ 1 door+1 fireplace (12 to 18%)
(7)	1Apt				148	84	50 Pa	375	Background (48)
(35)		C					1 Pa	22	Facades (42), Ducts (58)
		C					1 Pa	25	Facades (17), Ducts (76), Unidentified (7)
(8)	3S end flat		Acst. wndw.	67.0			10 Pa	163. cm2	Background (24.6), Electrical outlets (2.9), Vent.inlet in kitchen (2.9), Windows (11.3), Front Door (23.2), Vent inlet in bathroom (8.5), Kitchen fan (20.8), Bathroom outlet (5.9)
	1S end flat			73.6			10 Pa	277. cm2	Background (10.1), Electrical outlets (0.3), Windows (33.2), Entrance door (38.3), Kitchen fan (13), Vent. outlet in bathroom (5.1)

(63)	room 1						100 Pa	.429ach	Windows (32.3), Skirting board (29.6) Doors (17.7), Electrical outlets (12.5) "curtains" (1.3), Remainder (6.8)
	room 2						100 Pa	.386ach	Skirting boards (40.3), Windows (20), Doors (15.4), "curtains" (6.8), Electrical outlets (5.4), Drainage pipes (1.5), (Missing label (9)), Remainder (1.5)
	avge of rooms						tracer gas		Components (27), Background (73)
AIC MVDS	5S	CW	Wlg	96	250	...	(1 Pa) (50 Pa)	23.1 218	NL1, Delft, a) by component group, Facades inc. Windows (16.0){22.4}, Vent shafts (81.8){74.9}, Front door (2.2){2.64} b) by room calc. from given C & n values Bathroom (21.2){22.4}, Living room (6.06){8.7}, Bedroom 1 (0.87){1.24} Bedroom 2 (0.87){1.24}, Bedroom 3 (2.6){3.17}, Bedroom 4 (4.3){5.28} Kitchen (39.4){34.4}, W.C. (22.5){20.9}, Hallway (outer) (2.16){2.64}

Table A.3 Parts of Buildings

	Description			Cond.	Tot.Flow dm3/s.m2	Component (%)
(64)	Fac. CPb ...			200Pa	1.39	Horiz.joints (50), Crossover joints panel-window (50)
	Fac. WFsiPb			200Pa	4.17	Horizontal joint to floor-ceiling (80), Window-wall (20)
	" inc bottom joint			200Pa	8.33	Horizontal joint to floor-ceiling (30), Window-wall (10), Bottom horizontal panel joint (60)
	Fac. MsiI			200Pa	12.5	5 vertical joints between panels (45), Top and bottom horizontal joints (35), side joints to other walling (20)
	Fac. STIPb			200Pa	13.89	Top and bottom horizontal joints (80), Vertical joints between wall lining panels (20)
(26)	5S BCIvPb (Wall)			75 Pa	2.6	(whole building) Floor-wall joint and window sill (35), window and window frame-wall joint (65)
	10S CIPb (Wall 1)			75 Pa	1.53	Floor-wall joint and window sill (78), window and window frame-wall joint (22)
	(Wall 2)					Floor-wall joint (50), window sill (10), window (39), window frame-wall joint (1)
	20S BIvPb (Wall)			75 Pa	...	Floor-wall joint (51), window sill (28), window (11), window frame-wall joint (10)
	15S CIvPb (Wall)			75 Pa	...	Floor-wall joint and window sill (39), window and window frame-wall joint (61)
	12S CIvPb (Wall 1)			75 Pa	...	Floor-wall joint and window sill (29), window and window frame-wall joint (71)
	(Wall 2)			75 Pa	...	Floor-wall joint and window sill (38), window and window frame-wall joint (62)
(65)	Wall B	200	30 (wall)	200 Pa	1.28	Vertical joints (43), Horizontal joints (36), Bricks (21)

Table A.4 Frequency of Occurrence of Leakage Locations

(17)
a) For a survey of 29 houses around Denver, Colorado, the following leakages were detected: -

Paths or Locations of Leakages	No. of Houses (%)
Bottom of drywall	29 (100)
Window fit including sill	25 (86)*
Plumbing fixtures, inside and outside walls	23 (79)*
Electric fixtures including medicine cabinet	22 (76)*
Bathroom vent	17 (59)*
Outside door fit	16 (55)
Access to attic space	15 (52)*
Basement door fit	14 (48)
Fireplace fit	13 (45)*
Stair steps and risers over unheated space	13 (45)*
Garage door fit	11 (38)
Clothes dryer vent	10 (34)
Garage-house connection	9 (31)
Fireplace damper	8 (28)
Heating ducts	7 (24)
Bathtub fit	7 (24)
Kitchen fan vent	7 (24)*
Closet door trim	5 (17)
In-wall air conditioner	5 (17)*
Sill plate	5 (17)*
Door to unheated storage	4 (14)
Door bell	4 (14)
Smoke alarm	4 (14)
Crawl space opening	4 (14)*
Baseboard heater	4 (14)*
Crawl space vent	4 (14)
Shower stall fit	4 (14)
Closet door runners	3 (10)
Kitchen cabinets, behind or on top	3 (10)
Philips control box	3 (10)
Sewer pipe penetration	2 (7)
Wood panelling on studs or furring	2 (7)
Intercom	2 (7)
Cellar floor drain	2 (7)
Toilet paper holder	2 (7)
Construction discontinuities	2 (7)
Telephone cord	2 (7)
Abandoned furnace flue	1 (3)
Soil pipe to basement	1 (3)
Bathroom cabinets, behind	1 (3)
Door latch	1 (3)
Sky light	1 (3)
Masonry seems porous	1 (3)
False ceiling beam	1 (3)
Stove damper	1 (3)

* = caulked when detected during retrofit

(18) Finnish data set
b) Survey of 35 buildings of assorted style (paper in Finnish- translation to be checked)

Paths or Locations of Leakages	No. of Observation
Ceiling-wall joint	29
Electrical penetrations	20
Corners of the building	17
Windows	15
Floor-wall joint	12
Ventilation shutters	9
Smoke stack-ceiling joint	9
Wall "seams"	8
Stove ventilation duct-ceiling joint	8
Valves/devices etc.	7
Walls (apart from the "seams"	5
Doors	4

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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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