INTERNATIONAL ENERGY AGENCY
energy conservation in buildings and
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5th AIC Conference

The implementation and effectiveness of air infiltration standards in buildings

Proceedings

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Annex V Air Infiltration Centre

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The implementation and effectiveness of air infiltration standards in buildings

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Proceedings

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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.

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

THE IMPLEMENTATION AND EFFECTIVENESS OF AIR INFILTRATION STANDARDS IN BUILDINGS

5th AIC Conference, October 1-4 1984, Reno, Nevada, USA

PAPER 1

REVIEW OF BUILDING AIRTIGHTNESS AND VENTILATION STANDARDS

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SYNOPSIS

Increased attention to the reduction of energy consumption in buildings and greater awareness of the need to maintain acceptable standards of indoor air quality have led to the development of new or revised standards of building airtightness and ventilation requirements. In this review of the existing standards of twelve countries, an attempt has been made to compare their main features and criteria. In many cases, direct comparison is not possible because of different ways of expressing the significant parameters. However, where comparison is possible, some differences between countries are evident. Recognition and further consideration of these differences may be important in the further development of relevant national and international standards.

1. INTRODUCTION

The design and construction of buildings are governed by a broad range of standards, regulations, codes of practice and legal requirements to ensure that conditions for safety, health and well-being are maintained. In some countries standards are applied on a national basis, in others the primary enforcement is through regional or local codes with, sometimes, significant variations from place to place.

The requirement for reduced energy consumption in buildings, has resulted in new or more stringent standards covering many of the features which affect the efficient provision of an acceptable internal environment. Of these features, the ability of the structure to resist the leakage of air to and from outdoors is becoming recognised as one of increasing importance. In this respect, the lead has been taken by those countries which have the more severe climates and have been particularly vulnerable to the effects of increase in the price of oil. In others, airtightness standards have recently been, or are currently being, developed.

The specification of particular airtightness qualities requires the formulation of suitable test methods to enable the leakage characteristics of component, assemblies and whole buildings to be measured. Standard methods for testing the air leakage of windows have been in existence for many years, but more recently new standards have been developed for measuring the leakage of other components and, in two Scandinavian countries, of complete buildings. Further progress on the standardisation of measurement techniques is continuing.

While it is important to minimise extraneous air leakage, it is of paramount importance to maintain acceptable indoor air quality. For this, minimum ventilation rates have been specified for various types of building and occupancy. Recent concern about the over-tightening of naturally ventilated buildings and the current re-assessment of the basis of the early standards of ventilation, is leading to new appraisals of the ventilation rates appropriate to modern buildings and lifestyles.

As a background to consideration of these developments, this paper reviews the existing standards of the eleven countries participating in the Air Infiltration Centre. In addition, relevant standards from West Germany, the European Committee for Standardisation and the International Standards Organisation have been included as these are used as the basis for standards in other countries.

The main emphasis has been on mandatory standards, although it has not always been easy to distinguish between those which are legal directives, models for locally enforced codes or mere recommendations. At the commencement of each section is a list of those standards included in this review. Although the review has been made as extensive as possible, there is no claim that it is totally comprehensive.

2. AIRTIGHTNESS REQUIREMENTS

Belgium:	*STS 52.0* *External joinery - general principles* *INL Draft 1983*
Canada:	*Measures for energy conservation in new buildings* *Associate Committee on the National Building Code* *National Research Council of Canada, No. 16574, Ottawa, 1978*
Netherlands:	*NEN 3661* *Windows: Air permeability, water tightness, rigidity and strength* *Requirements* *Netherlands Standards Institute (NNI), 1975*
New Zealand:	*NZS 4211:1979* *Specification for performance of windows* *Standards Association of New Zealand, 1979*
Norway:	*Chapter 54. Thermal insulation and airtightness (revised 1980)* *Building Regulations of 1st August 1969* *Royal Ministry of Local Government and Labour*
Sweden:	*Chapter 33. SBN 1980. Thermal insulation and airtightness* *Swedish Building Code with Comments* *National Swedish Board of Physical Planning and Building (1981)*
	SIS 81 81 03 *Windows. Classification with regard to function* *Swedish Standards Commission, 1977*
Switzerland:	*SIA 180/1* *Thermal insulation of buildings in winter* *Swiss Engineering and Architectural Association, 1980*
United Kingdom	*BS 6375:Part 1:1983* *Performance of windows. Part 1: Classification for weathertightness* *British Standards Institution, 1983*

United States of America: *ASHRAE Standard 90-80*
Energy conservation in new building design
The American Society of Heating, Refrigerating and Air-conditioning Engineers Inc., 1980

West Germany: *DIN 18055*
Windows: Air permeability of joints and driving rain (water tightness) protection. Requirements and testing
German Standards Institute (DIN), 1981

2.1 Whole Building

Currently Norway and Sweden are the only countries that have recommendations for the airtightness of whole buildings. As described in other papers presented at this Conference, there are proposals being discussed in Canada and USA on this subject.

Tabulated summaries of the Norwegian and Swedish requirements are given below:

Norwegian Building Regulations	
Building type	Airchange rate/hr at 50 Pa
Single family dwellings	4
Buildings up to 2 floors	3
Buildings exceeding 2 floors	1.5

Swedish Building Code	
Building type	Airchange rate/hr at 50 Pa
Freestanding single-family houses and linked houses	3
Other residential buildings of not more than 2 storeys	2
Residential buildings of 3 or more storeys	1

The Swedish specifications are the more stringent.

2.2 Windows

The standards of several countries specify the maximum allowable leakage of windows with some grading according to application. In others, a leakage classification system is detailed but with no reference to acceptability for particular uses.

The following list summarises the requirements or classifications given in the relevant standards.

Belgium: Standard STS 52.0

Maximum rate of leakage at 100 Pa for different grades of window

	Window classification		
	PA2	PA2B	PA3
Exposure level - height of building in which window is situated (m)	0-10	10-18	>18
Air leakage m^3/h per metre	6	3	2
(dm^3/s m)	(1.67)	(0.83)	(0.56)

Canada: Measures for energy conservation in new buildings

Air leakage of windows is not to exceed 0.775 dm^3/s per metre of joint at a 75 Pa pressure differential.

Netherlands: Standard NEN 3661

Test pressures for different window categories for which air leakage must not exceed 5 dm^3/s m.

Height of building in which window is situated (m)	Exposure	Pressure difference Pa
15	Normal	150
40	"	200
100	"	250
15	Coast	300
40	"	350
100	"	400

New Zealand: Standard NZS 4211

The rate of leakage at all test pressure differences up to 150 Pa shall not exceed those in the Table below.

Grade	dm^3/s per m of opening joint	dm^3/s per m^2 of total window area
A	0.6	2
B	2.0	8
C	4.0	17

Norway: Norwegian Building Regulations - Chapter 54

Windows shall be sufficiently airtight so that air leakage at a pressure difference of 50 Pa does not exceed 1.7 $m^3/h\ m^2$ (0.47 $dm^3/s\ m^2$)

Sweden: Standard SBN 1980

The maximum air leakage of windows is specified as follows:

Pressure difference Pa	Leakage rate $m^3/h\ m^2$ ($dm^3/s\ m^2$) for windows in building height (number of floors)		
	1 - 2	3 - 8	>8
50	1.7 (0.47)	1.7 (0.47)	1.7 (0.47)
300	5.6 (1.56)	5.6 (1.56)	5.6 (1.56)
500	-	-	7.9 (2.19)

Standard SIS 81 81 03 (1977)

Windows are classified as A, B or C and the permissible air leakage (q) for windows in each class is determined by the equation:

$$q = kp^{2/3}$$

where q = air leakage in m^3/h per m^2 of window area.
k = a coefficient (0.2 for Class A and 0.125 for classes B and C).
p = pressure difference in Pa between inner and outer surfaces of window.

The lines corresponding to these classes have been plotted in Figure 2.

The values quoted above from SBN 1980 coincide with classes B and C.

Switzerland: Standard SIA 180/1

Maximum leakage rates for the various classes of windows

	Class			
	A	B	C	D
Test pressure difference Pa	150	300	600	>600
Height of building m	<8	8-20	20-100	-
Allowable coefficient of air permeability $m^3/h\ m\ Pa^{2/3}$	0.44	0.22	0.22	0.22
($dm^3/s\ m\ Pa^{2/3}$)	(0.12)	(0.06)	(0.06)	(0.06)

UK: Standard BS 6375 Part 1

Four categories are specified with the following test pressure classifications. The acceptable rates of air leakage are expressed graphically and are shown on Figure 1.

Class	Test pressure
I	150
II	200
III	300
IV	600

The standard also specifies that the air leakage through fixed lights shall not exceed 1 m^3/h (0.28 dm^3/s) per metre length of the visible perimeter of the glass when tested at the same pressures as for opening lights.

USA: ASHRAE Standard 90-80

Leakage rate of windows at 75 Pa pressure difference to be no more than 0.77 dm^3/s per metre of sash joint.

West Germany: Standard DIN 18055

The classification of windows is as follows:

	Window classification			
	A	B	C	D
Test pressure (Pa) up to	150	300	600	unspecified
Height of building (m) up to	8	20	100	

The air leakage requirements are presented graphically and these have been reproduced in Figure 1.

Most standards specify the leakages in relation to unit length of the opening joint while a few specify them in terms of unit window area. Thus direct comparison of all the standards is not possible. However, comparison has been made in each of the two forms by plotting the allowable leakage values on Figures 1 and 2 . The plot of leakages expressed per metre of joint length show, surprisingly, that the highest classifications are to be found in countries having relatively mild climates, i.e. Belgium, New Zealand and UK. The high Scandinavian standards are evident in the other figure where they are compared with the New Zealand classifications which are expressed in both forms.

2.3 Doors

Canada: : "Measures for energy conservation in new buildings"

The following maximum air leakage rates at a pressure differential of 75 Pa are specified for doors separating heated spaces from unheated spaces or the exterior:

Manually operated sliding doors	2.5 dm^3/s per m^2 of door area
Swing doors (residential)	6.35 dm^3/s per m^2 of door area
Other types	17.0 dm^3/s per m^2 of door crack

Norway: : Norwegian Building Regulations

External doors are required to comply with the same requirements for airtightness as windows, i.e. 1.7 $m^3/h\ m^2$ (0.47 $dm^3/s\ m^2$).

Sweden: Swedish Building Code SBN 1980

Same classification is given for external doors and windows (see Section 2.2)

USA: ASHRAE Standard 90-80

Maximum air leakage rates at a pressure differential of 75 Pa are specified as follows:

Sliding glass doors (residential)	2.5 dm^3/s per m^2 of door area
Entrance swinging doors (residential)	6.35 dm^3/s per m^2 of door area
Swinging, revolving, sliding doors for other than residential use	17.0 dm^3/s per linear metre of door crack

These criteria are similar to those of Canada.

2.4 Building Sections

Leakage criteria for sections of buildings exposed to outdoors are only found in the following Scandinavian standards.

Norway: Norwegian Building Regulations

The maximum air leakage at a pressure difference of 50 Pa is specified as 0.4 $m^3/h\ m^2$ (0.11 $dm^3/s\ m^2$) for individual external building sections, i.e. external walls, ceilings and floors.

Sweden: Swedish Building Code SBN 1980

The maximum air leakage for various building sections is specified as follows:

	Pressure difference Pa	Maximum air leakage $m^3/h\ m^2$ ($dm^3/s\ m^2$) in building height (number of floors)		
		1-2	3-8	>8
Exposed walls	50	0.4(0.11)	0.2 (0.056)	0.2(0.056)
Roof and joist structures exposed to outdoors next to ventilated space	50	0.2 (0.056)	0.1 (0.028)	0.1(0.028)

3. TECHNIQUES FOR MEASURING AIR LEAKAGE

3.1 Whole Buildings

Canada:	*149-GP-10M* *Determination of airtightness of buildings by the fan depressurization method.* *Canadian General Standards Board. Fifth Draft. March 1983.*
Norway:	*NS 8200* *Airtightness of buildings. Test method.* *Norwegian Building Standard Council, 1981*
Sweden:	*SS 02 15 51* *Thermal insulation - determination of airtightness of buildings.* *Swedish Standards Commission, 1980*
United States of America:	*ASTM E779-81* *Standard practice for measuring air leakage by the fan pressurization method.* *American Society for Testing and Materials, 1981*
	ASTM E741-80 *Standard practice for measuring air leakage rate by the tracer dilution method.* *American Society for Testing and Materials, 1980*

With the exception of ASTM E741-80, these standards describe a basically similar test method involving the generation of measured air flow rates to produce a range of pressure differences between the inside and outside of a building. The Canadian Standard is the most detailed but it is the only one which limits the testing to depressurization; the others specify tests with both negative and positive internal pressures. The Norwegian and Swedish standards are almost identical.

There are no major differences in the specification of the equipment or the instrumentation except in respect of the measurement of external pressure. The Canadian standard specifies at least four pressure taps around the external facade of the building. Each pressure tap is connected to a suitable manifold to enable the measurement of an average pressure value. The two Scandinavian standards specify an external pressure sensing point 10m from the building. The external pressure sensing position is not clearly defined in the USA standard although the diagram of an acceptable test arrangement seems to indicate that a single pressure tap in a door would be sufficient.

The Canadian standard is unique in that it specifies a procedure for verifying the test data. If any one of four conditions is not met then the test is considered invalid.

One of the most significant variations in the prescribed methods is the detail of the preparation required before testing commences. The Canadian procedure is the most detailed as it includes a listing of the preparation required for all of the purpose-provided openings and vents such as fireplaces, exhaust fans, water traps, etc. The two Scandinavian standards specify that all ventilation openings in the enveloping structure should be closed, including openings for mechanical ventilation. The Swedish standard also includes the requirement to ensure that plumbing installations connected to outside air are sealed, e.g. water traps must be filled with water. No specification of preparatory sealing is given in the USA standard (ASTM E779-81). In comparing the results of testing to these standards, it is most important to note the degree of sealing that has been applied.

All of the standards specify the presentation of the test results as a plot of air flow rate against pressure difference. The Swedish standard also recommends the inclusion in the test report of the value of air leakage (expressed in air changes per hour) at 50 Pa pressure differential. The mean of the leakage at +50 Pa and -50 Pa should be quoted. The Norwegian standard similarly requires the leakage at 50 Pa but the value to be quoted is the mean of the values measured at 45, 50 and 55 Pa in both positive and negative modes. The Canadian standard gives a method of calculating the equivalent leakage area and calls for it to be quoted in the test reports.

Summarised below are the comparative specifications of instrumentation precision, test pressure range and limits of the outdoor climate conditions under which tests may be conducted.

Although tracer gas methods have been used in research for many years, only one standard exists on the use of this technique to measure the air leakage of a building. ASTM E741-80 (USA) specifies a procedure in which tracer gas is introduced into the building, is thoroughly mixed with the air within the building, and then sampled over a period of time. Alternative methods for analysing the decay of tracer gas concentration are presented from which the air change rate is determined. Safety precautions are included and an appendix lists the common tracer gases, their main characteristics and the associated methods of detection.

Standard	Precision	Pressure range	Climatic limits
Canada (149-GP-10M)	Flow rate ± 5 % Pressure ± 2 Pa Temperature ± 1 °C	0 to - 50 Pa	Windspeed ⩽ 5.5 m/s
Norway (NS 8200)	Flow rate ± 6 % Pressure ± 2 Pa Overall ± 8 %	0 to ± 55 Pa	Windspeed ⩽ 6 m/s
Sweden (SS 02 15 51)	Flow rate ± 6 % Pressure ± 2.5 Pa Overall ⩽ ± 8 %	0 to ± 55 Pa	Windspeed ⩽ 10 m/s
USA (ASTM E779-81)	Flow rate ± 6 % Pressure ± 2.5 Pa Temperature ± 0.5°C Overall ⩽ ±10 %	0 to ± 75 Pa	Windspeed ⩽ 4.4 m/s Indoor-outdoor temperature difference ⩽ 11°C

3.2 Components

Europe: *EN 42*
Methods of testing windows: air permeability
European Committee for Standardisation

International: *ISO 6613*
Windows and door height windows - air permeability test
International Organisation for Standardisation, 1980

Belgium: *STS 52.0*
External joinery - general principles
INL Draft, 1983

Denmark: *DS/EN 42*
Methods of testing windows - air permeability test
Danish Standard, 1976

Netherlands: *NEN 3660*
Windows. Air permeability, water tightness, rigidity and strength. Methods of test.
Netherlands Standards Institute (NNI), 1975

Norway: *NS 3206*
Methods of testing windows. Air tightness.
Norwegian Standards Institute (NBF), 1974

New Zealand: *NZS 4211:1979*
Specification for performance of windows (Appendix C9)
Standards Association of New Zealand, 1979

Sweden: *SS 81 81 26*
Windows and doors - airtightness - testing.
Swedish Standards Commission (SIS), 1983

United Kingdom: *BS 5368:Part 1:1976 (EN42)*
Methods of testing windows. Part 1: Air permeability test.
British Standards Institution, 1976

BS 4315:Part 1:1968
Methods of test for resistance to air and water penetration. Part 1: Windows and structural gasket-glazing systems.
British Standards Institution, 1968

United States of America: *ASTM E283-73*
Standard test method for rate of air leakage through exterior windows, curtain walls and doors.
American Society for Testing and Materials, 1973

ASTM E783-81
Standard method for field measurement of air leakage through installed exterior windows and doors.
American Society for Testing and Materials, 1981

3.2.1 Windows

The two international standards EN 42 and ISO 6613 are virtually identical and as most of the European member countries have adopted these as the basis for their national standards, there is a substantially common approach to the air leakage testing of windows.

Specifically, the standards of Denmark (DS/EN42), Netherlands (NEN 3660), Norway (NS 3206), Sweden (SS 81 81 26), UK (BS 5368) and West Germany (DIN(EN42)) are either identical to or closely related to the international versions. The window under test is installed over the opening of a chamber by which controlled pressures are applied across the window assembly. Before the main testing commences, extraneous air leakage from the chamber is measured and preferably eliminated. In addition, three pressure pulses are applied - each of 3 seconds duration and up to at least 500 Pa. The window is then opened and closed five times and finally secured in the closed position. Pressure is applied in stages of 50, 100, 150, 200, 300 and at 100 Pa intervals thereafter up to the maximum test pressure difference. Then the pressure is reduced to the same levels in reverse order. Of these standards, the Swedish version is unique in also specifying tests with pressure differences in the opposite direction. The international and other national standards include the reversal of pressure as an option.

The remaining standards while not so clearly akin to the international standards, specify a very similar test procedure though without the initial pressure pulsations. The Belgian method specifies test pressures up to 500 Pa and in both the positive and negative directions. The New Zealand (NZS 4211), UK (BS 4315) and USA (ASTM E283-73) standards are specific in requiring the extraneous leakage from the test chamber to be subtracted from the leakage rate measured with the window in place.

The maximum test pressures specified range from 1000 Pa in BS 4315 (UK) to 75 Pa in ASTM Standard E283-73 (USA) if no other pressure difference is designated.

3.2.2 Doors

In general, doors do not seem to have had as much attention as windows although some of the test procedures are specifically applicable to both types of component, e.g. SS 81 81 26 (Sweden) and ASTM Standard E283-73 (USA).

3.2.3 Other building components and joints

The ASTM Standard E283-73 (USA) includes in its scope curtain walls as well as windows and doors.

The only standard specific to joints in buildings is ISO 6589-1981 which is based on the test method for measuring the air permeability of windows (ISO 6613). Laboratory tests are specified for the measurement of joint air leakage with nominal, minimum and maximum specified joint widths and with the joint varying from minimum to maximum width along its length. A method for determining leakage at junctions is also described. The application of pressure differences is similar to the window test and includes the three initial pressure pulses. Tests at both positive and negative pressure differences are specified and reference is made to the requirement for corrections to take account of extraneous air leakage from the test chamber.

3.2.4 On-site testing

The one standard specifically related to component air leakage testing on site is ASTM E783-81. It describes a procedure for determining the air leakage characteristics of exterior windows and doors but it is stated that the method may also be adapted for other leakage routes in the building structure. The test involves sealing a substantially airtight enclosure to cover the internal or external face of the window or door and maintaining a specified pressure difference across the component by supplying air to, or exhausting air from, the enclosure. The required air flow rate is measured and recorded as the leakage through the component. The measurement and correction for extraneous leakage through the test enclosure is also detailed.

4. MINIMUM VENTILATION REQUIREMENTS

Canada:	*Residential Standards, Canada* *Associate Committee on the National Building Code* *National Research Council of Canada, 1977* *The National Building Code of Canada* *Associate Committee on the National Building Code* *National Research Council of Canada, 1980*
Denmark:	*The Danish Building Regulations* *Ministry of Housing, 1982*
Finland:	*D2* *Ventilation in Buildings* *National Building Code of Finland* *Ministry of the Interior, 1978*
Netherlands:	*NEN 1087* *Ventilation in dwellings. Requirements.* *Netherlands Standards Institute (NNI), 1981* *NPR 1088* *Ventilation in dwellings. Indications and examples of constructional performance of ventilation supplies.* *Netherlands Standards Institute (NNI), 1975*
New Zealand:	*NZS 1900* *Model building by-laws. Part 4: Residential buildings* *Standards Association of New Zealand, 1964*
Norway:	*Chapter 47. Ventilation and installation.* *Building Regulations of 1st August 1969* *Royal Ministry of Local Government and Labour*
Sweden:	*Chapter 36. SBN 1980. Air Quality.* *Swedish Building Code with Comments* *National Swedish Board of Physical Planning and Building (1981)*
Switzerland:	*SIA 384/2* *Thermal load of buildings for the design of heating plants* *Swiss Engineering and Architectural Association 1982.*

United Kingdom:	*Building Regulations (Second Amendment)* *Her Majesty's Stationery Office (HMSO), 1981*
	The Building Standards (Scotland) *Her Majesty's Stationery Office (HMSO) 1981*
United States of America:	*ASHRAE Standard 62-81* *Ventilation for acceptable indoor air quality* *The American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc. 1981*
West Germany:	*DIN 1946 Part 2* *Air conditioning. Health requirements.* *German Standards Institute (DIN), 1983*

Considerable attention is currently being paid to the specification of the rates of ventilation required in occupied buildings. Pressures to avoid excessive energy consumption have resulted in a tendency to reduce ventilation rates while increasing concern over indoor air pollution is producing a reverse trend. As a result of these two opposing influences the minimum ventilation rate requirement often becomes the maximum as well.

A summary of the required ventilation rates specified in the various countries is presented in Table 1. The rates are variously expressed in terms of flow rate per person, per room and per unit floor area so comprehensive comparison is impossible. Some variations between countries and between types of rooms are evident.

For dwellings, Denmark, Finland and Sweden have a general requirement which corresponds to 0.5 air changes/hour in rooms of normal height, whereas double that requirement is specified in Canada for mechanical ventilation.

Comparing the requirements for offices reveals that the minimum ventilation rate now specified in the USA (ASHRAE Standard 62-1981) is 2.5 dm^3/s per person whereas the West German equivalent is over three times higher at 8.3 dm^3/s (DIN 1946 Part 2 1983), It is also interesting to compare the increase in the ventilation rates required when smoking is allowed. In West Germany, ventilation has to be increased by a factor of 1.7, in Finland by a factor of 2 and in the USA by a factor of 4.

In most countries, mechanical ventilation is not mandatory in dwellings and so ventilation requirements are also specified in terms of the minimum area of ventilation opening, at least for the more critical rooms. Table 2 shows considerable variation between countries.

The latest version of ASHRAE Standard 62 (1981) reveals an interesting development. It contains two procedural options.

One is a prescriptive method in which, as in most other relevant standards, minimum ventilation rates for a number of building types and usage are specified. The alternative approach is based on specifications of limits of concentration of the most common contaminants but it does not prescribe the method for maintaining the concentrations below the specified levels. Both objective measurement and subjective evaluation of the resulting environment are incorporated though not clearly prescribed. While this approach allows the innovation of alternative methods of contaminant control, it is recognised that insufficient or incompatible data exists on the acceptable limits of concentration of many contaminants and that objective measurement techniques for some of the contaminants are either non-existent or expensive.

FIGURE 1: Window air leakage rates - per m joint length

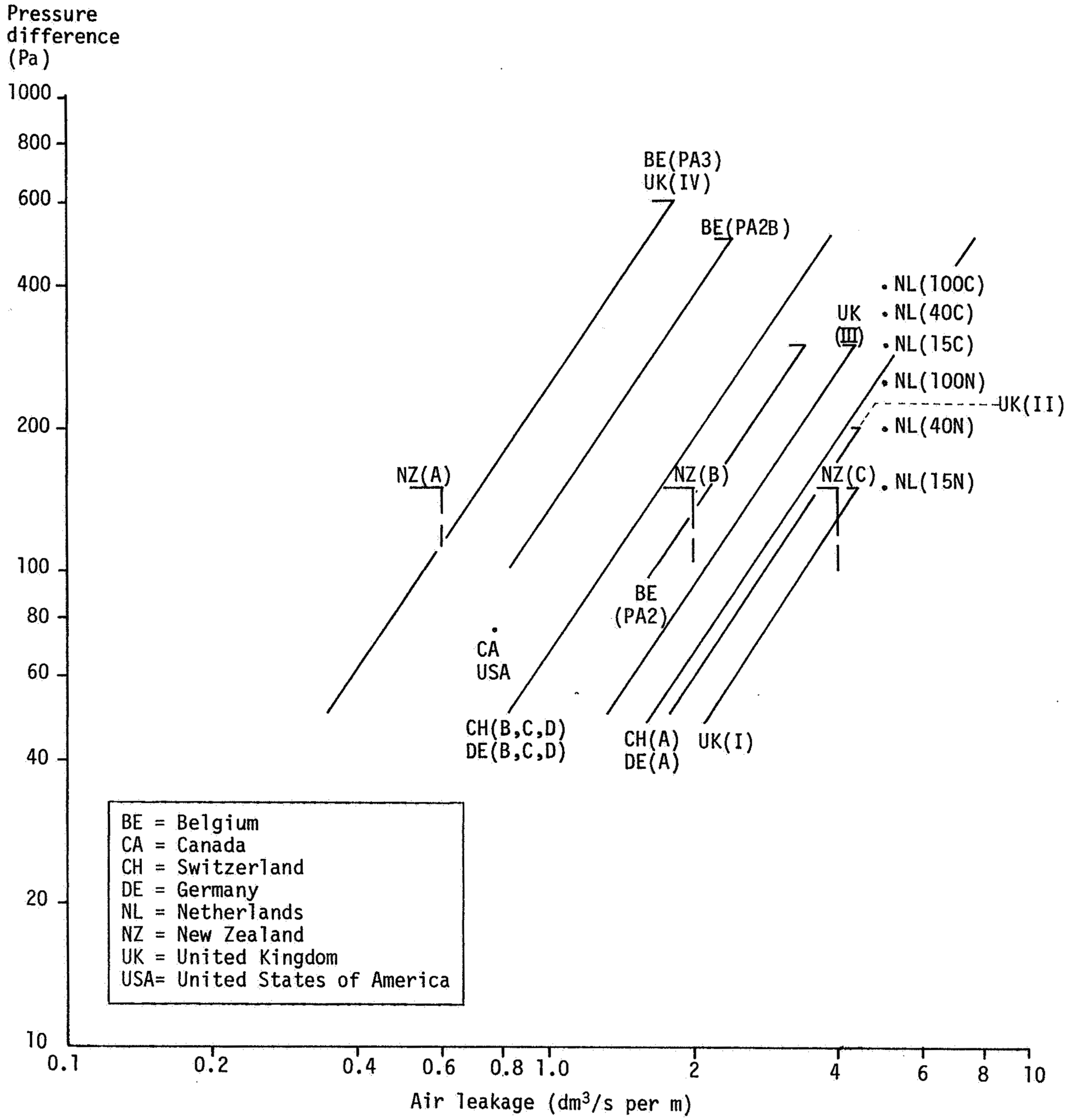

FIGURE 2: Window air leakage rates - per m² window area

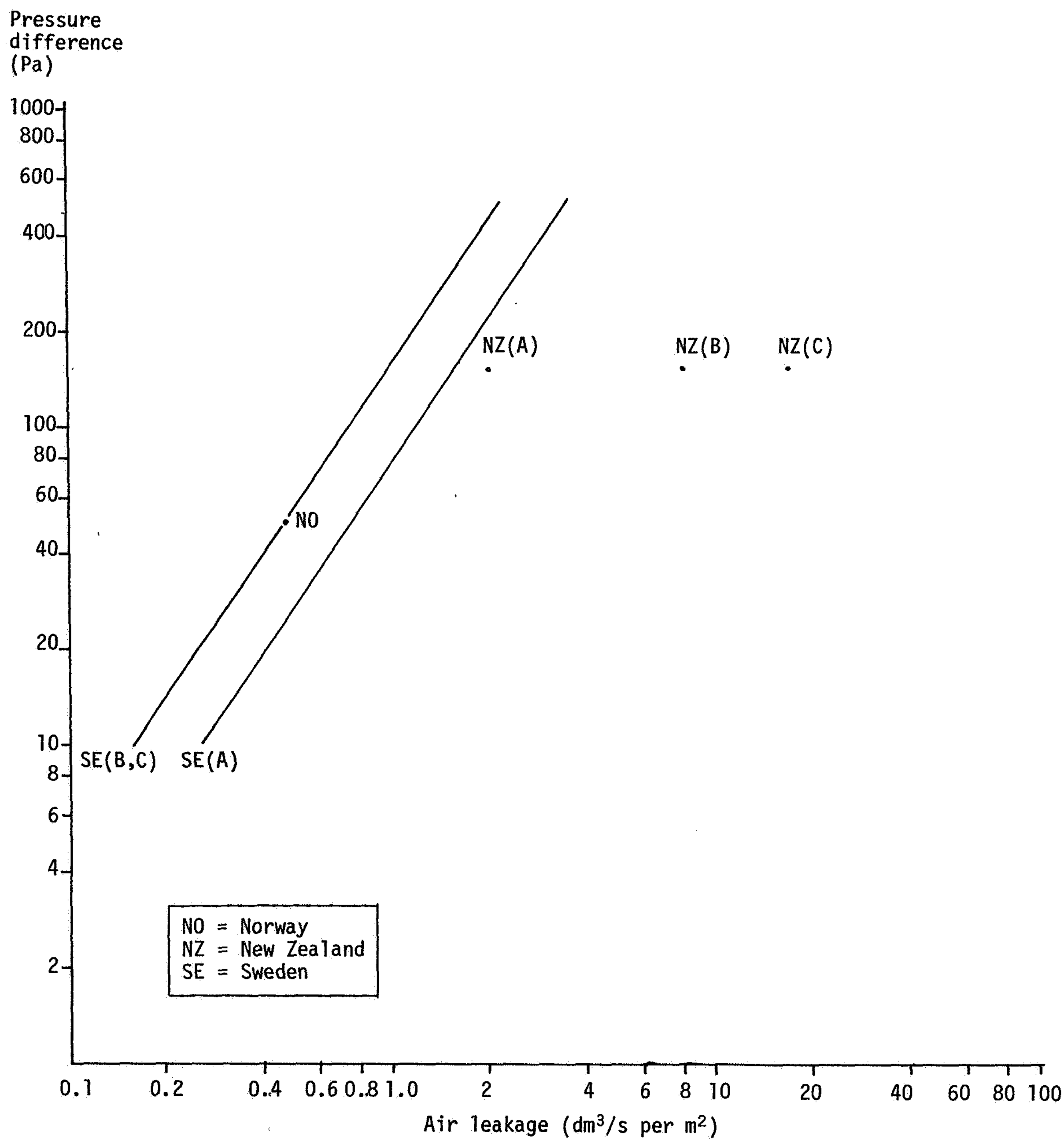

TABLE 1: Minimum ventilation rates

		Canada	Denmark	Finland	Netherlands	Norway	Sweden	Switzerland	UK	USA	W. Germany
Residential	Whole dwelling	1 ac/h [3]	0.5 ac/h	0.35 $dm^3/s\ m^2$ [2]			0.35 $dm^3/s\ m^2$ ≡ 0.5 ac/h				
	Living room				21 - 42 $dm^3/s\ m^2$				3 - 8 dm^3/s pers. [4]	5 dm^3/s	1 - 1.5 ac/h
	Bedroom				1 $dm^3/s\ m^2$				3 - 8 dm^3/s pers. [4]	5 dm^3/s	1 - 1.5 ac/h
	Kitchen		15 - 20 dm^3/s [3]	8.8 dm^3/s	21 - 28 $dm^3/s\ m^2$	22 dm^3/s [3]	10 dm^3/s	22 - 33 dm^3/s	6 ac/h [1,4]	50 dm^3/s [1]	33 dm^3/s
	Bathroom/WC		15 dm^3/s [3]	6.4 dm^3/s	14 $dm^3/s\ m^2$	17 dm^3/s [3]	10 dm^3/s	17 dm^3/s	3 ac/h [1,4]	25 dm^3/s [1]	17 dm^3/s
Offices	No smoking	refers to ASHRAE Standards		0.8 $dm^3/s\ m^2$		1.4 $dm^3/s\ m^2$				2.5 dm^3/s pers.	8.3 dm^3/s pers.
	Smoking			1.6 $dm^3/s\ m^2$						10 dm^3/s pers.	13.9 dm^3/s pers.

Notes:
- [1] Installed capacity for intermittent use
- [2] Values also given per person related to occupancy density for smoking and non-smoking
- [3] If mechanical ventilation is used, otherwise ventilation openings are specified (see Table 2)
- [4] Scotland only, for England and Wales see Table 2 . Separate regulations apply to Inner London.

TABLE 2: Minimum ventilation openings

		Canada	Denmark	Netherlands	New Zealand	Norway	Sweden	UK
Residential	Living room	0.28 m^2		0.02 to 0.04 m^2	5% [3]			5% [1,3]
	Bedroom	0.28 m^2		0.02 to 0.04 m^2	5% [3]			5% [1,3]
	Kitchen	0.28 m^2	0.015 to 0.02 m^2	0.02 to 0.03 m^2	5% [3]	0.02 m^2 [2]	0.02 m^2	5% [1,3]
	Bathroom/WC	0.09 m^2	0.015 m^2	0.01 m^2	5% [3]	0.015 m^2 [2]	0.015 m^2	5% [1,3]

Notes:

[1] England and Wales only. Different specifications apply to Inner London and Scotland.

[2] Requirements for exhaust air, additional requirements are specified for supply air.

[3] % of floor area.

THE IMPLEMENTATION AND EFFECTIVENESS OF AIR INFILTRATION STANDARDS IN BUILDINGS

5th AIC Conference, October 1-4 1984, Reno, Nevada, USA

PAPER 2

IEA ANNEX IX "MINIMUM VENTILATION RATES" - SURVEY AND OUTLOOK

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SYNOPSIS

To establish guidelines for minimum ventilation rates which are sufficiently large to meet the demand for outdoor air in buildings without unnecessarily wasting energy, in Annex IX "Minimum Ventilation Rates" of the IEA Program "Energy Conservation in Buildings and Community Systems" eleven countries are co-operating. The participants had in a first step summarized existing knowledge, national standards and current and required research.

The IEA provides with the Annexes IX and V a highly suitable mechanism for coordinating the research in such diverse fields as e.g. hygiene, medicine, engineering etc. and for encouraging the necessary contributions from the various countries.

As indoor pollutants being of most importance have been identified: Carbon dioxide, tobacco smoke, formaldehyde, radon, moisture, body odour, organic vapours and gases, combustion products and particulates.

To a certain degree some of the substances which had been under investigation can be used as an indicator for acceptable air quality with respect to establish recommendable ventilation rates.

The paper gives a general view of the objectives of Annex IX, the first results and of the relation to the subject area of Annex V. It additionally gives an outlook on the future co-operation of the participating countries.

1. INTRODUCTION

From the viewpoint of energy conservation air infiltration and ventilation have to be minimized. A certain amount of outdoor air, however, has to be supplied to a building in order to maintain healthy, safe and comfortable conditions for the occupants and to avoid damage to the building fabric. The optimization of these conflicting requirements will result in guidelines for minimum ventilation rates that are sufficiently large to meet the demand for outdoor air without unnecessarily wasting energy.

The work that was and is required to define such minimum ventilation rates covers a wide range of disciplines, from hygiene and medicine on one hand to engineering and building science on the other. Therefore in 1980 the Annex IX "Minimum Ventilation Rates" within the International Energy Agency's (IEA) programme "Energy Conservation in Buildings and Community Systems" has been established in which experts in the various fields and from different countries decided to co-operate for identifying objective criteria and other background data needed to establish ventilation standards including minimum ventialion rates.

In the last years the international interest in indoor air quality (IAQ) problems has increased clearly. The reason for this increase may be that efforts to conserve energy by reducing indoor-outdoor air exchange have worsened the problem of pollutant buildup from indoor sources. On the other side many constructions materials as well as furnishing and household appliances have been shown to emit pollutants.

Considering the AIC Technical Note 12[1] it appears that about one third of r and d projects*) in the field of energy conservation in buildings refer now to air quality problems as against a few per cent some years ago. Only as an example it should be pointed out here that the latest Annex IX participant Finland has just started the extensive r and d programme "The Quality of Indoor Climate and Ventilation Requirements".

2. ANNEX IX OBJECTIVES AND PARTICIPANTS

Since January 1984 phase II of Annex IX is in progress. As reported in the AIR[2] nine countries have co-operated on a task sharing basis to complete phase I involving a review of existing knowledge, national standards and current and required research for a number of specified pollutants. A detailed report of this work is published[3]

The objectives of the phase II are:

- to quantify more closely the factors which determine the concentrations of the pollutants identified in the first phase and to determine the inter-relationships between these factors
- to establish minimum ventilation rates and all other suitable methods for ensuring that these pollutants are kept at acceptable levels
- to summarize the information that is available about various techniques and their merits for controlling air quality and conserving energy
- to catalogue and assess pollutant measurement and sampling techniques that may be useful in solving the problems connected with maintaining acceptable air quality in buildings.

Over the next two years, the participating countries will each be conducting research to meet these objectives in relation to specific pollutants or to some more general aspect of pollution control. The pollutants under consideration include formaldehyde, tobacco smoke products, radon, moisture, body odour and carbon dioxide, and combustion products.

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*) recorded 187 projects in 23 countries

The working points within the running working programme are as follows:

(i) Emission rates and time dependence for different materials and sources and their dependence on:

- composition and processing
- installation and handling
- human behaviour
- indoor climate.

(ii) Indoor transfer and interactions:

- ad-, ab-, and desorption
- dilution
- chemical reactions and other interactions

(iii) Control

- pollution measurement, sampling and identification
- ventilation
- air cleaning and dehumification
- separation and recovery
- reduction of emission rates.

(iv) Modelling indoor pollution including economic and social factors, health aspects.

(v) Strategies for indoor air pollution control under the restraints of energy conservation.

The following countries are participants in phase II of Annex IX: Canada, Denmark, European Community, Finland, W. Germany, Italy, The Netherlands, Sweden, Switzerland, United Kingdom, United States of America.

3. CONNECTION WITH FURTHER INTERNATIONAL PROGRAMMES

There are some aspects in which the work of Annex IX and Annex V "Air Infiltration Centre" are closely related. As explained by D. Curtis[4] in the AIR, Annex IX is investigating the pollutants which affect indoor air quality with the aim of establishing acceptable concentration levels and defining corresponding minimum ventilation rates whereas Annex V is concerned with air infiltration and its effects on ventilation. There are no overlaps and to ensure that a suitable level of liaison is maintained these two Annexes are co-operating very closely by an information exchange.

To a certain extent there are connections with Annex VIII "Inhabitants Behaviour" too. Convection and, in particular, infiltration is least understood and most affected by the individual behaviour of the inhabitants. Therefore one of the main objectives[5] of Annex VIII will be:

> To determine the actual behaviour of inhabitants regarding ventilation and to correlate it to outdoor and indoor climate, and facing problems of minimum ventilation.

Germany, the Operating Agent of Annex IX, is also participant of Annex VIII and thus a suitable transfer of knowledge is ensured.

It should be noted here that Working Groups convened by the WHO Regional Office for Europe are for years active in the field of indoor pollutants and health effects. The information exchange in the last time showed that a further co-operation could be of advantage for our Annex IX work.

4. FIRST RESULTS OF THE ANNEX IX WORK

The results of the first phase can be summarized as follows:

If the generation rate of CARBON DIOXIDE is known, the quantity of outdoor air required to maintain carbon dioxide concentration below an acceptable level can be calculated. In some standards a minimum supply of outdoor air is specified based on the maximum acceptable concentration of carbon dioxide for physiological requirements. Other standards specify higher minimum outdoor air requirements to control odour and other air contaminants.

Measurements in schools showed that CO_2 was the only measured contaminant that increased significantly when outdoor air supply was reduced. The maximum CO_2 levels were found to be generally below 2500 ppm, a recommended limit in North America. In these studies, the levels of carbon dioxide and other contaminants were measured at reduced rates of mechanical supply of outdoor air. Similar measurements in an office building and eight energy efficient houses indicated CO_2 levels below 2500 ppm. From these measurements it seems that carbon dioxide is not a serious pollutant in buildings without unvented indoor combustion appliances. The level of CO_2, however, is an indicator of the amount of outdoor air supplied. More field studies are required to determine the relationship between CO_2 and other air contaminants in buildings of various occupancies.

The control of air quality based on the controlled dilution of naturally produced CO_2 appears to be satisfactory as long as there are no other contaminants that exceed their respective limits. Continual sensing of the CO_2 concentration to control the outdoor air supply can result in significant reductions in the energy required for conditioning the ventilation air. Experimental installation of CO_2-controlled outdoor supply air in a school, department store and an office building verify that substantial saving in energy can be obtained compared with conventionally controlled ventilation systems. Further studies are required to demonstrate the practicality of CO_2-controlled outdoor supply air in terms of indoor air quality, reliability and cost effectiveness.

TOBACCO SMOKE is one of the most important pollutants of indoor air. The concentrations of indoor air pollutants and their effects have been studied in various investigations in recent years. Smoke concentrations usually prevailing in smoking rooms could cause irritations of eyes and respiratory organs for a short while and could also cause annoyance. Epidemiological studies on long-term effects indicate that passive smoking may increase the susceptibility of the respiratory illnesses, especially for children and sick persons. The question of increased risk to lung cancer is not satisfactorily answered.

The irritations are caused primarily by the particle phase while annoying odours mostly come from the gas phase of smoke. The annoyance caused by smoke corresponding to carbon monoxide concentrations of 1 to 2 ppm is an acceptable level for healthy persons. Air ventilation rates should be adjusted accordingly so that this level is not exceeded in smoking rooms. For the protection of non-smokers, specially for children, sick and elderly, nonsmoking rooms should be provided so far as possible.

FORMALDEHYDE is a chemical substance widely used as a component of insulation material (Urea-Formaldehyde-Foam), and for glue specially in wood products, such as particle boards, paneling, plywood etc. It is also used on a large scale in disinfectants and household cleaning materials.

Due to the fact that formaldehyde evaporates from the above mentioned materials it becomes an unnegligible component of indoor-air.

Only in recent years gaseous formaldehyde has been incriminated to cause short/long terme irritations to the eye, nose, throat and other respiratory organs.

It has therefore become necessary to agree upon regulations concerning safe levels for formaldehyde concentrations in homes. Some European countries have suggested the maximum tolerable level to be 0,1 ppm as an indoor standard. In this connection it is indispensable to formulate regulations regarding the tolerable amount and/or emission rate of formaldehyde containing products.

The investigation on BIOCIDES started from the question if it is possible to reduce ventilation rates without creating health problems from indoor air pollution. No definite answer is possible for the present.

In order to put the problem in perspective one should know the future trend of biocide application in households. Due to the lack of statistics no extrapolations are available. We can only presume that the Chemical Industry even in the future will continue to expand with new products and we know that up to now there are few - if any - administrative regulations for these markets. If we therefore pressimistically assume an increasing trend of indoor biocide application this could certainly limit the further reductions of ventilation rates.

The RADIATION in dwellings has traditionally been regarded as part of the natural radiation, as for example the cosmic radiation and the radiation we all get from our body burden of natural potassium and thus not been subject to any international regulations. During recent years there has been discussions within different international bodies on how to deal with the part of natural radiation that is increased by technical activities. This radiation has been referred to as Technologically Enhanced Natural Radiation (TENR). These discussions, however, have not yet resulted in adoption of any international guidelines.

Sweden is the only country for the moment where the authorities has adopted nation wide guidelines for both existing buildings and future constructions.

The chapter gives an overview of the status of the present knowledge and to some selected references where more exhaustive information may be found. It also tries to give information about indoor radon in relation to other sources of radiation and its implication on public health. It presents a brief overview of the three major sources of indoor radon: building materials, soil under the building and ground water. Further the guidelines in Sweden are outlined, and the need for research and exchange of experience on measures to avoid infiltration of soilgas and epedemiological studies of possible health effects is presented.

It is important to emphasize that there is no general conflict between energy conservation and radon if infiltration rates are only slightly reduced. In untight buildings the major part of the possible reduction of infiltration rate and energy conservation can be used with a moderate increase in radon concentration. One further step to extremely low infiltration rate of course reduces the energy demand to a slightly lower level, but at the cost of a dramatic increase in radon. In a small fraction of the building stock, where the building materials show a very strong emanation of radon, a mechanical ventilation system has to be used and its net energy consumption might cause some increase in the energy consumption of these buildings. Those buildings, however, constitute a very small fraction of the building stock in any country and have little impact on the average potential for energy conservation. It is very important to notice that the highest radon concentration will be found in untight houses built on strongly radon emissing grounds on gravel and solid rocks, i.e. granite.

The assumed relation between inhalation of radon in dwellings and increased risk for lung cancer is very uncertain. The only data that can reduce this uncertainity would be results of epidemiological studies, which by statistical signification indicate a certain risk factor or an upper limit for the risk factor. Such studies are very complicated. The Radon Commission in Sweden has avaluated the possibility of such studies on exposed populations in Sweden.

The most common sources of microbial contamination of indoor air by MICROORGANISMS are the aerosol generators, air humidifiers, air ventilation units, wet surfaces and the human being. In most cases such contamination does not have any health consequences. But certain bacteria, fungi mites and their dissociation products could cause allergies or infections in respiratory organs. A higher risk does exist in the operating theaters and intensive care units of hospitals and in the sterile production of drugs.

By taking appropriate preventive measures the microbial contamination of indoor air can practically be avoided. Special care should be taken to keep the water of the spraying units used for humidifying air clean and to prevent the water condensation on wet surfaces by having a sufficient supply of air by keeping the relative humidity below about 40 %, thus the growth of dust mites in dwellings can be controlled to acceptable levels. Hospitals, pharmaceutical laboratories and food industries request an extra attention. Additional desinfection as well as a sufficient filtration of the air can be necessary. However, desinfection of air by chemicals and/or UV-radiation is e.g. not allowed by the Health Council in the Netherlands within hospitals.

The outgassing from building materials, furnishing, households and consumer products results in an air contamination by ORGANIC SUBSTANCES. From these substances especially the following have been investigated and considered: HYDROCARBONS, halogenated hydrocarbons and some other compounds as e.g. methanol, ethanol acetone and higher aldehydes and fatty acids.

Little is known of the effects upon the human organism of the compounds at concentrations observed in indoor air. For this reason, only brief references can be made to the general effects of these compounds which, however, in most cases will occur only at considerably higher concentrations.

Skin effects including eczematous contact dermatitis and skin paresthesia are common to many gaseous organic substances. In particular, water-soluble gaseous compounds will exert a general irritant action on the mucosae. A number of solvents and halogenated hydrocarbons may at high concentrations cause kidney and liver damage. Highmolecular halogenated compounds such as polychlorinated biphenyls are mostly deposited in body fat. They reduce cell growth and lessen enzyme activity. A number of polycyclic aromatic hydrocarbons have been identified as the cause of various types of cancers in animals.

Further and more detailed investigations have to show how these compounds and their effects will influece the need for air exchange and ventilation rates in non-industrial buildings.

The review of COMBUSTION PRODUCTS is principally concerned with flueless appliances as e.g. cooking ranges and ovens, small portable space heaters and water heaters.

Inadequate air supply to openflued appliances, which may include gas and oil-fired central heating and hot water boilers (furnaces), solid fuel fired boilers and open fires, may result both in incomplete combustion and the "spillage" of the flue gases. They then become partially flueless appliances, albeit with a higher total (indoor and outdoor) emission rate of combustion products since they generally have a much higher rating.

Prevention of mal-operation of open-flued appliances has been the subject of a number of studies and requirements for air supply are contained within Building Regulations, Codes of Practice and professional guides in many countries.

The report[3] covers the products of the main fuels used in buildings, including both those which result from complete combustion and those which occur when combustion is incomplete. This is followed by a brief review of health effects and then a section dealing with field studies which covers the data available on indoor concentrations found in practice and the limited number of epidemiological investigations specifically related to combustion appliances.

It has become conventional to describe the degree of vitiation in terms of the carbon dioxide. This can be misleading, because the relative quantities of water and vapour and carbon dioxide vary with fuel. The same percentage CO_2 will correspond to different oxygen concentrations for different fuels.

The HUMIDITY of ambient air varies considerably with time and location, being determined by geographical and climatic factors. In the centre of a land mass in winter, with temperatures perhaps reaching typically as low as -40°C, moisture content my be only 0.08 g/kg dry air, whereas in the warm moist climat of a maritime region moisture content may be above 10.0 g/kg dry air. In any given locality annual variations of this magnitude are unlikely but even in the mild climate of the British Isles a ten-fold range between winter and summer is not uncommon.

In the Annex IX report[3] the factors which affect indoor humidity are discussed, followed by a brief review of the possible effects of humidity on occupants and the fabric of buildings, with particular reference in the latter case to condensation. Finally possible methods of control are considered and topics for research suggested.

Further and more detailed investigations will contribute to statements about the influence of the humidity to the need for air exchange and ventilation rates.

BODY ODOUR is the main reason for ventilation of many densely occupied spaces. It is therefore surprising that so little research has taken place in this area. The review[3] presents the principal findings of two major studies on body odour and ventilation requirements. Shortcomings of the studies are discussed and reasons for the large differences in the results obtained in the two investigations are discussed.

None of the two studies provide completely satisfying data for fixing a required ventilation rate. One used an arbitrary "moderate" mean vote of test persons on his psycho-physical scale as criterion. Another based his recommendation of 4 l/s person on 75 % acceptability of his judges. But the situation for the judges may have been a little unrealistic. After having entered their head in the sniffing box for a moment the test persons were supposed to vote whether the odour was acceptable or not. The meaning of "acceptable" may be quite different when entering a real space than for a judge under these rather artificial conditions. This may also explain the small influence of ventilation rate on acceptability in some experiments. Field validation of the observations would be essential.

The Annex IX report[3] on PARTICULATES AND FIBERS gives, beginning with some general definitions, a review of sources of indoor particulates and fibres pollution, of measurement techniques, of effects of particulate and fibres inhalation on human health and finally lists open questions and future research fields. Investigations on the effect of ventilation rate on indoor particulate and fibres pollution are needed.

The dilution of indoor air contaminants with outdoor air requires a considerable amount of energy to condition that air. The amount of outdoor air, and consequently the energy for its conditioning, can be reduced through the use of air cleaning devices for TREATMENT OF RECIRCULATED ROOM AIR.

There are commercial air cleaning devices that provide filtering to remove airborne particles, disinfection to control airborne contagion, and sorption materials to control some odour and gaseous contaminants. These devices are not used extensively because the most common control strategy, dilution, involves low capital and maintenance costs and gives a safty margin to also the many non-identified air contaminants in buildings. The concept of using air cleaning devices to permit reduction of outdoor supply air rate is relatively new. Hence, data are required on the performance of ventilation systems using such devices to control all the relevant indoor air contaminants involved.

Further, to permit the proper design of contaminant removal systems, the efficiencies of various devices must be expressed on a common basis. Standard test methods are available for evaluating particulate removal devices and are required for gaseous contaminant removal devices.

The RELATIONSHIP BETWEEN OUTDOOR AND INDOOR AIR POLLUTION depends substantially upon whether the major sources of pollutants of concern are indoor or outdoors. Major indoor pollutants are radon, formaldehyde, and combustion products principally carbon monoxide, sulfur dioxide, nitrogen dioxide and suspended particles.

In many cases radon and formaldehyde have lower concentrations outdoors than indoors, and the indoor pollutant concentrations are not significantly affected by outdoor concentrations. This is also sometimes true for some combustion pollutants, when an unvented appliance is used indoors and the outdoor pollutant levels are low. Indoor/outdoor relationship may be considered most simply in the context of a single-chamber (well-mixed) mass-balance model that utilizes first-order indoor pollutant reactivity rates and building shell pollutant penetration factors.

In considering ventilation requirements for various building types, the indoor/outdoor ratio itself is not often the parameter of interest. For indoor-generated pollutants, the ratio is often large and not relevant to ventilation requirements, which are determined directly from pollutant generation rates. For pollutants that are generated only outdoors, concentrations are generally the same or less indoors, as a result of which applicable outdoor standards could ordinarily provide suitable protection of the general public (except when outdoor air contains unusually high pollutant levels, either average or peak). When pollutants can arise from either indoor or outdoor sources to a comparable degree, the structure affects indoor concentrations in two offsetting ways of comparable importance. The structure reduces the indoor concentrations of outdoor-generated pollutants while confining indoor-generated pollutants. However, ordinarily the indoor pollutant generation rates themselves are the principle guide to ventilation requirements.

5. CONCLUDING WORDS

Annex IX is a highly suitable means for coordinating the research in the above outlined wide-ranging topics and for stimulating the necessary cooperation from participating countries. The result of this international programme will be as follows:

- A document identifying more closely the factors which determine the concentrations of the pollutants and the interrelationships between them, minimum ventilation rates and all other suitable methods for acceptable air quality levels, further a document summarizing information about ventilation techniques for controlling air quality and conserving energy, and a document cataloging and assessing measurement and sampling techniques.

- A final report integrating the results of this task and containing recommendations for such additional research activities as may be appropriate.

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THE IMPLEMENTATION AND EFFECTIVENESS OF AIR INFILTRATION STANDARDS IN BUILDINGS

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PAPER 3

A STANDARD FOR MINIMUM VENTILATION

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SYNOPSIS

The air infiltration associated with ventilation in buildings is recognized in ASHRAE Standard 62-1981, Ventilation for Acceptable Indoor Air Quality. Especially in the residential sector, and particularly in houses, infiltration is assumed to supply most of the required ventilation. In the light of recent trends toward increasingly tight housing, which limits air infiltration, dependence on this source of outside air is one point that must be carefully considered in the Revised Standard.

Giving credit to either air infiltration or ventilation air as the means to dilute sources of indoor pollution, and thereby maintain acceptable indoor air quality, depends upon the degree of mixing with the interior air. The mixing efficiency is an important question that must be properly evaluated in the Revised Standard. Recent studies have pointed out how widely this "ventilation efficiency" can vary from building to building.

Activities within the living space such as smoking have prompted the previous standard committee to carefully discriminate between smoking and nonsmoking areas. Ventilation rates for smoking areas were raised as much as a factor of five times that of nonsmoking areas. Are these ratios sufficient in the light of recent studies involving necessary dilution of particulates? Flows between smoking and nonsmoking zones also require further consideration in the Revised Standard.

As with any pollutant, maintaining suitable interior environments means understanding the significance of building operation, the systems that move the air (such as variable air volume systems) and the effects of both interior and exterior environments. Changes in humidity, air temperature and local heating may alter pollutant levels in buildings due to the building materials and must be considered in revising the Standard.

1. INTRODUCTION AND HISTORY

The need for ventilation of inhabited, enclosed spaces was undoubtedly recognized by early cave men when they brought their campfire into the cave. The first recorded effort to quantify ventilation needs appears to be the work of Tredgold in 1836.[1] He determined that four cubic feet per min (2 L/s) of outdoor air per person was needed to dilute the carbon dioxide exhaled by the occupants of a space. As stoves and controled heating systems displaced open fireplaces during the last century, and building technology improved, the recommended ventilating rates had increased to 30 cfm (15 L/s) per person by the beginning of the 20th century. These higher ventilating rates were found necessary to control body odors. Personal hygene began to improve about that time, and recommended ventilation dropped to 10 cfm (5 L/s) of outdoor air per person when Yaglou published his work in 1936.[2]

1.1 First U.S. Standard

The first ventilation standard was published by the American Standards Association in 1946.[3] It included recommendations for both lighting and ventilation. ASHRAE up-dated the ASA Standard when it published Standard 62-73 in 1973.[4] Both ASA A53.1 and ASHRAE 62-73 recommended basic rates of 10 cfm (5 L/s) of outdoor air per person based on Yaglou's work. The ASHRAE Standard specified an absolute minimum of 5 cfm (2 1/2 L/s) per person to control the carbon dioxide level. This was in agreement with Tredgold's original recommendation. At 5 cfm (2 1/2 L/s) per person sedentary occupants can raise the steady state CO2 level to about 2500 ppm (0.25%). This is considered to be an acceptable upper limit for normally healthy people. Nuclear-powered submarines, and spacecraft operate at CO2 levels as high as 1%, however, odors are sometimes noticable at those high CO2 levels.

1.2 Energy Considerations

The 1973 oil embargo suddenly created a strong emphasis on energy conservation in buildings. While Standard 62-73 presented both minimum and recommended outdoor air ventilating rates, the ASHRAE Energy Standard 90-75 first published in 1975, specified use of the minimum rates.[5] Thus, one objective of the review of Standard 62-73, begun in 1978, was to rectify differences between Standard 90 and Standard 62. The result was Standard 62-1981.[6]

1.3 Standard 62-1981

The 1981 Standard addressed air quality much more directly than earlier Standards. The basic outdoor air ventilating rate was reduced to 5 cfm (2 1/2 L/s). Only minimum rates were presented for various applications. Tobacco smoke was recognized as a special problem that could not be handled with an outdoor air flow rate of only 5 cfm (2 1/2 L/s) per person. Thus the "perscriptive part" of Standard 62-1981, the ventilation rate procedure, specifies substantially higher rates when smoking is permitted. The recommended rates, based on the dilution of particulates, assumes that one third of the population smokes at a rate of two cigarettes per hour. The recommended minimum outdoor air flow rate for this case is 20 cfm (10 L/s) per person, four times the non-smoking rate. (This rate is specified for all occupants, both smokers and non-smokers when the smokers are not segregated). The recommended rate is increased to 35 cfm (17 1/2 L/s) for applications such as bars where the incidence of smoking is generally higher. Standard 62-1981 also defined acceptable contaminant levels for the outdoor air used for ventilation.

1.4 Air Quality Procedure

A new feature of Standard 62-1981 was the inclusion of an alternate, "Air Quality Procedure." This procedure specifies recommended limits for the most common contaminants and allows the designer to use whatever amount of outdoor air he finds necessary to dilute the containants to the recommended level. Under this procedure it is possible to use a high efficiency filter to remove particulates from the recirculated air and thus reduce the outdoor air requirements to nearly equal the non-smoking rate even when smoking is permitted. The committee that wrote Standard 62-1981 felt it was desirable to include the air quality procedure so that innovative methods to achieve energy efficient ventilation could be permitted.

One pollutant level, the recommended limit of 0.1 ppm for formaldehyde (based on comfort criteria rather than health risk) created a problem with the manufactured housing industry. Although that industry can exercise controls over emissions from widely used urea-formaldehyde-bonded plywood and chipboard (through low emissions specifications or substitute materials), and from choices made with regard to urea-formaldehyde foam insulation, they have no control over carpeting, drapery, and furniture all of which also emit formaldehyde vapors. Thus the publication of a low recommended formaldehyde limit in the ventilation standard, even though it was part of an alternate procedure, was perceived as a threat to the industry. Since single-family residences do not usually have mechanical ventilation systems, which can be evaluated by building inspectors, it was feared that the air quality procedure would be adopted as the only choice in building codes. This situation has served to emphasize the residential problem: if there is no mechanical ventilation system, now can we deal with infiltration which approaches zero flow under mild weather conditions?

2. HOUSES AND MINIMUM VENTILATION

Past AIC conferences have revealed the variation in ventilation rates between the different rooms in European residences.[7] Such room-to-room variations, as large as 10 to 1, most certainly take place in US homes as well, but because of restricted constant-concentration tracer gas testing to document such variations, the data base has been very limited. Except for the mechanically ventilated, very tight home which is almost weather independent, the conventional US home experiences major variations in ventilation rate over the seasons and during any one season. This has been dramatically pointed out in recent testing in two side-by-side homes in Gaithersburg, Maryland.[8-10] The testing program has extended over the entire weather year which is a rarity in infiltration testing. Typical seasonal data are shown in Fig. 1 and illustrate that these two houses with noticeably different tightness, approximately 6 and 10 air changes per hour at 50 PA based on fan pressurization tests, exhibit a marked variation in infiltration rates over the year and differ by about 25%. Only in

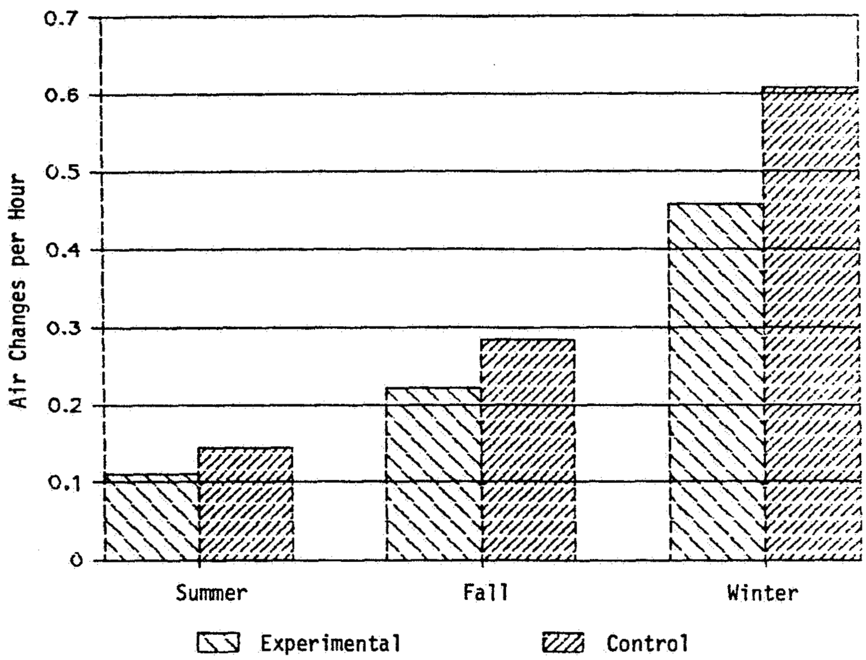

Fig. 1 Effect of Retrofit, by Season, on Infiltration Rates[10]

the most severe winter climate do the air infiltration rates measured by the tracer gas method approach the same ventilation differences between these houses as measured by the pressurization tests (i.e., 40%). Throughout the testing, the air infiltration fluctuates day-to-day, or even hour-to-hour due to weather variations and clearly causes significant variations in the ventilation rate as shown in Fig. 2.

One technique that has been employed in these two house tests is to generate a "synthetic' yearly ventilation rate profile.[10] It provides an improved approach to quantifying average ventilation rates but questions of meeting a "ventilation standard" during all periods of house operation remain. This yearly ventilation rate profile is shown in Fig. 3 and points out the average infiltration rate is only 0.25 ACH for the tighter, retrofitted house and 0.34 ACH for the control house (compared to 0.5 ACH which has often been viewed as a desirable lower ventilation limit).

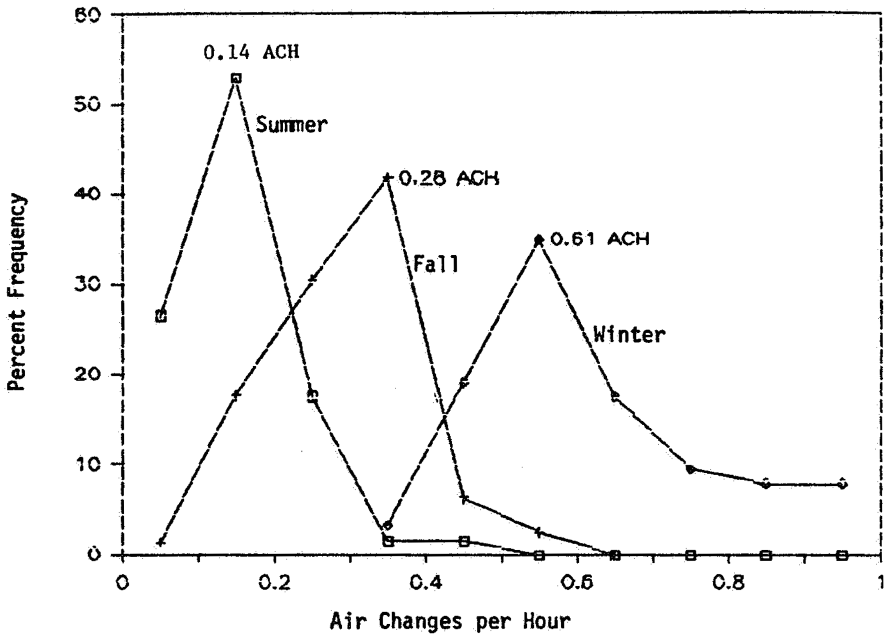

Fig. 2 Seasonal Frequency Distributions of Infiltration Rates[10]

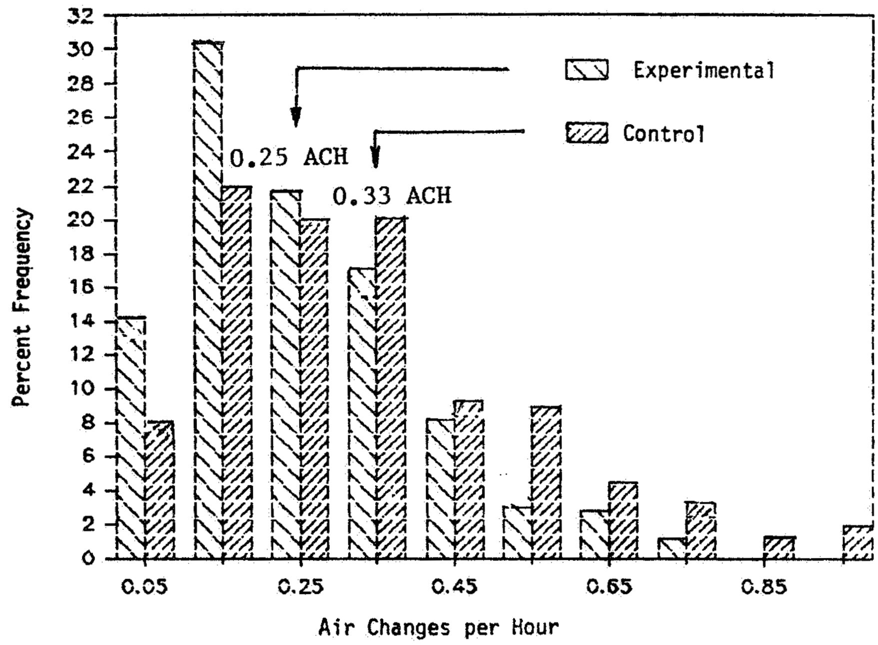

Fig. 3 Synthetic Annual Frequency Distribution of Infiltration Rates[10]

Standard 62-1981, as now constituted, states (in Section 5.1) that adequancy of ventilation via natural ventilation and air infiltration "shall be demonstrable". Have the detailed tests (just discussed) only proved what we have all suspected, namely as our housing becomes tighter there will be periods - sometimes extended periods - when air infiltration will be inadequate to supply the ventilation requirements of our homes? How adequate was the actual ventilation in the past? How can we treat this problem in the Revised Standard is a question that must be resolved within the committee. Should we move away from statements that "ventilation rate shall be demonstrated" to a statement that specifies an improved method of measurement? How cautiously should we proceed to improved tightness standards in our residential housing, such as in ASHRAE SPC-119,[13] in light of our present knowledge? These are just some of the questions that must be answered in the months ahead.

3. MEASUREMENT OF AIR EXCHANGE RATES

Since ASHRAE 62-1981 was written, marked improvements in our ability to measure air exchange rates have taken place and our knowledge of air exchange in buildings both large and small has been considerably advanced. In our larger buildings we are now able to document the amounts of outdoor air entering the buildings under various seasonal conditions. Differences between floors are also evident.[11,12] What is still missing is how the amount of outside air changes with the different settings of the ventilation systems, especially the variable air volume systems. Since VAV systems are today's standard method of providing ventilation air in our larger buildings, it is important that the Revised Standard address questions that deal with the VAV operations that affect ventilation. The fresh air or recirculated cleaned air requirements in the Standard are a function of the occupancy levels, and/or floor space. Thus, it is important that there be no reduction in these air flow levels when the total amount of air flow is reduced to a given zone based upon comfort considerations. Measurements of these air quantities are now being undertaken by such groups as the National Bureau of Standards and hopefully will impact the Standard as it is being revised.

4. POLLUTANT LEVELS AND LARGER BUILDINGS

Viewing the ventilation question from the standpoint that pollutants must not exceed a prescribed level, the Indoor Air Quality Procedure of ASHRAE Standard 62-1981, one would like to find a simple testing approach. Some have proposed CO2 and particulate levels as surrogate measures of this adequacy. CO2 levels have been the basis for determining ventilation rates incorporated in the ASHRAE 62 Standard over the years. Although maximum CO2 levels have been set at 2500 ppm (0.25%), recent data have indicated that level may be too high. Canadian studies point to 1,000 ppm as a level that eliminates occupant problems such as mild headaches. Japanese data would appear to confirm those values placing the desired maximum in a similar range. This adjustment in CO2 level would have a profound influence on Standard 62. To meet the Canadian and Japanese recommendations would mean that the minimum ventilation rate would be 12.5 cfm (6.3 L/s) not the 2.5L/s 5 cfm (2.5 L/s) as in Standard 62-1981. Before discussing this question of minimum ventilation rate further let us turn our attention to particulates.

4.1 Particulates

In the discussions that have taken place in Atlanta and Kansas City (sites of ASHRAE semiannual and annual meetings) the topic that has received the most attention in the 62-1981R Subcommittee on Building Performance has been particulates. Even before these deliberations, there has been a high degree of interest in particulates that are a result of smoking. Representatives in the tobacco industry question the concept of smoking versus non-smoking ventilation rates where the ventilation rates have often been specified to be five times that in the non-smoking zones, in Table 3 of the 62-1981 Standard. The discussions in the subcommittee covered more than the smoking issue and are looking at particulates in the 0.3-1, 1-3, and 3-5 micron sizes, covering a range that includes and exceeds those particles that could be attributed to smoking alone. One explanation was that the particles larger than 1 micron (i.e., larger than those associated with smoking), were often "people generated." By this we are speaking of skin shedding and other occupant related activities. New monitoring techniques have allowed these different sizes of particulates to be measured and the results interpreted in terms of ventilation efficiency. The early results are revealing that constant volume and variable air volume systems perform differently using these particulates as "tracers". Questions have been raised as to whether the "mixing efficiency" is the same over this range of particle sizes, i.e., that the possibility exists that some particles may concentrate in the occupied zones of a building.

4.2 Ventilation Efficiency

The whole question of ventilation efficiency is a key to the application of Standard 62. The pioneering works of Sandberg[14] and Skaret[15] point out the key elements of ventilation efficiency. If the ventilation air, whether it be outside air or cleaned and filtered recirculated air, is not reaching the occupants of the building because air mixing is inadequate in the rooms in which they are located, then the purpose of the Standard has been compromised. The achievement of suitable ventilation efficiencies must be a key element in satisfying the goals of the Revised Standard.

Dilution of contaminated indoor air with less contaminated outdoor air is the main method used for controlling indoor air contaminants. Commercial buildings use mechanical air handling systems to condition and distribute the ventilation air. The amount of outdoor air required is defined by building codes which usually depend on ASHRAE Standard 62. System designs are approved on the basis of the building plans and specifications. After the systems are installed they are balanced by measuring the volume of air discharged from each supply diffuser. This, however, does not assure a proper distribution of the outdoor air within the occupied space. Incomplete mixing of outdoor air with return air can result in a non-uniform distribution of the outdoor air. Further, the common practice of locating both the supply outlets and return inlets on or near the ceiling can permit short circuiting of some of the supply air directly to the returns without complete mixing at the occupied level in a room. When this happens effective dilution is compromised.

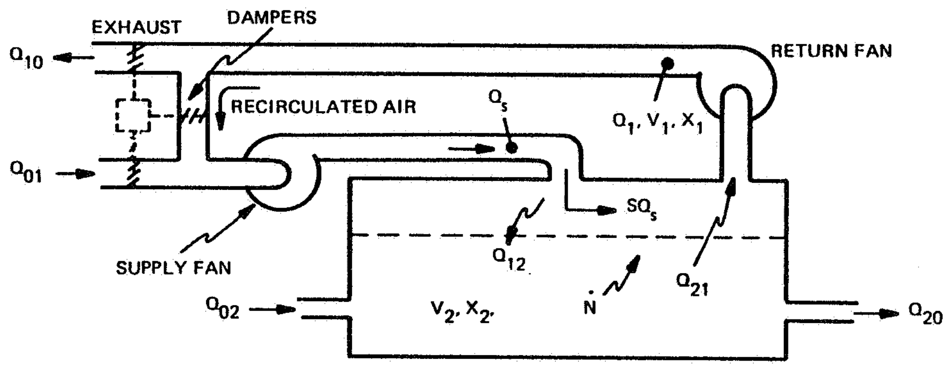

Fig. 4. Typical Air Distribution System.

Consider a typical distribution system as shown in Fig. 4.[16,17] Outdoor air, Q01 is mixed with recirculated air and supplied to the space. A fraction, s, of the supply air, SQs may flow along the ceiling to the return inlet or otherwise bypass the occupied part of the room. A fraction, r, of the return air may be recirculated to be mixed with the outdoor air. The remainder, 1-r, will be exhausted. The amount of this outdoor air that bypasses the occupied space and is exhausted is Q10-s and the relationship is:

$$Q_{10-s} = s(1-r)Q_{01}\ [1 + rs + (rs)^2 + \ldots] \qquad (1)$$

$$\frac{Q_{10-s}}{Q_{01}} = \frac{s-sr}{1-sr}$$

The ventilation efficiency, η, can be defined as:

$$\eta = \frac{Q_{01} - Q_{10-s}}{Q_{01}} = \frac{1-s}{1-sr} \qquad (2)$$

Eqn. 3 defines the efficiency with which the outdoor air is circulated to the occupied space in terms of a stratification or mixing factor, s, and the recirculation factor, r. If there is no exhaust flow, r=1 and the efficiency is 100%. If there is no stratified or bypass flow, s=0, and the efficiency is also 100%. If, however, there is both stratified flow and recirculation, outdoor air can pass through the system without ever being used to dilute contaminants at the occupied level. This ventilation loss also represents an energy loss. Fig. 5 presents a set of curves describing Eqn. 3.

It has been shown[17] also that tracer gas decay measurements can be used under the proper conditions to measure ventilation efficiency. A suitable tracer gas such as methane or sulfur hexafluoride can be

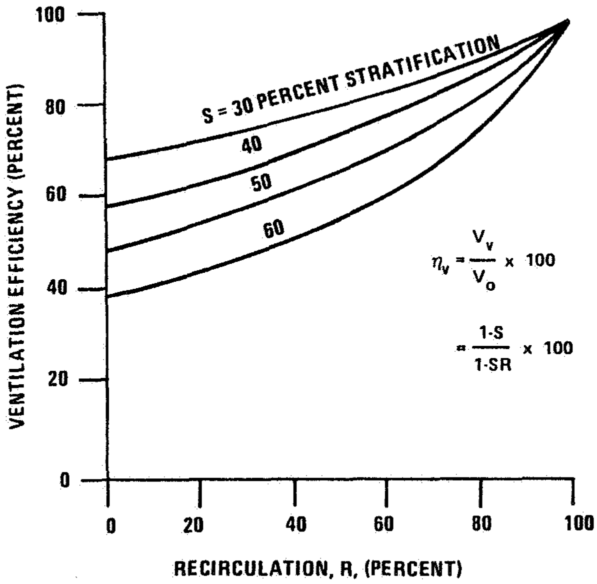

Fig. 5 Ventilation Efficiency

added to the supply air at a sufficiently rapid rate to build up a measureable concentration at the return inlet before there is a significant rise in concentration at the occupied level. The semi-log plot of the tracer gas concentration decay over time may reveal two curves similar to Fig. 6. The slopes of the lines are proportional to the outdoor air flow rate in volumetric air changes per unit time. In this case, Volume 1 refers to the supply and

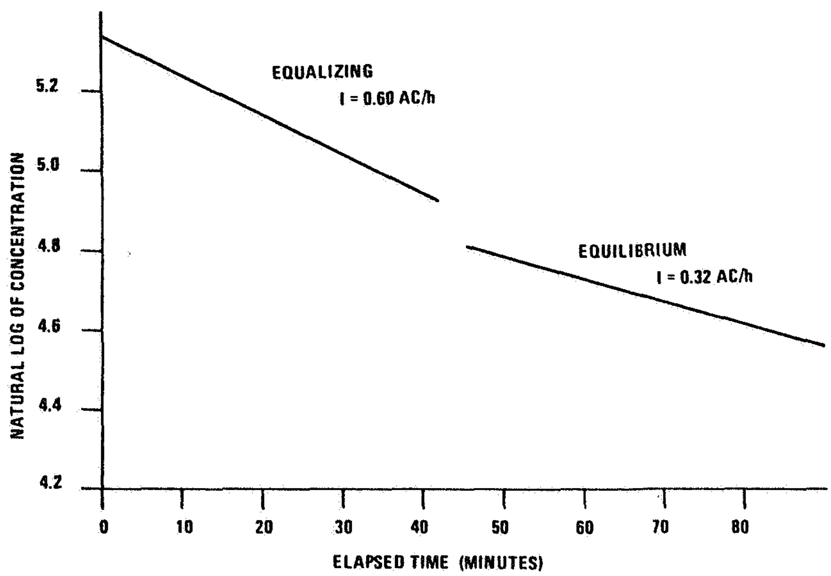

Fig. 6 Tracer Gas Decay in Volume 1 in a Two Chamber Study[16]

return duct volumes and the upper part of the room as shown in Fig. 4 Volume 2 is the lower or occupied part of the room.

The apparent change in infiltration or ventilation rate is caused by the initial loss of tracer gas both to Volume 2 and to the exhaust flow plus the infiltration loss. The final or equilibrium decay line is revealed when mixing between the two volumes is complete. This represents the actual outdoor air plus infiltration air flow rates. It can be shown [17] that the efficiency with which the outdoor air is used to dilute contaminants in Volume 2 (i.e., the occupied part of the room) is approximated by:

$$\eta = \frac{I_o - I_{oo}}{I_o} \qquad (4)$$

where I_o = initial apparent infiltration rate

I_{oo} = final infiltration rate.

For the case represented in Fig. 6,

$$\eta = \frac{0.60 - 0.32}{0.60} = \frac{0.28}{0.60} = 0.47 \qquad (5)$$

This low ventilation efficiency was approximately confirmed by energy balance calculations.

The ventilation efficiency obtained with tracer gas tests and calculated from Eqn. 5 can be equated to Eqn. 3 to obtain the stratification factor, s :

$$s = \frac{1 - \eta}{1 - \eta r} \qquad (6)$$

The recirculation rate during the tracer decay measurements must be specified since this will influence the ventilation efficiency.

Duct systems similar to Fig. 4 can be expected to have a substantial reduction in ventilation efficiency as shown in Fig. 5. However, if the return inlet is located near the occupied level or if the exhaust is separated from the return system and is located in the occupied level, the ventilation efficiency can be high. ASHRAE Standard 62-1981 does not recognize this problem, but the revision to 62-1981 must address the issue.

Variable air volume systems tend to exacerbate this problem. Under heating conditions, the body heat-loss from a group of people in a room will offset some of the heat requirement for the room. This will reduce the air flow and ventilation air at the very time when it is most needed. The lower air velocities also reduce mixing efficiency. Such a system should be designed to increase the fraction of outdoor air in the supply air under these conditions. Use of a carbon dioxide sensor to measure the actual outdoor air requirement would be one way to correct this problem.

4.3 Smoking

Tobacco smoke presents the HVAC system designer and building operator with particular challenges. Approximately 30% of the US population smokes. The 70% non-smoking population has demanded special consideration in recent years. Standard 62-1973 recognized the requirements in a very superficial and indirect manner. The recommended outdoor air supply rates, for applications where the incidence of smoking could be expected to be high, was therefore increased to control the smoke and associated odors. In contrast, Standard 62-1981 addressed smoking directly. Outdoor air supply rates are specified for either smoking or non-smoking applications.

The average generation rate for total suspended particulates is 31.9 mg/cigarette[18]. The National Ambient Air Quality Standard specifies 0.260 mg/m^3 as the concentration limit for total suspended particulates for 24 hour exposure[6]. A mass balance for the particulates in indoor air is Eqn. E-1, Appendix E, Standard 62-1981:

$$\dot{V}_o \; (C_s - C_o) = \dot{N} \qquad (7)$$

where $\dot{V}_o$ = Flow rate of outdoor air

C_s = Particulate concentration in space

C_o = Particulate concentration outdoors

$\dot{N}$ = Particulate generation rate

The flow rate of outdoor air needed to achieve a given indoor particulate concentration is given by:

$$\dot{V}_o = \frac{\dot{N}}{(C_s - C_o)} \qquad (8)$$

If we assume the outdoor particulate concentration is zero, $C_o = 0$:

$$\dot{V} = \frac{31.9}{0.260} = 150 \text{ m}^3\text{/hr per cigarette} \qquad (9)$$

If we assume 25% of the occupants in a room smoke two cigarettes per hour, the outdoor air flow rate needed is:

$$\dot{V}_o = \frac{(0.25)\ (2)\ (150)}{60} = 1.25\ m^3/\text{min-person}$$

$$\dot{V}_o = (1.25)\ (16.67) = 20.8\ \text{L/s or } 41.7\ \text{cfm} \qquad (10)$$

The flow rates recommended in Table 3 of Standard 62-1981 were adjusted up and down from this basic rate. Smoking in areas such as bars tends to be greater than the assumed rate, but the duration of exposure is substantially less than 24 hours. There are always some particulates in outdoor air which would increase the amount of outdoor air needed. The National Ambient Air Quality Standard specifies 0.075 mg/m^3 as the maximum particulate concentration for continuous (1 year) exposure.

Appendix E of Standard 62-1981 also shows how filters can greatly reduce the amount of outdoor air needed. The total circulation rate must be increased, however. This may present a problem in variable ventilation systems. Recent work by Repace[19] has confirmed the basic recommendation of 20 cfm (10 L/s) of outdoor air per person (in an office where smoking is permitted) as a practical ventilation level. Repace calculated the lifetime lung cancer risk as a function of the cigarette smoke concentration associated with various dilution rates. He found that at a minimum ventilation rate of 5 cfm (2 1/2 L/s) there would be ten extra cases of lung cancer per 1000 people over a lifetime. Increasing the outdoor air flow rate to 20 cfm (10 L/s) per occupant reduces the risk to about two extra lung cancer cases per 1000 people. Beyond this point the curve is quite flat; over 50 cfm (25 L/s) of outdoor air is needed to reduce the risk to one lung cancer case per 1000 people.

Odor research of Leaderer, Cain[20] and Fanger, Berg-Munch[21] has shown that an outdoor air supply rate of 20 cfm (10 L/s) per person to a space where smoking is permitted will satisfy only about 50% of the visitors to the space. Acceptance increases after a minute or two due to saturation of the olfactory senses. Outdoor air flow rates of about 40 cfm (20 L/s) are needed to satisfy 80% of the visitors.

Although more than 2000 different species have been identified in tobacco smoke, particulates are the dominant contaminant. These can be effectively removed with electrostatic filters or high quality media filters. It can be shown (see Ref. 6, Appendix E) that the outdoor air flow rate can be reduced from 35 cfm (17 1/2 L/s) per person to 7 cfm (3 1/2 L/s) in a bar if a 90% efficient filter is used and a circulation rate of 31 cfm (16.5 L/s) per person is achieved. Thus efficient filters can greatly reduce the amount of outdoor air required.

A second method for reducing the amount of outdoor air needed to dilute tobacco smoke is to segregate smokers from non-smokers. ASHRAE Standard 62-1981 permits the outdoor air flow rate to be calculated separately for each group when they are segregated, and air from the smoking section does not flow into the non-smoking section. Location of smokers close to the exhaust inlet permits the supply air to sweep the smoke into the exhaust, then limitations imposed by diffusion and mixing no longer apply.

Based upon the latest findings on particulate levels in representative building, and measurements of ventilation adequancy, the 62-1981R Subcommittee on Building Performance will pursue these points and make certain that the most relevant performance criteria are emphasized in the Revised Standard. At present the subcommittee is rewriting the material in Appendix E - Rationale for Use of Cleaned, Recirculated Air. This Appendix deals with the problem of removing particulate matter, and depending upon the removal efficiency, states how much the flow of outside air can be reduced. Total suspended particulate concentrations of the outside air are part of the ventilation rate determination. The question of ventilation efficiency describing how effectively the ventilation air is reaching the occupants must be either incorporated into the calculation procedure at this point or a separate appendix must be addressed to the influence of ventilation efficiency. In the subcommittee discussions, suitable minimum ventilation rates were suggested as 20 cfm (10 L/s) based upon the mixing efficiency information resulting from particulate measurements. This matter is of highest priority in setting the Revised Standard.

5. BUILDING ENVIRONMENT AND EMISSIONS

How the building maintains temperature, relative humidity and air flow can directly influence the building indoor air quality. One example is formaldehyde outgassing, which is affected by both temperature and humidity. Formaldehyde compounds are very common in buildings and thus from a building performance standpoint the way in which we maintain the interior building environment can directly influence source strengths and thus dictate the required ventilation. This example only points out that we must be concerned with building materials and their associated ventilation requirements as well as the needs of the occupants.

In Standard 62-1981, under the heading of Variable Occupancy (Section 6.1.5 and associated Fig. 2), the Standard deals with transient or variable occupancy and allows the building operator to adjust dampers or even turn off the ventilation system during specified periods. These system adjustments may lag or lead occupancy depending upon whether occupant ventilation needs or pollutants associated with building materials are the principal concern. The 62-1981R Subcommittee on Building Performance is looking more deeply into these matters to determine in the light of more recent information whether or not this portion of the Standard should be altered.

6. SUMMARY

The discussions in this paper have traced the history of ASHRAE Standard 62, and point out the important current questions that are being addressed during the present revision. Building performance aspects of the standard have been emphasized in this paper with principal concerns for ventilation efficiency, handling special problems such as particulates especially those associated with smoking, and the variability of residential ventilation which has been highlighted by modern instrumentation.

This is a consensus standard and the various subcommittees and the committee as a whole will be seeking to provide the most realistic and up-to-date ventilation standard when the revision process is completed. What should be clear from this paper is that the standard revision is an ungoing process in the light of new information such as that supplied in abundance from the Air Infiltration Centre's prime function of promoting information exchange.

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THE IMPLEMENTATION AND EFFECTIVENESS OF AIR INFILTRATION STANDARDS IN BUILDINGS

5th AIC Conference, October 1-4 1984, Reno, Nevada, USA

PAPER 4

AIRTIGHTNESS STANDARDS FOR BUILDINGS - THE CANADIAN EXPERIENCE AND FUTURE PLANS

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SYNOPSIS

The situation in Canada with regard to building regulations affecting the airtightness of buildings is reviewed with emphasis on a new standard test method for measuring airtightness which departs somewhat from methods used in other countries. The purpose of this test is held to be primarily to determine an important aspect of building envelope quality, namely the degree to which unintentional openings have been avoided, rather than to determine energy conservation potential. The procedures used in the method, the rationale behind those procedures and the experience to date in using the method are summarized. The reasons why there is very little regulation of building airtightness in Canada at present and the prospects for increased regulation are given. It is concluded that it is unlikely there will be widespread regulation in this area in the near future.

1. INTRODUCTION

The purpose of this paper is to present the current status of Canadian building standards relating to airtightness and to speculate on how the situation might change in the future.

I will first establish the context with a brief synopsis of the standards writing and implementation process in Canada and then concentrate principally on the Canadian General Standards Board Standard 149.10, "Determination of Airtightness of Buildings by the Fan Depressurization Method"[1]. I will review its main features, giving the rationale for each, and relate some of the results of its use to date. I will close by suggesting how this standard and others might be used to a greater extent in the future to improve the airtightness of Canadian buildings.

2. THE CANADIAN STANDARDS WRITING AND IMPLEMENTATION PROCESS

To understand the current situation regarding standards affecting airtightness and other building characteristics related to energy conservation, it is first necessary to have an appreciation of the the process by which standards are developed and implemented in Canada.

Virtually all our standards affecting buildings, and most other products, are developed by the consensus process. Even government agencies with the mandate to do so are reluctant to simply impose standards on the building industry without fairly thorough prior consultation. The consultation process is facilitated by the existence of five "Standards Writing Organizations" recognized by the Standards Council of Canada. The Canadian Standards Association (CSA) is one of these "Standard Writing Organizations" (SWO's) you might be familiar with. The Canadian General Standards Board is another.

When the need for a new standard is identified, the SWO in whose area of expertise or experience the standard is recognized to fall forms a committee and attempts to establish membership on that committee that will have a balanced matrix of "producers", "users" and neutral third parties. The terms "producers" and "users" are often not very appropriate; but the general concept of balancing those who might be expected to argue for a less stringent standard with those who might be expected to argue for a more stringent one is the guiding principle. Usually several drafts are required before a standard is developed which may represent a reasonable compromise between these two groups.

Once developed, the standard has no force until referenced, usually in a building code, by some government agency, normally a provincial government. The process provides such agencies with some degree of assurance that the standards they thus invoke are not likely to be unreasonably stringent or unreasonably lenient, because they know there has been some input by those likely to be affected by the standard's being implemented.

Even our National Building Code[2] is developed and updated by a similar consensus process and it too has no force until adopted or adapted by a provincial government, since our Constitution gives the provinces the mandate to regulate building. Although the National Building Code is only a model code, it nevertheless has a great deal of influence as most of the provincial codes are modelled quite closely on it.

3. THE CURRENT SITUATION

There are currently two standards in Canada relating to the airtightness of buildings - the above-mentioned CGSB Standard 149.10, "Determination of Airtightness of Buildings by the Fan Depressurization Method" and "Measures for Energy Conservation in New Buildings", a supplement to the National Building Code.

3.1 CGSB Standard 149.10

The CGSB Committee on Airtightness and Air Leakage Testing of Buildings was formed in April 1982. The committee believed it had completed work on this standard in September 1983 but the final draft was not approved by the necessary majority on the last ballot due to some last minute concerns regarding temperature corrections and curve fitting procedures. Even though it has not been published in final form, the standard is being fairly widely used as a testing protocol to ensure uniformity of approach in research projects on airtightness of houses and ways of improving that airtightness. An airtightness testing procedure more-or-less along the lines described in the CGSB draft is also being used by the small but growing number of air sealing contractors, who use the before and after results to demonstrate to homeowners what their work has accomplished. Finally, this test procedure is used in a federal government program of subsidies for the construction of low energy houses. Among other criteria in this program, a house must be demonstrated to experience no more than 1.5 air changes per hour at 50 Pa test pressure to be eligible for the subsidy.

I should emphasize that this standard is a standard test **procedure** only - it includes no pass/fail criterion for airtightness nor does it even provide any guidance as to what constitutes high or low, good or bad airtightness. It merely establishes a definition for airtightness (which I will look at more closely below) and a method of testing to determine the airtightness of a particular building. It is left to others to establish criteria.

3.2 Measures for Energy Conservation in New Buildings[3]

This supplement to the National Building Code is one place where one might reasonably expect to find such a criterion. However, the energy "Measures" (the verbal shorthand name adopted by most people who have occasion to talk about this document) was first published in 1978 and revised in early 1983. The committee responsible for developing and maintaining the "Measures" was reluctant to specify such a criterion until a standard test method was established - something of a "chicken-and-egg" situation. Thus this document's only requirements regarding airtightness, thus far, are some rather vague statements about the need to caulk or seal likely points of air leakage and infiltration test criteria for windows and doors.

Like the document it supplements, the "Measures" is another model document with no force unless adopted by some authority with a mandate to regulate buildings, such as a provincial government. Thus far only one province - Quebec - has seen fit to do so. However, the federal government's housing agency, Canada Mortgage and Housing Corporation, applies the 1978 edition of the "Measures" to houses built under its mortgage insurance and subsidized housing programs - about one third of new housing starts.

4. A CLOSER LOOK AT CGSB STANDARD 149.10, "DETERMINATION OF AIR-TIGHTNESS OF BUILDINGS BY THE FAN DEPRESSURIZATION METHOD"

Let us now look in more detail at the testing and reporting procedure described in Standard 149.10.

4.1 What Does the Test Set Out to Measure?

In contrast to the practice used in several other countries, it was decided at the outset that the result of the test should be expressed as an "equivalent leakage area" rather than as air changes per hour at some test pressure. There were two principal reasons for this decision -

- One reason was the committee's concern that an air change per hour figure would be inadvertantly or deliberately confused with the natural air change rate of the house under wind and buoyancy forces. I mention "deliberately" because there had already been reports of sealing contractors using the air change at 50 Pa figures, divided by some unsubstantiated factor (often fanciful and sometimes equal to 1) to exaggerate claims about the benefits of their service. Even the honest contractors were looking for such a factor that could be used with confidence. Many members of the committee were skeptical that such a factor or even a more complicated correlation could be found and wished to choose a method of expressing the results of an airtightness test that would discourage this direction of thinking.

- The other principal reason for avoiding the air change per hour approach was that an airtightness test was seen as being primarily a test of the general quality of construction of the building envelope and not just a test of potential energy conservation qualities. Indeed, it is being increasingly recognized that, in new construction at least, avoidance of interstitial condensation is probably a more compelling incentive for improved airtightness than energy conservation. A recent study[4] has shown that the level of airtightness already achieved in ordinary new Canadian housing is often high enough that further improvements will result in the need for installation of mechanical ventilation. This, of course, is not necessarily undesireable since a perfectly airtight house with a reliable controlled ventilation system would be free of the risks of both interstitial condensation and poor air quality. The point is, however, that, if one starts with one of our ordinary new houses, improving its airtightness, on its own, will save little if any energy since the reduction in air leakage will have to be replaced by ventilation. It is only when heat recovery is added to the ventilation system that energy is saved and this is an additional cost which must be weighed against the value of the energy saved.

Thus, if an airtightness test is conducted primarily to measure the quality of the building envelope, "equivalent leakage area" is a way of expressing the results of the test which seems to relate more closely to this way of thinking of the test.

Equivalent leakage area also relates better than air change rate to the definition of airtightness used in the standard -

> "the degree to which unintentional openings in the building envelope have been avoided".

This is an appropriate point to emphasize the title chosen for the standard. Please note that it is an "airtightness" test and not an "air leakage" test. The committee chose to regard air leakage as the normal accidental exchange of air between the interior and exterior under the action of wind and buoyancy forces - the phenomenon which ASHRAE and AIC refer to, incorrectly or at least incompletely, as "infiltration". This is not what the fan depressurization test measures.

To summarize this point then, CGSB Standard 149.10 seeks to measure "the degree to which unintentional openings in the building envelope have been avoided" and the results are expressed as an equivalent leakage area (ELA).

4.2 The Test Procedure

In establishing a test procedure and a procedure for processing the test data, the committee has strived for precision and reproducibility, envisioning the standard being used in a context where failure to get below some target ELA will have negative consequences, such as denial of an occupancy permit or withholding of a low energy housing program subsidy. It is too early to tell whether these objectives have been achieved.

Briefly, the process involves the following steps:

- All intentional openings in the building envelope, such as windows or chimney flues, are closed or sealed.
- A variable speed fan with a top speed flow capacity of from 1000 to 3000 L/s is sealed into a window or door opening so that it will blow outwards. The fan will have been previously calibrated to obtain a correlation between its speed and flow or between the pressure drop at its inlet orifice and flow. Sometimes a calibrated inlet nozzle is used to measure flow through the fan.
- The fan speed is then varied to create a number of interior/exterior pressure differences ranging from 10 Pa to 50 Pa. The fan flow required to create each pressure difference is recorded.
- The flow readings are corrected for differences between the atmospheric pressure and interior temperature of the house and the pressure and temperature at which the fan was calibrated, and for the difference between interior and exterior temperatures. This latter correction is required because interior air flow through the fan is being measured but it is really exterior air flow through the envelope that we are interested in.
- To the corrected flow and pressure difference readings, a curve is fitted to the form -

$$Q = C \quad p^n$$

where: Q = flow (L/s),
C = a constant, and
P = interior/exterior pressure difference (Pa).
n is an exponent between 0.5 and 1.0

The curve fitting is done using the least squares method modified to give less weight to the low pressure difference values because these are the most difficult to make accurately. Statistical analysis tests are applied which invalidate the test if the fit of the curve is not within prescribed limits.

- The regression coefficients C and n are then used in the following formula to calculate the equivalent leakage area:

$$ELA = 0.001157 \quad {}_{o} \cdot C \cdot 10^{n-0.5}$$

where: ELA = equivalent leakage area (m^2)
$_o$ = density of the exterior air (kg/m^3)

Committee member William Jones of Ontario Hydro derived this formula[5] by equating the flow at 10 Pa from the fitted curve to the flow through a sharp-edged orifice at 10 Pa. 10 Pa is used because it is the test pressure closest to the pressures the house will actually experience.

Figure 1 shows a typical test set-up and Figures 2 and 3 show typical processed test results.

4.3 Experience in Using the Standard So Far

Achieving reliable ELA values has been a problem. In some cases where the test is being used to monitor the results of sealing work, the ELA has appeared to increase after sealing even though the flow at 50 Pa has decreased. This is attributed to the fact that the ELA value derived from the above formulae is strongly influenced by the results at low test pressures and these, in turn, are strongly influenced by the wind. Thus ELA's derived from test results taken on other than calm days must be regarded with some suspicion even if the results have passed all the required statistical tests. Often it is not possible to delay testing to wait for calm conditions. The committee may have to consider revisions to the procedure to make the results less sensitive to wind influence on low pressure difference readings. Perhaps dropping some of the lower pressure readings would accomplish this.

Another issue has been the aforementioned quest for a correlation between the results of an airtightness test and the normal air leakage experienced by the house. While some researchers[6,7] claim to have found such a correlation, we are not aware of any research into this issue which was **both rigorous**, in terms of the method and length of time of air leakage measurements, and **broad-based**, in terms of the number and variety of houses studied. Indeed, we have reason to be skeptical about the derivation of any generalized correlation since, in using the fan depressurization test to track the results of air sealing work, we have become aware of one shortcoming of the method, which seems obvious in retrospect. The fan depressurization test tests all of the leaks in the envelope in parallel; but many of those leaks will act in series under normal wind and buoyancy forces. Once one of the leaks in a series is sealed, sealing the others will have no effect on normal air leakage; but each sealing effort shows up as an improvement in an airtightness test, whether or not it is redundant in its effect on normal air leakage. Since the arrangement of parallel and series leakage paths is likely to vary from house to house quite randomly, is it likely that a generalized correlation exists?

I hasten to add that this latter point does not negate the value of the fan depressurization test as long as one bears in mind its primary purpose, which is to act as a quality control check on the envelope.

5. POSSIBLE FUTURE APPLICATION OF CGSB STANDARD 149.10

I mentioned earlier that improvements in the airtightness of our new houses would not likely yield substantial direct reductions in energy consumption. This does not mean that such improvements should not be strived for. The most important reason to do so is to reduce the incidence of interstitial condensation in the building envelope - a significant and apparently increasing problem, as we increasingly tend to operate our houses in a "flueless" mode without an active chimney flue to depressurize the house and reduce exfiltration. Another is to make heat recovery capabilities in ventilation systems more effective when and if it becomes economic to incorporate such facilities on a widespread basis.

There are two ways to encourage the building industry to adopt better practices in operations affecting airtightness - the "carrot" approach and the "stick" approach. Both can make use of CGSB Standard 149.10.

The "carrot" approach is already being used in the federal government subsidy program for low energy houses I mentioned earlier. This is the "R2000" Program, operated by the Department of Energy, Mines and Resources, in which a builder qualifies for a grant if his house meets certain criteria including an airtightness criterion. However, this program thus far has affected only a small number of houses.

The "stick" approach - incorporation of airtightness requirements in building regulations - has not been used yet and may not be for some time. There is reluctance on the part of provincial building code authorities to implement requirements perceived as being related to energy conservation and not to the traditional objectives of building regulations - health and safety. The fact that, in the six years since it was published, only one province in ten has implemented the "Measures for Energy Conservation in New Buildings" is eloquent testimony to this observation. Thus, although the "Measures" committee is contemplating incorporating a requirement for an airtightness test according to the CGSB Standard (with an appropriate criterion) in the next edition of the "Measures", it will have little immediate effect.

On the other hand, it is being increasingly recognized that the vapour barrier requirements in the National Building Code and its provincial offspring, with their emphasis on preventing vapour diffusion and their failure to effectively address the real cause of interstitial condensation (i.e. outward air leakage), are not very relevant in terms of protecting the structure from this growing menace. Perhaps, therefore, we can hope that airtightness test requirements and criteria might be incorporated in building codes proper rather than in energy conservation supplements. I know of no such plans at present; but these things take time. Our consensus approach to standards writing and implementation has many advantages; but speed is not one of them.

6. SUMMARY

My summary can be quite brief. We are very close to having in place a standard method for measuring the airtightness of houses which we believe addresses the relevant issues in this area and, with a few refinements, will yield accurate, reproducible results; but it is unlikely that this standard method will be used in any broad regulatory way in the near future.

ACKNOWLEDGEMENTS

The author gratefully acknowledges the contribution of Energy, Mines and Resources Canada towards the cost of preparing and delivering this paper.

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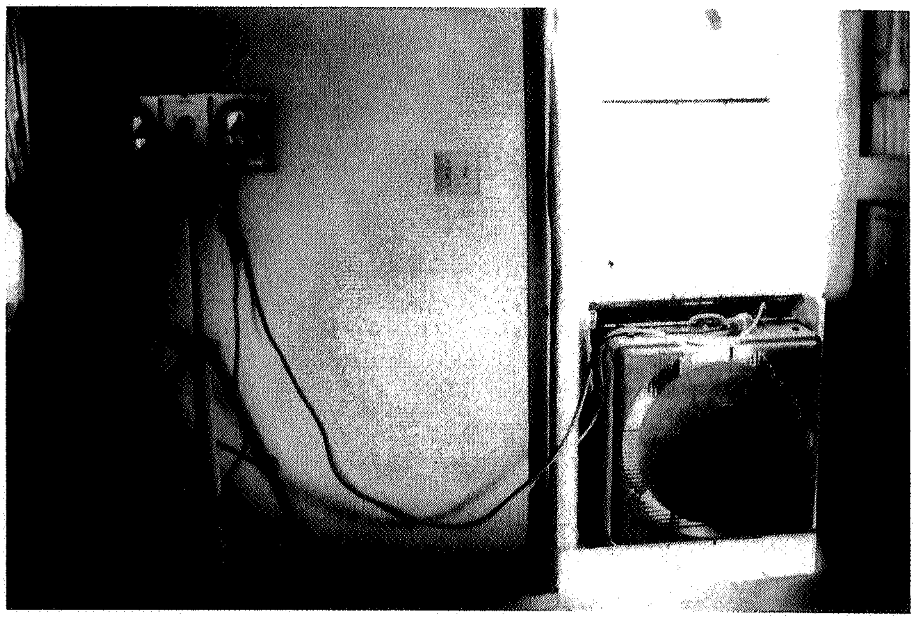


FIGURE 1

Depressurization fan installed in an exterior doorway; speed control and gauge unit on left. Disk in fan orifice reduces flow for tighter houses.

AIRTIGHTNESS TEST RESULTS (as per CGSB Draft 6)

85 KING ST.
AUG. 16,1983 Ext.Temp.= 23.8 C
Bar.Press. = 102 KPa Wind Speed = 4 km/h

PRESS. (PA)	TI (C)	MEAS'D.	FLOW(L/S) ADJ'D.	FITTED	RELATIVE ERROR(%)
10.0	24.0	675.00	678.11	670.18	1.17
15.0	24.2	850.00	853.63	865.42	1.38
20.0	24.2	1050.00	1054.49	1037.56	1.61
30.0	24.2	1300.00	1305.55	1339.83	2.63
40.0	24.2	1625.00	1631.94	1606.32	1.57
50.0	24.2	1835.00	1842.84	1849.02	0.34

C = 156.898007 n = .630573117

E.L.A. = 0.2682 m^2 Volume = 461 m^3

Q @ 10Pa = 670.18 L/S Q @ 50Pa =1849.02 L/S

Air Change per Hour @ 50Pa = 14.439

SXX= 2.10046194E+13 SXY= 1.32449483E+13

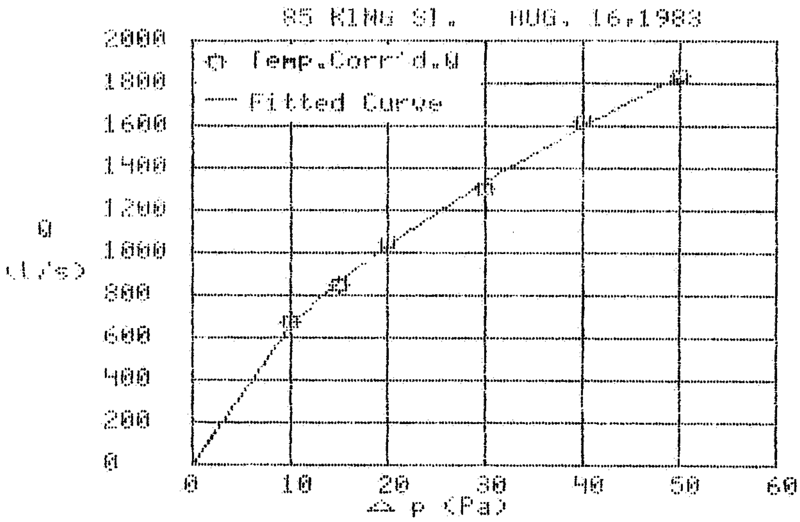
SYY= 8.37553855E+12 SYX= 24.2277571

Correlation Coefficient= .998588337

Relative Standard Error = 2.16%

FIGURE 2

Processed data from a typical airtightness test of a 2-storey, pre-war house.



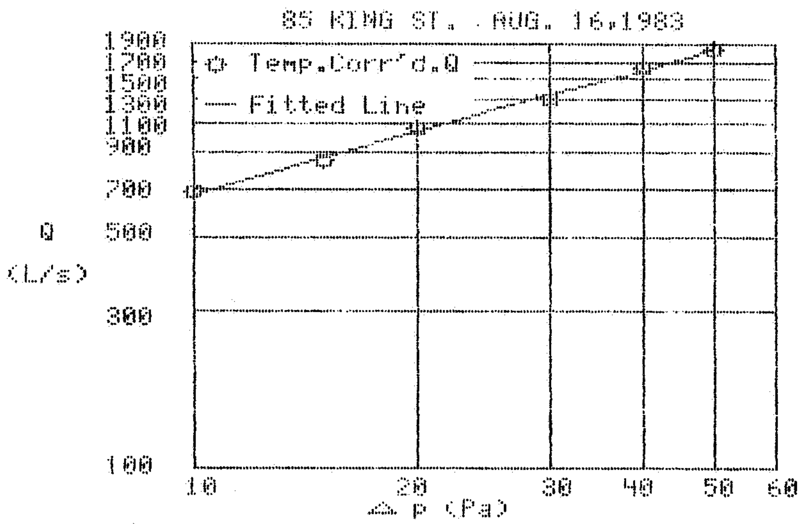


FIGURE 3

Plots of typical results from an airtightness test of a 2-storey, pre-war house.

THE IMPLEMENTATION AND EFFECTIVENESS OF AIR INFILTRATION STANDARDS IN BUILDINGS

5th AIC Conference, October 1-4 1984, Reno, Nevada, USA

PAPER 5

BETTER AIRTIGHTNESS: BETTER OR WORSE VENTILATION?

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SYNOPSIS

In Finland there are not yet any regulations or standards concerning the airtightness of buildings. Drafts have caused discussions: would a controlled airtightness increase the building costs too much, and would improved airtightness worsen the indoor air quality?

In modern Finnish buildings, a good or satisfactory airtightness can be achieved with a normal careful workmanship. To secure a good indoor air quality, a functioning ventilation system is also necessary. There seems to be no return to traditional "breathing" structures and natural ventilation.

Airtightness standards are still being discussed in Finland. A draft one, including also proposed requirements for a functioning ventilation system and its operation, is reported here.

1. INTRODUCTION

This paper is mainly based on several research and experimental projects carried out by the Technical Research Centre of Finland (VTT).

Airtightness standards have been discussed in Finland since about 1976. At that time some calculations were presented showing significant energy losses due to air infiltration. Since then, the airtightness of buildings has been improved, without standards, and with practically no extra costs, though leaky houses are still being built due to bad workmanship.

Traditionally, detached houses and row houses have been generally provided with natural ventilation plus (recently) a kitchen hood fan, but mechanical systems are gaining in popularity. In blocks of flats mechanical exhaust systems are dominant, with only a few exceptions with also a mechanical supply. Non-residential buildings are generally provided with a mechanical supply and exhaust ventilation system.

In natural or exhaust ventilation systems, as a rule, no attention has been paid to the supply air intake. In new airtight buildings, many air quality problems have been reported, especially in bedrooms.

Thus if any airtightness standards were given, they should also include guidelines for ventilation arrangements. Attitude among builders and designers should also be developed: the traditionally separate structural and HVAC designs are interrelated. The main aspects to be considered in developing the standards are: first, health and air quality, second, thermal comfort, third, energy effectiveness.

2. REPORTED RISKS ON AIR QUALITY

2.1 General

Several factors may affect the indoor air quality. Risks have been increased because of many reasons:

- improved airtightness
- increased energy prices - reduced ventilation rates
- declining outdoor air quality especially in cities
- new building and furnishing materials
- no internal fireplaces providing a good air change.

2.2 Common impurities

Carbon dioxide concentrations can become high - even up to a hazardous level - in bedrooms not provided with any ventilation arrangements.

High humidity seldom occurs in the Finnish climate with a few exceptions in extremely poorly ventilated occupied rooms. Moisture problems, e.g. condensation and mould growth have been reported.

The spreading of cooking fumes can be prevented with a properly used kitchen hood plus fan. Dusty exhaust air terminal devices are still very common and cause complaints especially in older buildings.

Tobacco smoke is considered one of the most common and harmful impurities. The official guidelines give higher design air flows for rooms where smoking is allowed.

Radon is a local problem in Finland. In certain smaller regions the soil is exceptionally radioactive. In underground spaces with low ventilation rates, radon can still cause health risks in other regions as well.

Formaldehyde may be the most common reason for complaints concerning air quality. It can be smelled in almost every new house expecially if ventilation is minimized. In many cases harmful, irritative concentrations remain even after the first one or two years.

2.3 The "bedroom problem"

At the time when the airtightness was not good, the natural ventilation and mechanical exhaust system worked well with no severe problems in air supply - there were enough leakage routes. New buildings are airtight, but they seldom have any supply air arrangements in the building envelope. The risks for the "bedroom problem" are evident.

This problem can be prevented, of course. But it requires a new way of thinking, a cooperation between the structural and ventilation consultants and the builders.

"The bedroom problem" has been presented at many occasions /1/. In table 1, experimental results are presented showing low measured air change rates in rooms without any ventilation arrangements. An extreme "energy-saving" effort can thus cause discomfort and even health problems!

TABLE 1

The breakdown of outdoor air flows and air change rates measured in various ventilation systems. (The PIKO experiment project, Helsinki, winter 1983-84)

Test flat no.	1	2	3	4
Ventilation system	Mechanical (plus warm-air heating)	Mechanical exhaust	Mechanical exhaust	Natural exhaust
% of outdoor air into:				
bedroom 1 (u)	20	11	4	1
bedroom 2 (u)	12	12	4	18
bedroom 3 (u)	12	11	-	8
living room (g)	16	15	6	7
kitchen (g)	15	28	18	34
corridor (u)	2	3	16	0
hall (g)	10	9	12	20
sauna, bathroom	13	11	40	12
Total	100 %	100 %	100 %	100 %
Air change rates in bedrooms				
bedroom 1	0,80	0,58	0,23	0,07
bedroom 2	0,42	0,55	0,23	0,68
bedroom 3	0,61	0,73		0,34
Total air change rate ac/h	0,5 h^{-1}	0,66 h^{-1}	0,72 h^{-1}	0,61 h^{-1}
Average pressure difference (-=internal underpressure)				
upper floor	0 Pa	-28 Pa	-9 Pa	0 Pa
ground floor	-5 Pa	-24 Pa	-6 Pa	-3 Pa
Airtightness	good	good	satis-factory	poor
Weather during measurements:				
Outdoor temp.	3 °C	0 °C	0 °C	0 °C
Wind velocity	6 m/s	4 m/s	4 m/s	6 m/s

u = upper floor, g = ground floor

2.4 Problems caused by the use of small local fan

A kitchen hood fan is very common in detached houses, and also in renovated flats provided with a natural ventilation. In airtight buildings, while the kitchen hood fan is on, the supply air flows in through the natural exhaust ducts from bathrooms and toilets. In winter the walls of these (generally masonry) ducts turn cold and it becomes difficult to change the air flow direction even after the fan is turned off.

3. PRINCIPLES OF AIRTIGHTNESS AND VENTILATION REQUIREMENTS

3.1 Existing regulations and guidelines for ventilation

Part "D2" (ventilation requirements and guidelines) of the Finnish Building Code, was published in 1978. /2/

The most essential part (in practice, i.e. among consultants and inspecting authorities) has been the table giving guidelines for airflows into (and in some cases from) various types of spaces. Parts of that airflow table are presented in table 2 (Residental buldings, offices). Corresponding values are included in e.g. ASHRAE Standard 62-1981 and British Standard BS 5720:1979.

It is also stated that an assumed infiltration of 0,1 or 0,2 ac/h can be included in minimum outdoor airflows. This detail has been widely criticised: in new airtight residential buildings the exhaust air ventilation is very often adjusted to give a mechanical ventilation rate of merely 0,3 ac/h.

TABLE 2

Recommended supply and return air volumes in different areas (According to the National Building Code)

Area	Ventilation quantities	Remarks
DWELLINGS		The units are $dm^3/s(m^3/h)$, if not otherwise stated
kitchen kitchenettes mini-kitchens	22(79)	12(43) is sufficient, if ventilation can be rendered more effective during food preparation or if the total ventilation rate in a small dwelling exceeds 1.5 air change per hour.
utility rooms	12(43)	
bathrooms	16(58)	8(29) is sufficient, if venting is possible through an easily openable window or ventilation can be rendered more effective after bathing.
toilets	8(29)	2(14) is sufficient, if ventilation can be rendered more effective after use. Toilet must be subjected to less pressure than the adjacent areas.
walk-in cupboards(>1 m^2	3(11)	An easily openable window or sash window replaces ventilation
OFFICE BUILDINGS		The units are dm^3/sm^2, if not stated otherwise
office rooms		
- smoking	1,6(5,8)	
- non-smoking	0,8(2,9)	
toilets	16(58)	$dm^3/s(m^3/h)$ per seat
conference rooms		
- smoking	10(36)	
- non-smoking	5(18)	
corridors and hallways.	0,8(2,9)	
storage areas and archives.	0,33(1,25)	
areas for the storage of cleaning equipment and materials.	3(11)	
common areas for smoking	16(58)	

3.2 Revising the requirements

A proposal for revised ventilation requirements have been worked on since September 1983. The purpose has been to develop requirements based on the best knowledge of today concerning principles rather than means.

Because the proposal is still being prepared for the Ministry of the Environment, no details can be published yet. The general contents are:

- definitions
- indoor climate
- principles for ventilation
- design, construction, commissioning
- operation and maintenance

Existing foreign standards are applied as reference material, e.g. ASHRAE 62-1981, BS 5920:1979 and the Nordic guidelines NKB 40(1981).

In the "Principles of Ventilation", a controlled supply air intake will probaly be required in buildings without mechanical supply air ventilation. Some guiding values for pressure conditions may be also given. Airtightness, as a structural property, is not determined in the ventilation requirements, and no numerical values would yet be stated for air infiltration, which in fact is a complicated result of structural and ventilation parameters.

3.3 Draft proposal for airtightness requirements

This preliminary proposal is reported in ref. /3/. It is mainly based on air quality and thermal comfort criteria rather than on energy aspects.

Entire buildings: a certain maximum air change is allowed to be verified in the building inspection with a pressure test. The main purpose is to secure the owner a certain quality of workmanship.

Parts of buildings: a certain airtightness should be achieved between flats etc. Numerous cases of leakage between flats, floors etc. via e.g. penetration and cracks have been reported lately -complaints about neighbours' tobacco smoke or cooking fumes are common.

Building elements: as in most countries airtightness standards are given for windows, in Finland as well. If the required airtightness is achieved, air leakages through the structures will remain a minor problem compared to those through structural joints.

Joints between structures: for comfort, cold leakage flows should be rather strictly limited. A suggested value will be about 0,2 litres per second and a meter of crack width. The airtightness of certain joints should be measured at the owner's request (see point 4.2).

Supply air intake: because of the reasons stated previously, this belongs to ventilation requirements in which it will probably be included (see 3.2). Recommended airflow -pressure difference characteristics shall, however, be included in the development of design guides and product standards.

The future development of airtightness standards - official and unofficial - is still an open question, because even moderate values raise a certain opposition.

4. MEASUREMENT METHODS

Measurements are necessary to verify the function of the ventilating system, including the tightness of the building envelope. In fact, infiltration itself is difficult to measure but the operating efficiency of the ventilating system can be measured with tracer gas methods.

4.1 Measurement of airtightness using the existing ventilation system for pressurization

There has been a lack of suitable methods for measuring the airtightness of large high-rise buildings. A new version of the pressure method has been developed in which the building's own mechanical ventilating system creates a suitable underpressure inside. In high-rise buildings, this method has proved successful.

Airflows in each supply or exhaust terminal device and pressure difference between outdoors and indoors as well as between apartments and stairwells are measured. Generally, the measuring procedure is quick and easy. The accuracy of the method is not high but adequate for practical purposes. It shows whether the building envelope is airtight enough (pressure differences high, 30 - 100 Pa, small deviation) or too leaky (difficult to create a measurable pressure difference). Simultaneously, the test can show whether the ventilating system is properly adjusted or not.

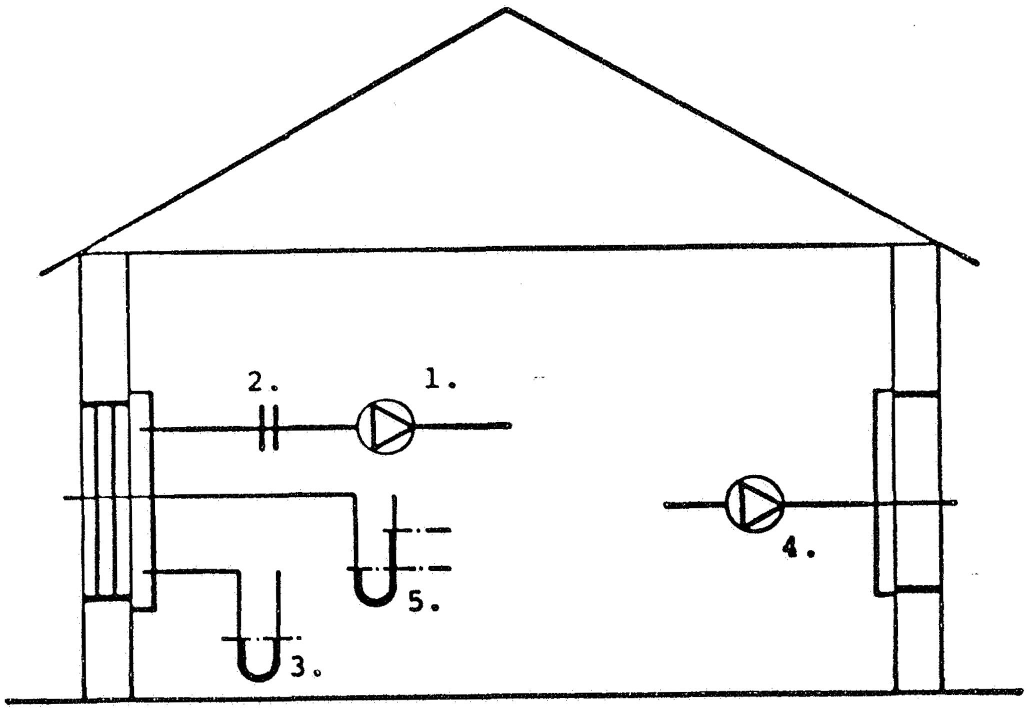
4.2 A statistical procedure in measuring local airtightness

Figure 1 indicates the equipment for measuring local air leakages by the collector chamber method /4/. The method is used for field measurements and it is the only way to get quantitative information about infiltration through structures,and especially structural joints. The method is highly accurate if the outdoor conditions are steady during the measurements. It is almost impossible to obtain the same pressure in the chamber and in the room if the wind is fluctuating.

The collector chamber method has been successfully utilized for quality control testing in actual buildings. This procedure was found necessary for testing the results of an experimental window sealing project ordered by the National Board of Public Buildings. Thirty-three similar openable double-paned windows were chosen for test objects. Nine window-sealing companies were then given the opportunity to show the quality of their workmanship by re-sealing a few windows each. High deviations in the airtightness were observed both between various test groups and within each group.

Because of the high number of structural joints in a high-rise building, it has been necessary for practical purposes, such as inspecting, to develop a statistical analysis for evaluating the local leakages (or the quality of workmanship in structural joints) with a minimum of measurements, see table 3. The measuring procedure is likely to remain very slow, and the practical applications of the method may be limited to case of complaint or for testing rooms in which an almost absolute airtightness is required. Even so, the existence of the method is important for the user of the building.

FIG. 1



Measurements of the total air leakage of a window with collector chamber method

1. Adjusted fan
2. Air flow meter (orifice plate)
3. Pressure difference between collector chamber and indoor air (eletric manometer)
4. Auxiliary fan (adjustable)
5. Pressure difference across the structure

TABLE 3

Sampling plan for inspection of local tightness in building /4/

lot size N	sample size n
≤ 15	3
16 - 25	4
26 - 50	5
51 - 90	7
91 - 150	10
151 - 280	15
281 - 400	20
401 - 500	25
501 - 1200	35
1201 - 3200	50
3201 - 10000	75

This statistical analysis has been applied also in estimating the airtightness of a new public building.

The building consisted of about 1000 office rooms; of these were about 70 chosen at random for measurements. The measurements were carried out in about three man-days (incl. preparations), the fans were run at both full capacity - giving about 1 ac/h at 150 Pa pressure difference - and half capacity, when the actual leakage factor at 50 Pa was about 0,5 ac/h, with only minor deviations between individual rooms.

5. DEVELOPMENT IN CONTROLLED SUPPLY AIR INTAKE THROUGH THE BUILDING ENVELOPE

To avoid the problems of uncontrolled air supply, there have been many efforts to develop systems and devices to control the supply air intake through the building envelope, both for new and existing buildings. The problems can be solved easily in new construction as various devices can be installed in walls, etc. In existing buildings, the installation of new equipment in the walls can usually be done only as part of a major retrofit project. One such possibility is to replace the windows with a better quality product.

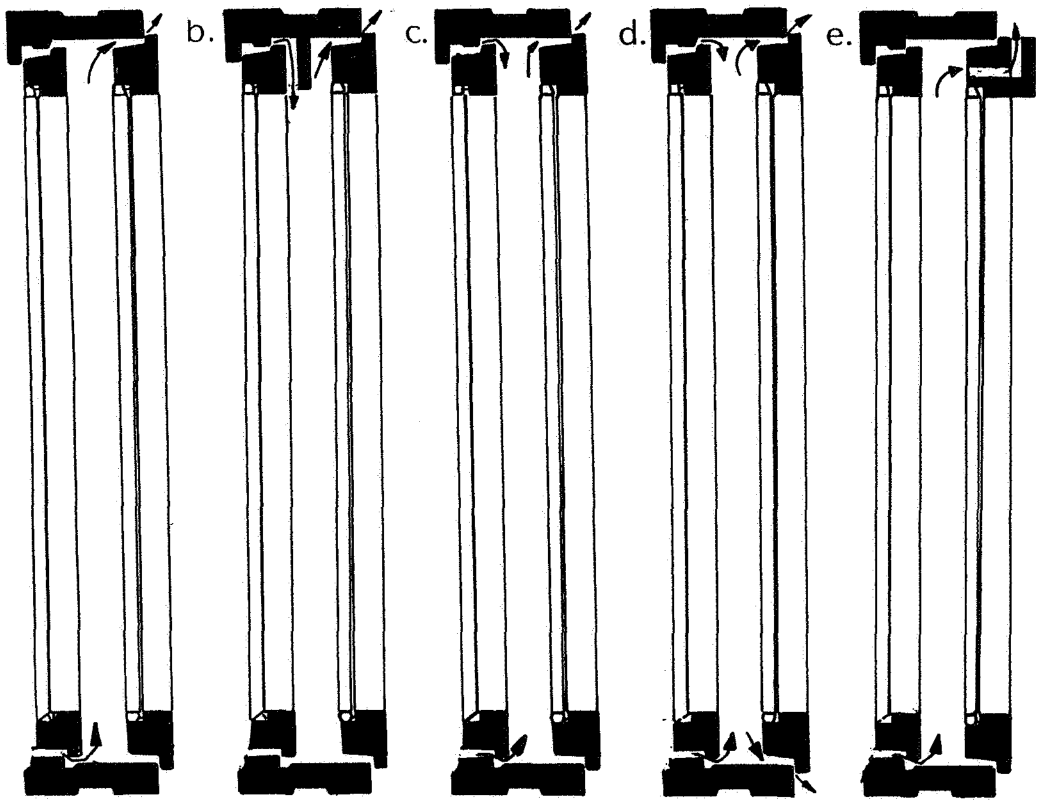
Supply Air Windows /5/. Among the several alternatives for the intake of outdoor air to a ventilated space is the supply air window which provides a designed path for the airflow. The window itself may be double or triple pane casement type window with various weatherstripping possibilities. The air may be taken in through the airspace between the window panes or through designed holes in the sash. Airflow through the window has in principle an opposite direction to the heatflow and the incoming air is heated by that heatflow in transmission at the window. This phenomenon is known in heat transfer text books as flow in porous material. The amount of heat transfer depends on the pattern of flow. The overall effect is an improvement in the energy balance of the indoor space. If the heat transfer from the room to the window is increased, that heatflow is used to warm up the incoming (ventilation) air and the heatflow from the exterior pane of the window is decreased.

The critical parameter in the operation of a supply air window is the pressure difference at the window. It should be high enough to decrease the effects of the wind and outdoor temperature on the ventilation and low enough not to cause difficulties in the operation of doors and windows. The optimum pressure difference determined through practical experience seems to be 10 - 20 Pa. Another important parameter is the airflow through the window. It affects all the properties of the window. Airflow through the window is critical because of the thermal conditions in the indoor space. The main concern in practice is to find the maximum airflow through the window that does not cause thermal discomfort to the occupants. The most critical thermal comfort parameter is the draught. Laboratory tests has been made to find out the influences of the supply air window on thermal comfort. Previously, laboratory tests were carried out also to find temperature conditions, overall heat transfer coefficients and condensation risks for various types of supply air windows.

On the basis of these tests it seems that the most efficient airflow pattern is the one with outdoor air flowing to the window space through the bottom edge of the outer pane and to the rooms from the upper edge of the inner pane. The surface temperature of the inner pane is important in respect of condensation and thermal comfort. Reduced surface temperature is a drawback of the supply air window system.

The supply air windows, as described above must be considered as a "not good but much better than nothing" -solution. Its properties in use cannot be controlled as those of the supply air devices especially designed for the intake and diffucion of outdoor air. Such devices can, of course, be integrated into a window element, as shown in fig. 2.

FIG. 2



Various types of air flow arrangements for a supply air window. Alternative e represents a more controlled air diffusion arrangement .

6. INFORMATION FOR OCCUPANTS AND MAINTENANCE PERSONNEL IS ALSO NECESSARY

Standards for infiltration and airtightness, as well as for ventilation, will remain too theoretical if they are only controlled randomly and in new buildings only. Unfortunately, in Finland (and probably also in many other countries) many problems are caused by incorrect operation and maintenance of structures and HVAC systems.

Keeping structures and building services in good condition is often assumed to be unnecessary and expensive. People forget that the building must some day be totally renovated. High renovation costs are generally related to poor maintenance.

Concerning the airtightness, it is easy to find out if complaints about draught have increased; the condition of windows and window sealing can be seen with bare eyes. The maintenance must, of course, be done by skilled operators, especially in ventilation, but with a proper schedule many unnecessary repair costs can be avoided.

User information and training, including service instructions in product information are means for improving the quality of maintenance. The quality of information is continuously being developed in Finland.

For an ordinary inhabitant (=for everyone) we must point out the following:

- kitchen terminal devices, and kitchen hood filters should be cleaned according to the instructions. Request instructions if you do not have any.
- avoid unnecessary airing in wintertime. You are of course allowed to open your window - but please keep it open for a few minutes only at a time.
- report on difficulties in opening/closing windows
- report on problems with the ventilation system

7. CONCLUSIONS

Standards for airtightness and/or air infiltration will have a great importance in securing a good building practice. But they alone are not enough, because ventilation is also necessary. Good standards or regulations should thus be a combination of

- requirements for airtightness for the whole building envelope (excl. ventilation arrangements) for building details and structural joints
- requirements for sufficient and controlled ventilation, both supply and exhaust
- guidelines for airtightness, infiltration and ventilation measurements (in building inspection etc.)
- instructions for use and maintenance

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THE IMPLEMENTATION AND EFFECTIVENESS OF AIR INFILTRATION STANDARDS IN BUILDINGS

5th AIC Conference, October 1-4 1984, Reno, Nevada, USA

PAPER 6

ENERGY PERFORMANCE STANDARDS REGARDING AIR INFILTRATION OF BUILDINGS IN SWITZERLAND

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SYNOPSIS

The Swiss performance standard for energy conservation in buildings SIA* 380/1 is explained. This standard leaves air infiltration and other detail decisions to planners if minimum performance levels are met. Calculation procedures for heat balances based on a standard-occupancy are described. Tools to achieve optimum space heating and ventilation rates are explained. Instrumentation for checking the thermal performance of the house in operation is defined.

*SIA: Swiss Society of Engineers and Architects

1. PERFORMANCE STANDARDS VS COMPONENT STANDARDS

Different countries have chosen different ways so far to limit building energy consumption. Most countries have started with component standards, established as a means to protect the consumer against deficient products. The large number of DIN-Standards in Germany [ref. 1] and the Californian Energy Conservation Standards [ref. 2] are typical examples for sets of building component standards. As for quality standards in complex systems as cars, buildings or some industrial products (tv-sets etc.) another method is equally established: the performance standard of an entire system which is treated as a black box. Standards for the fuel consumption of cars are a good example of this method where clear testing situations have been established. The advantage of this latter approach is a larger freedom for designers and producers to come up with solutions they find best under given economical and technical conditions. The standard serves only as a precisely stated goal, where the solution can be freely chosen among a multitude of always changing paths. Switzerland has chosen with SIA 380/1 [ref. 3] this latter method to limit energy consumption of buildings after a period of increasing numbers of component standards and responding to a growing concern of the professional community not to be completly regulated by detailed state legislation. Heating in the system "HOUSE" is devided into two subsystems:

- net heat consumption
- annual coefficient of performance

Both have to comply with the respective sets of standards. Electric consumption, the use of ventilation, air conditioning and cooling equipment are defined separately.

The SIA standard 380/1 (1984) gives a calculation procedure to compute the two sets of standards and also allows the use of an easier method for small buildings below 500 m2 gross floor area which is based on the older component standards with more stringent values.

Air infiltration is therefore not treated in detail in this standard. But it is included in the calculation procedures for heat loss, it is specified in the standard-occupancy and it is also treated in the component standards for small buildings (window joints etc.). According to a set of recent simulations on test houses the air infiltration share amounts to some 20 - 40 % of the net heat loss [ref. 4], with well insulated houses tending to the upper value.

2. TOOLS TO ACHIEVE OPTIMAL ENERGY PERFORMANCE

It is obvious that an optimisation of the heat balance of a building including losses and gains places great concern on the "optimum" ventilation. This means that in order to comply with a legal standard you may not design airtight buildings and prevent people from getting a sufficient amount of fresh air. Therefore, the standard is divided into three information sets:

- construction details to improve airtightness, avoid unnecessary hvac equipment, or/and to utilize heat recuperation (table 1)
- standard-occupancy defined as a set of air change rates depending on use; these values have to be applied in the calculation procedures (table 2)
- user related air infiltration of a well designed house should not be totally dependent on everyday compliance of all occupants. Advice and training has to be given to the normal user because most still open windows in wintertime to "moisten" the dry room air!

As for meeting the performance standard of a project in the design stage only this standard-occupancy is relevant; construction details can be freely chosen according to local practice*.

Table 1: Criteria for use of mechanical ventilation and air conditioning

- External influences	. noise . air pollution . safety . extreme alpine conditions
- Building parameters	. offices with deep spaces (< 6 m2) . offices with large spaces (> 200 m2) . internally located and underground areas . high rise (> 12 stories)
- Use conditions	. high occupant concentration (< 3 m2/person) . toxic fumes and smells (smoking) . high internal heat production (>45 W/m2)

Note: the Swiss climate is relatively moderate with an average outdoor temperature in Zurich in January of -1°C and in July of +18°C; of course there are southern zones with some 3 K higher average temperatures and extreme temperatures in the mean summer day of 33°C.

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* Many of the details in the AIC-handbook of 1983 will probably be rejected by the average Swiss craftsmen because the details involve elaborate fitting, which are infeasible as on-site work.

Air change rates in table 2 in the standard-occupancy are defined as minimum and maximum values. This means that without specific technical installations they cannot be reduced and they should not be increased. Of course the air change rates can be reduced during non-occupied times (nights, weekends, holidays) to a minimum of some 0.2 h^{-1} according to necessary humidity levels (figure 1). With the introduction of heat-recuperators and controlled ventilation the net air change rate can be reduced. Due to the minimum air flow and additional resistance of filters in used conditions, the air change rates cannot be very far below the rates stipulated in the standard-occupancy.

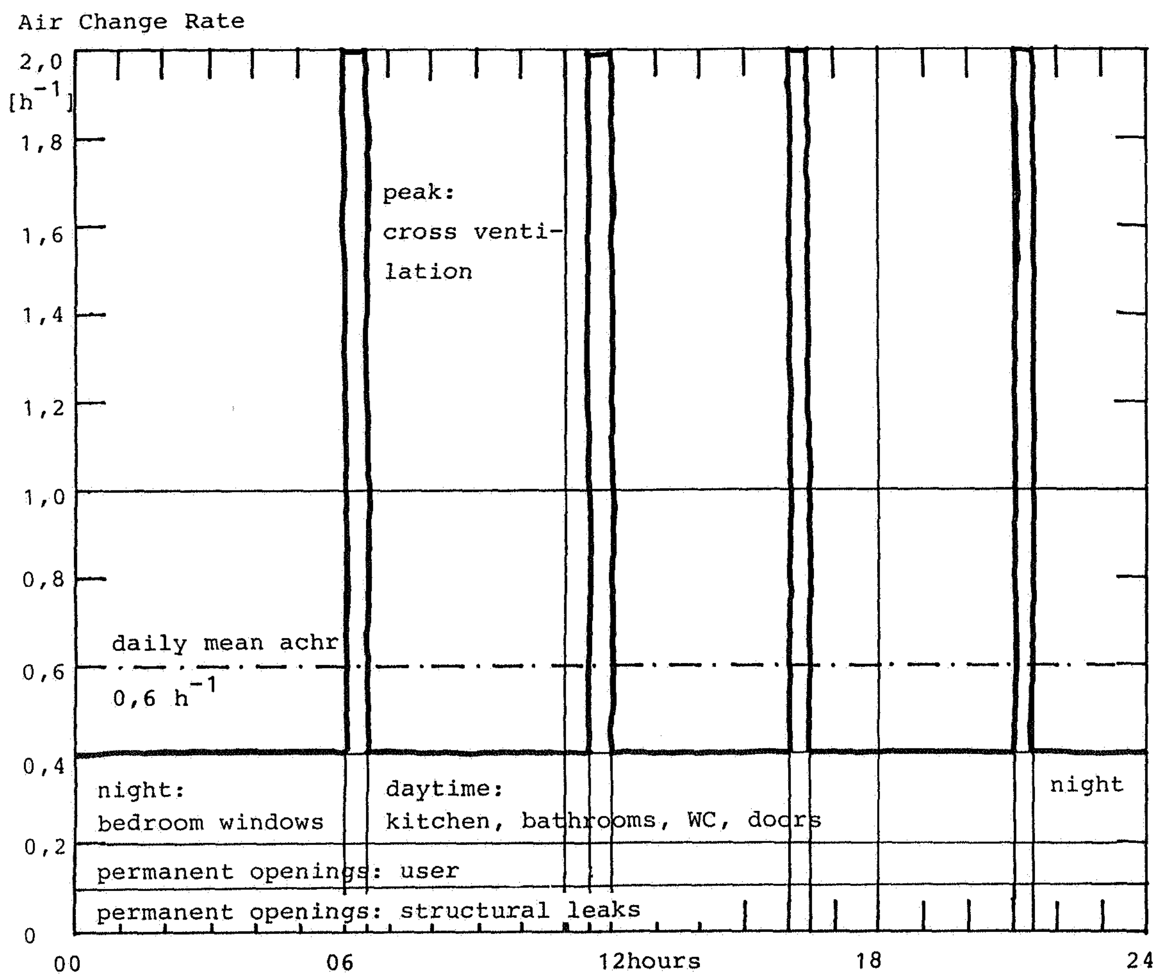
Table 2: Standard-occupancy: air change rates (annual mean values)

One family housing	0.4 h^{-1}
Multi family housing	0.6
Offices, commercial	0.8
Air tightness of entire building*	0.2

* With all doors, windows and other openings closed.

Figure 1: Air change rate (one day cycle)

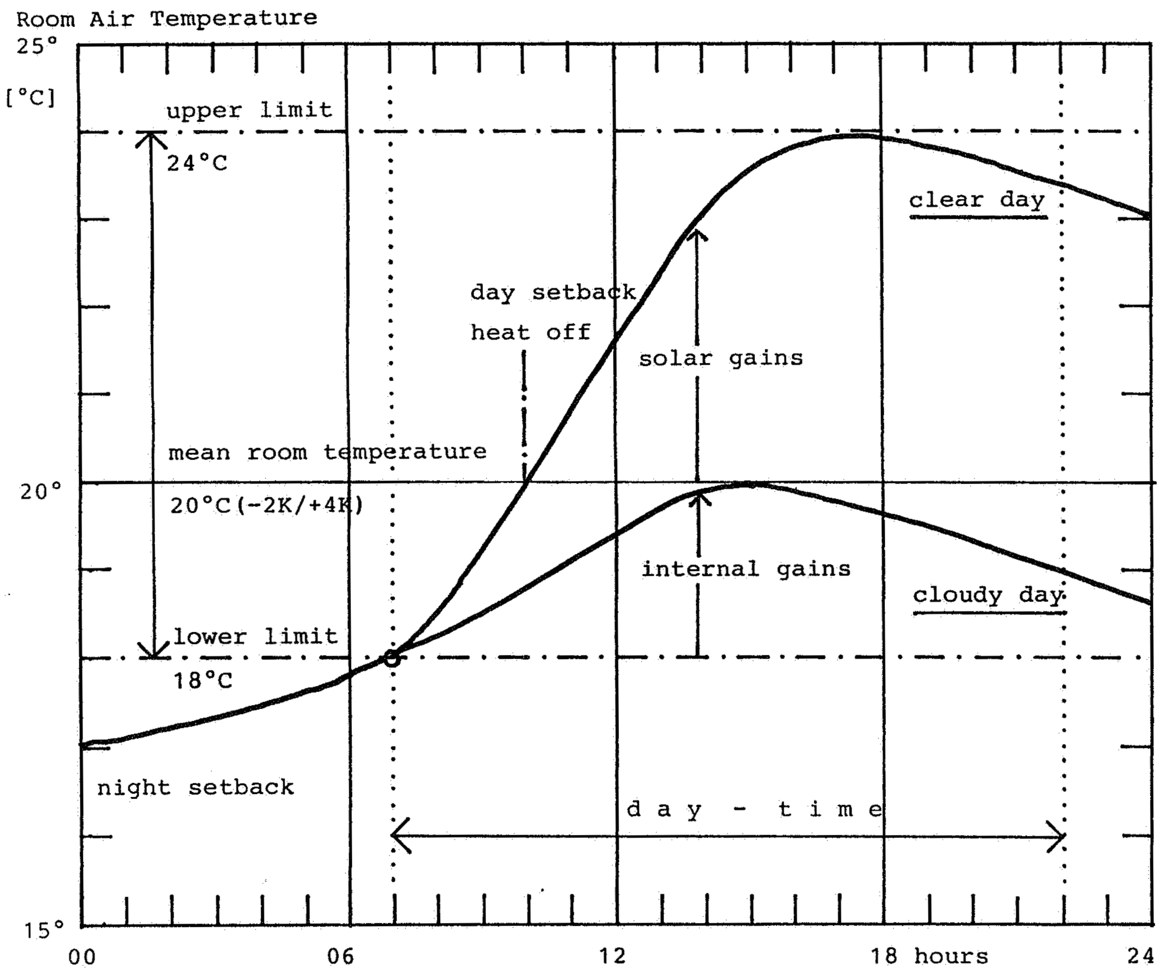
(Example for multy family housing)



The main issue is to achieve superior indoor temperature control in order to use the available free heat from solar and indoor sources to the maximum. This will prevent ill-advised users from opening windows excessively to control overheating (figure 2). Therefore, it is not only a question of educating users, but of giving them the proper tools to get the amount of heat they really want [ref. 5]. An additional feedback to users is cost-sharing according to the amount of heat consumed. This will of course dramatize this effect in a positive way.

Figure 2: Room temperature (one day cycle) [ref. 6]

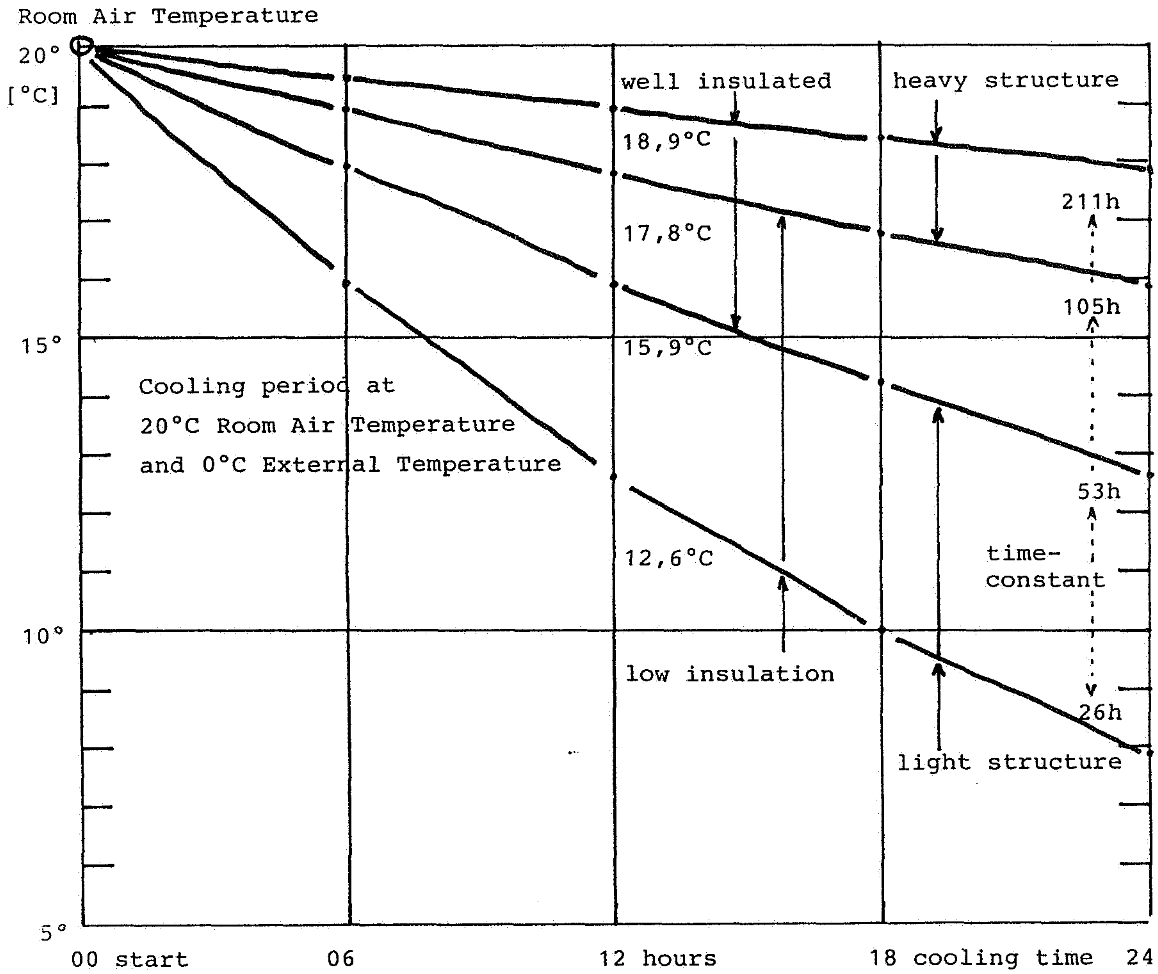
(Example for one family housing)



On the other hand it should be emphasized, that any quick change during the day in the desired room air temperature will not bring large heat savings due to the inertia involved in well insulated and tightly fitted houses (figure 3). This is especially true in the relatively heavy structures (over 600 kilograms per square meter) common in Switzerland and Central Europe. Such houses have a time constant of 150 to 250 hours, which leads to a temperature reduction due to night setback in normal winter conditions of only 1 K during night hours.

Figure 3: Night setback: cooling effect of air temperature

[ref. 6]



Any heating system depending solely on north oriented external temperature sensors and a fixed linear relationsship with heating system-temperatures cannot satisfy the stated objective of superior internal temperature controls.

The other central issue is to minimize heat loss due to infiltration which is generally not synonimous to minimal air change rates. Good room temperature controls of the heating system invite users naturally to a energy conscious behavior. The "synergetic link" [ref. 5] increases the effect of energy savings: good insulation and tight joints plus indoor sensitive room air temperature controls improves comfort conditions for the user and reduces energy consumption at the same time.

3. MEASURING ENERGY CONSUMPTION

In order to assess the process of designing, building and occupying an energy efficient building the ultimate performance check is only possible with measuring techniques. Therefore, a minimum set of measuring instruments is defined for a heating system (table 3). With these instruments every owner or controlling board can check, after a starting period of 2 years, the actual energy consumption and compare it to the design values according to the following formula:

$$E_h = \frac{N_h}{eta} \quad (MJ/m2 \cdot a)$$

E_h: annual specific end-heat use (MJ/m2·a)

N_h: computed annual specific net heating demand (MJ/m2·a)

eta: mean annual COP (-)

Table 3: Measuring instruments

- Counter of operation hours
- Start impulse counter
- Fuel consumption measurement (oil, gas, electricity etc.)
- Thermometer for temperatures of the exhaust stack
- Meter for domestic hot water

There is a tendency to include all these instruments in a package in the standard heating plant and to install performance meters that show an annual mean COP on a LCD.

Of course there will be a large band of deviations between calculated and measured values that can be divided into the following four categories:

- design changes (macro of detail) after the energy calculations have been made
- bad in situ details due to bad site supervision
- unnormal climate conditions (severe winter etc.)
- unnormal user behaviour (higher temperatures or ventilation rates etc.)

Initial drying-out and wood-shrinking periods have to be monitored and can generally be excluded from an analysis after the first two years of normal operation. First year of operation problems with regulation and optimisation efforts have to be taken into account, also. The band of deviation that generally is accepted with standard climate data are deviations of -10 % to +20 % of the annual energy consumption. Larger deviations have to be investigated and causes identified.

For this procedure it is necessary to stipulate the duty of house owners to keep energy consumption records and to offer them for public checks annually. For larger buildings monthly records are recommended. For the safe handling of possibly polluting fuels this rule has long been established in Switzerland. The data of gas, electricity and district heat consumption on the other hand are readily stored in sufficiently accessible data bases.

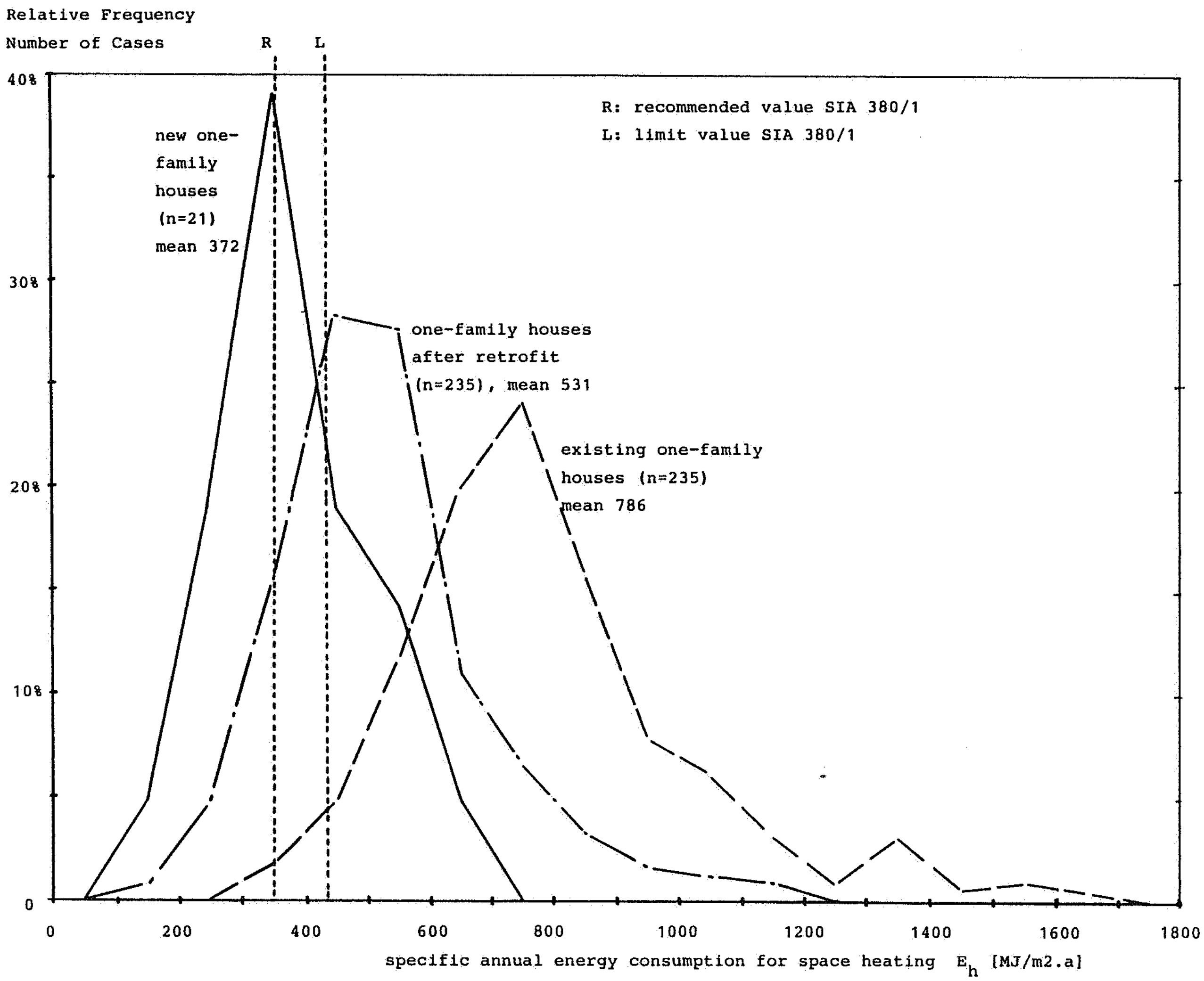
Such a measuring procedure is the new and final check of the building quality that should be included in every builder's contract.

4. POLITICAL AND ADMINISTRATIVE IMPLICATIONS

The administrative boards can control one set of standards that characterize the entire energy system or can go back and try to check all the detail components that have been regulated so far. A certain resistance to change from component to performance standard exists also in Switzerland, even if the new system seems easier to handle and less time consuming with limited manpower. Due to intervention of the local states the formal legal introduction of SIA 380/1 will be granted only after an initial testing period of some 2 years wherein all public buildings will have to comply already with the new standard.

The Swiss building stock has tended towards more efficient energy use since 1975 as can be shown in figure 4. This initial success will continue in the future with the introduction of SIA 380/1.

Figure 4: Specific heat consumption in housing [ref. 7, 8]



ACKNOWLEDGEMENTS

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THE IMPLEMENTATION AND EFFECTIVENESS OF AIR INFILTRATION STANDARDS IN BUILDINGS

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PAPER 7

DESCRIPTION OF ASHRAE'S PROPOSED AIR TIGHTNESS STANDARD

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SYNOPSIS

Because the load due to air infiltration typically accounts for one-third of space conditioning loads, ASHRAE (American Society of Heating, Refrigerating and Air-conditioning Engineers) is in the process of writing a standard which addresses the maximum leakage associated with good construction. This standard 119P, is a link between ASHRAE Standard 90,[1] which addresses energy conservation in new residential construction, and Standard 62,[2] which specifies the minimum acceptable ventilation to achieve adequate indoor air quality. Within Standard 119P there is currently a classification scheme that groups building tightness into categories depending on envelope leakage, floor area and building height. In addition to being used for this residential leakage standard, this classification scheme is intended to be used to label the tightness of any building residential or commercial, new or existing. This report will present the background around Standard 119P, indicate a proposed form that the standard may take, and present some of the rationale behind it.

Keywords: Air Leakage, Standards, Air Infiltration, Leakage Area.

SYMBOL TABLE

A	Floor Area [m^2]
ACH	Air Exchange Rate [hr^{-1}]
C_p	Volumetric Heat Capacity of Air [1234 J/K-m^3]
E	Infiltration Load [J/hr]
ELA	Effective Leakage Area [cm^2]
h	Building Height [m]
h_1	Height of a Single Story [2.5m]
H	Enthalpy [J/m^3]
H_{base}	Base value of enthalpy [82,000 J/m^3]
H_{in}	Inside Enthalpy [J/m^3]
H_{out}	Outside Enthalpy [J/m^3]
HDD	Heating Degree-Days (as calculated by ASHRAE) [^{o}C-days]
k_n	nthe constant (arbitrary)
IDD	Infiltration Degree-Days [K-days]
IDD_o	A specified number of IDD [450^{o}C-days]
NL	Normalized Leakage
Q	Infiltration [m^3/hr]
s	Specific Infiltration [m^3/hr-cm^2]
s_{ave}	Average specific infiltration for North America
T	Air Temperature [^{o}C]
T_{ave}	Average Annual Temperature [^{o}C]
T_{base}	Base value of air temperature [18.3^{o}C]
T_{in}	Average Indoor Temperature [22^{o}C]
T_{max}	Maximum no cool temperature [25.5^{o}C]
T_{min}	Minimum no heat temperature [15.5^{o}C]
v	Meteorological (10 m.) wind speed [m/s]
$\langle x \rangle$	Annual sum of the hourly values of x

1. INTRODUCTION

In this report will be discussed the details of a generic leakage standard for residential buildings. While based on the same objectives, principles, and methods that are being used in the proposed ASHRAE standard (119), the standard discussed herein need not be the same as the proposed ASHRAE standard.

2. BACKGROUND

Prior to the 1973/74 oil embargo, the primary infiltration concern in the heating and ventilating profession was the estimation of peak loads for the sizing of HVAC equipment. In the intervening decade, however, it has become clear that the energy loss due to infiltration represents a significant energy loss that can no longer go unchecked. To put this in perspective, buildings use over one-third of the total resource energy consumed in the U.S. with residential building accounting for about two-thirds of that share. Space conditioning (i.e. heating and cooling) account for over half of the energy used in buildings and infiltration accounts for at least a third of that. Putting this all together infiltration energy losses account for approximately one-fifteenth of the resource energy used in this country -- over 5 Quads (120 million ton oil equivalent). [See reference 3.]

The enormous expense (on the order of $50 billion) of heating and cooling air that has leaked into a building has caused the professional societies involved, primarily ASHRAE, and government agencies, primarily DOE, to re-examine their priorities regarding infiltration. The technical committee responsible for infiltration and ventilation in ASHRAE (TC4.3) has been an extremely active one; they are responsible for the revamping of the infiltration and ventilation chapter in the Handbook of Fundamentals and for administering several research proposals. Government sponsored research in the area of infiltration and ventilation has increased during the last decade and reflects the importance of the topic.

As technical research efforts mature and a consensus forms among the research and professional community regarding what can and what should be done, the time is ripe for the adoption of standards. The purpose of such consensus standards is to guide the practitioner in proper methods and to assure the ultimate consumer that he is purchasing something that meets some generally accepted criteria. In the field of energy conservation it is ASHRAE standard 90, "Energy Conservation in New Building Design", that is most widely used. This standard deals with both loads and systems, but refers little to air infiltration. Although it does not address the issue of overall infiltration performance directly, standard 90 does state that doors, windows, and curtain walls must meet certain performance specifications and that all joints must be sealed.

As the realization spread that plugging leaks was a cost effective method of saving energy, a concern arose that the indoor air quality of tightened buildings was being threatened as houses grew tighter. Many research programs have been and are being done on the sources and sinks of pollutants and on the interaction between ventilation and indoor air quality. One outcome of this research is ASHRAE standard 62, "Ventilation for Acceptable Indoor Air Quality"; this standard has both a performance part, which specifies maximum acceptable levels of certain pollutants, and a prescriptive part, which specifies minimum ventilation rates.

Currently there is an area that is not covered by either standard 90 (which is an energy conservation standard) and standard 62 (which is a health and safety standard) -- namely that of overall envelope tightness. Standard 90 deals with the thermal resistance of the envelope and standard 62 deals with minimum ventilation requirements, but not where is the acceptable tightness of the envelope for energy conservation addressed. It is for this reason that ASHRAE has convened a new standard committee, Standard 119P, to determine the minimum tightness levels that should be required.

3. OVERVIEW

This standard is limited in scope to those structures that can reasonably be expected to economically benefit from the application of the standard and to those types of structures in which there is a significant body of knowledge. Specifically, the standard applies only to detached single-family residential structures and does not apply to those structures that are conditioned for only a small fraction of the year.

This standard has two purposes: classification and limitation. The standard introduces a classification scheme that allows each structure to be ranked and categorized by its air tightness from class A (the tightest class) to class J (the leakiest class). These classes span the range from the very tightest measured houses to some of the leakiest measured houses. This classification scheme can stand alone as a method for comparing or labeling houses as to their air tightness. Even though the scope excludes buildings other than single-family residential ones, it is reasonable to expect that this classification method could be used on some of these excluded structures as soon as the measurement procedures warrant it.

The limitation section of the standard uses a new measure of the severity of climate, Infiltration Degree-Days (IDD), to set a maximum leakage class, as defined in the classification section. Infiltration degree-days are discussed in detail in a following section, but, simply, they are a measure of the severity of the climate in relation to infiltration in the same way that common degree-days are a measure of the severity of the climate in relation to thermal conduction through the envelope. Thus, for each site the number of IDD can be calculated from typical weather data and from that the acceptable leakage classes can be determined. In addition to the calculation methods the standard has a list of over one hundred cities for which IDD and acceptable leakage classes have been determined.

The standard contains two informational sections which, while not part of the standard proper, contain information that may be useful to the intended user. The first one concerns the estimation of typical annual air change rates for houses in each of the leakage classes. Although the purpose of the standard is to limit infiltration, nowhere in the standard proper is infiltration discussed. This is due to the fact that the details of the house, its environment and the microclimate around may have a substantial effect on the infiltration, but the air tightness can still be unambiguously measured. An attempt, however, is made to give an estimate of the lower limit of the average infiltration. It is expected that the users of standard 62 might wish to have some sort of method for estimating the contribution infiltration may make to the total ventilation.

The second informational section contains a map of the U.S. and southern Canada and on it are marked the cities that are contained in the standard. From the IDD values of each city an interpolation is made to cover the map with the different acceptable leakage zones. Because the values far away from measured cities and near the zone borders are sensitive to the details of the interpolation, this map cannot be used as part of the standard. It is, however, very informative in that it gives one an idea of the severity of climate over the entire area.

4. THEORETICAL CONSIDERATIONS

In order to come up with a standard, one must use a model of the physical processes involved and manipulate the results to come up with expressions for quantity of interest in terms of measurable quantities. For example, an energy conservation standard may set limits on R-values because the standards committee understood how R-values affected energy loss. In our case, we want to control infiltration and infiltration energy loss by setting standards for air tightness.

In deriving the expressions for this standard many specific details of individual buildings are averaged out. Therefore, the model that we use to connect air tightness to infiltration can, in general, be a generic one, rather than a specific one. For those few times when it is necessary to use a specific model to calculate a number we have used the LBL infiltration model.[4,5]

Generally speaking the infiltration can be thought of as a product of the leakage of the envelope and a driving term. We can write the expression for the infiltration for a single-story house as follows:

$$Q = ELA * s \tag{1}$$

The calculation of the driving term, s, need not concern us yet as long as we realize that it is some combination of the wind and stack pressures and may contain other details about the structure. The expression above is for a single-story house; we may generalize this to any height with the addition of a term to account for the fact that both the wind and the stack effects increase with increasing height:

$$Q=(h/h_1)^{0.3} * ELA * s \tag{2}$$

The exponent of 0.3 is chosen to approximate the height dependence of the stack effect (0.5) and wind effect (0.1 - 0.25).

This expression gives the instantaneous infiltration as a function of the driving forces, leakage, and building height; but, if we wish to compare houses, we must have a way of normalizing the infiltration to account for house sizes. We have elected to use the floor area as the normalization; we do so for two reasons: 1) the leakage is measured by an area and so some other area is an appropriate normalization, and 2) floor area is usually easily obtainable for almost any house. The normalized expression then becomes the following:

$$Q/A = (h/h_1)^{0.3} * (ELA/A) * s \tag{3}$$

We now define a dimensionless quantity called the normalized leakage, NL, that is a quantification of the air tightness of the envelope:

$$NL = 0.1 * (h/h_1)^{0.3} * (ELA/A) \tag{4}$$

If we substitute this definition into equation 3 we get the following:

$$Q/A = 10 * NL * s \tag{5}$$

In addition to the infiltration we are also interested in the infiltration-induced load. The load can be calculated from the infiltration by multiplying the air infiltration by the amount of energy required to bring the infiltrating to indoor conditions (i.e. the enthalpy difference between indoor and outdoor air):

$$E = Q * (H_{in}-H_{out}) \tag{6}$$

We can find the infiltration load normalized by floor area by combining the two previous equations:

$$E/A = 10 * NL * s * (H_{in}-H_{out}) \tag{7}$$

4.1 Selection Criteria

In constructing an air tightness standard two prospective criteria come to mind: 1) setting the maximum infiltration to be a constant, and 2) setting the maximum infiltration load to be a constant. The former concept would set the annual infiltration to be less than a specific number:

$$\langle Q/A \rangle < k_1 \tag{8}$$

where k_1 is a constant

Inserting equation 5 into this limit yields the following:

$$10 * NL * \langle s \rangle < k_1 \tag{9}$$

If we use the LBL model to find the annual average of the specific infiltration, $\langle s \rangle$, we discover that it only varies about 20% throughout North America. Thus for our purposes we can treat it as a constant. We then find that the normalized leakage is constrained to be below a constant value:

$$NL < k_2 \tag{10}$$

where $k_2 = k_1/(10*\langle s \rangle)$

An alternative to constant infiltration is constant infiltration load. This can be represented as follows:

$$\langle E/A \rangle < k_3 \tag{11}$$

where k_3 is a specified constant.

Substituting the definition for the infiltration load, equation 7, yields the following results:

$$10 * NL * \langle s*(H_{in}-H_{out}) \rangle < k_3 \tag{12}$$

The average quantity (in brackets) is a measure of the severity of the climate. Because the concept of degree-days is relatively well understood in the buildings community, we wish to make our climate severity term in a similar form. We, therefore, define infiltration degree days to be proportional to the bracketed term:

$$IDD = \langle s*(H_{in}-H_{out}) \rangle / (24*C_p*s_{ave}) \tag{13}$$

Combining the definition of infiltration degree-days (eq. 13) with the limitation on the infiltration load (eq. 12) we get the following limit for the normalized leakage:

$$NL = k_4/IDD \tag{14}$$

where $k_4 = k_3/(240*C_p*s_{ave})$ is a constant.

4.2 Choosing a Form

We have derived two possible functional forms for the basis of our standard: 1) constant normalized leakage (i.e. constant infiltration), and 2) normalized leakage inversely proportional to infiltration degree-days (i.e. constant infiltration load). Unfortunately, both these functional forms have serious drawbacks. If we choose constant infiltration, then the houses in the mild climates must meet the same tightness criterion as the severe climates. Since it would cost about the same for them to tighten their houses to this level, it would put an unfair burden on the mild climates.

Conversely, if we choose constant infiltration load, then both climates are paying about the same for their energy, but the severe climates had to tighten their houses more and thus it cost them significantly more. The law of decreasing marginal returns implies that the severe climates are then at a disadvantage relative to the mild ones.

Although both suggestions have disadvantages, we have delineated the two extremes; the optimum must lie in between. The exact optimum depends on many details of both the model and the structure -- ones we do not wish to deal with. Therefore, we choose a functional form which is approximately half way between the two positions and assume that there is no need to improve it further. Specifically, we assume that the normalized leakage decreases as the square-root of IDD:

$$NL = (IDD/IDD_o)^{-0.5} \tag{15}$$

Like the previous two criteria, this form contains a single adjustable parameter (IDD_o) to specify the standard, but it must lie closer to the true economic optimum than do they.

4.3 Classification

The previous section completely defines a standard once the value of IDD_o has been chosen. It would be possible to measure the normalized leakage and determine the IDD for each site and verify if the standard is met. It was felt, however, that this method of using the standard could lead to ambiguity and abuse. Small changes in local weather would change the appropriate value of NL; changes in the way in which NL is measured could have a significant effect. Finally, application of this standard would require repeated calculations to be made, and might not be appropriate for many users.

In order to solve most of these problems a system of classifications was developed, based on the equations above. For each measured NL there is a unique leakage class (A-J) and certain classes are acceptable for certain IDD zones. Because of the square-root in the previous equation, the top of each leakage class is root two times the bottom of the class and the top of each IDD zone is twice the bottom of that zone. Thus, an easy-to-apply set of leakage classes and IDD zones replace all the equations as a means for meeting the standard.

5. OPERATIONAL DEFINITIONS

The sections above give an overview of the standard and the theoretical background behind it. A standard, however, is a set of operational definitions and instructions that must be followed. In this section we summarize these instructions as they currently exist within the standard.

5.1 Measurement Procedures

There are two types of data required by the standard: weather data and building data. Unless the site of interest is one in the table contained within the standard, hourly weather data is necessary to calculate the infiltration degree-days. Weather tapes from the National Oceanographic and Atmospheric Administration (NOAA) may be used for this purpose; either TMY or TRY type tapes are adequate but they must contain hourly temperature, humidity and wind speed. For those few sites that neither are close enough to a listed site nor have hourly weather data, the standard provides a alternate method. To use this standard it is always necessary to make a measurement of the air tightness of the envelope, as well as related quantities. This standard uses the concept of effective leakage area (ELA) to quantify the leakage of the envelope.

The ELA is defined as the equivalent amount of open area (of unity discharge coefficient) that would pass the same amount of air under a specified reference pressure. The ELA can be calculated from fan pressurization measurements by extrapolating the measured flows to the reference pressure which is taken to be four pascals. The other quantities that are required for the standard are floor area and building height. All these quantities as well as the fan pressurization test method are as specified in ASTM standard E779-84[7] and, accordingly, E779 is required as part of this standard.

There are two quantities that are used in the standard and calculated from the measured data: normalized leakage and infiltration degree-days. Normalized leakage is calculated from the measured structure data and infiltration degree-days are calculated from the weather.

5.2 Leakage Classification

Leakage classification is quantified by the leakage class, which in turn is calculated from the normalized leakage. Normalized leakage is a quantity that depends only on the structure and not on the surrounding environment; as such it can be used to compare the air tightness of houses in different environments. It is a dimensionless quantity that uses the ELA normalized by floor area and contains a height correction term. All measured quantities can be found in the report section of ASTM E779-84. The numerical form of the normalized leakage (as presented in a previous section) is as follows:

$$NL=0.1*(ELA/A)*(h/h_1)^{0.3} \qquad (16)$$

The normalized leakage is used to determine the leakage class of the building from table 1:

TABLE 1: CLASSIFICATION OF LEAKAGE

Normalized Leakage	Leakage Class	Leakage Category
<0.10	A	
0.10-0.14	B	I
0.14-0.20	C	
0.20-0.28	D	
0.28-0.40	E	II
0.40-0.57	F	
0.57-0.80	G	
0.80-1.13	H	III
1.13-1.60	I	
>1.60	J	

(The category labels are included for convenience only, and correspond to the qualitative descriptions tight, medium, and loose.)

5.3 Leakage Limitations

The standard limits the amount of leakage that a building envelope may have depending on the severity of the climate of the building site. Infiltration degree-days are a measure of the severity of the climate as it affects infiltration loads in much the same way that heating degree-days are a measure of the severity of the heating season as it affects conduction through the building envelope. In the standard infiltration degree-days must be calculated by one of the two methods below or taken from a Locations Table.

The primary calculation method requires the following hourly data for a typical year: outdoor dry-bulb temperature, humidity and wind speed. For every hour in which the dry-bulb hourly data for a typical year: outdoor dry-bulb temperature, humidity and wind speed. For every hour in which the dry-bulb temperature is below T_{min} or is above T_{max} infiltration degree-days are accumulated as follows:

$$IDD = 1/(24*s_{ave}) * \Big[\underset{\text{for } T<T_{min}}{\langle s*(T_{base}-T)\rangle} + \underset{\text{for } T>T_{max}}{\langle s*(H-H_{base})\rangle}/C_p \Big] \tag{17}$$

We use the following definitions for the specific infiltration:

$$s = 0.044 * (v^2 + |T-T_{in}|)^{0.5} \tag{18}$$

This expression is derived using the concept of a standard house and the LBL infiltration model.[6]

$$s_{ave} = 0.27 \tag{19}$$

The secondary calculation method, which may only be used if it can be demonstrated that hourly data are not available and that no pre-calculated site is close enough, requires only two values: the "base 65" degree-days as calculated in the ASHRAE Handbook of Fundamentals, and the average annual temperature. Using the same definitions as above the total infiltration degree-days can be expressed as follows:

$$IDD = 2*HDD + 365*(T_{ave} - T_{base}) \tag{20}$$

Having defined the severity of climate through IDD, we may now go on to define the limitations imposed by the standard. For each range of IDD there are a set of acceptable leakage classes. The following table displays those classes:

TABLE 2: ACCEPTABLE LEAKAGE CLASS

Infiltration Degree-Days [°C-days]	Acceptable Classes
<625	A-H
625- 1250	A-G
1250- 2500	A-F
2500- 5000	A-E
5000-10000	A-D
>10000	A-C

Compliance is demonstrated if the measured leakage class is acceptable for the calculated number of infiltration degree-days. (This table was generated assuming IDD_o=450°C-days.)

6. ESTIMATION TECHNIQUES

Because this standard govern air tightness for infiltration reduction, estimation of actual infiltration rates do appear within the body of the standard. As we show below, in order to estimate infiltration from leakage and climate it is necessary to make more detailed assumptions about the house (i.e. use a specific model) than was necessary for the tightness standard itself. Furthermore, if an estimation of air change rate were part of the standard, liability questions could arise if a problem occurred because of actual infiltration rates below the estimated ones in the standard.

This section gives a technique for the estimation of air exchange rates from normalized leakage values and climate. These air change rates are seasonal average ones based on the average climate; instantaneous values of air exchange may differ quite radically from the averages calculated herein. The results in this section assume a typical structure that is typically shielded from a typical wind; these factors can easily vary by a factor of two.

In order to estimate the air change rate we can begin with equation 5, dividing through by the height of a single story:

$$Q/(A*h_1) = 10 * NL * s / h_1 \tag{21}$$

We recognize that the left hand side of this equation is the air change rate. Averaging over the year we get that

$$ACH = 10 * NL * \langle s \rangle / h_1 \tag{22}$$

One should take care when applying a formula like this because of the in-built assumptions. This air change rate is the annual average assuming that there is no mechanical ventilation, natural ventilation (e.g. open windows) and no occupant effects (e.g. door openings).

If we choose a particular model, we may evaluate the specific infiltration and thus find a numerical result for the air change rate. We therefore use the LBL model to evaluate $\langle s \rangle$ for the average conditions in North America. To within the 20% spread in specific infiltration values we can use the following expression as a "rule-of-thumb":

$$ACH = NL \tag{23}$$

The most important assumption that has gone into this evaluation is that the structure is typically (moderately) shielded. Variations in the shielding can cause errors of up to 50% in the air change rate.

Table 3 gives the range of seasonal infiltration rates for houses of different leakage class. The minimum value is calculated assuming a reasonable lower bound of $\langle s \rangle = 0.18 m^3/hr\text{-}cm^2$ and a reasonable upper bound of $\langle s \rangle = 0.36 m^3/hr\text{-}cm^2$. The standard value is calculated assuming that the structure exactly meets the air tightness standard.

TABLE 3: TYPICAL SEASONAL INFILTRATION RATES

	Leakage Class	**ACH RANGE $[hr^{-1}]$ Min**	**Standard**	**Max**
	A*	0.00	0.14	0.14
Category I	B*	0.07	0.20	0.20
	C	0.10	0.28	0.29
	D	0.14	0.36	0.40
Category II	E	0.20	0.48	0.58
	F	0.29	0.62	0.80
	G	0.40	0.77	1.15
Category III	H	0.58	0.99	1.60
	I*	0.80	--	2.30
	J*	1.15	--	--

* Leakage classes above H, do not meet the requirements for any climate and, therefore, do not have a standard value; class J has no maximum value because it has no upper limit on leakage. Leakage classes A and B are more than sufficient to meet any climate and therefore their standard entries and equal to their maximums.

6.1 Estimation of Average Loads

In the same way that we derived the average air change rate from equation 5, we may derived the average load per unit floor area from equation 7. If we combine equation 7 with the definition of IDD and using the LBL model to evaluate it, we get the following:

$$\langle E/A \rangle = 240 * C_p * NL * s_{ave} * IDD \qquad (24)$$

which, upon substituting for s_{ave} and evaluating numerically, leads to the following numerical (i.e., dimensioned) expression:

$$\langle E/A \rangle = 80{,}000 * NL * IDD \qquad (25)$$

7. DISCUSSION

The concepts presented in this report allow us to define a standard for air tightness that is based on the economic goal of minimizing the life cycle cost of infiltration. We may now use these concepts to predict some of the effects that the standard will have on North American housing.

We begin by compiling a Locations Table (Table 4). This table will have a set of representative cities for which good weather data was available. We then use the hourly weather data to calculate the specific infiltration, the number of infiltration degree-days, and the acceptable leakage classes according to the standard. This table, combined with a measurement of leakage, becomes the entire standard for the sites that can be represented by the included cities.

While the locations table is the best way to determine what the standard requirements are at a particular site, it does not give one a very good overview of what the standard requires for North America in general. In figure 1 we present a map of North America that contains values from the locations table, interpolated to cover the entire map. The crosses indicate the position of a city from the locations table; the contour lines are of infiltration degree-days; and the shaded areas represent different areas of acceptable leakage classes. The dashed lines indicate the mid-point of each class. Note that occasionally a site in the middle of a shaded region may be of a different range than the shading indicates; this is done to avoid the map looking spotty -- the locations table contains the correct values.

As indicated in figure 1, the majority of the southern plain of Canada and the northern plains of the U.S. are in acceptable classes A-D. Although not on the map, but reflected in the locations table, the north of Canada (including Alaska) has some extreme climates in the A-C range. The majority of the

U.S. (contained in a broad band from the northwest to the southern plain to the east and northeast) is in the A-E range. This band extends northward on the coasts into to Canada, but in the case of eastern British Columbia may be an artificial result caused by the paucity of weather sites. The southwest and southeast of the U.S. are in the relatively mild A-F class; southern California is the only section of North America to be in the A-G class.

We may use the equations developed in the previous section to make an estimate of annual infiltration rate for houses that exactly meet the standard. Combining eqs. 18 and 22, with the data from the locations table, we calculate an average infiltration rate. Care must be taken in interpreting this number, however, as this value represents the annual contribution neglecting occupant and mechanical effects and only for the period in which the building is conditioned. The total ventilation rate will, in general, be higher than this estimate and monthly values could easily vary by a factor of two from these estimates, hourly values by a factor of five or more.

With the above caveats in mind figure 2 gives an estimate of the infiltration rate for a house that exactly meets the standard. Most of Canada would have seasonal infiltration rates of approximately 0.3 air changes per hour -- the temperate parts slightly higher and the far north (including Alaska) slightly lower. The northern half of the U.S. would have air change rates between 0.3 and 0.4 ach with the Pacific northwest and eastern seaboard at or above 0.4 ach. The southern third of the U.S. would virtually all have infiltration rates above 0.4 with the populated regions of California lying between 0.5 and 0.7 ach.

In a similar manner to the air change plot of figure 2, we may combine eqs. 19 and 24 to estimate the average seasonal infiltration load (per unit floor area). While this procedure may give a reasonable estimate of the annual energy cost (in units of resource energy) associated with air infiltration, it is only a crude predictor of instantaneous infiltration load. Like the air change estimate, the load estimate is subject to large hourly variations, in addition it is subject to systematic monthly variation -- in the same way that conduction losses vary with the seasons.

Figure 3 is a plot of the average infiltration load for North America for a house that exactly meets the standard. Because the standard requires tighter houses for more extreme climates, the range of values is not large; the load goes from just under 50 MJ/m^2-yr for southern California to almost 150 MJ/m^2-yr for the Canadian plains. With the exception of the mild southwest and cold northern plains, the U.S. appears to lie in the range of 75-125 MJ/m^2 for annual infiltration resource energy.

7.1 Summary

In this report we have presented the derivation of and thoughts behind a generic standard on air leakage which should be very similar to the proposed ASHRAE Standard 119P on the air tightness of residential buildings. As this standard progresses through the consensus process it will undoubtly change, but the physical underpinnings presented here will most likely remain. This physical basis on which the model was developed allows an estimation of the impacts that such a standard will have on average infiltration rates and building loads. The classification scheme inherent in the model gives the standard flexibility so that should it become necessary to quantitatively change the standard, the requirements could be tightened (loosened) by simply adjusting the value of the constant within the standard, IDD_o, and hence the IDD ranges for each leakage class.

8. ACKNOWLEDGEMENTS

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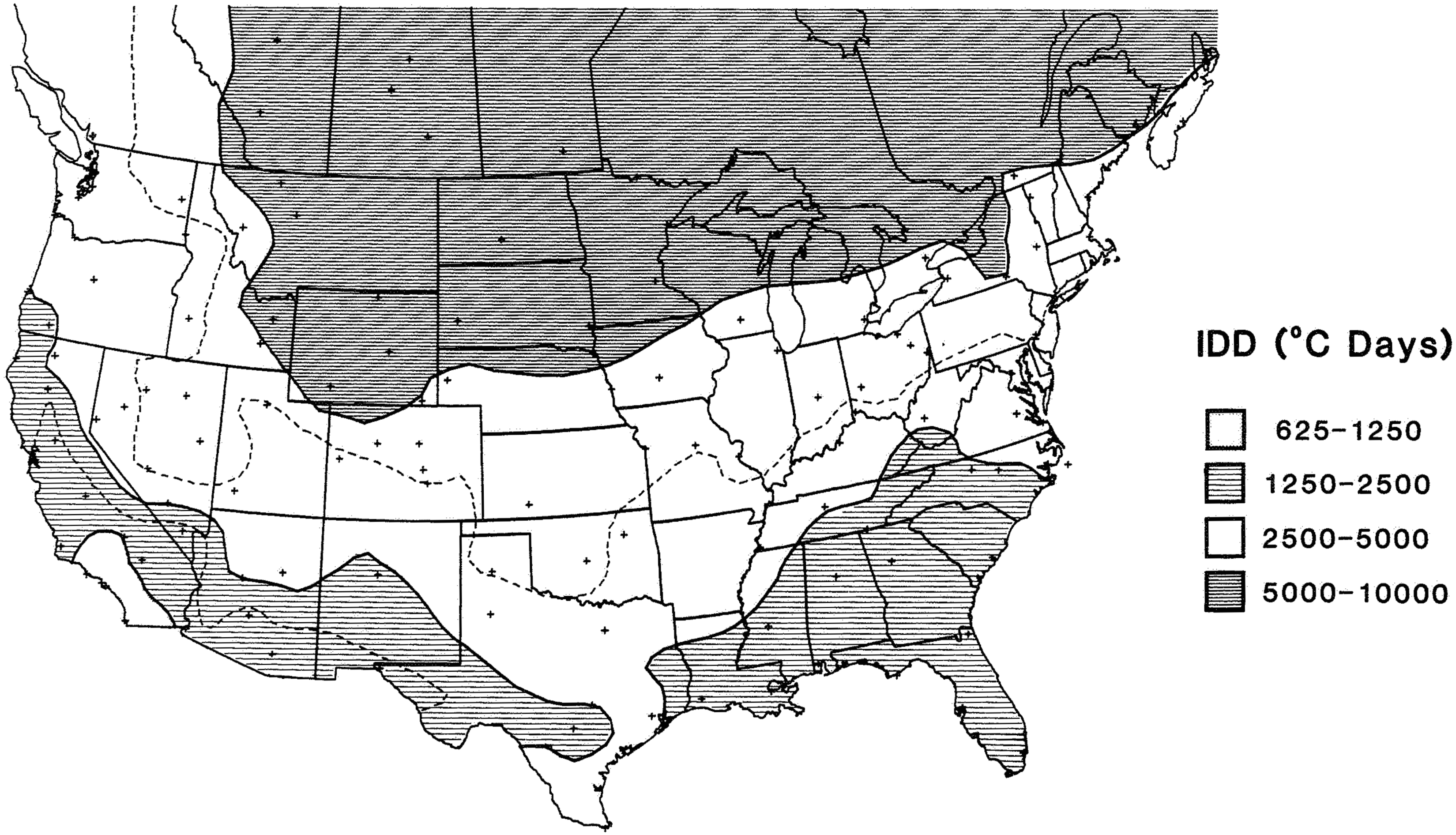
INFILTRATION DEGREE DAY ZONES



XBL 847-3060

Figure 1: Zones of infiltration degree days that correspond to unique acceptable leakage classes for north america.

STANDARD INFILTRATION RATES

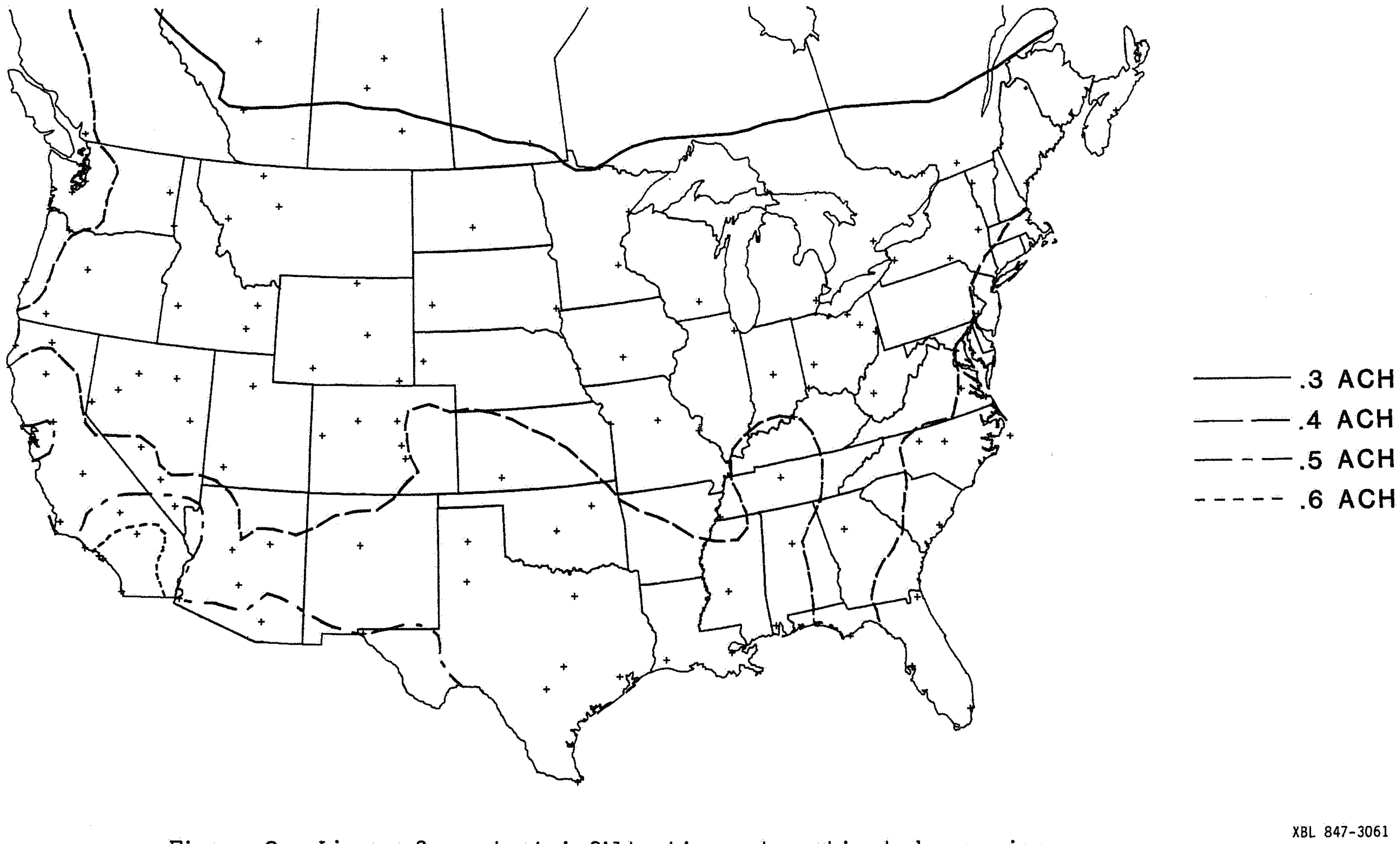


Figure 2: Lines of constant infiltration rate estimated assuming leakage standard is exactly met.

STANDARD INFILTRATION LOAD

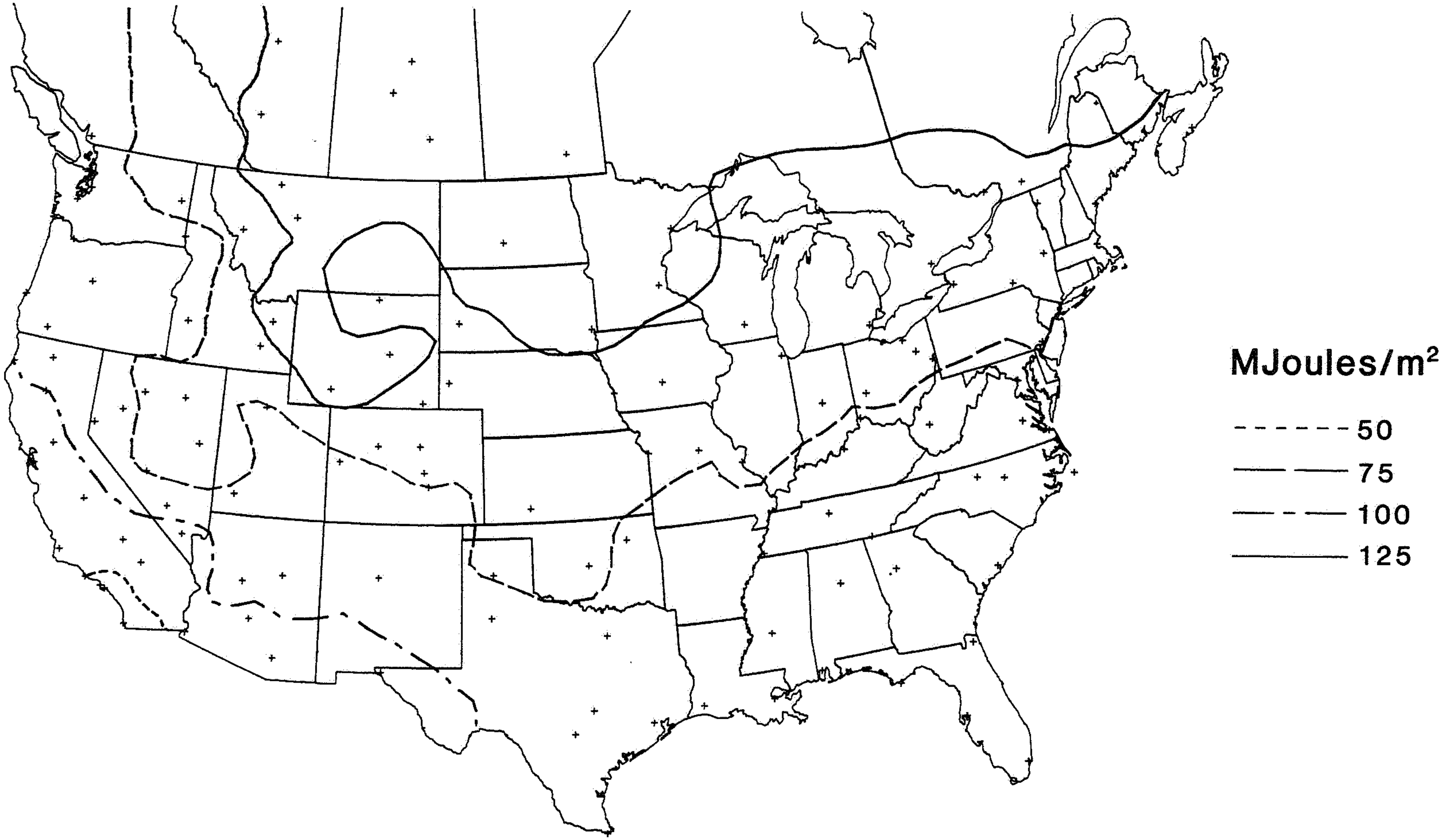


Figure 3: Lines of constant annual infiltration-induced load (per unit floor area) assuming leakage standard is exactly met.

XBL 847-3062

TABLE 4: LOCATIONS TABLE

CITY	Infiltration Degree-Days<s>				Acceptable
	Heating	Cooling	Total		Classes
BIRMINGHAM,AL	1424	606	2031	.22	A-F
MOBILE,AL	875	1124	1999	.24	A-F
PHOENIX,AZ	709	682	1390	.18	A-F
PRESCOTT,AZ	2690	52	2742	.26	A-E
TUCSON,AZ	946	371	1316	.24	A-F
WINSLOW,AZ	2678	64	2742	.26	A-E
YUMA,AZ	472	1244	1717	.24	A-F
ARCATA,CA	2028	0	2028	.20	A-F
CHINA LAKE,CA	1138	79	1217	.22	A-G
DAGGETT,CA	1329	208	1537	.29	A-F
FRESNO,CA	1306	182	1488	.20	A-F
LONG BEACH,CA	687	58	745	.20	A-G
LOS ANGELES,CA	650	7	657	.20	A-G
MOUNT SHASTA,CA	2952	25	2977	.24	A-E
OAKLAND,CA	1417	0	1417	.23	A-F
POINT MUGU,CA	843	3	846	.19	A-G
RED BLUFF,CA	1698	131	1829	.26	A-F
SACRAMENTO,CA	1503	107	1610	.23	A-F
SAN DIEGO,CA	417	11	428	.18	A-H
SAN FRANCISCO,CA	1850	4	1854	.26	A-F
SANTA MARIA,CA	1426	1	1426	.20	A-F
COLORADO SPRINGS,CO	3992	18	4010	.30	A-E
DENVER,CO	3550	5	3555	.28	A-E
EAGLE,CO	4624	2	4627	.24	A-E
GRAND JUNCTION,CO	3124	12	3136	.25	A-E
PUEBLO,CO	3049	31	3079	.25	A-E
WASHINGTON,DC	2180	444	2624	.24	A-E
APALACHICOLA,FL	643	1392	2036	.19	A-F
JACKSONVILLE,FL	652	1212	1864	.25	A-F
MIAMI,FL	72	2446	2517	.23	A-E
TAMPA,FL	249	1407	1657	.23	A-F
ATLANTA,GA	1741	461	2202	.25	A-F
BOISE,ID	3226	13	3238	.26	A-E
IDAHO FALLS,ID	6329	29	6358	.33	A-D
LEWISTON,ID	2929	11	2941	.24	A-E
POCATELLO,ID	4747	6	4752	.31	A-E
CHICAGO,IL	3709	204	3914	.28	A-E

TABLE 4: LOCATIONS TABLE (Cont.)

CITY	Infiltration Degree-Days <s>				Acceptable
	Heating	Cooling	Total		Classes
INDIANAPOLIS,IN	3744	333	4077	.28	A-E
DES MOINES,IA	4144	267	4411	.28	A-E
DODGE CITY,KS	3920	459	4379	.34	A-E
LOUISVILLE,KY	2713	409	3122	.27	A-E
LAKE CHARLES,LA	949	1280	2229	.23	A-F
NEW ORLEANS,LA	1022	1222	2244	.24	A-F
BOSTON,MA	4358	267	4624	.36	A-E
CARIBOU,ME	6481	20	6501	.31	A-D
PORTLAND,ME	4302	86	4387	.26	A-E
DETROIT,MI	4193	320	4513	.29	A-E
SAULT STE MARIE,MI	5967	34	6001	.29	A-D
DULUTH,MN	6873	55	6927	.32	A-D
INTERNATIONAL FALLS,MN	6867	29	6896	.30	A-D
MINNEAPOLIS,MN	5573	353	5926	.31	A-D
JACKSON,MS	1328	1062	2390	.24	A-F
COLUMBIA,MO	3146	458	3604	.27	A-E
KANSAS CITY,MO	3093	843	3937	.28	A-E
ST LOUIS,MO	3276	609	3884	.28	A-E
CUTBANK,MT	6520	1	6521	.34	A-D
GREAT FALLS,MT	5744	1	5745	.36	A-D
MISSOULA,MT	3928	4	3932	.23	A-E
OMAHA,NE	4029	589	4618	.29	A-E
SCOTTSBLUFF,NE	4780	90	4870	.31	A-E
ELKO,NV	3723	3	3727	.23	A-E
ELY,NV	4914	0	4914	.29	A-E
LAS VEGAS,NV	1295	189	1484	.25	A-F
LOVELOCK,NV	3214	4	3218	.25	A-E
RENO,NV	3087	8	3094	.23	A-E
TONOPAH,NV	3661	9	3670	.29	A-E
WINNEMUCCA,NV	3650	1	3650	.26	A-E
YUCCA FLATS,NV	2607	17	2624	.25	A-E
ALBUQUERQUE,NM	2353	35	2388	.24	A-F

TABLE 4: LOCATIONS TABLE(Cont.)

CITY	Infiltration	Degree-Days<s>		Acceptable	
	Heating	Cooling	Total		Classes
ALBANY,NY	4487	161	4648	.28	A-E
BINGHAMPTON,NY	4904	92	4996	.30	A-E
BUFFALO,NY	4740	65	4805	.32	A-E
NEW YORK,NY	3128	201	3329	.31	A-E
CAPE HATTERAS,NC	1714	901	2616	.29	A-E
GREENSBORO,NC	2074	381	2454	.24	A-F
RALEIGH,NC	2028	418	2446	.25	A-F
BISMARCK,ND	6552	167	6719	.31	A-D
AKRON,OH	3978	193	4171	.29	A-E
CINCINNATI,OH	2781	280	3061	.26	A-E
CLEVELAND,OH	4187	238	4426	.29	A-E
DAYTON,OH	4067	469	4537	.30	A-E
OKLAHOMA CITY,OK	3049	1162	4211	.33	A-E
TULSA,OK	2201	1088	3289	.28	A-E
ASTORIA,OR	2629	6	2636	.25	A-E
MEDFORD,OR	2153	20	2172	.20	A-F
NORTH BEND,OR	2492	0	2492	.26	A-F
PORTLAND,OR	2843	14	2857	.26	A-E
REDMOND,OR	3441	3	3443	.24	A-E
PHILADELPHIA,PA	3383	377	3760	.29	A-E
PITTSBURGH,PA	3619	184	3804	.29	A-E
CHARLESTON,SC	1178	883	2061	.25	A-F
RAPID CITY,SD	5199	117	5315	.32	A-D
FALLS,SD	5544	375	5919	.33	A-D
CHATTANOOGA,TN	2048	313	2362	.23	A-F
MEMPHIS,TN	1752	1001	2754	.24	A-E
NASHVILLE,TN	2013	543	2556	.25	A-E
AMARILLO,TX	3209	462	3672	.34	A-E
AUSTIN,TX	1072	1434	2506	.25	A-E
BROWNSVILLE,TX	321	3077	3397	.29	A-E
EL PASO,TX	1394	261	1655	.24	A-F
FORT WORTH,TX	1436	1291	2726	.26	A-E
HOUSTON,TX	986	1581	2567	.26	A-E
LUBBOCK,TX	2497	469	2966	.31	A-E
SAN ANTONIO,TX	1066	1299	2365	.25	A-F
CEDAR CITY,UT	3334	5	3339	.26	A-E
SALT LAKE CITY,UT	3446	12	3458	.26	A-E

TABLE 4: LOCATIONS TABLE (Cont.)

CITY	Degree-Days<s> Heating	Cooling	Total	Infiltration	Acceptable Classes
BURLINGTON, VT	4885	106	4992	.28	A-E
NORFOLK, VA	2111	521	2632	.29	A-E
RICHMOND, VA	2464	453	2918	.24	A-E
OLYMPIA, WA	2850	7	2857	.24	A-E
SEATTLE, WA	3146	11	3157	.27	A-E
SPOKANE, WA	4047	2	4049	.27	A-E
CHARLESTON, WV	2385	231	2616	.22	A-E
MADISON, WI	4487	161	4647	.28	A-E
CHEYENE, WY	5076	1	5077	.32	A-D
CASPER, WY	6068	3	6071	.37	A-D
ROCK SPRINGS, WY	6039	0	6039	.32	A-D
SHERIDAN, WY	4449	12	4461	.27	A-E
CALGARY, ALTA	5708	0	5708	.27	A-D
EDMONTON, ALTA	6080	4	6084	.25	A-D
VANCOUVER, BC	2455	0	2455	.21	A-F
CHURCHILL, MAN	12375	5	12380	.33	A-C
WINNEPEG, MAN	7233	72	7305	.30	A-D
SAINT JOHNS, NF	6768	32	6800	.36	A-D
FORT SMITH, NWT	8531	4	8535	.26	A-D
FROBISHER BAY, NWT	12277	0	12277	.31	A-C
HALIFAX, NS	4274	41	4315	.27	A-E
OTTAWA, ONT	5247	65	5312	.27	A-D
TORONTO, ONT	4671	185	4856	.27	A-E
MONTREAL, QUE	4542	145	4687	.25	A-E
PRINCE ALBERT, SASK	7111	35	7146	.27	A-D
REGINA, SASK	7815	17	7832	.33	A-D
SASKATOON, SASK	7062	11	7073	.29	A-D
WHITEHORSE, YT	7369	0	7369	.27	A-D

THE IMPLEMENTATION AND EFFECTIVENESS OF AIR INFILTRATION STANDARDS IN BUILDINGS

5th AIC Conference, October 1-4 1984, Reno, Nevada, USA

PAPER 8

AIR QUALITY ISSUES IN VENTILATION STANDARDS

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SYNOPSIS

Ventilation standards in buildings are receiving increased attention because of energy conservation and indoor air quality. An important example of this is the current ASHRAE Standard 62-1981, "Ventilation for Acceptable Indoor Air Quality." This standard contains two distinct procedures that can be used to set ventilation rates. The first is a prescriptive specification that mandates ventilation rates for particular building types. The second is a performance specification that uses target concentrations of indoor contaminants as the basis for deciding the adequacy of ventilation rates. This paper comments on the latter procedure. Several issues are discussed: (1) the lack of a consistent basis for choosing concentration limits for indoor pollutants (2) the potential for adverse air quality if the performance specification is adopted in a building, and (3) the practical difficulties in implementing the second option. Several suggestions for improving the Standard are made.

1. INTRODUCTION

There are many questions and issues that must be considered when discussing ventilation standards. These range from the philosophical issue of regulating air quality in individuals' homes to the practical problem of measuring ventilation rates. This paper examines ventilation standards from the perspective of present knowledge of and current research efforts on indoor air quality. To focus on particular issues it examines a ventilation standard that is currently under review, Standard 62-1981 "Ventilation for Acceptable Air Quality", of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. (ASHRAE) [1]. This Standard is the first North American ventilation standard that has attempted to address the indoor air quality problem in any general way. While we do not agree with portions of 62-1981, we do recognize the importance of its attempt to treat indoor air quality explicitly in a ventilation standard.

Ventilation or indoor air quality standards for buildings can take many forms. The most straightforward is a standard that directly specifies required ventilation rates for particular building spaces, based on assumptions about occupant density and pollutant sources within the space. A second type, having the form more of an indoor air quality standard than a ventilation standard, specifies maximum concentrations of particular pollutants in a space, but does not mandate the control processes to be used to maintain concentrations below these targets. It may include also a baseline ventilation rate. This form allows innovation in indoor air quality control techniques. A third type of standard focuses directly on sources. Its form specifies the maximum emission rates of pollutant sources within the space. It assumes a nominal ventilation rate and standard environmental conditions in the space to assure that pollutant concentrations remain below some target value.

The present form of Standard 62 provides two options for assuring acceptable indoor air quality. The first, called the "Ventilation Rate Procedure", specifies minimum ventilation rates appropriate to a variety of building environments. The second type, called the "Indoor Air Quality Procedure", does not specify ventilation rates, but assures the acceptability of the indoor air directly based on measurements demonstrating that the air meets the limits specified for acceptable outdoor air, as well as additional limits associated with specific indoor-generated pollutants.

2. THE FORM OF ASHRAE STANDARD 62-1981

A useful summary of Standard 62-1981 and a description of the thinking that was used to cast it in its current form is presented by McNall[2]. The Ventilation Rate Procedure, referred to as the "Prescriptive Option" by McNall, has the following requirements:

a) The supply air must meet National Ambient Air Quality Standards [3]; if outdoor air, the source of supply air, does not meet these standards, it must be treated using a suitable air cleaner.

b) The air must be delivered at rates listed in the Standard's Table III which covers a multitude of types of interior occupied spaces.

McNall further notes that when the interior contamination is caused by human activity (cooking, smoking, exercise, etc.), the ventilation rates are specified per person, not per unit of floor area. A minimum of 2.5 L/s per person is necessary to dilute carbon dioxide produced by metabolism. On the other hand, when the interior contamination is produced by the building or its furnishings, ventilation per unit floor area, not per person, is used.

A recirculation option, to save energy, is allowed if air cleaning equipment is certified by the designer to operate at a specified efficiency on the important contaminants. The air-volume capacity of the space (theaters, office buildings, etc.) which can dilute contaminants is recognized for intermittent occupancy. This allows delayed start of ventilation for additional energy savings for human-generated pollutants but requires a lead time before occupancy in the case of space-generated contaminants.

By contrast, McNall refers to the Indoor Air Quality Option as the "Performance Option". In this option:

a) The designer would meet the requirements of the Standard by certifying that the system provides an interior environment that meets or exceeds the air quality limits as specified in Tables I, II, and IV of the Standard. Table I is a summary of the National Ambient Air Quality Standards[3], while Table II includes additional ambient air guidelines that have been adopted by various states, provinces, and foreign countries. Table IV is a list of guidelines of pollutants of strictly indoor origin.

b) In addition, the air quality must be found acceptable by 80% or more of a panel of 20 untrained observers on the basis of odors or other subjective sensations.

Substantial differences of opinion exist on the suitability of the Indoor Air Quality Option as presently constituted. The option was developed for 62-1981 to allow innovative ventilation control strategies and because of the perceived importance of indoor air pollutants that were not necessarily those associated with earlier formulations of minimum ventilation rates. Difficulties with this formulation range from concerns about the inadequate knowledge of health risks associated with some of these pollutants to the practical difficulties of applying this form of the Standard.

This paper will discuss three major difficulties with the present form of the indoor air quality or performance procedure and make recommendations for revisions that serve to correct these problems.

3. DIFFICULTIES WITH THE "INDOOR AIR QUALITY PROCEDURE".

The most general issues arising from the current form of Standard 62, primarily in connection with the second option, are (1) the lack of a consistent basis for choosing concentration limits that apply indoors, (2) the potential that the second option, if used indiscriminately, may lead to poorer air quality than the ventilation option, and (3) the practical difficulty of using the second option, especially when interpreted to include a large number of measurements or even an odor panel.

The value of using a consistent basis for setting limits for a wide variety of pollutants is clear. In the absence of such consistency trade-offs can result that lead to the detriment of occupants or owners, rather than the converse. For example, by avoiding an exposure that is given too much weight (i.e., for which the specified limit is lower than it ought to be), one may cause some other exposure that is more harmful but that, relatively speaking, is not given enough weight (has too high a limit). An example is control of the concentration of pollutant A by removing its source. The guidelines for both pollutants A and B may now be met with reduced ventilation. However, if the guideline associated with pollutant B is too high, removing the source of pollutant A coupled with the ventilation reduction, will have caused an excess exposure to pollutant B. One simple criterion for consistency, then, is that numerical limits for the various pollutants correspond to equal health risks. Even this simple criterion is not met in the present formulation. Nor is it clear that this is the proper criterion in any case: the acceptability of specific risks might be weighted by the value of (or by the difficulty of avoiding) the exposure(s) in question. The general difficulty with the present Standard is that it is not based on a consistent philosophical basis and related criteria for development of specific standards. The concentration limits were not developed in the context of even a tentative set of criteria. It is certain that the present numerical limits are not consistent, derived as they are from several contexts, each of which had different criteria. An example of the kind of consideration that is necessary is given below, in the brief discussion of estimated health risk as one criterion for development of indoor standards.

4. ESTIMATED HEALTH RISK AS ONE CRITERION FOR INDOOR AIR QUALITY STANDARDS.

Several aspects of the use of risk as a criterion have already been mentioned, especially the difficulty of using even this criterion in a consistent way. Another perspective on the use of risk as a criterion is indicated by the following nominal (and very approximate) levels of risk associated with various situations. In each case, we cite approximate lifetime risks of mortality associated with the indicated situations and exposures. Risk of death is, of course, not the only risk criterion that could be used.

- Personal criteria for risk aversion tend to be in the range of 10^{-1} to 10^{-2} lifetime risk for risks under the control of the individual (as opposed to those imposed externally and discussed below). The larger number (10% or more) is associated with cigarette smoking and the smaller (about 1%) with automobile accidents. One percent lifetime risk appears, approximately, to be the level at which people begin to worry about chronic risk over which they have some control (and even at this level many people will not do anything about the corresponding exposure).

- Occupational criteria for exposures (over which individual workers have little control) tend to lie in the range of 10^{-2} to 10^{-3} for exposures that are specifically related to the type of work (e.g., exposures to a substance that arises from an industrial process). These must be distinguished from exposures that occur merely because a worker is in an indoor space (e.g., an office discussed below).

- Finally, environmental criteria for risks that arise externally to the people exposed, over which they have no control, and which are not directly related to a benefit to them, are typically less than 10^{-3} and often in the range of 10^{-5} (a number that the Environmental Protection Agency appears to use commonly as a criterion for such risks [4]).

Environmental risks are to be distinguished from the risks that individuals suffer in connection with situations of direct benefit to themselves, specifically in their own home and places of work. The current level of risk in homes appears to be in the range of 10^{-2} to 10^{-3}. (Some homes are as low as 10^{-4}, while a significant number exceed 10^{-2})[5]. This is the range arising from radon exposures alone, with other exposures adding to this. And, although it is possible in principle to reduce typical risks to lower values, it is probably not practical - again thinking even of radon alone - to reduce the level of risk much below 10^{-3} as a common matter.

A second difficulty with the indoor air quality option is the potential that, by meeting limits for specified pollutants, concentrations of unspecified (and unmeasured) pollutants might rise to levels that would be unacceptable if they were identified. As an example, suppose that in a residence, instead of providing the 0.3 to 0.6 ach that corresponds to the ventilation rate option, the designer reduced the ventilation rate substantially and provided assurance that CO_2, radon, and formaldehyde levels were not excessive. If that residence had normal sources of other pollutants, then, in first order, the lower than normal ventilation rates would result in higher than normal concentrations of these pollutants. It would appear that this option ought to have a baseline ventilation rate, which depends on the size of the space rather than the occupancy, to provide for the possibility of unknown or uncharacterized indoor sources. (This same difficulty arises in connection with the specification of ventilation rates on an occupancy basis when the occupancy is low. Thus, in this sense, the ventilation rate option, except for specialized buildings, does not take account of pollutant sources that exist independent of the occupants. This would seem to suggest the provision of a lower limit for the ventilation rate per unit volume, even in the ventilation rate option. However, the need is more acute in the second option, where the entire orientation of the approach is to assure adequate air quality directly, permitting a reduction of ventilation rates.)

A third broad difficulty is that of implementation, specifically how a ventilation engineer is to ascertain what measurements ought to be performed under the Standard and in what way they are to be carried out. At the extreme, i.e., the interpretation that measurements are made of all the pollutants found in the three tables of the Standard (a literal reading of the Standard), the difficulty is clearly prohibitive. But even with a softer reading, how can the engineer know which pollutants to measure and how they are to be measured? The Standard provides no guidance on estimating pollutant levels or on measurement techniques and protocols, nor does it indicate where the engineer might go for help. Thus from a practical point of view, the present formulation merely raises the issue of indoor air quality in a way that the designer and the code writer cannot handle effectively.

The criterion for <u>commercial</u> buildings, including office buildings, ought to take account of this general picture. As a possible extrapolation from the situation in employees' homes, where the risk will probably remain in the vicinty of 10^{-3}, one might use this as a criterion applicable to offices and other workplaces. If a stricter criterion were adopted, this would mean pushing employers or building owners beyond the usual concept that "excessive" risk should be avoided in connection with work situations. What is acceptable (or unavoidable) in homes might be a reasonable criterion for what is acceptable in the workplace.

This discussion only suggests one of the perspectives that has to be developed in trying to formulate the risk aspect of an overall basis for choosing indoor air quality standards. Closely related is the development of a consistent basis for actually estimating the risks associated with the various pollutants appearing indoors. This, too, is a complex and difficult question, both from the point of view of the dose-response data base and from the difficulty of deciding what population groups ought to be considered in evaluating risks.

5. PROPOSED CHANGES TO ASHRAE STANDARD 62-1981.

On the whole, considerations such as those given above suggest that an approach to revising 62-1981 ought to 1) retain the ventilation rate procedure much as it is and 2) modify the second procedure to correct the difficulties with its present form, preferably while still providing effective guidance on the question of indoor air quality. An approach consistent with these objectives is given below. Undoubtedly it is not the only possibility, but most other suggestions have either neglected indoor air quality, specifically by dropping the second option entirely, or have retained the present difficulties, by retaining the basic formulation of the second option and modifying it only in detail (rather than concept). The formulation given below is an intermediate possibility that does not include indoor air quality as a second option but, for the present, adds such considerations as a specific form of guidance as part of the more traditional procedure. It asks the ventilation engineer for a statement of design assumptions that would continue to be associated with the building after its construction and occupancy. The assumptions would have several practical implications for the designer of the building, including providing a way of handling the question of indoor air pollutants.

The proposal is:

1. RETAIN the bulk of the 62-1981 language, particularly the section on the ventilation rate procedure, with modest changes - e.g., re-examining specific ventilation rates on the basis of new information, and perhaps specifying a minimum ventilation rate per unit volume, thereby coping with low occupancy situations and the presence of unidentified sources.

2. REPLACE the second procedure with a continuation of the ventilation rate procedure that:

a. notes that innovative ventilation techniques may be employed (e.g., controlling on CO_2), provided that:

- makeup air continues to meet the usual conditions;

- a minimum ventilation rate is provided to avoid difficulties with unspecificed pollutants that are building- rather than occupant- related;

- explicit consideration is given to the pollutant classes specified as part of the standard (as indicated below).

b. specifies that certain pollutants that do not originate with occupants can be of concern. This section would be for the information of the user and would specify pollutant classes that are reasonably well defined (e.g., radon and its decay products, formaldehyde, combustion emissions), indicating situations when they could be a problem, as judged by provisional indoor air quality guidelines. The following section would indicate explicitly an approach for the designer to handle these possibilities, as they occur for each of the pollutant classes specified.

3. ADD specifications for a one-page statement of source assumptions used in the design. This would include assumptions related to the occupants, as well as aspects of the building structure that are related to indoor pollutants. As elements in this statement, examples are:

a. The number of occupants assumed in area ________ is ________.

b. The percentage of smokers assumed in area ________ is ________.

c. The limit on the area of material emitting _____gm of formaldehyde per hour to meet the tentative IAQ guideline of (cite) is $\quad$ m^2 per m^3 of volume.

d. The limit on radon entry rate needed to meet the (e.g., NCRP limit of 8 pCi/l) is ______ pCi l^{-1} h^{-1}.

There may be some version of the source statement for combustion emissions. However, a statement of this kind would probably only be appropriate for building projects of a certain scale, i.e., largely to commercial buildings, which tend not to have combustion sources in the occupied spaces. On the other hand, most residences are now built as large-scale projects - called developments, apartments, etc.

Eventually, other classes than those mentioned might be added. For example, a specification might be added for organics as a class, with the practical implication that some standard must be developed. However, like the formaldehyde formulation given, this might be source-oriented, albeit different in concept. For example, an initial material-oriented measure might be odor as perceived in a test chamber. (This might be a more practical utilization of the odor-panel approach than that presently specified in the indoor air quality procedure.) Hence, the ASHRAE language might ultimately simply state the assumption that materials employed in the interior meet a materials standard, which might be developed separately.

Note that this source statement would tend to solve another important difficulty with the ventilation rate procedure. That is, although the designer may size systems for a certain number of occupants with a certain proportion of smokers, this information does not necessarily affect how the building is used or occupied. In this suggested approach, the builder and designer can choose design assumptions on ocupancy and smoking, complete the design, then include the assumptions in the source statement -- which would continue to be available.

ASHRAE could recommend that this "statement of source assumptions" be incorporated with the legal documents conveying ownership of the structure, so that it could always be referred to if necessary; the knowledge that this is available would provide an incentive for the building to be operated in a manner that is consistent with the design assumptions. And regardless of the association with deeds of ownership, the statement of source assumptions, if completed, solves the present difficulty of conveying basic information to, at a minimum, the initial operators of the buildings. Moreover, it provides the ventilation system designer with an easy and practical way of handling the IAQ question and of conveying essential information to those who design the furnishings and have influence over other potential sources. (It would also be appropriate for similarly straightforward procedures to be included in the ventilation rate procedures, indicating how the ventilation engineer ought to handle the pollutant limits specified in the first two tables of concentration limits. As a general rule, whenever a number is given, even if it is a national outdoor air quality standard, a way of using it ought to be specified.)

6. CONCLUSION

The three elements given above constitute an approach to revising Standard 62-1981 to meet the objectives indicated earlier. Although this is certainly not the only approach, it is straightforward and gives examples of some considerations in formulating a revised approach to the question of controlling pollutant concentrations.

As a final note, these brief comments cannot adequately explore the variety of considerations pertaining to revising the Standard, nor can they indicate a practical approach in any detail. They may provide some useful thoughts on some of the considerations and, if developed more fully, could lead to a specific and generally satisfactory result. To a significant degree, the approach suggested avoids the overwhelming difficulty inherent in ASHRAE formulating a consistent rationale for indoor air quality standards. Instead, we suggest that a simple approach be adopted that retains the Standard's present emphasis on ventilation rates, while giving the designer practical means to handle the question of indoor air quality.

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THE IMPLEMENTATION AND EFFECTIVENESS OF AIR INFILTRATION STANDARDS IN BUILDINGS

5th AIC Conference, October 1-4 1984, Reno, Nevada, USA

PAPER 9

AIR LEAKAGE OR CONTROLLED VENTILATION?

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SYNOPSIS

This paper compares the conventional exhaust system with a supply-exhaust system concerning which degree of control of the air exchange in the individual rooms is possible.

Ventilation efficiency and air exchange efficiency are defined. Some examples show the local concentration, mean ventilation efficiency and mean air exchange efficiency for some simple ventilation schemes. Exhaust systems require a very tight building with small make up air openings.

The different systems' ability to avoid leakage out from the building of indoor air is compared too. The calculations indicate that the exhaust system can give small duration of indoor air. The supply-exhaust system gives a greater duration, but the flow can be considerably reduced if the supply air flow rate is reduced. An extremely low velocity exhaust system will also reduce the unwanted outflow.

INTRODUCTION

Ventilation comes from the latin word "ventilare" which means "expose to the wind". In Rome, where the climate is nice, people then probably thought of a gentle, cooling breeze. In Sweden a more natural association is draught. The art of ventilation, as it is practiced in Sweden of today consequently aims at not being noticed. It is typical that the increased interest in ventilation the last few years originated from damage in buildings, especially in small detached houses used as family dwellings. The damages are due to moisture. They have to a great extent been attributed to lack of air exchange due to the tightness of many new buildings.

For a ventilation engineer it is natural to supply the required flow rate of ventilation air in a controlled way, matching the degree of control of the building itself. The answer for him is a mechanical supply and exhaust system with heat recovery from the exhaust air. The recovered heat can be used for preheating the supply air. However, in order to avoid overpressure inside the building, which could cause condensation of moisture from humid indoor air in the walls, it is customary to supply only 70 - 90% of the exhaust flow rate. This somewhat decreases the efficiency of the heat recovery, but more important is that in summertime no preheating of the supply air is needed. In order to make use of heat from the exhaust air the whole year the use of heat pumps is gaining popularity. The heat is then used for the preparation of hot water or for heating.

Ventilation air flow rates are low. The Swedish Building Code requires a flow rate corresponding to about 0,5 air changes. But the Code also recommends that when there is a heating demand the flow shall not exceed this minimum flow rate. In offices, for instance, this small flow rate is not sufficient for climatisation summertime. Consequently recirculation air is used during the heating season, which gives a better mixing. Return air is also used in other types of building sometimes, in order to increase total flow and avoid stagnation zones. One example is children's service homes.

For the building engineer, on the other hand, mechanical ventilation is not a natural choice. He will probably accept mechanical exhaust ventilation though, even if it is not required by the Building Code. But the supply system is often considered as "double" unneccessary ducting. (Also the official regulations of loans for building have this attitude). Often reference is given to the risk for overpressure and condensation in the walls, although there are very few indications that there really should exist such a risk when the ventilation air flow rate is the stipulated one, controlling air humidity. Another argument is of course the possibilities to use a heat pump for heat recovery.

In his Keynote Address to the 3rd AIC Conference, Mr. Billington pointed out that ventilation historically has been associated with heating : it aimed at removing smoke produced by fires. The fact that the smoke could be seen focused interest on its effective removal. The supply air, on the other hand, can not be seen. Also today removal of moisture and odours from kitchen and bathroom often are considered as the real purpose of the ventilation of dwellings neglecting other air quality and air distribution aspects. The consequence of this is that the exhaust air is taken only in the kitchen and the bathroom (in order to get as big removal flow rates as possible there) but also that the total exhaust air flow rate is controlled, not really the air exchange in the dwelling. Also this tradition is an argument for using only exhaust systems.

If a tight house is provided with a mechanical exhaust ventilation system, special make up air openings are made in the walls. Of course these artificial air leakage openings mean better control than "natural" leakage openings but they also give problems, especially for comfort. A concentrated cold air flow entering a room is more likely to cause draught problems than the diffuse flow from many small openings. The make up air can be heated, by for instance placing the opening behind a radiator, but then the risk for freezing has to be dealt with.

Another aspect is the quality of the air. It is easier to filter supply air than make up air, especially as effective filtering of make up air means that the indoor air pressure has to be decreased because of the necessary pressure loss. A supply system also means possibilities for cooling the supplied air, for instance.

In practice make up air normally is not treated in any way, neither heated nor cleaned, which then is a significant difference in quality compared with supply air. Draught problems often cause the make up air opening to be closed, which of course considerally changes the planned ventilation, especially as they are reopened only after long time.

But which degree of control of the air exchange in the individual rooms in a dwelling is possible with a conventional exhaust system? This will be discussed in this paper and illustrated by means of simple examples. First, however, the means of expressing differences in the efficiency of systems to distribute air and remove contaminants will be defined.

VENTILATION EFFICIENCY AND AIR EXCHANGE EFFICIENCY

As mentioned in the introduction ventilation has traditionally been associated with removal of contaminants. The customary definition of *ventilation efficiency* reflects this fact as it is a measure of the systems ability to remove contaminants emitted in the room.

Figure 1 illustrates what happens when a contaminant is emitted. The mean ventilation efficiency $\langle \varepsilon \rangle$ for the room is defined as

$$\langle \varepsilon \rangle = \frac{C_e(\infty) - C_s}{\langle C(\infty) \rangle - C_s}$$

where $C_e(\infty)$ = Steady state concentration of contaminant in the exhaust air (kg/m^3)

$\langle C(\infty) \rangle$ = Steady state mean concentration of contaminant in the room (kg/m^3)

C_s = Concentration of contaminant in the supply or make up air (kg/m^3).

$\langle \varepsilon \rangle = 1$ can be used as a reference value. Then the exhaust air has the same concentration of contaminants as the mean concentration in the room. This can happen for instance if the contaminants and the room air are well mixed. $\langle \varepsilon \rangle < 1$ indicates changes in $\langle C(\infty) \rangle$ as $C_e(\infty)$ has a fix value, due to mass continuity. $\langle \varepsilon \rangle$ bigger than 1 indicates good function, clean room air.

It can be noticed that the size of the room has no direct influence on the ventilation efficiency, but on the length of the transient period before steady state is reached. It is natural to relate the air flow rate q to room value V.

$$n = \frac{q}{V}$$

where n = the specific air flow rate $\left[\frac{m^3/s}{m^3}\right]$

q = ventilation air flow rate (m^3/s)

V = room volume (m^3)

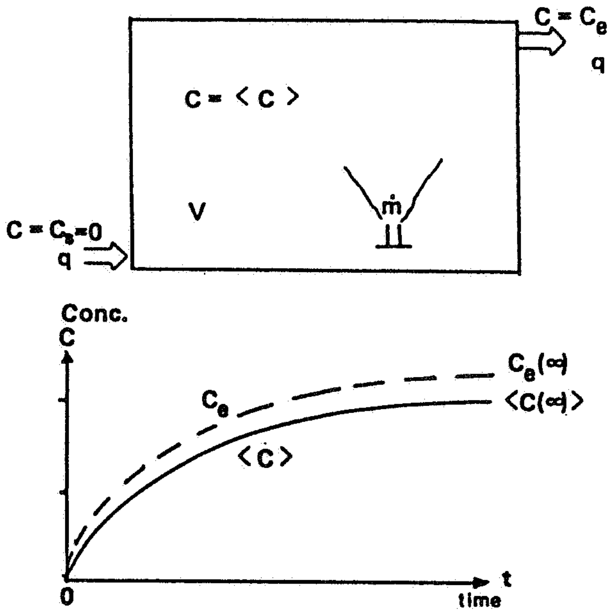


Figure 1. Emission of a contaminant in a room. The emission starts at time t=0. The concentrations are then zero because the concentration in the supplied air is supposed to be zero. V is the volume of the room (m^3) in the emission rate of contaminant (kg/s) and q the ventilation air flow rate (m^3/s). Density of air is supposed to be constant.

The specific flow is often expressed in $m^3/h/m^3$ or h^{-1} and is then called "air changes per hour". The value n^{-1} obviously indicates the time for one "air change", which time is called τ_n.

$$\tau_n = \frac{1}{n} = \frac{V}{q}$$

τ_n is a measure of the average residence time in the room of the air leaving the room that is the time between passing the supply device and passing the exhaust device. The average residence time in the room of the contaminants leaving the room τ_t^c, can also be defined, see Sandberg (1983). As τ_t^c is the time in which an amount of contaminants corresponding to the total content in the room (corrected for C_s) is exhausted from the room, mass balances give (compare fig. 1):

$$\dot{m}\,\tau_t^c = V\cdot(\langle C(\infty)\rangle - C_s)$$

$$\dot{m} = q\cdot(C_e(\infty) - C_s)$$

This gives

$$\langle\varepsilon\rangle = \frac{\tau_n}{\tau_t^c}$$

The mean ventilation efficiency $\langle\varepsilon\rangle$ for the room can also be expressed as the ratio between the mean residence times in the room of the exhaust air and of the contaminant in the exhausted air. Big ventilation efficiency indicates rapid removal of contaminants.

Obviously the ventilation efficiency depends not only on the ventilation of the room but also on the location of the contaminant source.

τ_n is the time it takes to remove an amount of air corresponding to the volume V of the room. If in the time τ_n all the air in the room shall be exchanged too the air must flow as a piston through the room, see fig. 2. This of course is impossible.

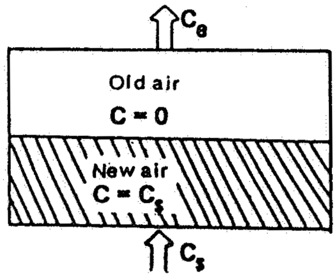


Fig. 2. Piston flow of air through a room, with no mixing of "old air" and "new air". The "new air" is thought to be marked by means of tracer gas, starting at time t=0. At $t=\tau_n$ all the "old air" is removed.

Piston flow is the upper limit, the most effective way of exchanging the air in the room. The concentration of "old air" is the maximal, 100%, until there is no more. Another popular reference case is "complete mixing". Then the concentration of "old air" is the same in all the room. This means that the location of the exhaust terminal device in this special case is unimportant. It means also that the exchange of air is less effective than for "piston flow" because all the time also some new air is exhausted. For "complete mixing" the exchange of air is described by the well-known equation:

$$\frac{\langle C\ (t) \rangle}{\langle C(\infty) \rangle} = 1 - e^{-\frac{t}{\tau_n}}$$

where $\langle C(t) \rangle$ is the concentration of "new air" in the room (and in the exhaust air) at the time t.

In fig. 3 a graph of this equation is plotted and also a straight line showing how air is exchanged in the piston flow case. The curves also show the distributions of residence time (in the room), that is the time from passing the supply device,for the room air in the two cases. For instance, after a time τ_n 100% of the room air has a residence time shorter than τ_n for the piston flow case but only 63% for the "perfect mixing" case. The area above the curves is a measure of the mean residence time in the room $\langle\bar{\tau}\rangle$ .For the case piston flow this area is A in Fig. 3 which gives

$$\langle\bar{\tau}\rangle = \frac{\tau_n}{2} \qquad \text{("Piston flow")}$$

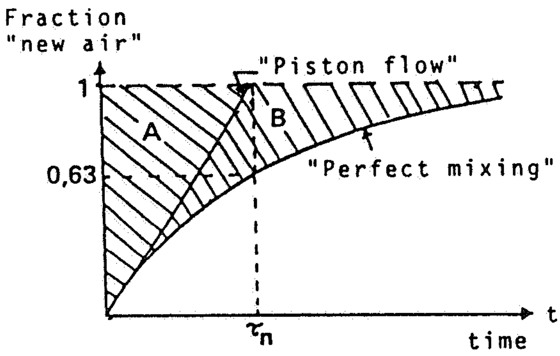


Fig. 3. Graphs illustrating the exchange of air in a room for the two cases "piston flow" and "perfect mixing".

For "perfect mixing" the area is A + B in fig. 3. This area can be calculated by integrating the basic equation given above:

$$\langle\bar{\tau}\rangle = \tau_n \qquad \text{("perfect mixing")}$$

The smallest possible value for the mean residence time for the room air is $\tau_n/2$, which is valid for piston flow. The *air exchange efficiency*, ε_a, is defined as the ratio between this minimum value and the value $\langle\bar{\tau}\rangle$ for the case in consideration:

$$\varepsilon_a = \frac{\tau_n}{2\,\langle\bar{\tau}\rangle}$$

"Perfect mixing" obviously gives $\varepsilon_a = 0,5$. $\varepsilon_a < 0,5$ means short-circulating ventilation air from the supply device to the exhaust device and consequent stagnation zones. $\varepsilon_a > 0,5$ means that there is a tendency towards piston flow which is good.

If τ_n is known, that is the ventilation flow rate q and the volume V, both $\langle\varepsilon\rangle$ and ε_a can be calculated from concentration measurements in the total exhaust air only.

DIFFERENT VENTILATION SCHEMES

In order to compare some different types of ventilation schemes, calculations of local concentrations, ventilation efficiency and air exchange efficiency have been made for the simple combinations of two rooms shown in fig. 4. "Perfect mixing" of air and contaminant has been assumed within each room and there is no circulation of air between the rooms. The efficiency values are valid for the total system. The results are shown in fig. 4, too.

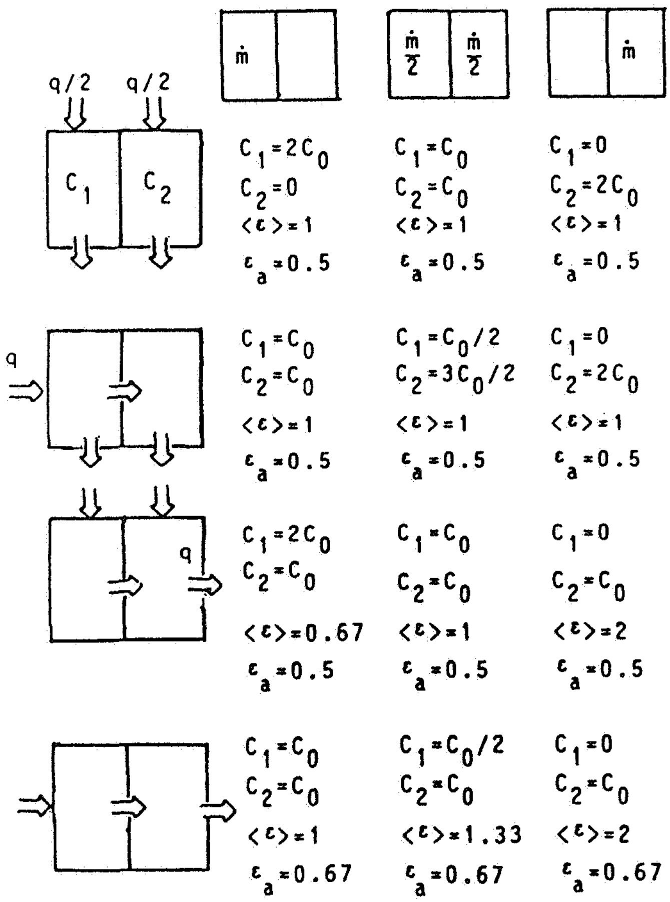


Fig.4. Local concentrations, mean ventilation efficiency $\langle\varepsilon\rangle$ and mean air exchange efficiency ε_a for four different, simple ventilation schemes and three different contamination sources. "Perfect mixing" in each room. $\frac{\dot{m}}{q} = C_o$, $C_s=0$.

The two extreme cases are that the rooms are ventilated separately or in series. With the assumption made the first case will have efficiencies as a single room with perfect mixing. The other extreme case, the connection in series, has a tendency towards piston flow and gives better efficiency values. Also the maximum local concentration that occurs is lower for this case.

The two intermediate cases both have the same air exchange efficiency as the first case, separate ventilation, and also the same maximum local concentration.

The case with only one exhaust point has different ventilation efficiencies, though. when the contamination emission is in one room only, illustrating the improved removal function when the exhaust air flow is big and close to the contamination source but also the deterioration when the contamination source is located so that the contamination is diluted by only part of the flow and the ventilation distributes the contamination to other rooms.

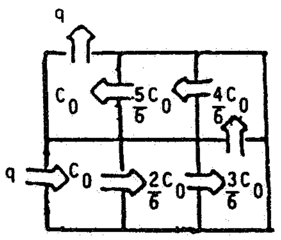
The example indicates the wellknown and obvious rules for ventilation lay-out:

- o as much air as possible shall flow through each room,
- o all rooms shall have a supply or an exhaust air terminal device or be connected in series between rooms with such devices,
- o exhaust air terminal devices shall be located as close to the main contamination sources as possible.

The limiting factors are

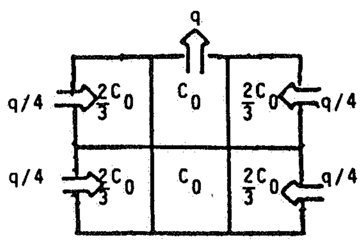
- can contamination from one room be allowed to flow through another,
- leakage for the outside, between rooms and circulation of air between rooms,
- draught problems and noise.

Other important functions are of course economy and practical construction problems.



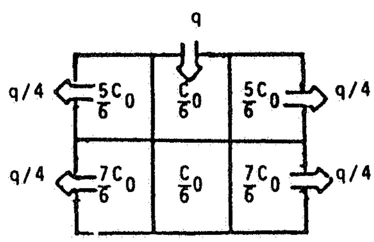
$\langle\varepsilon\rangle = \frac{36}{21} = 1.71$

$\varepsilon_a = \frac{36}{42} = 0.86$



$\langle\varepsilon\rangle = \frac{9}{7} = 1.29$

$\varepsilon_a = \frac{27}{42} = 0.64$



$\langle\varepsilon\rangle = \frac{9}{7} = 1.24$

$\varepsilon_a = \frac{27}{42} = 0.64$

Fig.5. Ventilation efficiency $\langle\varepsilon\rangle$, air exchange efficiency ε_a and local concentration for three ventilation schemes. Each room has a volume V/6 (V=total volume). Contamination emission $\dot{m}/6$ in each room. $\dot{m}/q = c_o$.

Another example is shown in fig. 5. It is a case also appearing in the next section of this paper.

As the total volume in this example is divided into six rooms instead of two, the "connection in series" case, used only for reference, results in a bigger value of the ventilation efficiency $\langle\varepsilon\rangle$ and the air exchange efficiency ε_a. The reason is that this case is closer to "piston flow" as "perfect mixing" is assumed in each room. It can also be noticed that for all three cases in fig. 5 $\langle\varepsilon\rangle$ is 2 ε_a. This is a consequence of the fact that the contamination sources are distributed evenly in the building, in this example.

The case with four supply air devices and one exhaust air device is a normal scheme, for instance for mechanical exhaust system. It has a good efficiency in the example, $\varepsilon_a = 0{,}64$. The reserved, third, case has the same efficiencies but a less favourable distribution of local concentrations.

The examples indicate that schemes like the second case in fig. 5, which are normal for mechanical exhaust systems among others are good. In the next section their possibilities to work as planned will be discussed.

INFLUENCE OF STACK EFFECT AND WIND

Consider a building with a mechanical exhaust system, fig. 6.

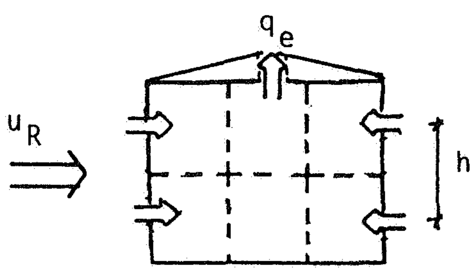


Fig. 6. Ventilation scheme for a building. The exhaust air flow is fixed, q_e. The wind velocity is u_R (m/s) and the height difference between the openings h (m).

The openings in the wall indicated in the figure are assumed to represent both make up air openings and the leakages. Flow resistances within the building are neglected. The exhaust air flow is fixed. The air flow when the system is influenced by wind pressure and stack effect has been calculated by Etheridge and Sandberg (1984). According to them the flow depends on the number

$$A_r = \frac{\Delta\rho\ g\ h}{\rho_o\ u_R^2}$$

where ρ_o = density of outside air (kg/m^3)

$\Delta\rho$ = difference of density between outdoor and indoor air (kg/m^3)

g = acceleration due to gravity (m/s^2)

h = height difference between openings (m)

u_R = wind speed at reference point (m/s)

A_r is a measure of the ratio between buoyant forces and wind forces. But the pressure difference acting across the building also depends on the form of the building and of the surroundings. This can be expressed by means of the difference between the pressure coefficients on the wind side and on the leeward side, ΔC_p. Etheridge and Sandberg consequently have expressed the flow as a function of

$$\frac{\Delta C_p}{A_r}$$

ΔC_p normally has values in the interval

$$0{,}2 < \Delta C_p < 1{,}0$$

In table 1 values are given for $\Delta C_p/A_r$ for different wind speeds u_R, for an indoor temperature of 21°C and an outdoor temperature of 6°C which is the yearly mean temperaturefor Stockholm. The height h is 3 m.

u_R (m/s)	1	2	3	5	7
ΔC_p = 0,2	0,13	0,50	1,13	3,15	6,17
ΔC_p = 1,0	0,63	2,52	5,67	15,7	30,9

Table 1: Values of $\Delta C_p/A_r$ for an outdoor temperature of 6°C, h = 3 m.

The flow through each opening is first supposed to vary as

$$q = 0{,}009 \cdot \sqrt{\Delta_p} \quad (m^3/s)$$

where Δ_p = pressure difference across the opening (Pa).

This gives a total flow through the four openings of $900\,m^3/h$ when $\Delta_p = 50$ Pa, which is the standard for leakage tests. If the volume of the building is 300 m^3 this flow corresponds to 3 air changes per hour, which is the maximum value stipulated for small buildings in the Swedish Building Code for leakage. As this value in our example includes also the flow through the make up air openings, the building is tighter than required.

In this example it is assumed that the openings discharge coefficients are 1.

Fig. 7 shows different flow configurations and the values of $\Delta C_p/A_r$ when the change occurs for a fixed exhaust air flow rate corresponding to 0,5 air changes per hour. When the change occurs the resulting air flow in the room, where the flow changes direction, obviously is zero. A comparison with table 1 shows that the first change is at a low value of $\Delta C_p/A_r$ valid for small wind velocities, which are normal and frequent. Compare fig. 8. If ΔC_p is big also the second change occurs at low and frequent wind velocities. Note that table 1 is valid for the yearly mean outdoor temperature, +6°C, and not for an extreme case.

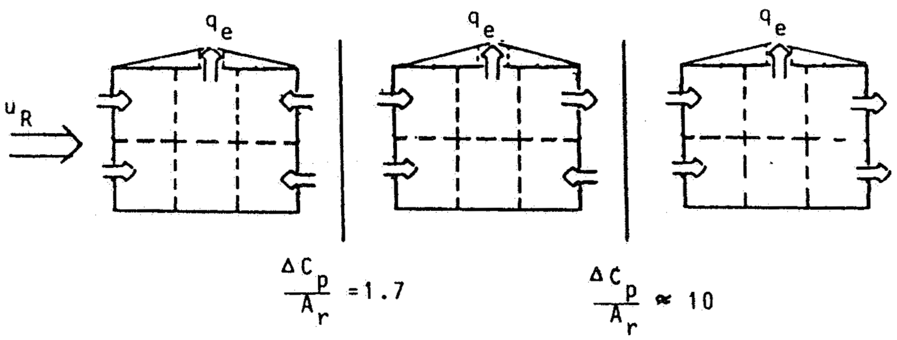


Fig. 7. Different flow configurations for a mechanical exhaust system. The total volume of the building is 300 m^3 and the fixed exhaust air flow $q_e = 150\ m^3/h$.

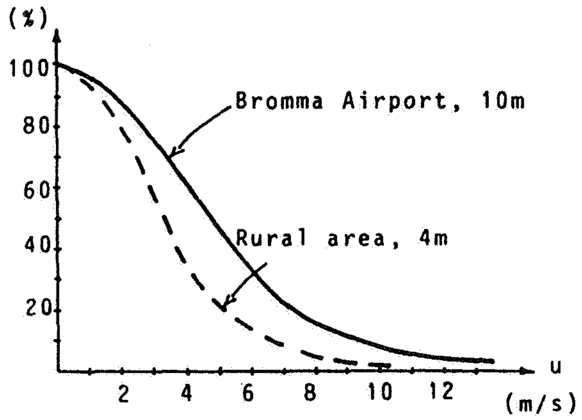


Fig. 8. Wind velocity in Stockholm at a height of 10 m in a free field and reduced to 4 m and rural area.

If the building is tighter , say corresponding to a total flow at 50 Pa of 2 air changes instead of three (including the flow through the make up air openings), the first change will occur at $\Delta C_p/A_r \approx 6$. Also this value corresponds to frequent wind velocities, if ΔC_p is not small. A total tightness value of 1 air change per hour at Δ_p = 50 Pa gives the first change at $\Delta C_p/A_r \approx 20$. It is evident from table 1 and fig. 8 that also this value is within the normal intervals although it will not occur frequently.

Consider again the first discussed case, corresponding to a total air change of 3 air changes per hour at 50 Pa. At an outdoor temperature of about -20°C and no wind all the exhaust air will enter through the two lower openings. This is because of the buoyant force. This does not only give bad ventilation but also draught problems.

The example indicates that in order to control the exhaust ventilation very tight buildings with small make up air openings are required. In reality for instance the turbulent nature of the pressure fluctuations and thermal connection improves the exchange of air. The tendency is correct, however. Experiments made at the National Swedish Institute for Building Research indicate that mechanical exhaust systems start to function properly only when the leakage at a pressure difference of 50 is smaller than 1 air change per hour (with the make up air openings closed), that is the building must be very tight.

LEAKAGE OF INDOOR AIR

As mentioned in the introduction, there is in Sweden much consideration about the risk for condensation in the walls. Mechanical exhaust systems are considered safer, from this point of view, than supply and exhaust systems. In this section a comparison between different systems will be made concerning their ability to avoid leakage out from the building of indoor air.

As an example consider the simple scheme according to fig. 9.

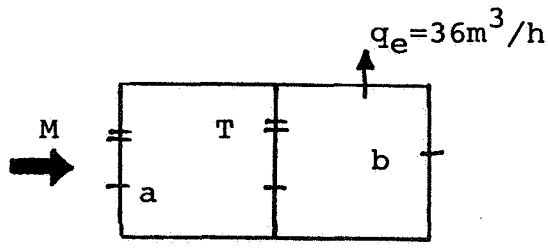


Fig. 9. The ventilation scheme for mechanical exhaust.

The volume of each room is 36 m^3. The exhaust air flow rate is fixed and 36 m^3/h, that is 0,01 m^3/s. In order to get the room connected in series the make up air opening M, the transfer air opening T (including leakage) and the leakages a and b, are concentrated only to the walls according to fig. 9. The total leakage a + b corresponds to 1 airchange per hour at Δ_p = 50 Pa. The flow rates are calculated from the appropriate pressure difference (in Pa) as shown below. At a pressure difference of 50 Pa 2 q_M is equal to 1 air change per hour and $q_a + q_b$ is also equal to 1 air change.

$$q_M + q_a = 0{,}0019\ \Delta_p^{0{,}6} \quad (m^3/s)$$

$$q_T = 0{,}011 \cdot \Delta_p^{0{,}55} \quad (m^3/s)$$

$$q_a = q_b = 0{,}00064\ \Delta_p^{0{,}7} \quad (m^3/s)$$

The wind pressure coefficient for the building is ΔC_p = 0,7 which is in the middle of the interval mentioned in the preceding section.

Fig. 10 shows the leakage flow. Note that it is defined positive inward and that it is given in m^3/h. The flows have been calculated for different wind velocities and the durations have been calculated from fig. 8, the lower curve. As can be seen from fig. 10, there will be a flow out of indoor air 12 % of the time. This is of course a little misleading as the wind is not blowing perpendicular to the building all the time. However for a detached house there will always be one windside and one leeward side. What the graph indicates is that there is a risk for outflow somewhere in the building 12 % (or a little bit less) of the time.

Fig. 11 shows results when there also is a fixed supply air flow, 90 % or 70 % of the exhaust air flow. For this case there are not make up air openings in the walls, only leaks. As can be seen there is a considerable reduction of outflow when the supply air rate is reduced. For the reduced air flow rate outflow has a duration of 30 % which is about three times the time compared with the example for the exhaust system, see fig. 10.

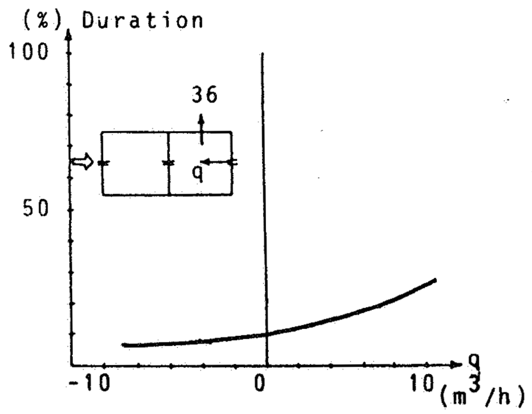


Fig. 10. Leakage air flow on the leeward side for a mechanical exhaust system.

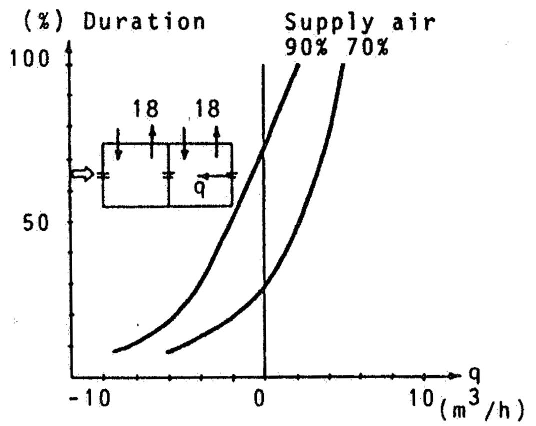


Fig. 11. Leakage air flow on the leeward side for a mechanical supply and exhaust system. The supplied air flow is fixed, as is the exhaust air flow. Calculations are made for two cases, supplied air flow rate 90 % and 70 % of the exhaust air flow rate.

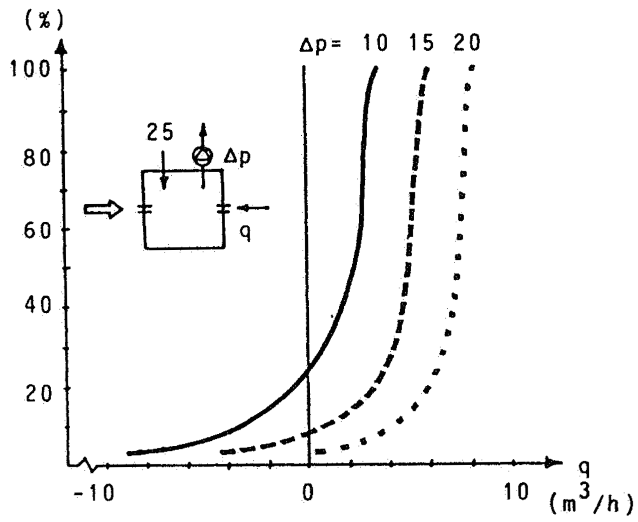


Fig. 12. Leakage air flows on the leeward side for a mechanical supply and exhaust air system. The supply air flow rate is fixed but the exhaust air system is of low pressure type.

Fig. 12 shown only for discussion. It is calculated for an extreme low velocity and low pressure exhaust system, which is supposed always to work against the leeward side pressure at its outside opening. The pressure loss in the exhaust ducting is

$$\Delta_p = 40\ 000 \cdot q^{1,8} \quad \text{(Pa)}$$

The pressure loss at nominal flow is 10 Pa. The parameter Δ_p in fig. 12 refers to the fan pressure which is very low. When the fan pressure is increased from 10 Pa to 15 Pa a negative pressure is created inside the building which counteracts outflow (the fan curve is supposed to be straight, giving the same pressure independent of the flow). If for instance a heat recovery system is used the pressure loss in the duct system will be too big. A similar effect could then be achieved by using a variable fan and control the pressure difference.

Fig. 11 shows that a considerable reduction of outflow can be achieved by using a supply air flow rate lower than the exhaust air flow rate. In order to maintain this advantage it is necessary to clean the exhaust ductwork regularly. Swedish experience is that reductions of about 50 % (of the flow) may happen within one year.

The example indicates that the exhaust system in a tight house and with small make up air openings can give a small duration of outflow of indoor air. The supply and exhaust system have a bigger outflow although a considerable reduction is achieved by reducing the supply air flow rate which is customary to do in Sweden.

CONCLUSIONS

In order to have good ventilation each room in a dwelling must have a controlled air exchange. This is not possible to get with a mechanical exhaust system unless the building is very tight. The outflow of indoor air is bigger with a supply and exhaust system than with an exhaust system. A considerable reduction is achieved, however, if the supply air flow rate is reduced.

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THE IMPLEMENTATION AND EFFECTIVENESS OF AIR INFILTRATION STANDARDS IN BUILDINGS

5th AIC Conference, October 1-4 1984, Reno, Nevada, USA

PAPER 10

DEVELOPMENT OF OCCUPANCY-RELATED VENTILATION CONTROL FOR BRUNEL UNIVERSITY LIBRARY

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SYNOPSIS

A microprocessor system is being developed for occupancy related ventilation control of mechanical ventilation in Brunel University Library. The objective is to reduce space-heating costs by decreasing the input of (cold) fresh-air to the building below existing (heating-season) levels, when the number of occupants in the building is sufficiently small to allow this. The occupancy levels can be measured in terms of CO_2 level in the exhaust duct.

The microprocessor control system is operational when linked to a CO_2 monitor. The control system senses the CO_2 level and the computer sends an appropriate signal to reset the fresh air, exhaust and recirculation dampers, to maintain a preset CO_2 level.

A previous study has indicated fuel cost savings of about £1500 per annum.

1. INTRODUCTION: THE PROBLEM

Previous studies (Windsor[1] and Buchanan[2]) led to the concept of ventilation control related to occupancy of the library at Brunel University. The objective is to reduce space-heating costs by decreasing the input of (cold) fresh-air to the building below existing (heating season) levels when the number of occupants in the building is sufficiently small to allow this. The library is a 4 storey building with a total floor area of approximately 6,400 m^2. It has a mechanical ventilation system which, during the heating season, ejects warm air to the atmosphere at the equivalent of about 16 kW per $^{\circ}C$ temperature difference between the interior and exterior of the building.

Buchanan's study[2] of heat recovery systems indicated that improved ventilation control was likely to have a shorter pay-back time (6.3 years) than various 'run-around coils' (6.6 to 8.9 years) designed to recover heat from exhaust air. It compared even more favourably with cavity wall insulation (14.7 years pay-back time) installed where possible. Present worth and internal rate of return analyses yielded similar comparisons. Actual fuel cost savings were estimated at about £1,500 per annum for the occupancy related control system. Other studies by Ogasawara et al[3] and Warren[4] have also given estimates of substantial fuel savings which should be possible (e.g. in departmental stores) by using similar systems.) The system under development has been designed to be flexible e.g. with more computer memory and input/output channels than required for ventilation control as such. The authors are aware of commercial systems based on the detection of CO_2 or O_2 levels which are already available.

2. EXISTING HEATING SYSTEM AND CONTROL IN BRUNEL UNIVERSITY LIBRARY

The overall Brunel heating system is of the district heating type with a centralised boiler and heat distribution to buildings via high pressure hot water mains (at $\sim 160^{\circ}C$, 10 bar pressure). Heat exchangers transfer heat to 'low pressure' heating systems in buildings. Warm air is the main heat distribution medium in the library building. There are fans ($\sim$ 3kW rating) to drive the fresh air and exhaust air-streams with provision for recirculation of air extracted from the library. (The fresh-air rate and percentage recirculation being set by the intake, exhaust and recirculation dampers indicated on Fig. 1). Typical operating conditions in the spring are 17 m^3s^{-1} of fresh air and 8 m^3s^{-1} of recirculated air with an exhaust rate of 16 m^3s^{-1}. The exhaust rate is slightly lower than the intake rate to maintain a small positive pressure in the library and so to minimise air infiltration through doors and windows. There are two heater batteries in the fresh air stream. The hot water supply rate to the heater batteries is modulated to achieve the desired set temperature of air input to the library. The above system is duplicated in East and West plant rooms located on the library roof. (There are also some additional 'booster' heater batteries located at various points in library duct work to the ceiling warm-air diffusers.) The existing (Honeywell) control system works in two regimes, i.e.'heating season' and 'non-heating season'. The proposed modifications will only be effective during the heating season. During this time the system is at present run on what is termed 'minimum fresh-air'. This corresponds to fixed damper settings giving a fixed proportion of recirculated air.

Excessive fresh air input rates to the library can occur with the dampers fixed, e.g. taking a rate of 17 m^3s^{-1} of fresh air to the library with say 300 people in the library yields an average rate of 57 ls^{-1} (per person) which is 7 times the rate recommended by CIBS[5] for open-plan offices. There is therefore scope for reducing the fresh-air input and exhaust rate of warm air to the atmosphere. Conversely surveys have shown that some users complain of 'stuffiness' in reading areas in the afternoon.

3. SYSTEM UNDER DEVELOPMENT FOR OCCUPANCY RELATED VENTILATION CONTROL

3.1 General Considerations

The original proposal was to use turnstile counters (in and out) to provide a measure of the number of occupants in the library. Turn stiles are already installed with a counter on the **exit** only. However, this system has now been rejected in favour of using CO_2 level in the exhaust duct to provide a signal related to library occupancy. (This is based on an average CO_2 exhalation rate per person of about 4.7×10^{-6} m^3s^{-1}.) Reasons for choosing this system are:

(a) more compact equipment - though the cost of CO_2 monitor (at least £1,000) is an additional cost balancing reduced wiring costs;

(b) wider applicability for retrofit to existing buildings which in general do not have turnstiles.

There are no standards for CO_2 levels in UK buildings and CIBS[5] indicates 0.5% as acceptable. However, some continental countries specify 0.1% by volume as an upper limit. (Ventilation rates to remove body odours are in any case often higher than those required to provide acceptable CO_2 levels).

3.2 Ventilation Control System

A schematic diagram of the control system under development is shown in Fig. 1. A Horiba CO_2 analyser is connected to the library exhaust duct air via a plastic tube. The analog signal from the CO_2 analyser is connected to the controller/logger equipment (see appendix for details) which registers the CO_2 level and gives a print out of this together with the time. A servo motor adjusts a potentiometer connected to the Honeywell control system to give the necessary setting of damper angle.

Software has been written such that the fresh-air intake (FAI) and exhaust dampers are nominally fully closed if the CO_2 concentration in the exhaust air is less than 500ppm. (In practice there would still be sufficient air flow for sampling purposes). The recirculation dampers would be fully open in this mode. The FAI dampers are effectively fully opened if the CO_2 concentration rises to 1000ppm. A linear relation between damper angle and CO_2 concentration is assumed.

4. MEASUREMENT OF CO_2 CONCENTRATIONS IN EXHAUST AIR

CO_2 concentrations in the library exhaust duct have been monitored by Hunt[6] on a number of days (as shown in table 1). On February 7th 1983 the recorded peak CO_2 concentration was 600ppm. This is relatively low compared with an acceptable value of 1000 ppm even though recorded at a time when the use of the library is usually fairly intensive. On April 26th (when only final year and postgraduate students are on the campus) CO_2 concentrations are even lower. The occupancy numbers generally show reasonable correlation with the CO_2 concentrations. Assuming a fresh air input rate of $17m^3/s$ the CO_2 concentrations are consistent with a CO_2 exhalation rate per person of about $6 \times 10^{-6} m^3/s$ per person.

Table 1 Library CO_2 Concentrations

Time	7 February	26 April	
	CO_2	CO_2	Occupancy
Hours	ppm	ppm	
09.00	420	300	35
10.00	430	315	82
11.00	490	320	92
12.00	520	335	122
13.00	580	325	98
14.00	600	320	110
15.00	510	315	108
16.00	480	315	94

5. SYSTEM TESTS

In a qualitative sense it has been shown that increase of CO_2 level in the exhaust duct will lead to increased opening of the fresh air dampers in the library building. However long term tests have not yet been made. The existing dampers and damper motors together with mechanical linkages are more suited to occasional manual readjustment rather than continuous modulation. These need upgrading before long term tests can be made in this particular building.

6. CONCLUSIONS

Observations suggest that the Brunel library is overventilated as the CO_2 levels which exist in the exhaust air are well below 1000ppm. However the problem of underventilation of certain areas reported by some users suggests that CO_2 analysers should be installed on every floor of the library.

The logger controller could then be programmed to respond to the maximum CO_2 level. An alternative transducer would be air quality monitors based on O_2 content of the air which are cheaper than CO_2 analysers and can also detect smoke.

It would also be desirable to monitor energy savings by heat metering of the hot water supply of the fresh-air heater battery. This could either be done by a separate heat meter or by using spare capacity of the controller logger together with suitable transducers. It is known that a number of installations of commercial equipment have led to substantial savings[7].

APPENDIX

VENTILATION LOGGER CONTROLLER

The ventilation controller is constructed in a box with commercially available microprocessor and analog input cards, plus memory and clock cards. The controller is thus versatile and can be readily re-programmed during development. It can indeed be used for other applications. The programs were developed using Motorola's version of Basic. This is particularly suited to hardware control applications, and allows future development by workers who could not be expected to work with low-level assembler programs.

Fig. A1 shows the components of the controller. The blocks make up a powerful general purpose computer with analog input and provision for an analog output card to be included. CO_2 levels are read in at pre-defined intervals, typically 10 minutes, and used to update the potentiometer position to set the dampers. This is achieved with timer chip programmed to provide variable length pulses to a rotating servo unit. A pulse of 0.8m sec sets the servo to fully anti-clockwise. A pulse of 1.4m sec rotates it clockwise to 90^o. The pulse length depends on the CO_2 reading. The servo is mechanically linked to the shaft of the potentiometer in the damper drive circuit.

The CO_2 level is logged using a printer which can be switched off. Alternatively, the printed message may be transmitted to a remote computer for further analysis and recording on disc.

The clock is used to initiate the CO_2 read operations, and is used also to print the date and time alongside CO_2 values. It can also be used to initiate different control regimes at different times of the day or year.

The control program is outlined in Fig. A2. Each block in the flow chart represents a call to an appropriate sub-routine. The program was developed in modular form both for clarity and to allow ease of future development.

Development of a specialised compact controller is possible by replacing the program and its sub-routines with equivalent assembler-code routines. The structure of the software remains the same but uses much less memory. A single chip microcomputer would thus support input/output channels using a single card, possibly installed in the CO_2 analyser box itself.

ACKNOWLEDGEMENTS

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is also acknowledged. Thanks are also due to Mr A. Harvey.

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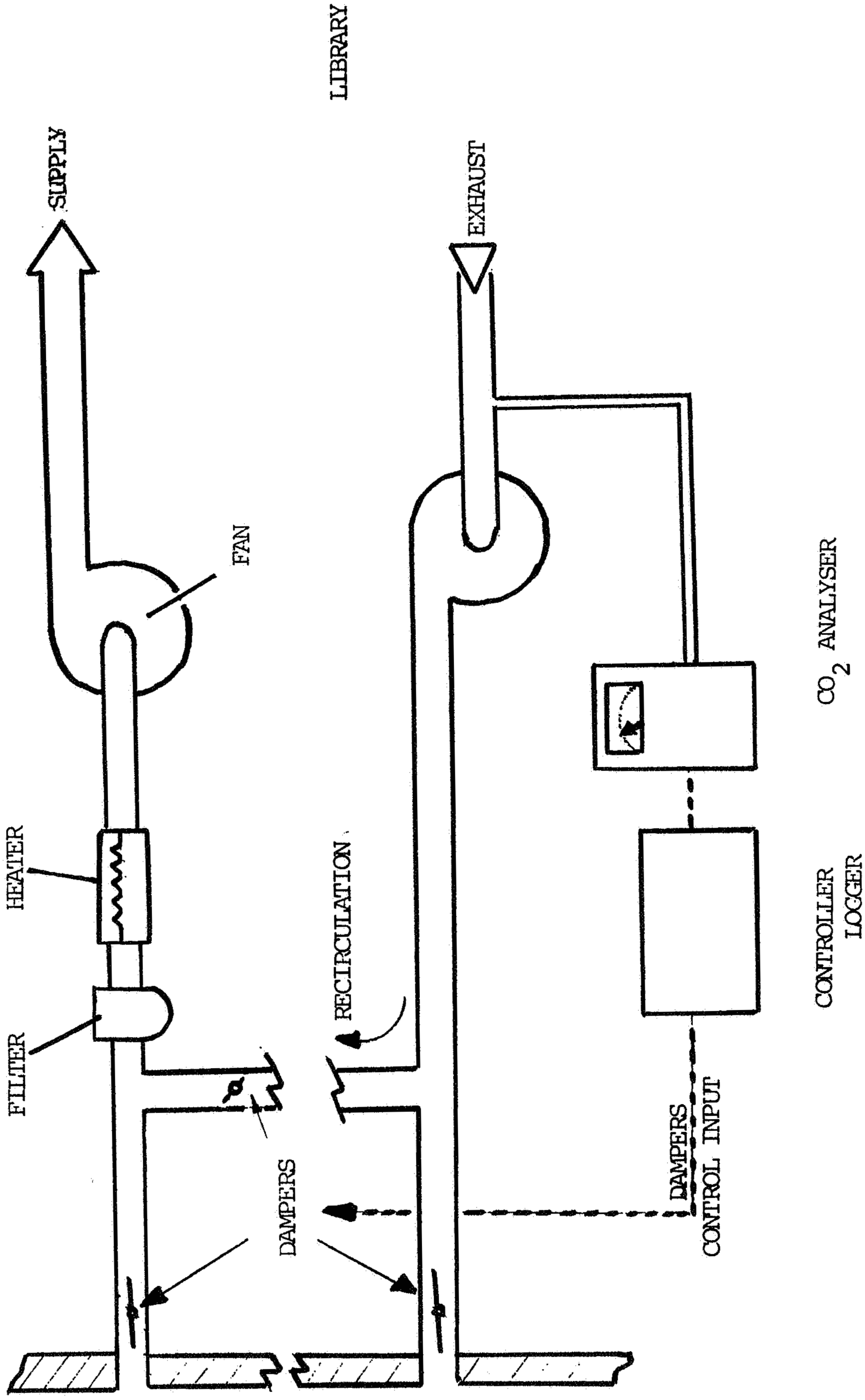

FIG 1 Ventilation control system

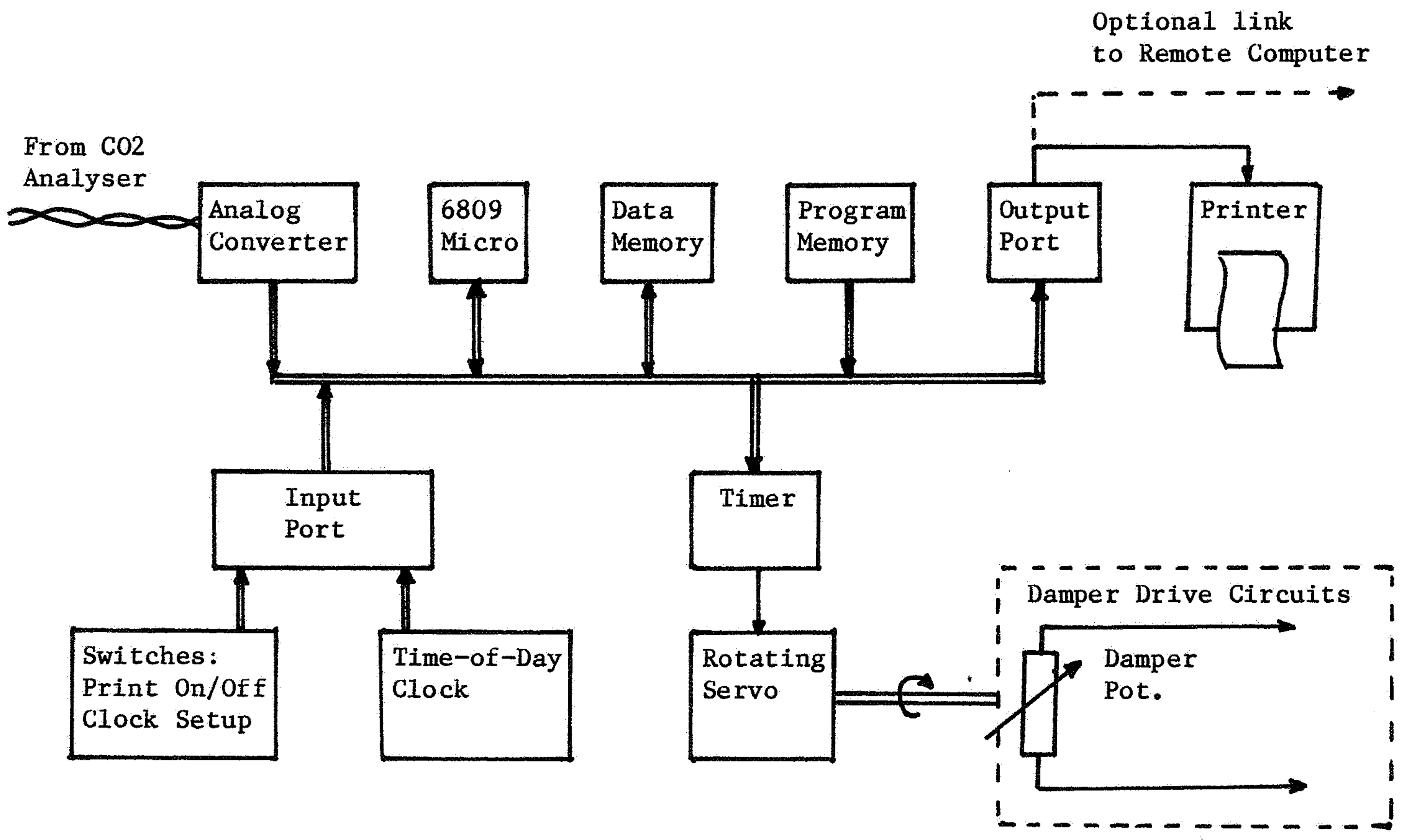

Fig A1: Ventilation Controller Hardware

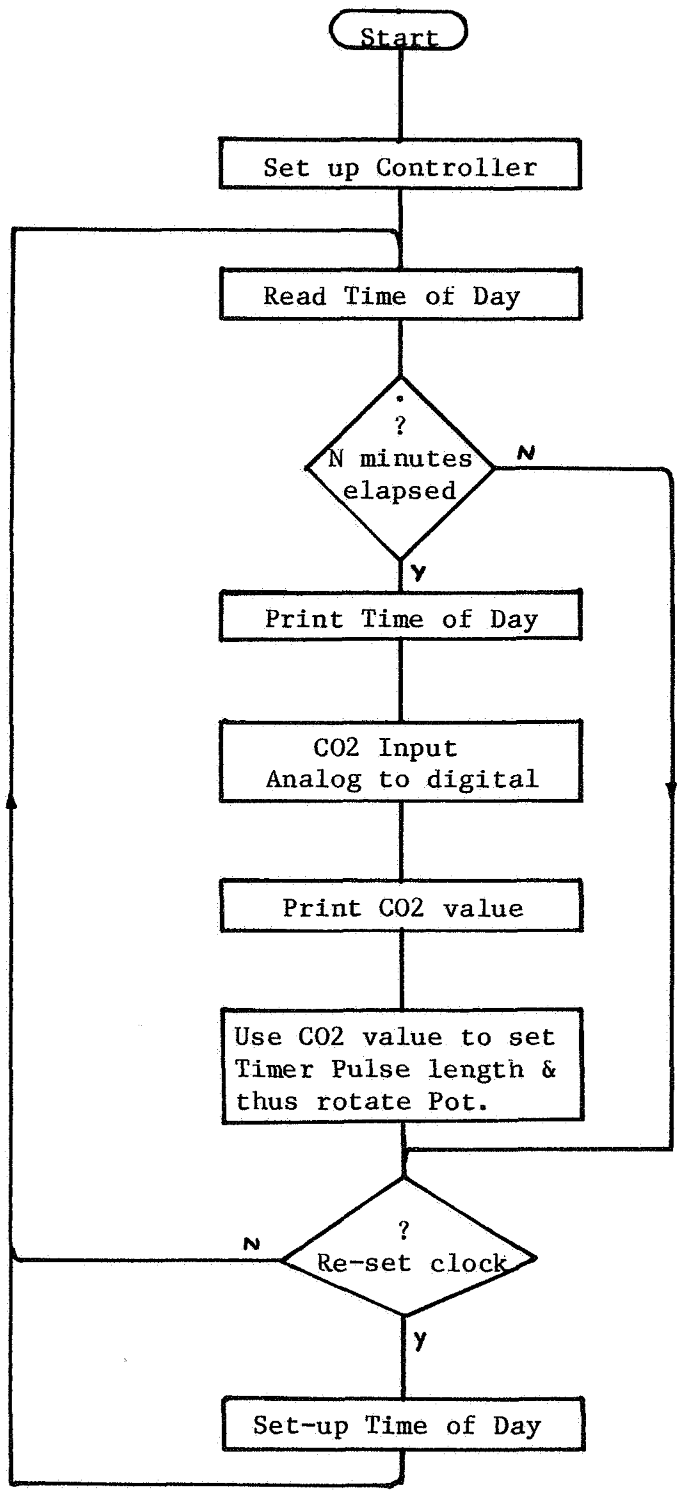

Fig A2. Outline Flowchart

THE IMPLEMENTATION AND EFFECTIVENESS OF AIR INFILTRATION STANDARDS IN BUILDINGS

5th AIC Conference, October 1-4 1984, Reno, Nevada, USA

PAPER 11

PERFORMANCE OF PASSIVE VENTILATION SYSTEMS IN A TWO-STOREY HOUSE

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ABSTRACT

Air change rates were measured in one two-storey detached house with five basic types of passive ventilation systems: an intake vent in the basement wall; an outdoor air supply ducted to the existing forced air heating system; an exhaust stack extending from the basement to the roof; and two combinations of the supply systems and the exhaust stack. An expression was developed for estimating house air change rate from house airtightness, neutral pressure level and indoor-outdoor air temperature difference. Good agreement was obtained for the test house between the predicted and the measured air change rates. The effects of furnace fan operation, air distribution system, and size and location of vent openings on house air change rates are also discussed.

1. INTRODUCTION

The air leakage characteristic of a house has a major effect on energy consumption, indoor air quality and moisture problems. To investigate the effect of weather, airtightness, and heating and ventilation systems on the air change and air pressure distribution of a house, several studies were undertaken on four detached two-storey houses. These studies were part of the Mark XI Energy Research Project co-sponsored by the Division of Building Research and the Housing and Urban Development Association of Canada (HUDAC).[1] The air change rates and the airtightness values measured for the four houses, and a discussion on the relationship between house air change rate and airtightness, wind and stack action, and the operation of a natural-draft gas furnace, have already been reported.[2, 3, 4] The results of a study on mechanical ventilation systems have also been reported.[5] This paper presents the results of a study on passive ventilation systems.

Interest in passive ventilation techniques has been increasing as more airtight houses are constructed and more moisture problem are reported. Passive ventilation usually takes the form of an air inlet in the exterior wall or an exhaust stack, or a combination of the two. Since the amount of outdoor air supplied by these means varies with outdoor weather conditions, passive ventilation has never been considered as a satisfactory means of providing ventilation air in tight houses. However, for houses in which air leakage provides most of the ventilation, a well-designed passive ventilation system can be a practical means of supplying the additional outdoor air required for controlling indoor humidity and improving indoor air quality.

The main objective of this study was to check expressions developed for predicting the air change rate of houses with passive ventilation systems.

2. EFFECT OF VENT OPENINGS ON HOUSE AIR CHANGE AND PRESSURE

In a previous study, the air change rates of one of the four houses (H3) were measured to determine the effect of venting through a chimney on the house air leakage characteristic.[4] The results are summarized in Fig. 1.

Figure 1a shows the temperature-induced air flow and pressure difference patterns for this house with the chimney capped. Because the air inside the house is warmer, and hence less dense than that outside, it tends to rise and leak out through the upper parts of the house; colder outdoor air leaks in through the lower parts of the house to replace it. The pressure difference across the exterior wall decreases linearly from a positive value at the grade level to a negative value at the ceiling level. Near mid-height, there is a level where the pressure difference is zero. This is called the neutral pressure level.

When a vent, such as a chimney or an exhaust stack, is installed in the house, the air change rate increases due to the air flow through the vent (Fig. 1b). The air flow through the vent depends upon the temperature difference between inside and outside, and the size and location of the vent. As a result, the pressure difference across the exterior wall is redistributed so that a mass flow balance is maintained.

The air change rate caused by stack action alone depends on the airtightness of the envelope and the indoor-to-outdoor air temperature difference. Figure 1c shows the air change rates for the house with and without a chimney. Without a chimney, the measured air change rates for wind speeds lower than 12 km/h agreed closely with the values predicted by Eq. 1 (derived previously for the other two chimneyless houses, H1 and H4, included in the Mark XI project).[3]

$$I = 0.32\ (A/V)\ C(\Delta t)^n \qquad (1)$$

where:

- I = house air change rate, ac/h,
- A = area of building envelope (area of exterior wall above grade and ceiling area of top floor) m^2,
- V = volume of building including basement, m^3,
- C = flow coefficient, $L/(s \cdot m^2 \cdot Pa^n)$,
- n = flow exponent,
- Δt = indoor-to-outdoor temperature difference, K,
- 0.32 = dimensional constant, $m^3 \cdot s \cdot Pa^n/(L \cdot K^n \cdot h)$.

With a chimney, the measured air change rates could be expressed by an equation similar to Eq. 1:

$$I = B(A/V)\ C_v(\Delta t)^{n_v} \tag{2}$$

where:

C_v = flow coefficient with vent, $L/(s \cdot m^2 \cdot Pa^n)$,
n_v = flow exponent with vent,
B = 0.43, a dimensional constant, $m^3 \cdot s \cdot Pa^{n_v}/(L \cdot K^{n_v} \cdot h)$.

As the ratio of the constants in Eqs. 1 and 2 was approximately equal to the ratio of the two neutral pressure levels, a general expression for the two equations was:[4]

$$I = 0.32\ (A/V)\ r\ C_v(\Delta t)^{n_v} \tag{3}$$

and

$$r = 1 + \left| (h_v - h) \right| /h$$

where:

C_v = flow coefficient with vent, $L/(s \cdot m^2 \cdot Pa^{n_v})$,
n_v = flow exponent with vent,
h_v = neutral pressure level with vent, m,
h = neutral pressure level without vent, m.

If both an intake vent and an exhaust vent are installed, the changes in neutral pressure level caused by the vents tend to cancel each other. When there are multiple vents, the expression for r is:

$$r = 1 + \sum^{J} \left| (h_{v,j} - h) \right| /h$$

where J is the number of vents and $h_{v,j}$ is the neutral pressure level corresponding to the j th vent if it were the only one.

Equation 3 requires values of the flow coefficient (C) and exponent (n) and the neutral pressure level of the house with ventilation system. These values can be measured directly or estimated using the methods described in Appendix A.

Although Eq. 3 was derived for stack action alone, it applies equally well where there is the combined effect of stack action and wind (Fig. 1d). The air change rates were measured in a test house and compared with the values predicted by Eq. 3 to check the validity of this equation.

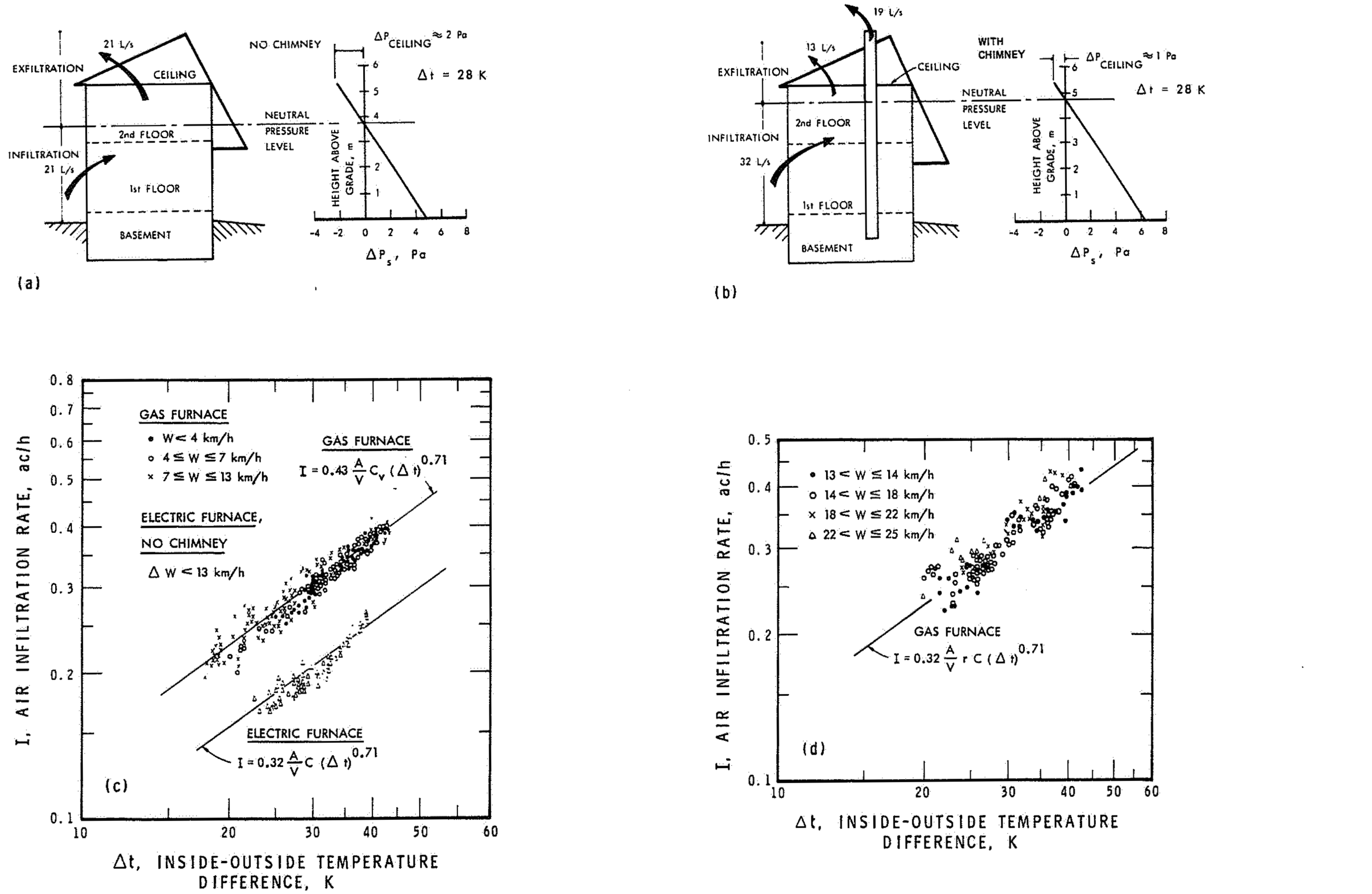

Figure 1. Temperature-induced air flow and pressure patterns, and air infiltration rates (from Reference 4)

3. TEST HOUSE AND PASSIVE VENTILATION SYSTEMS

3.1 Test House

The test house (H4) is a two-storey detached house with a full basement, located in a developed residential area in the city of Gloucester, Ontario. The house has a forced-air heating system with an electric furnace. It also has a 12.7 cm diameter chimney, which was capped when the electric furnace was in use. The volume of the house, including basement, is 386 m^3 and the area of the house envelope, including the area of the second floor ceiling is 227.7 m^2. The second-storey ceiling is 5.4 m above grade level.

3.2 Vent Openings

Each of the two basement windows in the south wall was replaced by a plywood panel with a 10 cm diameter pipe installed at the centre (Fig. 2). One of the pipes could be connected to the return air duct of the heating system. The existing 12.7 cm diameter chimney was used to simulate an exhaust stack. Provision was made for indoor air to exhaust through the stack from either the basement or the second storey.

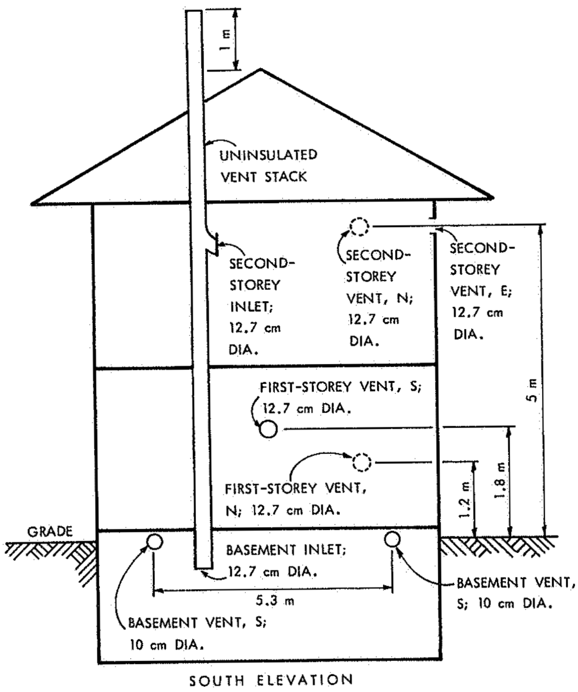

Figure 2. Test house with location of vent openings

Plywood panels with a 12.7 cm diameter circular opening were installed in the opening of one south window and one north window on the first storey, and one north window and one east window on the second storey. These openings could be closed by merely closing the casement windows.

The vent openings and exhaust stack were combined to simulate the five basic passive ventilation configurations shown in Fig. 3a, and the six additional configurations shown in Fig. 3b. The five basic configurations were:

(I) 10-cm diameter opening in south basement wall delivering air to the basement at grade level;
(II) 10-cm diameter pipe supplying outdoor air to the return duct of the forced-air heating system; intake opening at grade level;
(III) 12.7-cm diameter exhaust stack extending from basement to above the roof;
(IV) combination of I and III;
(V) combination of II and III.

Six more configurations were tested to demonstrate the ventilation capability of the different passive ventilation techniques in houses with and without an air distribution system. They were also intended to show how well the ventilation air (outdoor air) mixed with indoor air, and how the location of the vent openings

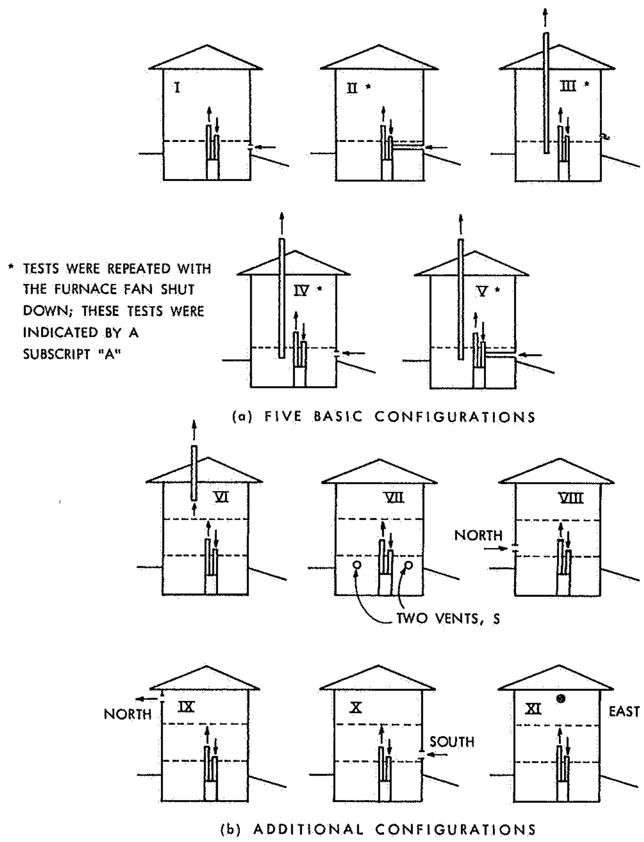

Figure 3. Test ventilation configurations

affected the ventilation rate. The six additional configurations were:

(VI) 12.7-cm diameter exhaust stack extending from second storey to above the roof;
(VII) two 10-cm diameter openings about 5.3 m apart in the basement wall, at grade level;
(VIII) 12.7-cm diameter opening in first storey north window, 1.2 m above grade;
(IX) 12.7-cm diameter opening in second storey north window, 5 m above grade;
(X) 12.7-cm diameter opening in first storey south window, 1.8 m above grade;
(XI) 12.7-cm diameter opening in second storey east window, 5 m above grade.

All of these configurations were tested with the air circulating fan of the forced-air heating system operating continuously. Configurations II to V were also tested with the fan off.

4. TESTS AND MEASUREMENTS

For each weather condition, the various configurations were tested, one after another and the following parameters were measured:

(1) indoor and outdoor air temperatures, measured and recorded on a computer-based data logging system;
(2) local wind speed and direction, measured 10 m south of the house and 18 m above grade, and recorded on the same data logging system;
(3) air change rate(s), (whole house, or living space and basement separately); and
(4) air flow rates through vent openings and exhaust stack.

Air pressure differences across the house envelope were only measured under calm conditions (wind speed less than 8 km/h) and only for some configurations (no vents, and configurations I to V and IX). Fan pressurization tests to determine the airtightness of the house, with and without vent openings, were performed once in early summer under calm conditions and only for select configurations (no vents, and configurations I, II, II_a, III, IV, V, VII, IX and X).

4.1 Air Change Rate

Air change rate was measured using the tracer gas decay method with N_2O (nitrous oxide) as the tracer gas.[6] The door to the basement was kept closed during the measurement. For each measurement, the tracer gas was injected into, and air samples were collected from, the forced air heating system with separate injection and sampling tubes. The furnace fan was operated continuously to mix the tracer gas with the indoor air.

For those special tests with the furnace fan off, the fan was only shut down after the tracer gas was thoroughly mixed (about 30 min. after an injection). During the tracer gas sampling period, mixing was handled by several portable fans located throughout the house. For these tests with furnace fan off, air samples were taken directly from the basement and from the main living area.

The N_2O concentrations were measured on site with an infrared analyzer. The analyzer was calibrated periodically using certified calibration gas.

4.2 Air Flow Rate

The air flow through the vent opening and the stack was measured using either a pair of total pressure averaging tubes or an orifice plate, with a diaphragm-type pressure transducer (static error band of 5% full scale).

4.3 Vertical Pressure Difference Profile

Values of indoor-outdoor pressure difference across the house envelope were measured under calm conditions at four locations along the north wall with a diaphragm-type pressure transducer (static error band of 5% full scale). Pressure probes were installed at the sill and head of a first floor window, and at the sill and head level of a second floor window directly above the first. The probes were located 1.1, 2.6, 3.9 and 5.2 m above grade, respectively.

5. RESULTS AND DISCUSSION

The results of the fan pressurization tests conducted in early summer, with tightness expressed in terms of C and n, are given in Table 1. Also given in Table 1 are the height of neutral pressure levels and the pressure differences at grade level measured under calm conditions with an indoor-to-outdoor temperature difference of 34 K.

The air change rates of the house and the air flow rates through the vents were measured during the 1982-83 heating season under a variety of weather conditions; air temperature difference ranged from 10 to 40 K, and wind speed varied up to 30 km/h. The results for the five basic configurations are shown in Figs. 5 to 9, and are discussed in the following sections.

To determine the effectiveness of these ventilation techniques, the measured air change rates were compared with those measured for the house without passive ventilation (measured in a previous study[3]). For a wind speed lower than 12 km/h, the air change rate increased with inside-outside temperature difference as defined by Eq. 1 (Fig. 4). For higher wind speeds, the air change rate exceeded the values that would apply for the same Δt with low wind speed. However, for temperature differences greater than 20 K and wind speed ranging from 12 to 40 km/h, typical winter conditions for this region of Canada, the air change rate was approximately constant at 0.2 ac/h. Thus, 0.2 ac/h was chosen as the seasonal average air change rate for the test house without passive ventilation.

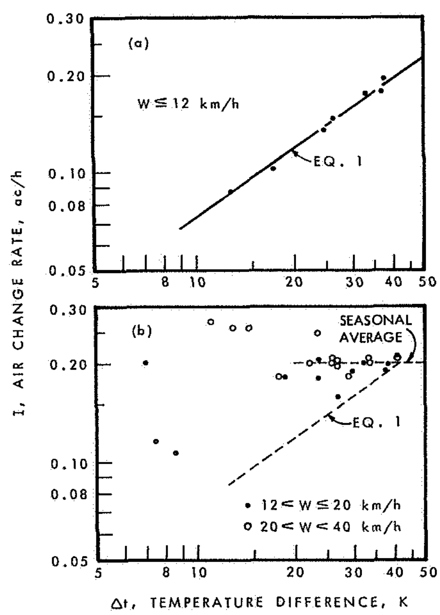

Figure 4. Air change rate without passive ventilation (Reference 3)

5.1 The Five Basic Configurations

Figures 5 to 9 indicate that the house air change rate increased with the indoor-to-outdoor air temperature difference but was relatively insensitive to wind for all systems. However, at a constant Δt, the influence of wind on house air change could be

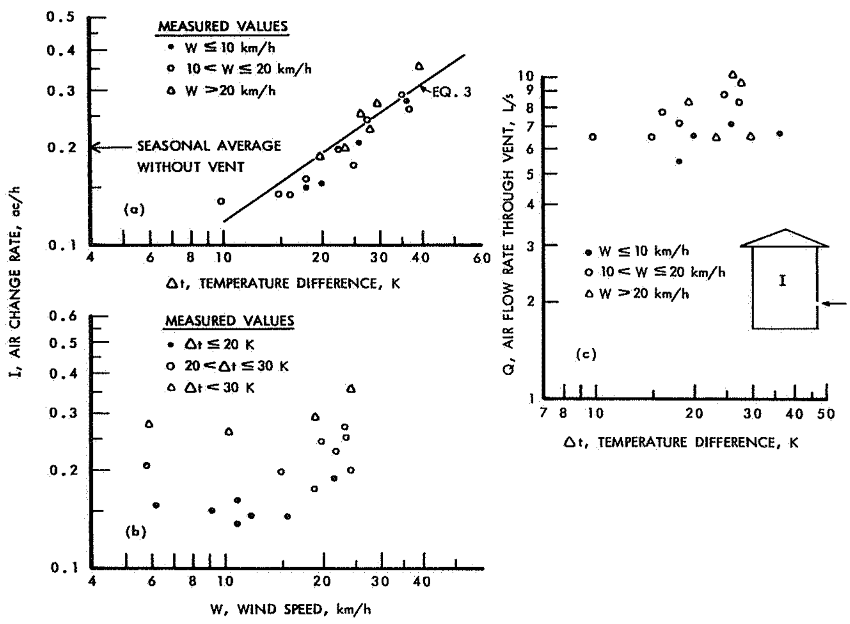

Figure 5. House air change rate and air flow rate through intake vent - configuration I

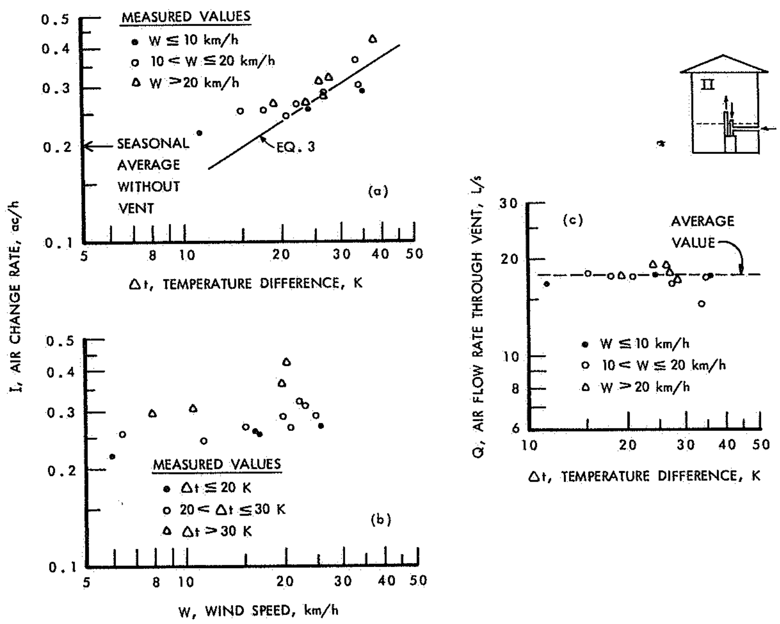

Figure 6. House air change rate and air flow rate through intake vent - configuration II

detected (5a to 9a). Likewise, for a constant wind speed, the scatter in the air change data was mainly caused by stack action (5b to 9b).

The measured air change rates for the five configurations are compared with those predicted by Eq. 3 in Figs. 5a to 9a. In general, the calculated air change rates were within 20% of the measured values.

A comparison between Eqs. 2 and 3 indicates that the ratio B/0.32 should be equal to r, if the values of n are about the same. Since the value of B can be estimated independently by fitting the measured air change rates to Eq. 2, another check on the accuracy of Eq. 3 was made by comparing the ratio B/0.32 with r. The results, listed in Table 1, indicate that the maximum difference between B/0.32 and r is about 10% of r for the five configurations.

5.1.1 Configuration I -- One basement intake vent

This configuration is similar to a house with a preponderance of leakage openings in the lower half of the house envelope, such as a window vent. The ventilation system became effective (i.e., air change rate exceeded that of the house with no vent, 0.2 ac/h) when the temperature difference was greater than 20 K, as shown in Fig. 5a. This figure also shows that Eq. 3 overpredicts the air change rate by about 6% in comparison with the best fit to the measured data.

Figure 5c shows that the air flow through the vent opening also increased with temperature difference. The air flow rate through the vent was also influenced by both wind speed and direction.

5.1.2 Configuration II -- Basement supply to forced-air heating system

This configuration is similar to configuration I, except that the venting action is now augmented by the operation of the furnace fan. The house air change rate exceeded that of the house with no vent (0.2 ac/h) for a temperature difference as small as 10 K (Fig. 6a). This suggests that the furnace fan is effective in increasing the supply of outdoor air to the house. This suggestion is reinforced since the air flow through the supply vent remained nearly constant at a value of about 18 L/s or 0.17 ac/h regardless of temperature difference (Fig. 6c); that is, the supply of outdoor air was controlled by the furnace fan rather than by stack action. As the outdoor supply air rate was constant, the house air change rate should always exceed 0.17 ac/h. The temperature difference corresponding to 0.17 ac/h is 12.5 K (Fig. 6a), suggesting that Eq. 3 should be used only when Δt is greater than 12.5 K. Figure 6a also indicates that Eq. 3 underpredicts the air change rate by about 10% in comparison with the best fit to the measured values.

5.1.3 Configuration III -- Basement exhaust stack

This configuration is similar to a house with a preponderance of leakage openings in the upper half of the house envelope. As Fig. 7a indicates, the house air change rate was greater than 0.2 ac/h when the temperature difference was greater than 20 K. Compared with the previous two systems, this system is more effective than configuration I (probably due to a larger size vent) but is less effective than configuration II, especially under mild weather conditions. Figure 7a also indicates that Eq. 3 coincides with the best fit to the measured data.

The air exhaust rate through the stack was more strongly influenced by stack action than in the two previous configurations (Fig. 7c). Under mild weather conditions, the exhaust rates were also influenced by wind. The wind influence, however, diminished as the temperature difference increased.

5.1.4 Configuration IV -- Combination of I and III

This configuration can be found in houses with a forced-air heating system when the outdoor air supply is disconnected from the heating duct. As shown in Fig. 8a, this system supplied more ventilation air to the house than any of the foregoing systems, and Eq. 3 overpredicts the air change rate by about 7% in comparison with the best fit to the measured data.

Data presented in Fig. 8c show that the air supply and exhaust flows through the intake vent and the exhaust stack were influenced strongly by stack action. Also the air flow through the exhaust stack was almost identical to that of configuration III, and the air flow through the intake vent was about the same as that of configuration I. This suggests that the house pressure, and hence the air flows through the intake vent and exhaust stack, were unaffected by the presence of the other vent.

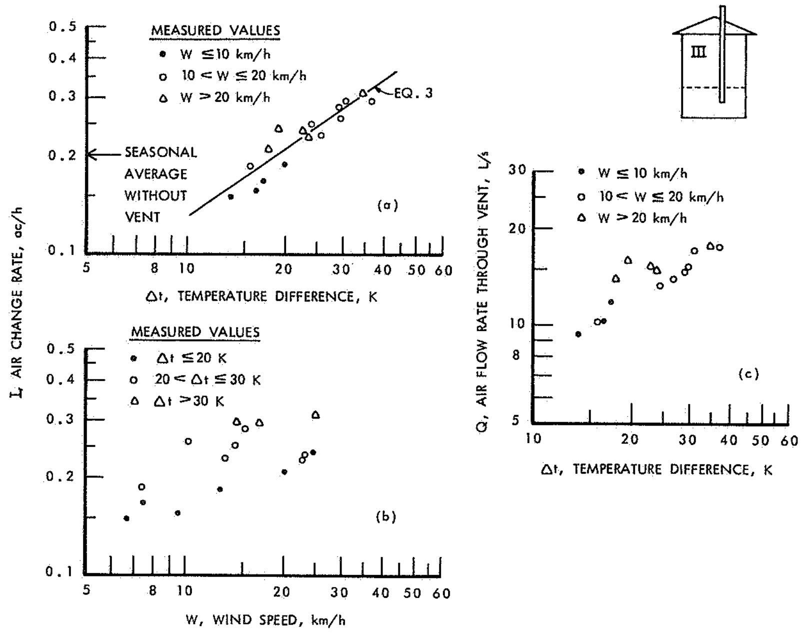

Figure 7. House air change rate and air flow rate through exhaust vent - configuration III

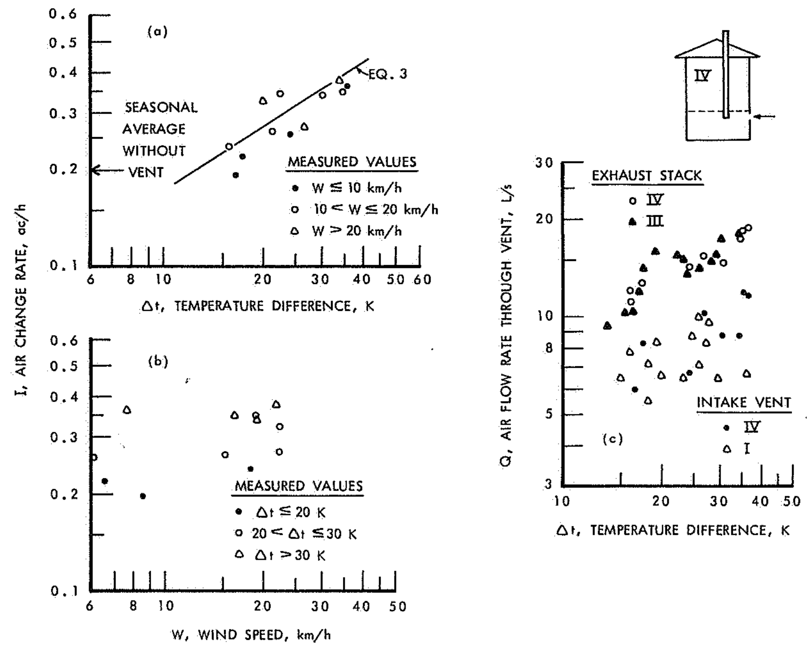

Figure 8. House air change rate and air flow rate through vents - configuration IV

5.1.5 Configuration V -- Combination of II and III

This configuraton can be found in houses with a forced-air heating system having an outdoor air supply connected to its return duct. The temperature difference corresponding to 0.17 ac/h, the outdoor air supply rate, is 10 K (Fig. 9a). As this was the minimum air change rate for this house, Eq. 3 is applicable for Δt greater than 10 K. The air change rates predicted by Eq. 3 are almost identical to those given by the best fit to the measured data.

As was the case with configuration IV, the air flows through the intake vent and exhaust stack were unaffected by the presence of the other vent (Fig. 9c).

Figure 10 shows the temperature-induced air flow and pressure differential patterns for the house with and without a passive ventilation system. The air change rates and the air flow rate through the vents were obtained from Figs. 4 to 9 for Δt = 34 K. Configuration V induced the highest air change rate at 0.42 ac/h, followed by configurations IV, II, III and I at 0.35, 0.33, 0.3 and 0.26 ac/h, respectively. The air leakage rate through the house enclosure for configuration V is greater than that for the house without vents, even though their neutral pressure levels are identical. This discrepancy may be caused by errors associated with neutral pressure level measurement and a possible change in the air leakage characteristic of the house enclosure.

The neutral pressure levels of configurations III, IV, and V, all with an exhaust stack, were higher than that of the house with no passive ventilation, as Fig. 10 shows. Further, the neutral pressure levels of configurations I and II, all without an exhaust stack, were lower than that of the house without passive ventilation. Thus it is not desirable to install a passive ventilation system similar to configurations I and II in houses. Such a system can lower the neutral pressure level of the house, which in turn, increases the amount of humid air leaking out through the upper walls and ceiling. Thus, it increases the potential for developing moisture problem.

6. EFFECT OF FURNACE FAN AND AIR DISTRIBUTION SYSTEM

Configurations II, III, IV, and V were retested with the furnace fan shut down to determine the effect of the furnace fan and air distribution system on ventilation efficiency and capacity. In this series of tests, tracer gas concentrations were measured in the basement and in the first storey living area. The door to the basement was kept closed, but the registers and grilles of the air distribution system remained unsealed.

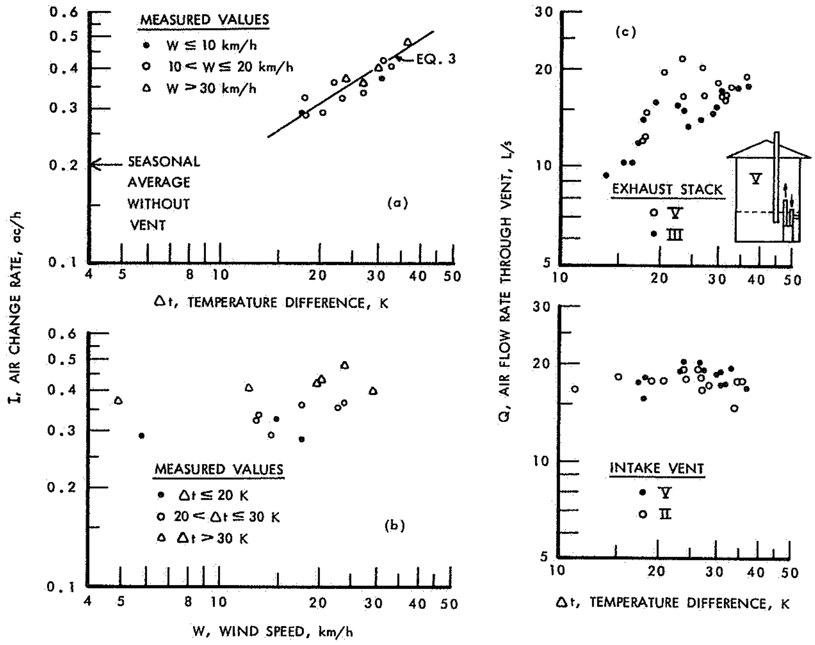

Figure 9. House air change rate and air flow rate through vents - configuration V

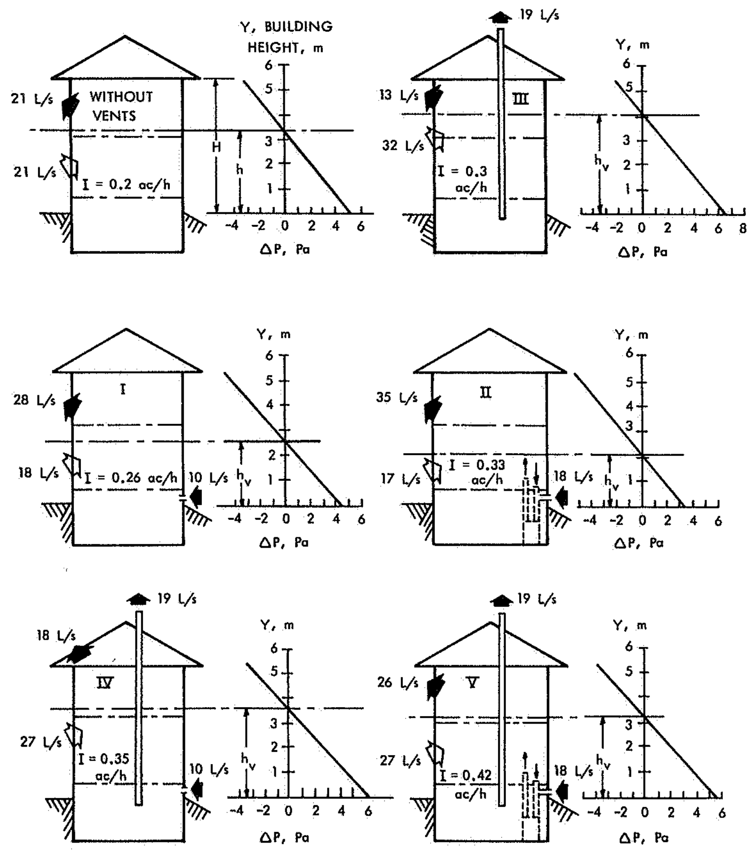

Figure 10. Temperature-induced air flow and pressure patterns for Δt = 34 K

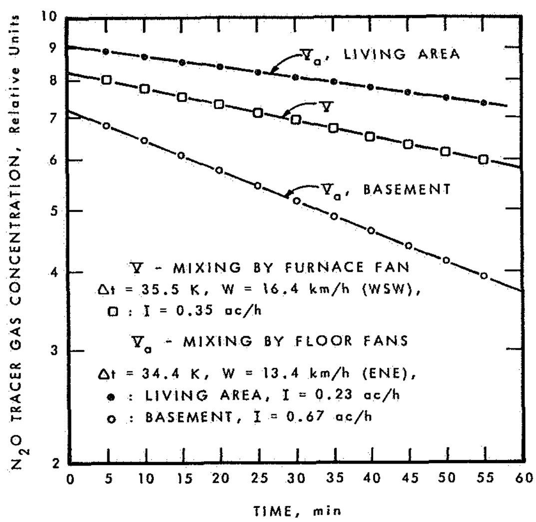

Figure 11. Sample plots of N_2O concentration versus time for air samples collected from return air duct, basement and main living area

Figure 11 shows three sample plots of N_2O concentration versus time; one for configuration V (with furnace fan on) and two for configuration V_a (furnace fan off), obtained under similar weather conditions. The results indicate a straight line relationship between the logarithm of tracer gas concentration and time for all three cases. This suggests that adequate tracer gas mixing was achieved in the test spaces. With the furnace fan off, the tracer gas decay rate for the basement is much greater than that for the first storey living area; that is, the local air change rate was greater in the basement than in the living area. The effect of furnace fan operation on local air change is shown in Figs. 12 and 13 for the four configurations.

Configurations II_a and V_a, shown in Fig. 12, have the outdoor air supply ducted to the heating system, as in houses with gas-heated, forced-air heating systems. Configuration II_a represents the off-cycle condition with high or medium efficiency gas furnaces. Configuration V_a represents the off-cycle condition with a natural-draught gas furnace. The air change rates measured in the basement and in the living space with configuration II_a (Fig. 12a) were almost identical, indicating reasonable mixing of air in the house even with the furnace fan off. This is because the air distribution duct of the heating system permits air entering through the vent opening to reach the living area. The air change rate with the furnace fan off was up to 15% lower than that with the furnace fan operating continuously. This is reflected in Fig. 12c; the air flow through the outdoor air duct with the furnace fan off was nearly constant at 6 L/s and about one-third of the flow with the fan on.

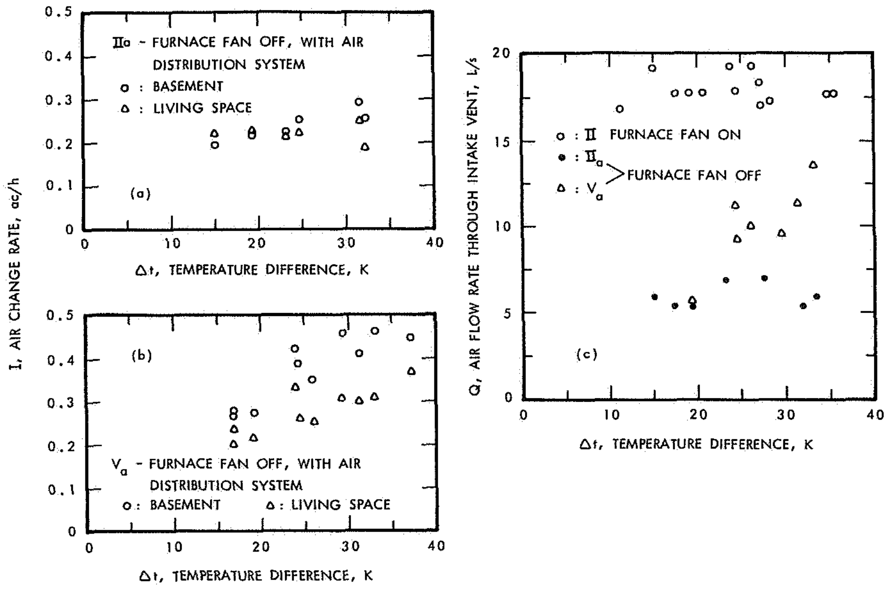

Figure 12. Effect of furnace fan on air flow rate through intake vent and house air change rate

With an exhaust stack in the basement (configuration V_a - Fig. 12b), the air change rate in the basement was consistently higher than that measured in the living space above. This suggests that much of the air leaking into the basement escaped directly through the exhaust stack. The air change rate in the living space, (the effective ventilation rate) with the fan off was about 25% lower than that with the fan on. This is also shown in Fig. 12c; the supply air flow with fan off, although strongly affected by stack action, remained lower than the flow with the fan on.

In Fig. 13, configurations III_a and IV_a, with the vents disconnected from the air distribution system, had a substantially higher air change rate in the basement than in the living space. The difference in air change rate was greater with configuration IV_a (Fig. 13b). With both intake vent and exhaust stack located in the basement, outdoor air entering through the vent opening in the basement bypassed the living area and went directly out through the exhaust stack. Consequently, outdoor air entering through the vent was not ventilating the living space. Moreover, the air infiltration through the basement wall was also bypassing the living space.

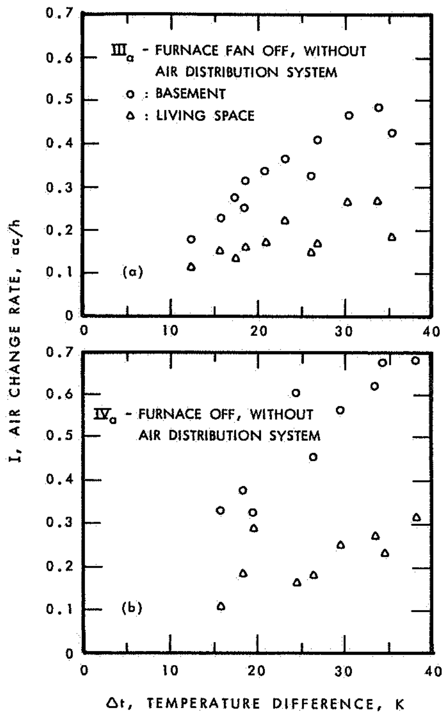

Figure 13. Effect of air distribution system on house air change rate

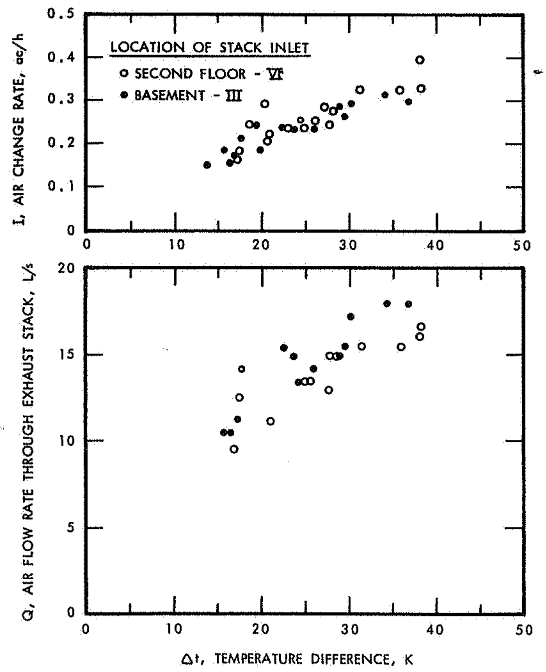

Figure 14. Effect of location of stack intake on house air change rate and venting capacity

7. EFFECT OF EXHAUST STACK CONFIGURATION

Figure 14 compares the house air change rate and the exhaust stack flow of configurations III and VI, which differed only in the location of the inlet to the exhaust stack. Both the house air change rate and the exhaust stack flow remained relatively unchanged regardless of whether the indoor air exhausted from the basement or from the second storey. The location of stack inlet has very little effect on the venting performance of an exhaust stack when the furnace fan is on. However, when the furnace fan is off, or when there is no air distribution system, the preferred location of the inlet to the exhaust stack is in the living space. This location will ensure that outdoor air entering the basement, either through the wall or through a ventilation inlet, will pass through the living space.

8. EFFECT OF VENT OPENING LOCATION

House air change rates were measured with a 12.7 cm diameter vent installed at various locations in the house enclosure (configurations I, and VIII to XI). The vent was located near the sill of a first storey window, or near the head of a second storey window (Fig. 15).

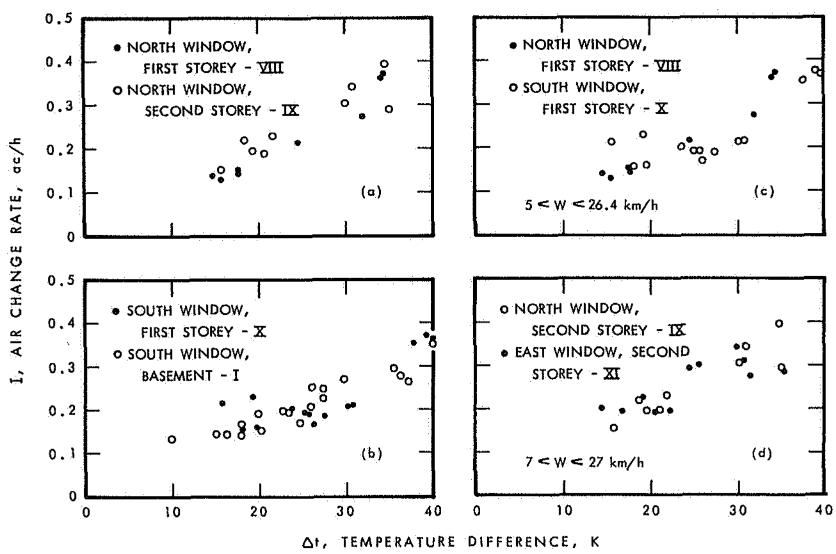

Figure 15. Effect of vent location on house air change for wind speeds up to 25 km/h

The house air change rate was not strongly affected by an elevational change of the vent opening, nor by whether the vent opening was acting as an intake vent (VIII) or as an exhaust vent (IX) (Fig. 15a). There was no apparent difference (Fig. 15b) in house air change rate between a basement vent location (I) and a first-storey location (X), even though the area of the basement vent was 38% less than that of the first storey vent. The directional orientation of the vent opening had no noticeable effect (Figs. 15c,d) on house air change for wind speeds up to 27 km/h. These results again support the conclusion that stack action is the dominant driving potential for passive ventilation.

9. EFFECT OF VENT SIZE

Figure 16 shows the measured house air change rates with two 10 cm vents (5.3 m apart) in the same wall (VII). The house air change rates with two vents were only slightly greater than those with one vent, probably because the air flow through the vents (on average 7.5 L/s per vent) did not have a significant influence on house air change. The air change rate calculated from Eq. 3 for two vents overpredicted the measured values.

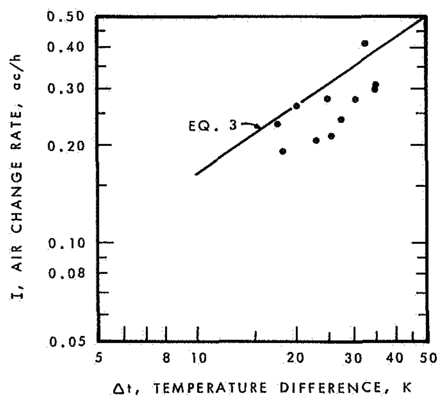

Figure 16. House air change rate - configuration VII

10. SUMMARY

10.1 All the passive ventilation systems tested increased the house air change rate over that of the house with no vents (Table 1). Of the five basic systems, configuration V produced the highest house air change rate, followed by configurations IV, II, III, and I. For example, at Δt = 34K, the measured house air change rates were about 0.42 and 0.35 ac/h for V and IV, and they were about 0.33, 0.3 and 0.26 for II, III and I, respectively.

10.2 Stack action was the dominant driving potential for passive ventilation with wind speeds less than 30 km/h. However, significant flow augmentation was provided by the air circulating fan of the forced-air heating system when the vent was connected directly to the heating system.

10.3 The orientation and elevation of the vent opening appeared to have very little effect on house air change with wind speeds less than 27 km/h.

10.4 The location where the exhaust stack withdraws indoor air had very little effect on house air change rate with the furnace fan operating, but could have a significant effect on the efficient mixing of outdoor air with the air in the living space.

10.5 An air distribution system significantly improves the distribution and mixing of outdoor air that enters through vent openings and infiltrates through openings and cracks in the basement wall with the indoor air.

10.6 Methods for estimating the airtightness characteristic of a house with vent openings and the effect of these openings on the neutral pressure level have been presented. The derived characteristics and Eq. 3 provide a reasonable estimate of house air change resulting from passive ventilation systems for temperature differences greater than 15 K.

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12. APPENDIX A ESTIMATION OF C, n AND NEUTRAL PRESSURE LEVEL FOR HOUSES WITH VENTS

12.1 Flow Coefficient and Exponent

The air leakage characteristic of a house before installation of a ventilation system can be defined by the equation,

$$Q = C\,A\,(\Delta P)^n \qquad \text{(A1)}$$

where:

Q = air leakage rate, L/s,
C = flow coefficient, $L/(s \cdot m^2 \cdot Pa^n)$,
A = area of building envelope, m^2,
ΔP = pressure difference, Pa,
n = flow exponent.

After the installation of a passive ventilation system, the total air leakage of the house as determined by a fan pressurization test, would be the sum of the air leakage through the building envelope and the air flow through the vent. Thus,

$$Q' = C\ A\ (\Delta P)^n + Q_v \tag{A2}$$

where:

Q' = air leakage rate with vent, L/s,
Q_v = air flow rate through the vent, L/s.

To estimate the value of Q_v, the following two cases are considered:

(a) If the vent is connected to the forced air heating system with the furnace fan operating continuously, then Q_v can be assumed to be constant because of the large suction in the supply duct induced by the furnace fan. Measurements conducted on the test house having a 10 cm supply duct indicate that Q_v was about 18 L/s under typical winter conditions. For similar or less airtight houses, Q_v would be proportional to the size of the supply duct,

$$Q = 0.18\ D^2\ \text{L/s} \tag{A3}$$

where D is the diameter of the supply duct in cm.

(b) If the vent is just an opening in the building envelope, Q_v would be a function of the pressure difference induced by the pressurization fan, ΔP. Thus, Q_v could be approximated by the orifice equation,

$$Q_v = 1000\ C_d\ (2/\rho)^{\frac{1}{2}}\ A_v\ (\Delta P)^{\frac{1}{2}}\ \text{L/s}$$

Let the orifice discharge coefficient $C_d = 0.6$, the above equation becomes

$$Q_v = 600\ (2/\rho)^{\frac{1}{2}}\ A_v\ (\Delta P)^{\frac{1}{2}}\ \text{L/s} \tag{A4}$$

where:

ρ = density of indoor air, kg/m^3,
A_v = area of the vent, m^2,
ΔP = pressure difference across house envelope as induced by a pressurization fan, Pa.

Substituting Eq. A3 or A4 into Eq. A2, values of Q' can be calculated for the range of ΔP normally used in a pressurization test. By fitting these data to the air flow equation (A1), the values of C and n for the house with vents can be derived.

Values of C and n were calculated for configurations I, II, III, IV, V and VII. Because the calculated and the measured values of n were very close, the values of C were recalculated using Eq. A1 and the measured values of n, to facilitate comparison of the measured and the calculated C. The calculated and measured values of C, presented in Table A1, show good agreement.

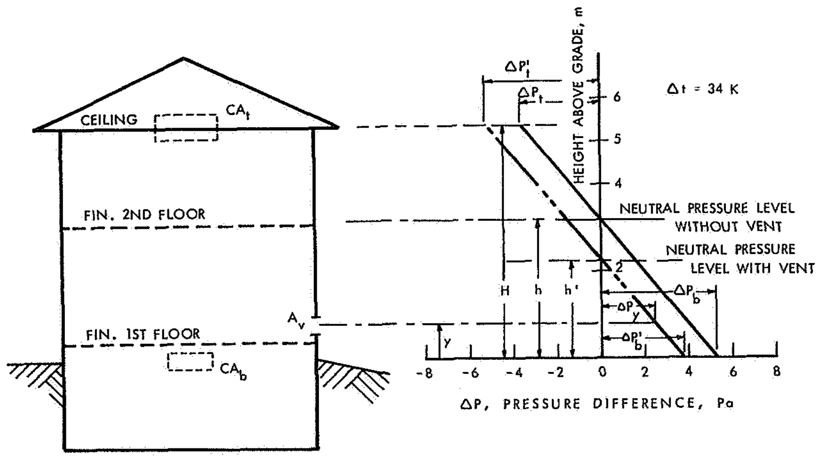

Figure A1. Distribution of leakage openings and pressure difference profile caused by stack action

12.2 Neutral Pressure Level

If vent openings are installed in a house envelope as shown in Fig. A1, the neutral pressure level (NPL) will shift to h' from h and the pressure difference across the house envelope due to stack action will change accordingly. Assuming that: (1) the air leakage characteristic of the house without vents can be represented by two openings: one located at grade level and the other at the ceiling level of the top storey, and that (2) the vertical distribution of pressure difference of the house without vents is known, the new neutral pressure level (h') can be estimated from the mass flow balance equation:

$$CA_b\ (\Delta P_b')^n\ \rho_o + (\Sigma Q_v \rho_o)_b = CA_t\ (\Delta P_t')^n\ \rho_i + (\Sigma Q_v \rho_i)_t \qquad (A5)$$

where:

CA_b = overall flow coefficient below neutral pressure level, $L/(s \cdot Pa^n)$,
CA_t = overall flow coefficient above neutral pressure level, $L/(s \cdot Pa^n)$,
$\Delta P'$ = inside-outside pressure difference due to stack action with vents, Pa,
n = flow exponent,
ρ = air density, kg/m^3

and subscripts b = grade level, t = ceiling level, o = outdoor, i =indoor.

In the above equation, the terms, CA_b and CA_t define the air leakage characteristic of the house before the installation of the vents. They can be estimated from the mass flow equation:

$$CA_b\ (\Delta P_b)^n\ \rho_o = CA_t\ (\Delta P_t)^n\ \rho_i \qquad (A6)$$

where ΔP is the pressure difference across the house envelope due to stack action.

Since,

$$\Delta P_t = \left[(H - h)/h\right]\cdot\Delta P_b$$

and

$$(\rho_i/\rho_o) = (T_o/T_i)$$

therefore, Eq. A6 can be rewritten as:

$$CA_b = CA_t\ \left(\frac{H-h}{h}\right)^n \cdot \left(\frac{T_o}{T_i}\right) \qquad (A7)$$

and,

$$CA = CA_b + CA_t \qquad (A8)$$

where:

h = neutral pressure level without vent, m,
H = ceiling height, m.

Equation A5 can be used to estimate the neutral pressure level for a house with a passive ventilation system. It can be simplified for the following three basic venting arrangements:

(1) One vent below NPL, $(Q_v)_t = 0$

The mass flow balance equation simplifies to,

$$CA_b\ (\Delta P_b')^n\ \rho_o + Q_v\rho_o = CA_t\ (\Delta P_t')^n\ \rho_i$$

However,

$$\Delta P_b' = (h'/h)\ \Delta P_b,$$

$$\Delta P_t' = \left(\frac{H-h'}{H-h}\right)\ \Delta P_t = \left(\frac{H-h'}{h}\right)\ \Delta P_b,$$

$$\Delta P_\gamma = \left(\frac{h'-y}{h'}\right)\ \Delta P_b' = \left(\frac{h'-y}{h}\right)\ \Delta P_b\ .$$

Hence, the mass flow balance equation can be rewritten as

$$CA_b\ \left(\frac{h'}{h}\right)^n + 600\ \left(\frac{2}{\rho}\right)^{\frac{1}{2}}\ A_v\ \left(\frac{h'-y}{h}\right)^{\frac{1}{2}}\ \Delta P_b^{(\frac{1}{2}-n)} = CA_t\ \left(\frac{H-h'}{h}\right)^n\ \left(\frac{T_o}{T_i}\right) \qquad (A9)$$

(2) One vent above NPL, $(Q_v)_b = 0$

The mass flow balance equation simplifies to,

$$CA_b\ (\Delta P_b')^n\ \rho_o = CA_t\ (\Delta P_t')^n\ \rho_i + Q_v\rho_i\ .$$

Substituting for $\Delta P_b'$, $\frac{\rho_o}{\rho_i}$, Q_v, and $\Delta P_t'$, we have

$$CA_b\ \left(\frac{h'}{h}\right)^n \left(\frac{T_i}{T_o}\right) = CA_t\ \left(\frac{H-h'}{h}\right)^n + 600\ \left(\frac{2}{\rho}\right)^{\frac{1}{2}} A_v\ \left(\frac{y-h'}{h}\right)^{\frac{1}{2}}\ \Delta P_b^{\ (\frac{1}{2}-n)} \quad \text{(A10)}$$

An exhaust stack would be treated as a vent opening located at the ceiling level of the top storey.

(3) Outdoor air supply to forced air heating system, Q_v = constant

If an outdoor air supply duct is connected directly to a forced air heating system with the furnace fan operating continuously, the air flow rate supplied by the system could be assumed as constant. Thus,

$$CA_b\ (h'/h)^n + (Q_v/\Delta P_b^{\ n}) = CA_t\ \left(\frac{H-h'}{h}\right)^n \left(\frac{T_o}{T_i}\right) \quad \text{(A11)}$$

For comparison, the neutral pressure levels for configurations I, II, III, IV and V were calculated using these equations. The results (Table A1) show good agreement between the calculated and the measured neutral pressure level.

Table A1 Measured and Estimated Flow Coefficients, Exponents and Neutral Pressure Levels

	Flow Coefficient and Exponent				Neutral Pressure Level	
	Estimate		Measurement			
Configurations	C $L/(s\cdot m^2Pa^n)$	n	C $L/(s\cdot m^2Pa^n)$	n	Estimate m	Measurement m
I	0.106	0.71	0.103	0.71	2.4	2.6
II	0.119	0.66	0.126	0.66	2.0	2.1
III	0.113	0.71	0.101	0.71	4.1	4.2
IV	0.150	0.66	0.134	0.66	3.4	3.6
V	0.144	0.66	0.139	0.66	3.2	3.2

Table 1 Measured Flow Coefficients; Exponent; Neutral Pressure Levels; House Air Change Rates; and Comparison of Measured and Calculated r

Configuration	Vent Size m^2 Intake	Vent Size m^2 Exhaust	Fan pressurization test: C Flow coefficient $L/(s \cdot m^2 Pa^n)$	Fan pressurization test: n Flow exponent	Pressure difference under no wind conditions: Approx. neutral pressure level above grade, m	Pressure difference under no wind conditions: ΔP stack at grade for Δt=34K Pa	r: B/0.32 (Measured)	r: $1+\Sigma^J\left\|\frac{h_v-h}{h}\right\|$ (Calculated)	House air change rate Δt=34K ac/h	Remarks
0	0	0	0.092	0.71	3.2	5.3	1	1	0.2	House as is
I	0.0081	0	0.103	0.71	2.6	4.3	1.13	1.19	0.26	Vent in south basement wall
II	0.0081	0	0.126	0.66	2.1	3.5	1.22	1.34	0.33	Supply to forced air heating system
IIa	0.0081	0	0.102	0.71	-	-	-	-	0.26	Furnace fan off
III	-	0.0127	0.101	0.71	4.2	6.9	1.31	1.31	0.3	Stack inlet in basement
IV	0.0081	0.0127	0.134	0.66	3.6	6	1.41	1.5	0.35	I and III
V	0.0081	0.0127	0.139	0.66	3.2	5.3	1.63	1.66	0.44	II and III
VII	2×0.0081	0	0.141	0.66	-	-	1.16	1.38	0.32	Two vents in south basement wall
IX	0.0127	0	0.132	0.66	4.2	6.9	-	-	0.34	Vent in second storey window
X	0.0127	0	0.135	0.66	-	-	-	-	0.32	Vent in first storey window

THE IMPLEMENTATION AND EFFECTIVENESS OF AIR INFILTRATION STANDARDS IN BUILDINGS

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PAPER 12

IMPLICATIONS AND ANALYSIS OF AIRTIGHTNESS AND VENTILATION STANDARDS

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SYNOPSIS

Airtightness and ventilation standards are forming an increasingly important role in building energy conservation strategies. Such standards were first introduced in Sweden where limited indigenous energy resources, coupled with a severe climate and a steadily increasing reliance on imported energy resources, resulted in a thorough appraisal by the Swedish government of future energy policy. The cornerstone of this policy is building energy conservation with a particular emphasis on the control of fresh air exchange rates. Subsequently, other countries have focussed attention on airtightness and ventilation standards as a method of minimising heat loss from buildings.

The purpose of this paper is to explore the implications and cost effectiveness of these requirements, particularly in relation to climate and ventilation needs. The objective is to show that universal standards may not necessarily be appropriate and that it is necessary for each country to pay careful attention to its own individual requirements. In particular, two fundamentally different approaches to the problem are considered. The first relates to a total airtightness policy, in which all fresh air needs are met by mechanical ventilation. While this method can provide ideal control, and can be attractive in terms of national energy conservation, it is not so easy to justify in terms of cost effectiveness especially in mild climates. Thus, where many competing demands are being placed on energy conservation budgets, this approach is unlikely to be adopted. The second method is to introduce limited airtightness measures to restrict excessive air infiltration rates. Again, it is shown that the value of this approach is governed by climate but, if properly introduced, has an important role to play in both new building design and retrofit programmes.

1. INTRODUCTION

Heat loss from buildings continues to represent a substantial proportion of the prime energy consumed in many countries. As measures to upgrade the thermal performance of buildings proceed, so air infiltration and ventilation account for an increasing segment of the space heating (or cooling) load. It is primarily for this reason that airtightness controls are beginning to form part of the building codes and recommendations in a number of countries. Such measures are already a feature of Swedish[1] and Norwegian[2] building regulations, while plans to incorporate them into North American and Australian standards are well advanced.

In addition to increasing the potential for energy conservation, airtightness construction or retrofit techniques can also contribute to a comfortable, draught-free environment. On the debit side, however, excessive levels of airtightness may result in a serious deterioration in indoor air quality. Consequently, it is of paramount importance that these measures are introduced with the utmost caution.

In formulating airtightness standards many factors need to be considered. These include climate, the sources and severity of indoor pollution, ventilation requirements, existing practices, cost and the overall impact of such controls on energy conservation. Requirements also vary according to building use. Airtightness and ventilation needs are therefore extremely diverse and hence solutions appropriate to one particular building or climatic region may not necessarily be satisfactory elsewhere. It is therefore essential that the concepts and implications of building airtightness are thoroughly explored before the introduction of such standards. Most importantly, airtightness and ventilation should not be approached in isolation but need, instead, to be considered in context with other energy conservation measures.The durability of components used to achieve the desired standard also needs to be verified, since any deterioration in the product will result in a long-term failure to achieve the desired level of energy conservation.

It is the intention of this paper to highlight the various parameters and difficulties which need to be considered in the preparation of airtightness and ventilation standards. The rationale behind existing approaches is illustrated and guidelines for the preparation of possible future standards are discussed.

2. CLIMATE

The primary purpose of building airtightness is to minimise excessive heat loss due to air infiltration. However, the amount of energy conserved depends not only on an overall air change rate but also on the severity of the climate. Thus climate has a significant influence on the choice of an appropriate level of airtightness. In particularly severe climatic zones, for example, there is a much greater scope for conserving energy than in less severe locations; consequently fairly elaborate design solutions can be contemplated.

For energy investigations, the severity of climate is frequently quantified in terms of degree days, where a degree day is the number of degrees of temperature difference on any one day between a given base temperature and the corresponding daily mean outside air temperature. Unfortunately there is no international agreement on base temperature, although it is normally regarded as the external temperature below which space heating is required. Typical values of both base temperature and design indoor temperature for dwellings, taken from the AIC Handbook[3] and other sources, are summarised in Table 1. The table also highlights divergencies from base temperatures at which space heating is required. Differences between design room temperature and the temperature at which heating is needed are assumed to be satisfied by incidental gains from solar radiation, building occupants and powered appliances, etc. In the United States the concept of degree days is also used for cooling load calculations where the cooling degree day is given by the number of degrees above a base temperature of 25.5°C. The heating and cooling load degree days are summed algebraically to give an "infiltration" degree day (IDD) for use in air infiltration calculations[4].

Typical degree day ranges for several countries are reproduced in Table 2. This shows values ranging from below 1000 in parts of New Zealand to above 12000 in the North of Canada. Despite the lack of uniformity regarding the definition of degree days, this concept nevertheless provides a convenient method for defining an approximate "climatic threshold" at which specific airtightness and ventilation approaches become cost effective options.

3. AIR INFILTRATION

Air infiltration is the uncontrolled ingress of air through adventitious openings in the building envelope and is caused by pressure differences generated by the actions of temperature and wind. In the past, this natural mechanism has been harnessed throughout the world to satisfy the ventilation needs of many buildings. However, this approach suffers from several disadvantages which often conflict with energy conservation requirements. In particular, the nature of the driving forces is such that a constant air change rate cannot be maintained. Thus a natural ventilation system designed to satisfy minimum fresh air requirements will frequently provide excess ventilation, with a consequential waste of energy. The variation in air infiltration rate throughout the year can be at least an order of magnitude. For a given building location and fixed leakage parameters, the rate of air infiltration is a function of climatic severity. Therefore high infiltration rates can be expected to coincide with periods when space heating is most required. The influence of climate on air infiltration rates can be readily assessed by using an appropriate mathematical model[5]. A typical example of the projected distribution in air change rates throughout a winter period for a single family dwelling situated in the United Kingdom is illustrated in Figure 1. Natural air movement within buildings is also subject to the vagaries of climate, with the result that internally generated pollution can linger within the building rather than being dispersed. This problem becomes especially significant if measures have been introduced to increase building airtightness without regard for the need to satisfy the demands of indoor air quality.

Although purpose provided vents, stacks and windows have all been used to improve the performance of natural ventilation, the inherent limitations of this approach has resulted in a trend towards the use of mechanical methods of ventilation in some countries.

4. AIRTIGHTNESS

The airtightness of a building may be determined by artificially pressurizing or depressurizing the structure and measuring the volume air flow rate necessary to maintain a given pressure difference. Measurements are normally made at several pressures so that the relationship between flow rate and pressure difference can be established.

The flow characteristics are approximated by the empirical flow equation

$$Q = K(\Delta P)^n \text{ m}^3/\text{sec} \tag{1}$$

where K = leakage coefficient
n = flow exponent
and ΔP = pressure difference

Although in theory the flow exponent, n, can have a value between 0.5 (fully turbulent flow) and 1.0 (laminar flow), in practice it usually lies between 0.6 and 0.7.

It has become common to express the airtightness of a building in terms of the measured flow rate at a pressure difference of 50 Pa. This reference pressure thus acts as a datum against which the airtightness performance of buildings can be compared. Extreme caution is necessary, however, because there is little international uniformity governing pressurization testing. It is therefore not always straightforward to use this method to make valid comparisons between the air leakage performance of buildings in different countries. It is also usual to divide the flow rate by the heated volume of the building to derive the air leakage at 50 Pa in terms of air changes per hour (ach). This again can lead to confusion and uncertainty since differing interpretations of "heated volume" are common.

In North America it has become popular to express airtightness in terms of "equivalent leakage area" (ELA) where ELA is defined as the size of an orifice opening that would pass the same flow rate at a specified pressure as would the entire building subjected to the same pressure differential. The specified pressure has yet to be standardised and at the present time 10 Pa is favoured in Canada while 4 Pa is preferred in some parts of the United States. Figure 2 illustrates an approximate comparison between each of the leakage definitions for a range of flow rates. The example illustrated compares the air leakage of a 250 m^3 dwelling conforming to Swedish airtightness standards of 3 ach at 50 Pa[1] with ELAs at 4 Pa and 10 Pa. The corresponding ELAs vary between 138 - 177 cm^2 and 165 - 194 cm^2 respectively, the spread in results being dependent on the flow exponent, n.

Neither of these airtightness definitions can be regarded as perfectly satisfactory since the effective leakage area is widely influenced by both the choice of pressure and the value of the flow exponent, while the leakage at 50 Pa need not be indicative of conditions in the pressure regime between 0-10 Pa at which air infiltration most often takes place. Nevertheless these have proved very useful concepts to incorporate into airtightness standards because the necessary measurement methods are fairly straightforward to perform and the results provide some indication of the relative airtightness performance of buildings.

5. VENTILATION NEEDS

The minimum fresh air supply necessary to meet respiratory needs is estimated to vary between 0.1 - 0.9 x $10^{-3}m^3$/sec/person depending on the intensity of activity[6]. Much higher rates of ventilation are required to maintain adequate indoor air quality and it is this problem which normally dictates overall ventilation needs. There is a direct link between modern airtightness practices and poor indoor air quality with the result that minimum ventilation studies have become inextricably linked to air infiltration and airtightness investigations. It is important therefore that standards introduced to minimise ventilation heat loss should not conflict with the need to supply sufficient fresh air to dilute and disperse internally generated pollution.

Common pollutants to be found within homes and commercial buildings include odour, moisture, the products of combustion, radon and formaldehyde. In rooms in which fuel burning appliances are installed, adequate air to supply combustion needs is also necessary. The ventilation requirements for other types of buildings are frequently more specialised, for example to prevent industrial pollution or to remove process heat in factories and to prevent bacteriological contamination in hospitals. These requirements must be expected to take precedence over energy conservation considerations.

In general, each pollutant requires a different ventilation rate to ensure sufficient dilution and removal. These rates are primarily dependent on the source and strength of the pollutant, external concentrations, disoomfort effects and toxicity. The minimum ventilation rate must at all times exceed the rate necessary to disperse the pollutant requiring most ventilation.

In common with airtightness testing, ventilation rates are frequently expressed in terms of air changes/hour. Typical ventilation rates necessary to dilute some common pollutants are illustrated in Figure 3 and are based on data published in British Standards 5925[6]. The ventilation rate has been expressed in terms of both volume flow rate and air changes/hour for an enclosed volume of $250m^3$. When more than one source contributes to the emission of a single pollutant (as occurs in the example with moisture and carbon dioxide) the ventilation needed to satisfy the requirement of each source is summed to obtain the total rate. Very often the pollutant source lies within a single room inside the building. Thus, while it is possible to translate the ventilation need in terms of a whole building air change rate, it does not necessarily follow that an overall air change rate of this value will provide adequate ventilation in the proximity of the pollutant source. Only if the entire air flow passes through the room in question will this be achieved.

Figure 3 also illustrates the significance of moisture as a dominant pollutant. The capacity for air to contain moisture is highly sensitive to air temperature and consequently a reduction in internal temperatures as a means of conserving energy can result in serious condensation problems. In addition, the use of unvented space heaters and warm air clothes dryers can further exacerbate the situation. Climatic differences also impart important regional differences to the moisture problem. Figure 4 indicates the average moisture content of outside air throughout the winter months for locations in Canada, New Zealand and the United Kingdom. This shows the average mid-winter water content of the atmosphere in London to be almost 3½ times greater than that in Ottawa, while in Wellington the water content exceeds the Canadian value by a factor of almost 5. Thus for a given rate of moisture generation within a building, a much higher rate of ventilation is necessary in some regions than in others.

Climatic conditions, as well as the occupants' choice of appliances, therefore have an important influence on ventilation requirements. Both problems need to be carefully addressed during the preparation of ventilation standards.

6. INFLUENCE OF AIRTIGHTNESS ON VENTILATION STRATEGY

The fundamental design criteria for energy efficient ventilation is to minimise space heating and cooling loads yet maintain adequate indoor air quality. The selected approach must also be cost effective. The efficient performance of ventilation systems is dependent on the level of building airtightness, thus the choice of airtightness standard has a significant effect on ventilation strategy.

There are essentially two approaches to building airtightness. The first is to follow an almost total airtightness policy in which separate provision is made to satisfy ventilation needs by mechanical means. The second method is to introduce limited airtightness measures such that passive ventilation is sufficient to meet most needs. The former technique offers good control over air change rates, so providing an opportunity to benefit from the full value of air infiltration reduction techniques. Its main disadvantage is that system expense and additional construction costs are high. Furthermore it is essential that the design airtightness is maintained throughout the life of the building. By comparison, the partial airtightness approach, incorporating natural ventilation involves a much smaller increase in expenditure. In addition, a margin of natural leakage ensures a certain degree of safety, while at the same time excessive rates of air infiltration are minimised. However, the latter technique does not offer the same degree of energy conservation as the former.

Nevertheless it still has important applications, especially in mild climatic regions where the cost of providing mechanical ventilation stands little chance of being recovered. This approach also provides a yardstick against which the energy efficiency and cost performance of mechanical ventilation systems can be compared.

A policy towards high levels of airtightness has been introduced for all new dwellings in Sweden[1] and Norway[2]. The introduction of these standards has therefore encouraged a substantial increase in the use of mechanical ventilation. On the other hand, proposed United States ASHRAE standards[4] consider a combination of techniques, with the level of airtightness being fixed according to infiltration degree days. In the severest climatic areas of the country a high degree of airtightness is proposed with a consequential need for mechanical ventilation. Elsewhere, progressively less stringent requirements are envisaged.

7. COST EFFECTIVENESS OF AIRTIGHTNESS MEASURES

For countries in which degree day base temperatures correspond to the threshold at which space heating is required, the annual ventilation space heating demand in given by

$$E = Q \times DD \times 24 \times 3600 \times \rho \times S \times 10^{-9} \text{ GJ} \qquad (2)$$

where Q = ventilation/infiltration flow rate (m^3/sec)
DD = number of degree days
ρ = air density $\simeq 1.29$ kg/m^3
S = specific heat of incoming air $\simeq 1012$ J/kg

In terms of hourly air change rate, this equation becomes

$$E = \frac{ACR \times V \times DD \times .1128}{3600} \text{ GJ} \qquad (3)$$

where ACR = hourly air change rate (h^{-1})
V = volume of heated space (m^3)

Elsewhere degree days need to be recalculated to the heating threshold temperature prior to performing energy calculations. These energy equations enable degree day data to be used to determine the cost effectiveness of airtightness and ventilation measures.

To achieve the Swedish recommended air change rate for single family dwellings of 0.5 ach[1] by natural ventilation, it has been shown that the air leakage of the building should not be much below 10 ach at 50 Pa[7]. Furthermore, to ensure the removal of pollutants at source, the intermittent use of local extract fans and cooker hoods may be necessary, adding a further 0.2 ach to the air change rate[8]. Thus an overall ventilation rate averaging 0.7 ach may be needed to satisfy the above ventilation requirement by natural means. It should also be noted that further airtightness of the building could be counter-productive, since it is probable that more use of window opening will take place to overcome noticeable indoor air quality problems.

In theory, mechanical ventilation can provide complete control with the result that the desired air change rate should be possible at an energy advantage over natural ventilation. Mechanical ventilation also provides the opportunity for heat recovery, either by incorporating a heat pump into the exhaust air duct or by using the exhaust air to pre-heat incoming air. Typically, these methods permit a heat recovery of approximately 70% (see Figure 5a). In practice, the degree of airtightness necessary to achieve this level of control is neither possible nor desirable, and measurements made in dwellings constructed to Swedish airtightness standards of $\leqslant$ 3 ach at 50 Pa reveal residual infiltration rates of up to 0.2 ach[9]. Thus the total air change rate will be closer to 0.7 ach, corresponding to the value estimated for natural ventilation. Therefore, for mechanical ventilation to be energy efficient, heat recovery is essential . However, because heat cannot be recovered from the infiltration loss, the net heat recovery reduces to 50% (see Figure 5b). Furthermore, to be cost effective, the annual saving in energy charges must outweigh the combined yearly operating and payback cost of the ventilation system. This can be expressed in the form

$$A + C_{(M)} + C_{(I)} = C_{(N)} \tag{4}$$

where A = combined yearly operating and payback cost.

$C_{(M)}$ = annual cost of heat lost through mechanical ventilation system.

$C_{(I)}$ annual cost of heat lost through residual air infiltration.

$C_{(N)}$ annual cost of heat lost through natural ventilation.

By combining equation (4) with equation (2), the number of degree days at which mechanical ventilation with heat recovery becomes cost effective is given by

$$DD = \frac{A}{E_c \times .1128 \left\{ Q_N - \left[Q_M \left(1 - H_{eff}/_{100} \right) + I_M \right] \right\}} \quad (5)$$

where E_c = cost of each GJ of useful energy
H_{eff} = efficiency of heat recovery (%)
Q_N = natural ventilation rate (ach)
Q_M = mechanical ventilation rate (ach)
I_M = residual infiltration rate (ach)

Using the example cited, equation (5) reduces to

$$DD = \frac{3600 \times A}{E_c \times 0.1128 \times 0.35V} \quad (6)$$

where Q_N = 0.2 ach, Q_M = 0.5 ach, I_M = 0.2 ach and H_{eff} = 70%

Harryson[10] indicates that the additional cost of including balanced ventilation with heat recovery in a new building in Sweden is as low as 8000 SEK. Thus, assuming a system life of 20 years, the annual "payback" is 400 SEK. Running costs ($\sim$ 600 kWh) will add another 150 SEK to the annual operating expense making a total of 550 SEK. At an approximate charge for useful energy of 66 SEK/GJ, the resulting economic degree day value is 3039. Based on these figures, air-to-air heat recovery can be regarded as cost effective throughout Sweden. Comparable costs in the UK yield a less optimistic degree day value of approximately 4500 and this approach could not therefore be justified on economic grounds for this size of building. The nomogram presented in Figure 6 enables approximate solutions to be found for a whole range of prices and conditions. Generally it can be expected that the threshold degree day value will be somewhere between 3000 and 5000. For larger buildings, proportionally lower degree day values may be expected. It is also possible to reduce the threshold value by a further 17% by lowering the mechanical ventilation rate to 0.3 ach. Combined with the residual air infiltration, it should still be possible to satisfy the Swedish ventilation requirement of 0.5 ach.

These calculations thus provide an approximate method of assessing the cost effectiveness of ventilation approaches and are applicable to a wide range of buildings. They also illustrate that, although heat recovery approaches can result in considerable energy savings on a national scale, "pay back" and operating costs must be low to be attractive to the building user.

8. CONCLUSIONS

Energy conservation cannot be achieved simply by reducing air change rates. Airtightness and ventilation standards must be introduced in conjunction with good building design to ensure that indoor air quality problems are avoided. Actual ventilation needs are dependent on building use, the source and strength of pollutants and local climate. Where stringent airtightness measures have been introduced, purpose provided ventilation is essential. Conversely if mechanical ventilation is installed, airtight construction is essential, otherwise the potential for energy conservation will not be achieved.

Ventilation standards must not be concerned solely with overall air change rates. The performance of ventilation in dispersing pollution at source also needs to be considered.

It is unlikely that mechanical ventilation alone will offer an energy advantage over a comparable natural ventilation system. Only by combining mechanical ventilation with heat recovery will a reduction in energy usage be possible. However, while heat recovery can be shown to be energy effective, i.e. can offer a considerable reduction in energy demand on a national scale, it is often difficult to justify this approach in terms of cost effectiveness to the consumer. It is possible to make an assessment of the viability of heat recovery by consideration of degree days. Typical installation and operating costs indicate that such a system is viable for single family dwellings over a 20 year payback period for degree days in excess of about 3K - 5K. More precise figures can be readily calculated given details of energy costs, ventilation needs, etc. For larger buildings where the relative cost of the ventilation system is lower in relation to the volume of air handled, this approach is more likely to be a cost effective proposition.

Unless the relative cost of mechanical ventilation can be considerably reduced, natural ventilation will continue to have a dominant role to play in mild climatic areas. By careful design and control over airtightness, a satisfactory balance between costs and energy conservation is possible.

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TABLE 1: Variations in degree day definition

Country	Indoor design temperature (living areas)	Base temperature	External temperature below which heating is required
Belgium	20.0	15.0	15.0
Canada	21.1	18.0	18.0
Netherlands	20.0	18.0	15.5
New Zealand	20.0	18.0	
Norway	20.0	17.0	
Sweden	20.0	17.0	
Switzerland	20.0	20.0	12.0
United Kingdom	18.3	15.5	15.5
United States	20.0	18.3	18.3

TABLE 2: Degree day data

Country	Degree day data (range for country)
Belgium	2021 - 2087
Canada	3200 - 12600
Netherlands	2714 - 3145
New Zealand	500 - 1400
Norway	4647 - 6402
Sweden	3006 - 5930
Switzerland	2620 - 5700[x]
United Kingdom	1835 - 2613
United States (IDD)	630 - 9363

[x] *Average for 80% populated area 3600*

FIGURE 1: Typical variation in air infiltration rate throughout heating season for a small dwelling.

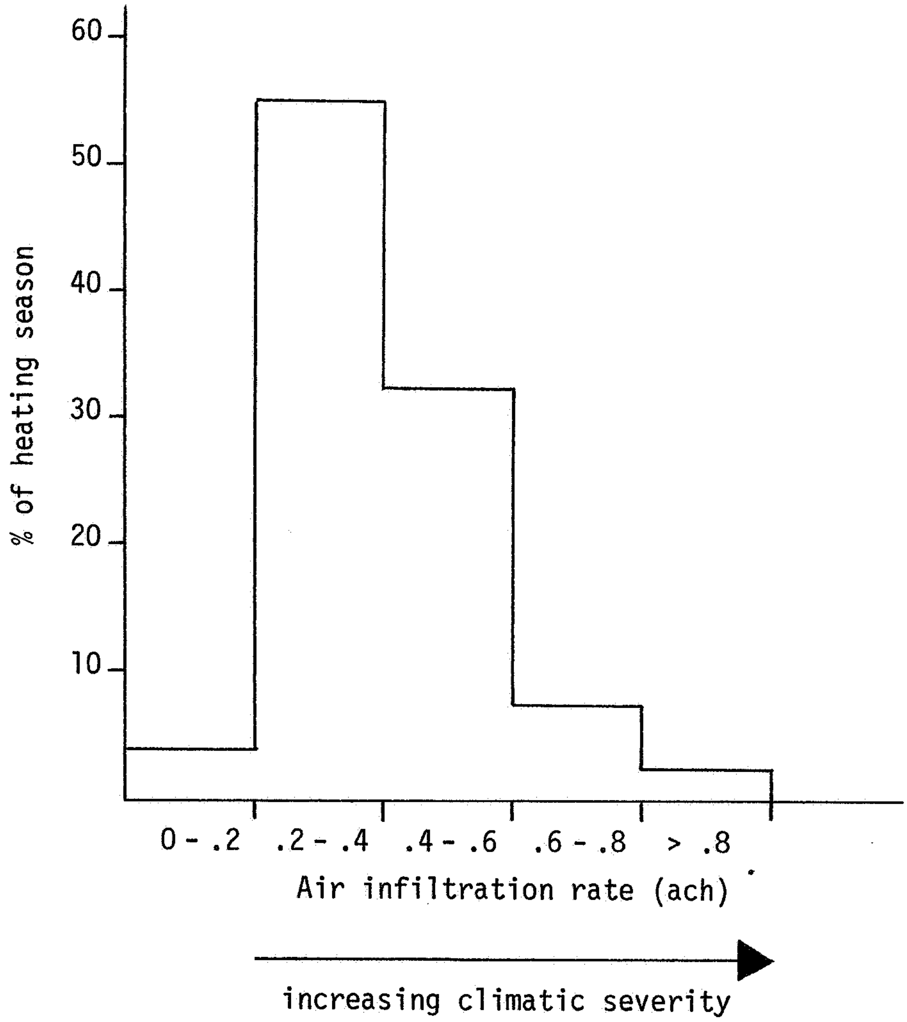


FIGURE 2: Relationship between air leakage at 50 Pa and effective leakage area

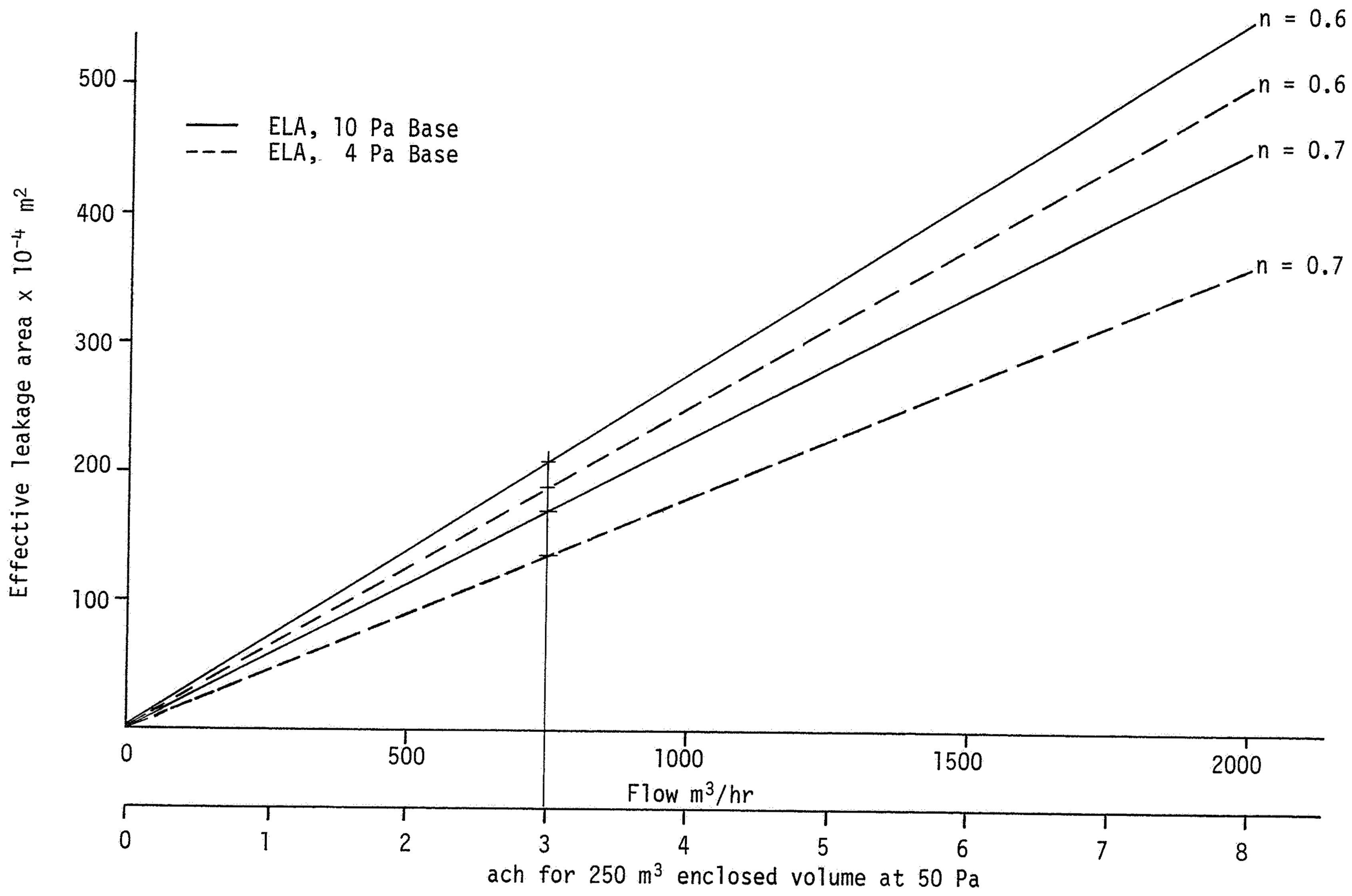


FIGURE 3: Ventilation requirements to dilute some common domestic pollutants

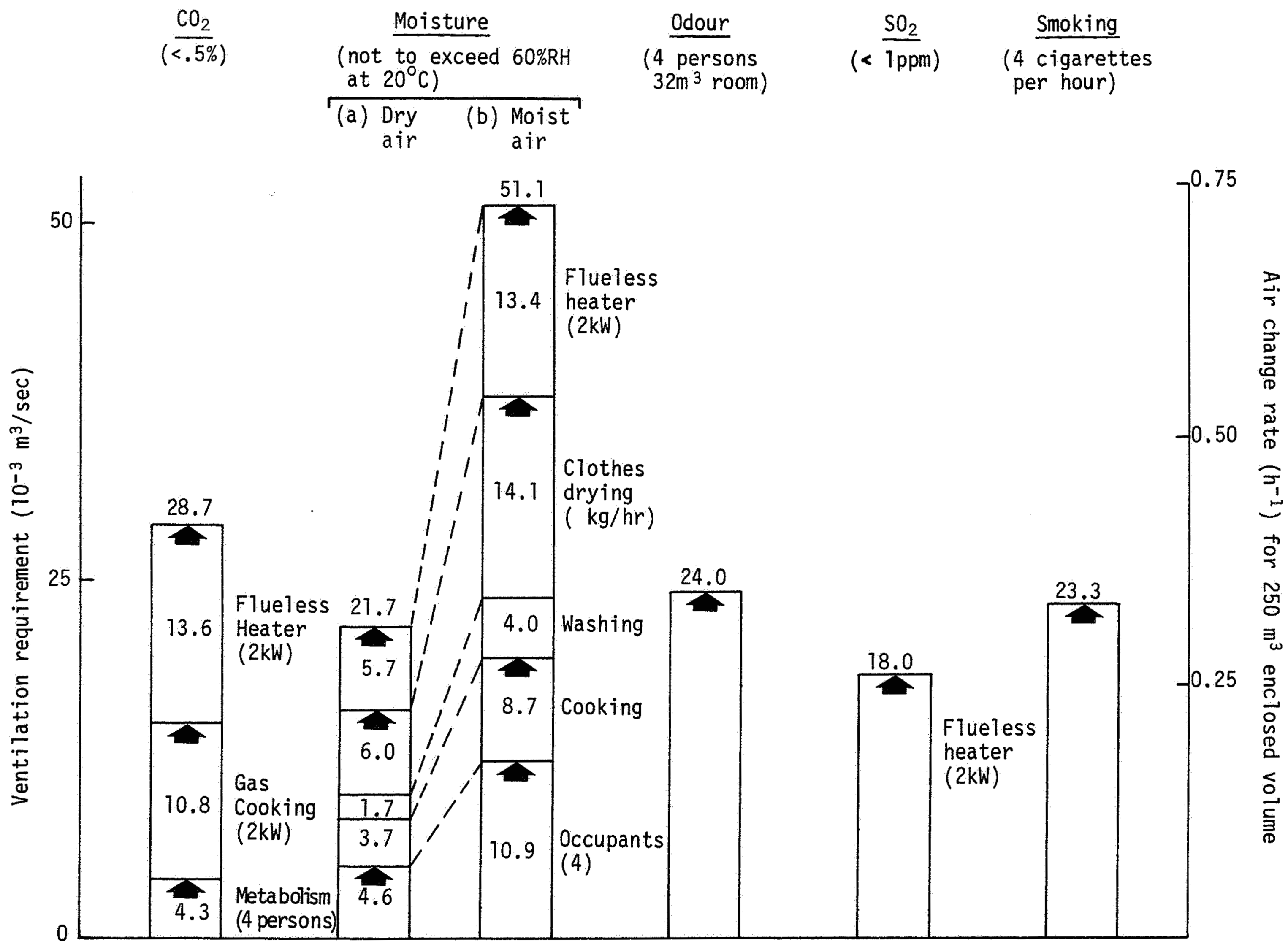


FIGURE 4: Average seasonal moisture content of infiltrating air

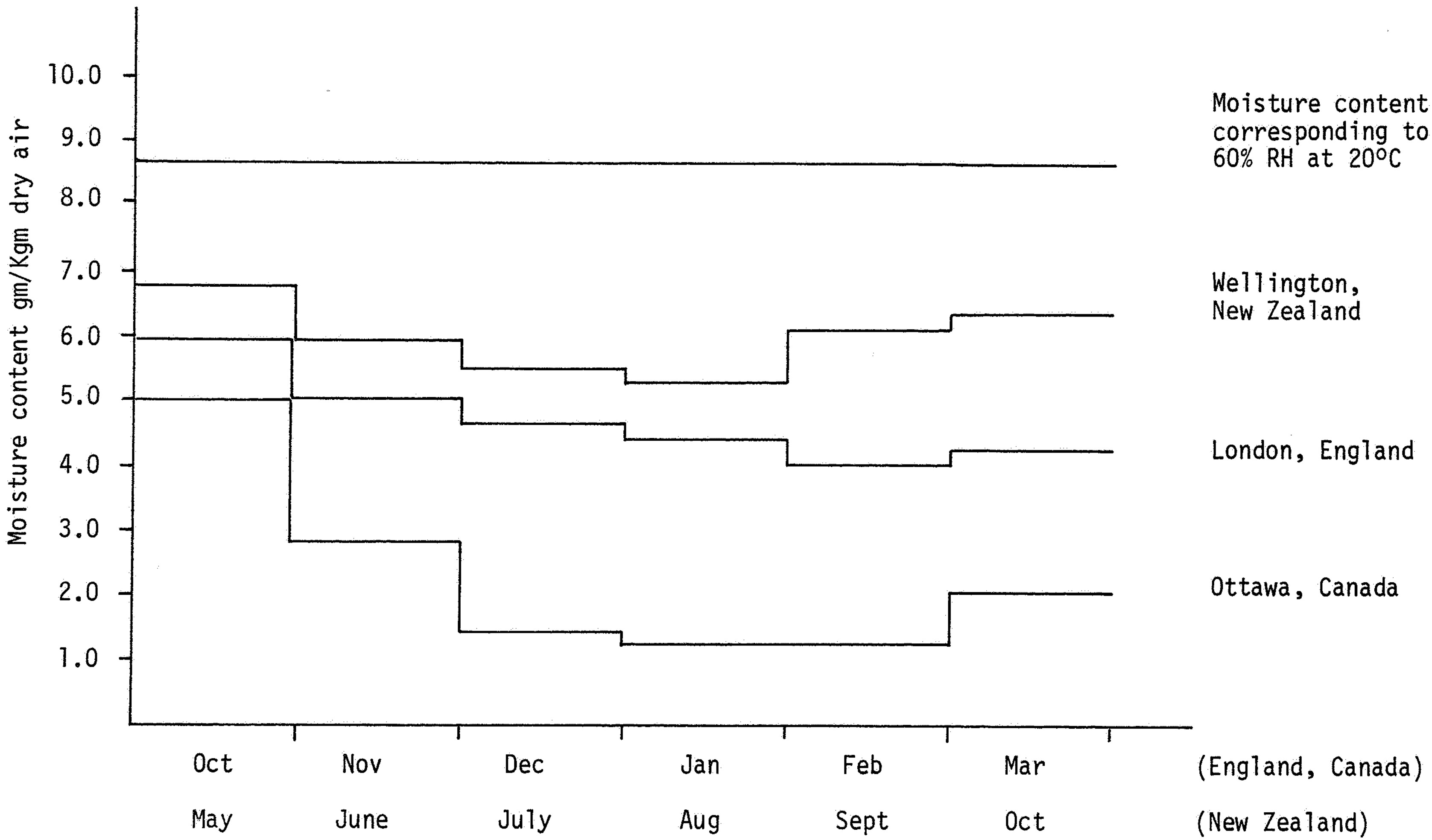
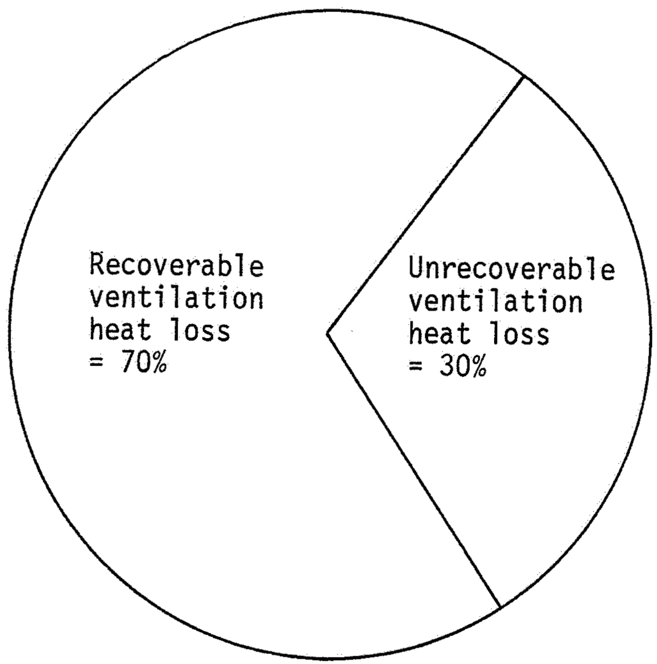


FIGURE 5: Proportion of recoverable ventilation heat loss (mechanical ventilation with heat recovery)

(a) Theoretical (for airtight building)



(b) Actual (for building conforming to ≤3 ach at 50 Pa)

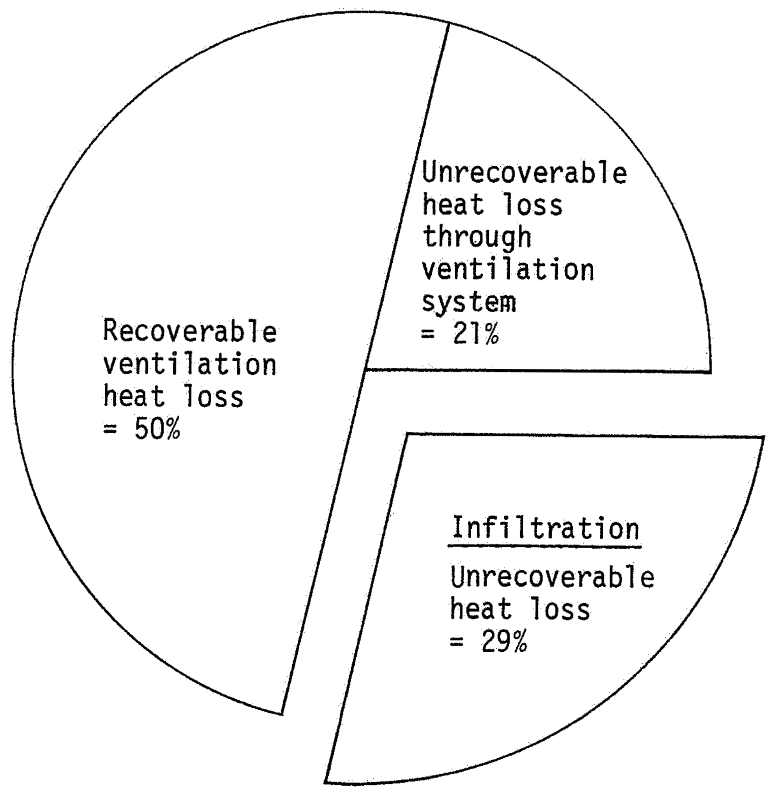
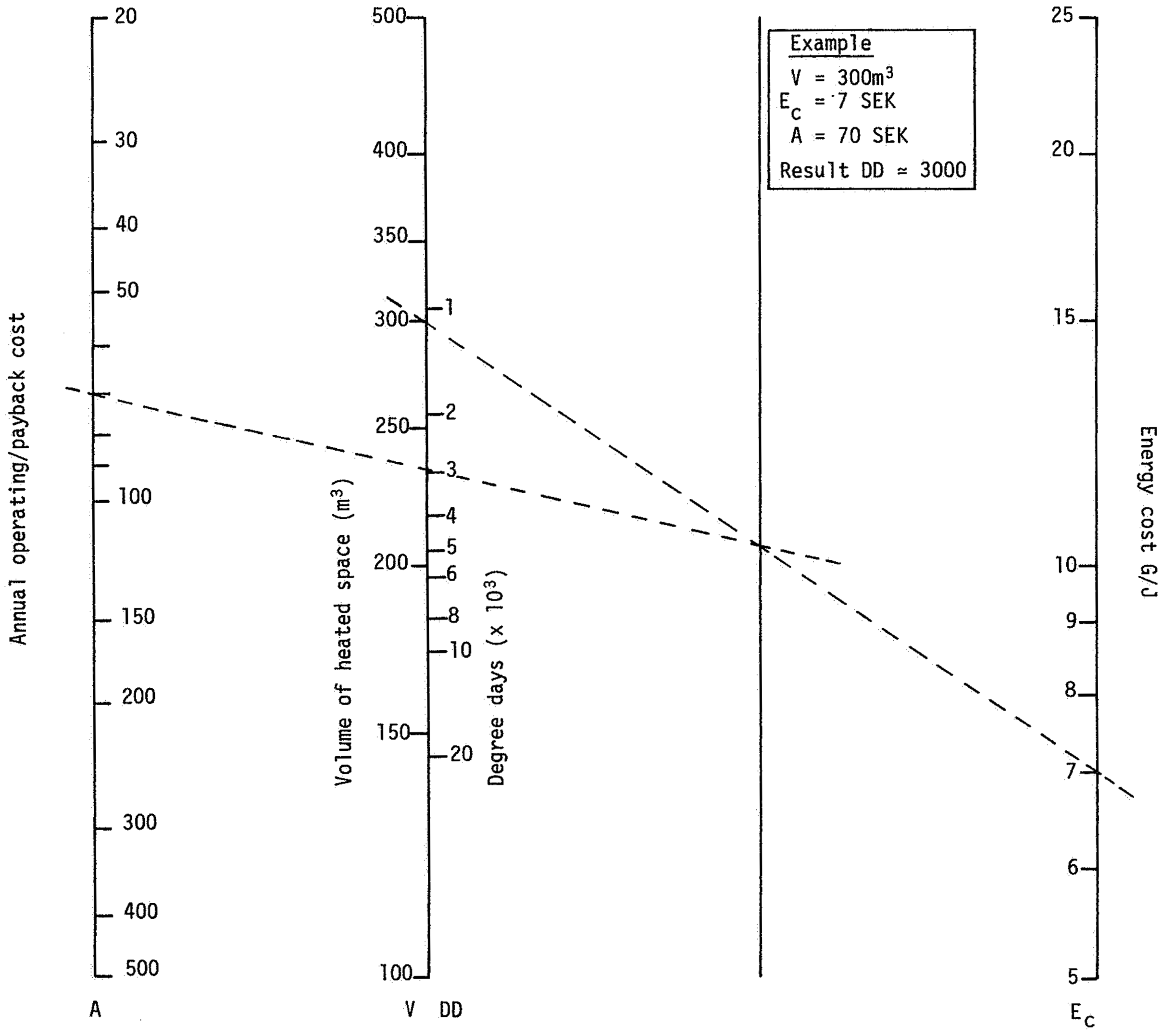


FIGURE 6: Calculation of degree day threshold at which mechanical ventilation becomes cost effective (0.5 ach)



THE IMPLEMENTATION AND EFFECTIVENESS OF AIR INFILTRATION STANDARDS IN BUILDINGS

5th AIC Conference, October 1-4 1984, Reno, Nevada, USA

PAPER 13

THE INFLUENCE OF CLIMATE AND VENTILATION SYSTEM ON AIRTIGHTNESS REQUIREMENTS

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1. INTRODUCTION

Air infiltration typically accounts for a third of the energy loss in a heated building. The driving forces for natural air infiltration are wind and temperature differences. For a given combination of weather conditions the amount of air infiltration is determined by the character of the building envelope, mainly its airtightness. A useful technique in characterizing this housing quality is to measure air leakage. An air leakage standard for new construction has been in effect in Sweden since 1975. Pressurization, using a fan to measure air leakage, is performed routinely in checking new Swedish dwellings.

In addition to these shorter tests, long-term measurements of air infiltration have been made possible with the constant concentration tracer gas technique. An automated system working on that principle has been developed at the National Testing Institute. Results from constant concentration tracer gas measurements and fan pressurization measurements in three houses were used to study the influence of climate and ventilation system on airtightness requirements. A period of one year was examined using an air infiltration model developed at Lawrence Berkeley Laboratory.

2. TEST METHODS

In order to perform the measurements necessary for this paper, two methods were used: the pressurization technique and the tracer gas technique (1,2).

The pressurization technique was used to test envelope airtightness of the three houses. The procedure was the following:

A fan was mounted into the building envelope. The entire house was first pressurized and then depressurized (i.e. a differential pressure was established between the inside and the outside of the house). All vents that were part of the mechanical ventilation system were sealed off during the test and all other vents were measured separately. Using a flow meter, the air flow through the fan was determined. It can be assumed that this rate was equal to the air flow through the building envelope at the same time. A pressure flow rate profile was established for the house.

The tracer gas technique was used for measuring air infiltration for natural running conditions in the tested houses. Tracer gas, a gas normally not present in buildings, was injected into the house and the amount injected and the concentration were measured. A completely automated constant concentration tracer gas technique (3) was used.

The measurement system maintains a constant concentration of a tracer gas in nine rooms simultaneously. Tracer gas is injected into each room and the concentration is measured in each room. A target concentration is maintained. The system measures the supply of fresh air to each room, i.e. air that comes directly to the room from the outside without passing through another room. The result is given in m³/h directly without any estimation of the effective volume.

3. MODEL

The results were further examined using a mathematical model of air infiltration developed at Lawrence Berkeley Laboratory (1). The primary input to this model is the air leakage of the entire building envelope, which is given as an effective leakage area:

$$L = Q \sqrt{\frac{\rho}{2\Delta P}}$$

where
- Q is the airflow |m³/s|,
- ΔP is the pressure drop across the building envelope |Pa|,
- L is the effective leakage area |m²| and
- ρ is the density of air |kg/m³|

Because the pressures driving infiltration are normally within a limited range (1 to 10 Pa), the effective leakage area is calculated for a pressure difference of 4 Pa.

The forces that drive infiltration are pressure differences across the building envelope caused by wind forces and by indoor-outdoor temperature differences. The stack-induced infiltration is calculated as follows:

$$Q_s = L\, f_s \sqrt{\Delta T}$$

where
- Q_s is the stack-induced infiltration |m³/s|,
- f_s is the stack parameter $|m/(sK^{1/2})|$ and
- ΔT is the inside-outside temperature difference |K|.

The stack parameter is given by the following expression:

$$f_s = \frac{(1+R/2)}{3} \left| 1- \frac{X^2}{(2-R)^2} \right|^{3/2} \sqrt{\frac{gH}{T}}$$

where $R = \dfrac{L_{floor} + L_{ceiling}}{L_{tot}}$

$X = \dfrac{L_{ceiling} - L_{floor}}{L_{tot}}$

g is the acceleration of gravity $|m/s^2|$,
H is the inside height of the structure $|m|$ and
T is the inside temperature $|K|$.

The wind-induced infiltration is calculated as follows:

$$Q_W = L\, f_W\, v$$

where Q_W is the wind-induced infiltration $|m^3/s|$
f_W is the wind parameter |dimensionless| and
v is the wind speed $|m/s|$.

The wind parameter is given by the following expression:

$$f_W = C' \left| (1-R)^{1/3} \right| \left(\frac{\alpha (\frac{H}{10})^{\gamma}}{\alpha' (\frac{H'}{10})^{\gamma'}} \right)$$

where C' is the generalized shielding coefficient,
α, γ are terrain parameters at the structure,
α', γ' are terrain parameters at the site of the wind measurements,
H is the inside height of the structure $|m|$ and
H' is the height of the wind measurement $|m|$.

The air flow resulting from the two driving forces must be combined to arrive at the total infiltration. If the expressions for wind- and stack-induced infiltration are interpreted as effective pressure differences across the leakage area of the structure, the total infiltration can be determined by adding these pressures. If the flow is proportional to the square-root of the pressure, then two flows acting independently must add as follows:

$$Q_{tot} = \sqrt{Q_w^2 + Q_s^2}$$

This equation is useful for a structure without any specially designed ventilation system. Most Swedish one-family houses do however have unpowered vents or a mechanical ventilation system. Unpowered vents protrude beyond the envelope and should therefore not be included into the total leakage area. Their ventilation should be calculated separately (4).

The ventilation through the vents should be combined with the other flows using superposition:

$$Q_{tot} = \sqrt{Q_w^2 + Q_s^2 + Q_{vent}^2}$$

where Q_{vent} is the ventilation through the unpowered vents |m³/s|.

If the house is equipped with an exhaust fan the same discussion as for an unpowered vent applies, i.e.

$$Q_{vent} = Q_{exhaust\ fan}$$

where $Q_{exhaust\ fan}$ is the rating of the fan |m³/s|.

A balanced ventilation system should not affect the pressure drop across the envelope caused by natural driving forces. The fan flow can therefore simply be added to the natural ventilation:

$$Q_{tot} = Q_{fan} + \sqrt{Q_w^2 + Q_s^2}$$

where Q_{fan} is the rating of the fan |m³/s|.

4. BUILDINGS

Three houses were tested. Each represents common residential constructions and ventilation systems.

Svaneholm: a one-family house built during the early sixties. It is a one-storey, 135 m² building with full basement. The external walls are made of pre-fabricated elements (0.3 m 1.2 m wide, 2.4 m high) each of which is a wood frame filled with cellulose filament. This kind of structure has a large number of vertical joints. The facade is brick with a vapour barrier consisting of tar-impregnated board. Heating is a hydronic system with an oil fired boiler. The furnace room was sealed off from the rest of the house during the tests. The house is ventilated without fans: air is exhausted through simple vertical ducts.

Borås: a 1 1/2-storey, 140 m² one family house with crawlspace. Built in 1977. It has a well insulated timber frame and a plastic air/vapour barrier. Heat is supplied by electric baseboard heaters. The ventilation system has an exhaust fan and air inlets in the exterior walls.

Skultorp: a one-storey house, 108 m² built in 1982. It has no basement but a crawl-space. It has a heavily insulated timber frame structure with a plastic air/vapour barrier. The ventilation system has both supply and exhaust fans. The house is heated by a warm air system.

5. RESULTS

The airtightness of the three houses are shown in table 1.

Table 1. Comparison of airtightness, number of air changes, with all vents sealed.

	Swedish Building Code	Built 1972 Svaneholm	Built 1977 Borås	Built 1982 Skultorp
Pressurization at 50 Pa, hr^{-1}:	3.0	5.0	4.8	1.1

For all three houses the ventilation rate of each individual room was monitored. There is quite a variation between different rooms for the Svaneholm house (5) i.e. fresh air coming directly into the room without passing through another room.This is a function of the ventilation system and the distribution of the envelope airtightness.

In the Borås house most rooms are adequately ventilated. The kitchen seem to be very poorly ventilated, i.e. hardly any fresh air comes directly into the kitchen. One of the bedrooms also has a very low ventilation rate, probably caused by too tight an exterior wall.

The Skultorp house has a ventilation rate which is almost constant with time (5). This is due to the fact that the ventilation system is coupled with a very tight building envelope. The ventilation rates of individual rooms depend on how well the ventilation system is adjusted.

In order to further examine these three houses during a complete year they were modelled using the LBL-model, as the measurements were taken only for a few days. The model was first applied to the houses for the same weather conditions as during the tracer gas measurements.

The results for the Svaneholm house showed a very close correlation between measurements and predictions (see fig. 1). The average measured value was 70.7 m^3/h and the predicted value 71.5 m^3/h. For the test period the model tracks the measured ventilation rate very well.

The results for the Borås house showed a discrepancy between model and real life. The model overpredicted by about 20 % (see table 2).

Table 2. Ventilation rates for the Borås house (air infiltration + exhaust fan ventilation) in m^3/h.

Measured	153	145
Predicted	176	181

For the Skultorp house the LBL-model overpredicts with 15 % (see fig. 2).

The size of the discrepancy between model and measurement is to be expected, when considering that the model is rather simple and that there are inaccuracies in the measurements as well.

Table 3. Parameter values used in the LBL-model.

House	Svaneholm	Borås	Skultorp
$L_{ceiling}$ (cm^2)	125	69	30
L_{floor} (cm^2)	0	72	30
L_{tot} (cm^2)	250	360	89
L_V (cm^2)	300/2	0	0
α	0.85	0.67	1.0
γ	0.20	0.25	0.15
C'	0.185	0.185	0.24
C_V	0.2	0	0
H (m)	3.0	5.0	2.4
H_V (m) is the height of the vent	4.0	0	0
T (°C) is the indoor temperature	22	20	20
$Q_{exhaust\ fan}$ (m^3/h)	0	159	20
Q_{fan} (m^3/h)	0	0	126

The model was used to predict the ventilation rates for each of the houses during one sample/year in the same city. Hourly weather data for Stockholm was used. With all windows closed, the Svaneholm house (unpowered vents) never reached the required minimum ventilation rate of 0.5 ach (155 m^3/h). Its monthly average ventilation rate varies very much (see fig. 3). The lowest values were for July and August (0.14 ach); the highest were for November and January (0.26 ach).

The Borås house (exhaust fan) had an almost constant ventilation rate of 0.52 ach (see fig. 4). Its lowest monthly average value was 0.48 ach and; highest was 0.56 ach.

The Skultorp house (balanced ventilation) had a constant ventilation rate of 0.60 ach (see fig. 5). The lowest monthly average value was 0.59 ach; the highest was 0.62 ach.

6. DISCUSSION

To evaluate the performance of the tested houses the ventilation rates were analyzed and the energy losses caused by air infiltration calculated using weather data from Stockholm. All changes in air tightness were proposed, based on calculations using the LBL-model.

The Swedish building code specifies a required minimum ventilation rate of 0.5 ach. The Svaneholm house with unpowered vents, never reaches this level unless windows are opened. The energy loss caused by ventilation is 2550 kWh for one heating season. If the house is to reach the minimum required ventilation rate during the heating season the effective leakage area must be increased from 250 cm^2 to 650 cm^2 (from 5.0 ach to 13.0 ach at 50 Pa). This would increase the energy loss to 5350 kWh, an energy loss which is hard to recover.

The Borås house meets the required minimum ventilation rate during most of the year. The energy loss caused by ventilation is 6350 kWh for one heating season. An exhaust air heat pump could be installed which would reduce the heat loss to only the loss due to the natural air infiltration, i.e. 1050 kWh. If we assume that this number should be below 500 kWh, the effective leakage area should be reduced from 360 cm^2 to 200 cm^2 (4.8 ach to 2.7 ach at 50 Pa).

The Skultorp house exceeds the minimum required ventilation. The natural air infiltration is very small. With no heat recovery the energy loss from ventilation is 5250 kWh. If "all" heat from the exhaust air could be recovered the heat loss from ventilation i.e. from natural air infiltration would be 400 kWh. The ventilation system should be optimized and adjusted to 0.5 ach.

7. CONCLUSIONS

Three typical Swedish one-family houses were examined, each with a different type of ventilation. If doors and windows were closed the one-family house with unpowered vents (airtightness of 5.0 ach at 50 Pa) would be inadequately ventilated all year around, although the house was not as tight as required by the Swedish Building Code. The ventilation rate for the summer was also very low. Airing during most of the year is hard to control, and means additional energy consumption. In summer it presents less of a problem, for people can easily be expected to open their windows to get fresh air.

The one-family house with an exhaust fan ventilation system (airtightness of 4.8 ach at 50 Pa) was adequately ventilated during most of the year. The heat loss caused by air infiltration could be reduced by making the house tighter, i.e. bringing it below the required level of 3.0 ach at 50 Pa.

The one-family house with a balanced ventilation system (airtightness of 1.1 ach at 50 Pa) was adequately ventilated all year although it is tighter than required. The heat loss from natural air infiltration was sufficiently low. The ventilation rate could be lowered to 0.5 ach by adjusting the fans.

In different climates,the above total ventilation rates and heat loss rates caused by air infiltration would be different, requiring different air tightness levels.

The best way of both supplying adequate ventilation and conserving energy is to insure that the building envelope is sufficiently tight and then install a mechanical ventilation system. To control the year round conditions the system should either be a balanced type or the exhaust air type with special vents to the outside for supplying fresh air.

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Fig. 1 Measured ventilation rate vs. predicted ventilation rates for the Svaneholm house (air infiltration + unpowered vent ventilation)

------- prediction

——— measurement

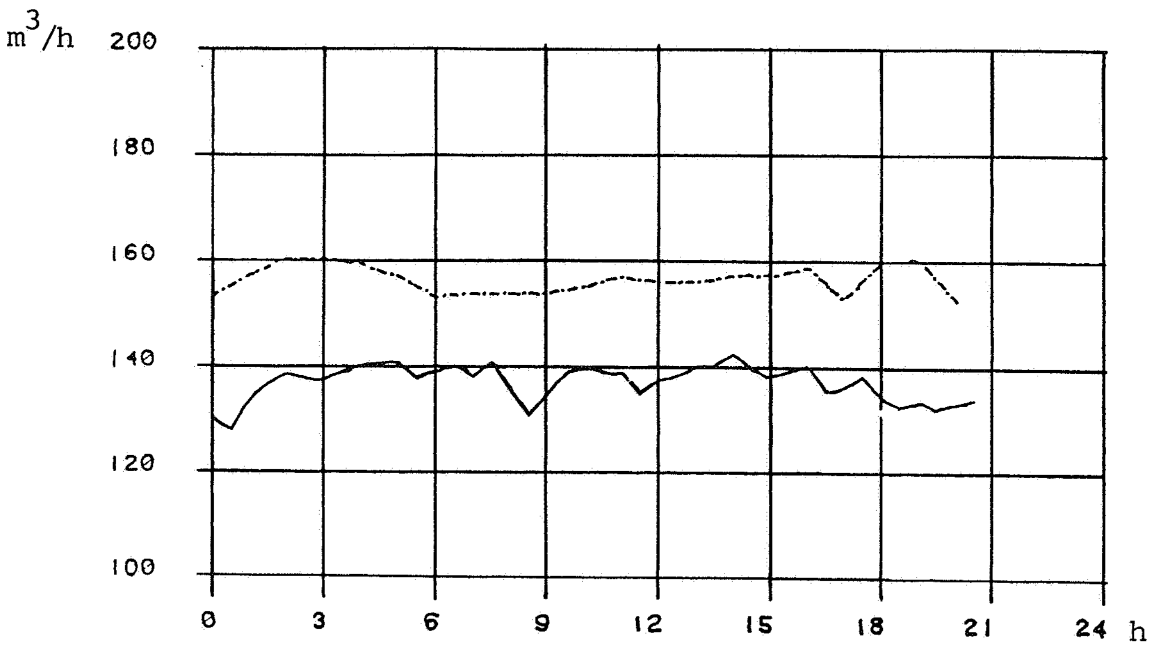

Fig. 2 Measured ventilation rate vs. predicted ventilation rate for the Skultorp house (air infiltration + balanced ventilation)

—·—·—·— prediction

———— measurement

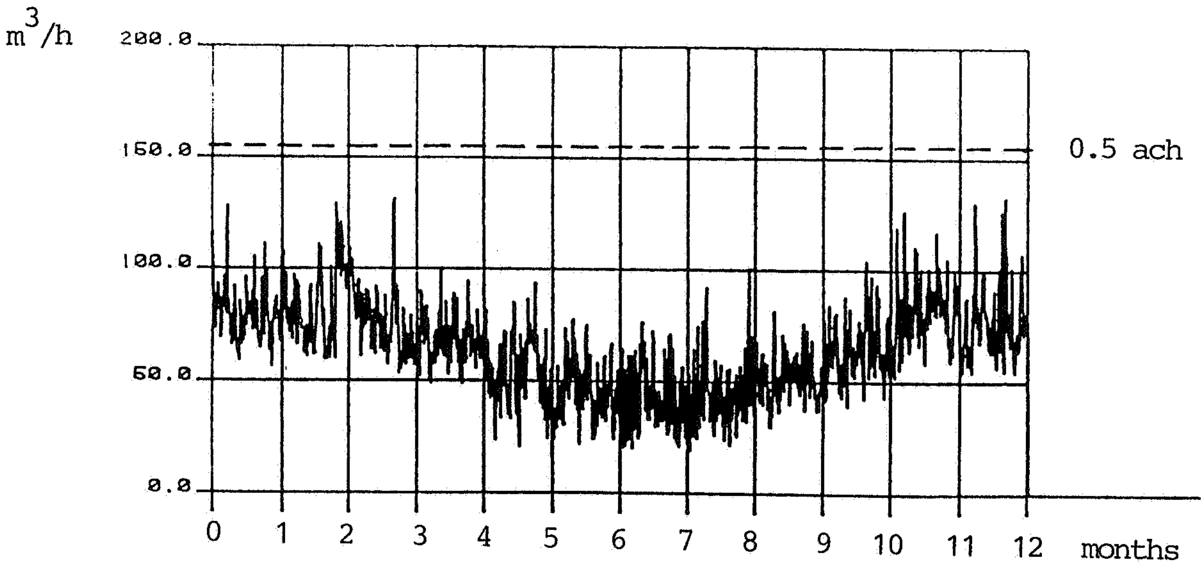

Fig. 3 Predicted ventilation rates for the Svaneholm house (air infiltration + unpowered vent ventilation)

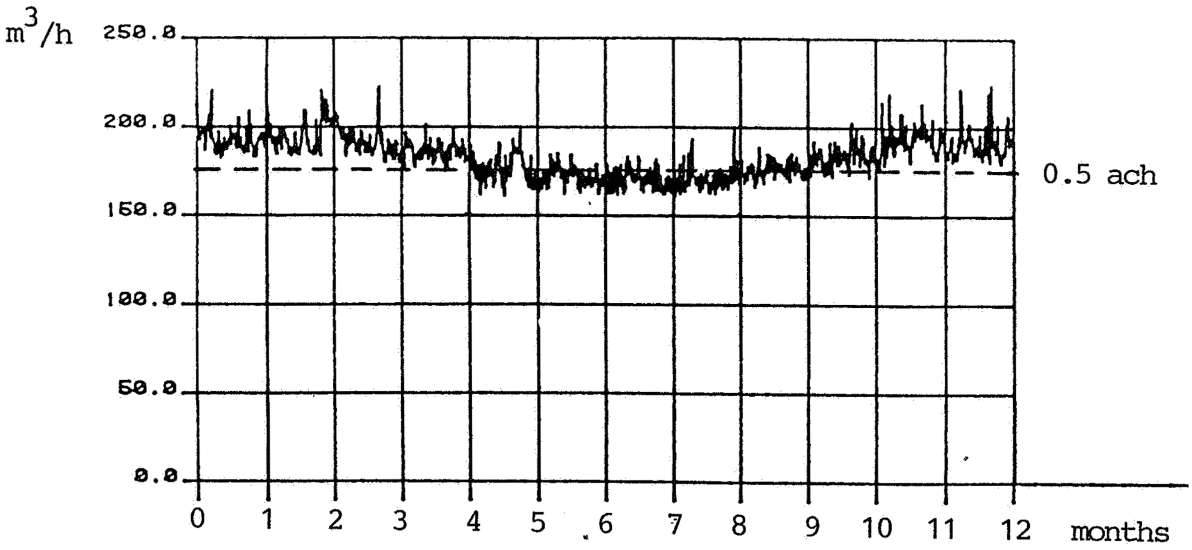

Fig. 4 Predicted ventilation rates for the Borås house (air infiltration + exhaust fan ventilation)

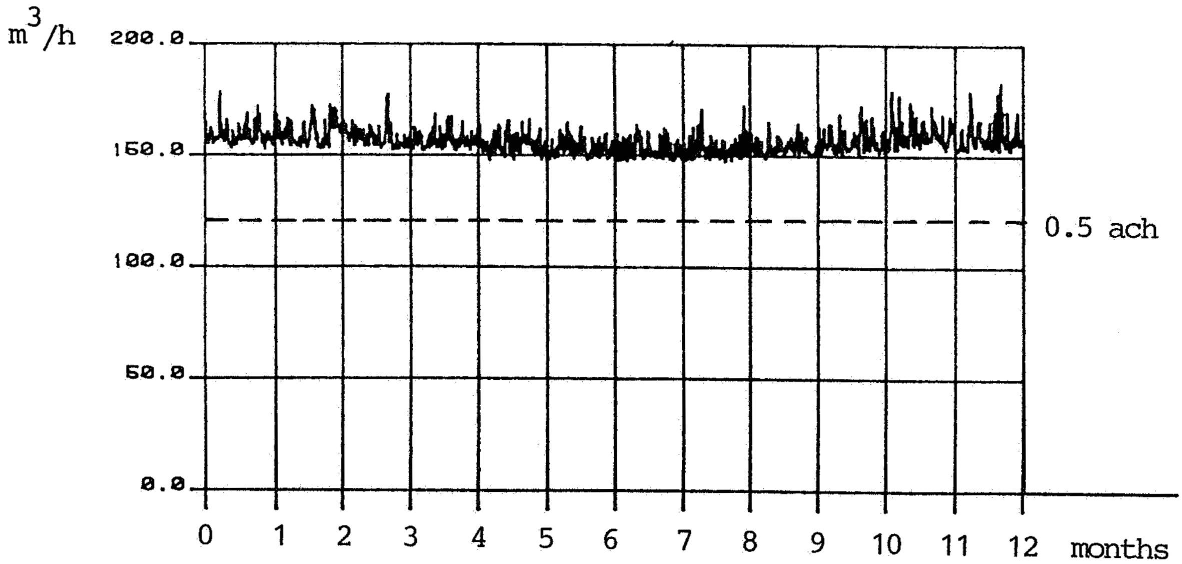

Fig. 5 Predicted ventilation rates for the Skultorp house (air infiltration + balanced ventilation)

THE IMPLEMENTATION AND EFFECTIVENESS OF AIR INFILTRATION STANDARDS IN BUILDINGS

5th AIC Conference, October 1-4 1984, Reno, Nevada, USA

PAPER 14

A CONSEQUENCE ANALYSIS OF NEW NORWEGIAN BUILDING REGULATIONS ON AIR INFILTRATION

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SYNOPSIS

In 1981 Norwegian building regulations introduced quantitative requirements to air leakages in different types of buildings. The requirements were formed as maximum allowed air changes per hour at 50 Pa pressure difference according to the pressurization method.

To evaluate the consequences of these new requirements imposed to Norwegian building industry a model proposed by the Nordic Committee for Building Regulations (NKB) was used.

The average air leakages of residential buildings, built before the new requirements, are known through a research project performed in 1979. Average air leakages of other buildings are not known.

Energy losses due to air infiltration are calculated with the computer program ENCORE.

Extra costs for achieving necessary tightness in detached houses are estimated to be NOK 1000,- in average per house, and the resulting energy saving is estimated to be 1200 kWh/year corresponding to NOK 360,- per year.

For block flats the new requirements are supposed to have none or little practical influence. For other buildings the influence is not known.

The most evident negative consequence is the possibility of reduced and too low air change rate in detached one storey houses with natural ventilation systems. In some of these houses it may be necessary to introduce mechanical ventilation systems to achieve air quality control.

DEFINITIONS

Air change rate:
- Air supply to a room/building divided by the volume of the room/building (m^3/m^3h).

Air leakage coefficient n_{50}:
- Measured air changes of a building at 50 Pa pressure differences (m^3/m^3h).

0. INTRODUCTION

This consequence analysis uses a model proposed by the Nordic Committee for Building Regulations (NKB) in 1983[1]. The model is generally used for all kinds of building regulation proposals, and may perhaps seem too extensive in this connection. The stringent system of the NKB-method may be of value also for others, and the chapters in this paper are therefore in correspondance with this method.

1. GOAL

In January 1981 the Norwegian building regulations[2] got a new chapter 54 dealing with heat insulation and air tightness of buildings. The main purpose of the new chapter 54 was to give a technical background for energy saving in buildings. Therefore increased requirements were introduced with regard both to heat insulation and air infiltration. The part goal as to air infiltration is to reduce heat losses from buildings due to air leakages.

2. FULFILLMENT OF GOAL

To fulfill the above mentioned goal, the Norwegian building regulations have introduced quantitative and controllable requirements to air tightness of building components and buildings. Earlier regulations contained only qualitative and hardly controllable requirements.

3. SPECIFICATION OF REQUIREMENTS

Qualitative and quantitative requirements regarding air tightness are assembled in chapter 54 of the building regulations, but some qualitative requirements are also found in chapters dealing with e.g. external walls, roofs and floors. The superior requirement says that buildings which are meant to be heated, should be insulated against heat loss and should be air tight in a way that maintains a good indoor climate without unnecessary energy consumption and risk of moisture damage . Connections and joints should be air tight to prevent annoying draughts and moisture problems.

The maximum allowed specific air leakages measured according to NS 3206 at 50 Pa pressure difference are:

Wall-, roof- and floor constructions:	0,4 m^3/m^3h
Windows (and doors in detached houses):	1,7 m^3/m^3h

The maximum allowed air leakage coefficients n_{50} of buildings measured according to NS 8200 at 50 Pa pressure difference are:

Buildings, more than 2 storeys	1,5 m^3/m^3h
Buildings, until 2 storeys	3,0 m^3/m^3h
Detached houses	4,0 m^3/m^3h

For detached houses the volume for air change calculation should be the volume of primary parts of the house (according to NS 3940) and for other buildings the heated volume.

4. PERFORMANCE ANALYSIS

The air barriers of walls, roofs and floors have two energy related functions. The prevention or reduction of air infiltration is taken care of in the new building regulation requirements. The prevention or reduction of cold air streams from the outside into the insulation is, however, not taken care of.

Laboratory measurement of air leakage through windows is done in accordance to Norwegian Standard (NS 3206). This method is originally developed and valid for windows, but is also used for doors, walls and roof constructions. At the Norwegian Building Research Institute (NBI) it is possible to perform measurements on building components up to 3,0 x 3,0 m.

Adequate equipment for testing air tightness of building components in situ is not available in Norway. This kind of testing is therefore very comprehensive, expensive and is hardly done.

Total allowed air leakages through the individual building components amounts to only 10-15 % of the allowed over all leakages through the building. The situation may then easily arise, that a building fulfills the over all requirement while e.g. the external walls have unacceptable air leakages. This could give some interpretation problems about which of the joints and connections that should be included in the building component.

The Norwegian Standard NS 8200 gives the instructions for the testing of a complete building. The capacity of available equipment in Norway gives a practical limit to the size of buildings that could be tested. Detached houses with floor area until 450 m^2 and larger buildings until 1000 m^2 may be tested within standard procedures. Larger buildings may be tested by extrapolation from low pressure differences or by using the ventilation system. These are not, however, standard procedures, and are therefore only seldom used. Air tightness control is in practice performed mainly on detached houses.

The definition "volume of primary parts" of detached houses gives interpretation problems, while e.g. the basements in new Norwegian houses very often are left uncompleted but heated, until the owner gets economy to fit up a second living room, trim room or similar. We have seen cases where different testing people have come to different results, which have given unnecessary juridical disagreement.

5. EXISTING PRACTICE

Most Norwegian producers of windows and doors have already adapted to the new requirements through their participation in a voluntary control organization driven by NBI. The most common wall- and roof- constructions also fulfill the new requirements, on the assumption of reasonable good craftmanship. Experiences through moisture damages, complaint cases and thermography show that the main part of the air leakages is found in connections between different building parts and components.

In 1979 NBI examined 61 detached houses and 34 block flats between 1 and 5 years old at that time[3]. Their air leakage coefficients are shown in figures 1 and 2. 40 % of the detached houses had an air leakage coefficient lower than 4 m^3/m^3h and 20 % more than 6 m^3/m^3h. 70 % of the block flats were already more air tight than prescribed in the new building regulations.

For larger buildings we have no statistical material. A few single control tests indicate that the deviaton in air tightness may be considerable.

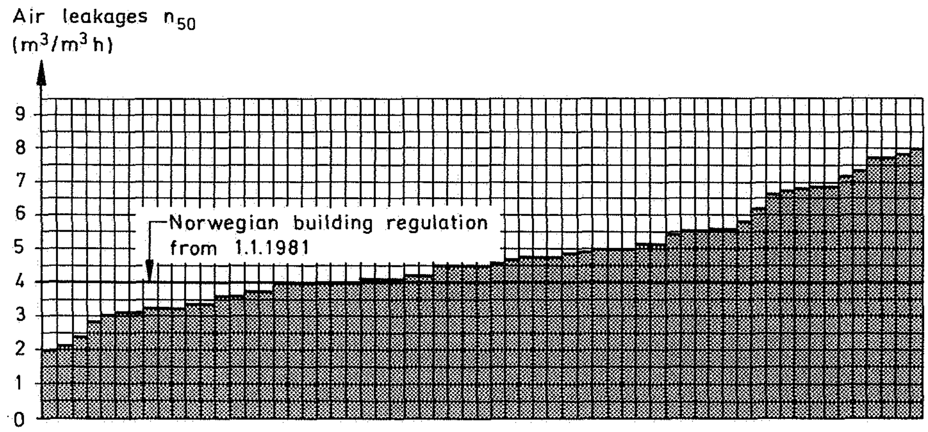

Figure 1. Air leakage coefficient n_{50} of 64 detached houses on different places in Norway. The measurements were performed by NBI on 1 to 5 years old houses in 1979.

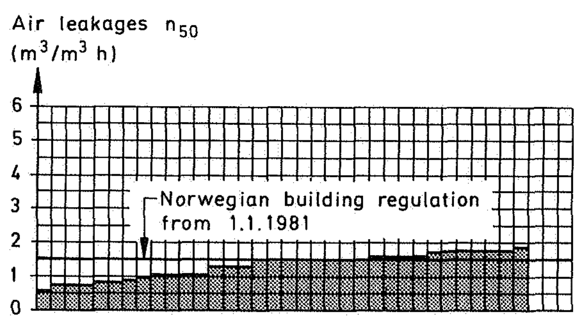

Figure 2. Air leakage coefficient n_{50} of 34 block flats on different places in Norway. The measurements were performed by NBI on 1 to 5 years old buildings in 1979.

6. NEW PRACTICE

The new air tightness requirements will scarcely have any effect on the basic construction principles for windows, doors and the common wall-, floor- and roof constructions.

A change of polyethylene film thickness from 0,04 mm or 0,06 mm to 0,15 mm is partly due to the new air tightness requirements. The thicker polyethylene film is less exposed to damages during the building period .

Some constructions with no separate water vapor barrier, like some metal wall systems, are not likely to fulfill the new requirements unless the jointing problems could be better solved.

The traditional Norwegian apartment building with in situ concrete and timber framework facades has sufficient air tightness, and no changes are necessary.

Detached houses must in general have a slight improvement of the air tightness, but no dramatic changes in building practice is necessary. A reasonable good craftmanship and avoidance of severe faults is of most importance. Several research projects have shown that thorough clamping of all joints and edges of the wind- and water vapour barriers gives an over all air tightness far below the new requirements.

We have no statistical material showing the air tightness level or the occurance of very leaky houses built after 1.1. 1981. A survey on new dwellings is planned, and will probably give the answer to this question.

A similar survey on larger buildings should be very comprehensive and is therefore not possible with the available resources.

7. IDENTIFICATION OF NEGATIVE AND POSITIVE CONSEQUENCES

Consequence field	Example	Influence
Planning	. Freedom of choice	-
	. Routines	0
Building process	. Wages	-
	. Materials	-
	. Capital	-
Building materials	. Limitations	-
	. Product development	-
Control	. Building authorities	-
	. Production control	-
	. Testing procedures	-

Consequence field	Example	Influence
Administration and maintenance	. Energy costs	+
	. Running	+
	. Maintenance	+
	. Damages	+
Use of building	. Quality	+
	. Health	?
	. Safety	0
	. Fire hazards	0
Community	. Social costs	0
	. Employment	0
	. Balance of payments	0
	. Environment	0
	. Diversion of production	+

8. DIRECT MEASURABLE CONSEQUENCES

8.1 Building costs

The cost increase for simple detached houses will be very moderate. For more complex houses there will be some cost increase. These houses are, however, also the most leaky ones, and considerable energy savings should be expected. We have no Norwegian experiences where extra costs are related to air tightness level. Figure 3 shows some Swedish experiences.

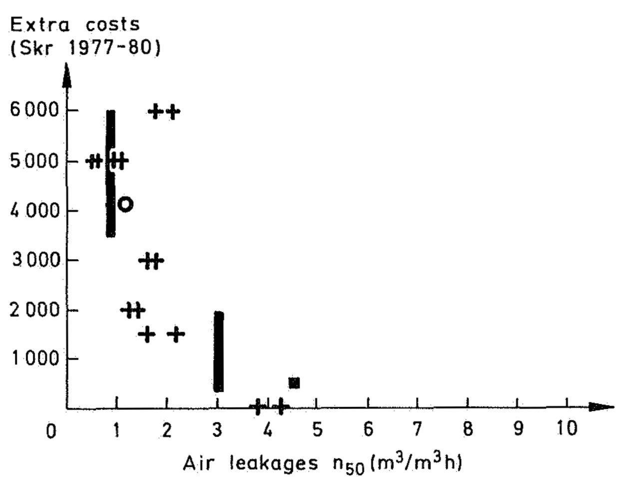

Figure 3. Extra costs related to air tightness level for Swedish detached houses.

The following table is based on figure 3 supplemented with some Norwegian experiences from field and laboratory measurements. Within these extra costs we assume that most dwellings could be built within the new air tightness requirements:

Extra costs per dwelling (NOK)

	Planning	Constructing	Windows and doors	Materials	Total sum
Block flat	0	0	0	200	200
Simple detached- and row house	0	0-600	0	400	400-1000
Complex detached- and row house	0-1000	0-2000	0	400-1000	400-4000

8.2 Energy costs

If we assume that figure 1 gives a representative picture of the air tightness level of new Norwegian detached houses before 1.1. 1981, it will be necessary with an average reduction of the air leakage coefficient by 1,0 m3/m3h to make most new houses fulfill the requirement. This corresponds to a certain reduction in the air infiltration heat loss depending on:

- air leakage coefficient n_{50}
- ventilation system
- number of storeys
- outside temperatures
- wind

By means of the computer program ENCORE, following energy savings are calculated under the above mentioned conditions. The table is valid for houses with natural ventilation, which is the most common system in Norway, and a building size of 120 m2 floor area:

Calculated air infiltration heat loss reduction (kWh/year) by reducing n_{50} from 5,0 to 4,0 m3/m3h

	1 storey	2 storey	3 storey
Oslo	700	1000	1200
Trondheim	900	1300	1500
Tromsø	1200	1700	2000

The energy price in Norway (electricity) is approximately 0,30 NOK/kWh. If we assume that the average heat loss reduction per detached- and row house is 1200 kWh, the corresponding cost reduction is 360 NOK/year.

9. OTHER CONSEQUENSES

The new air tightness requirements could cause financial implications other than building costs and energy savings. We have not sufficient information to take these aspects into account, and the most important other consequences are therefore only shortly described in the following:

9.1 Ventilation system

Most Norwegian detached houses from the 70's have natural ventilation system with an extract fan over the stove. Increasing attention to air tightness and ventilation problems will probably lead to more mechanical ventilation systems in the future, like the trends of e.g. Sweden. This means extra costs, but also the possibility of installing heat recovery systems. In very air tight houses ($n_{50} < 2\ m^3/m^3h$) heat recovery systems are normally profitable.

9.2 Control activities

To day only approximately 0,5 % of the total annual production of dwellings is controlled. A higher control rate would probably influence the building quality and thus be profitable for the nation. A control rate of 5 % would give an extra cost per dwelling of NOK 100-200.

9.3 Energy costs

Reduced air infiltration could lead to secondary energy saving effects, through e.g. better possibilities of reducing indoor temperatures and the reduction of cold air streams into the insulation.

9.4 Building faults

Air leakages have caused condensation and lots of moisture damages, especially in roof constructions. The costs of such damages may be considerable in single cases, but the frequency is not known. Better air tightness would undoubtedly bring savings for the country.

Reduced air leakages could on the other hand give reduced ventilation and an increased risk of condensation and mould growth.

10. QUALITATIVE AND SOCIAL CONSEQUENCES

10.1 Comfort

Reduced air leakages lead to less draught problems and thus a better thermal indoor climate.

Airtight houses may lead to problems in connection with open fireplaces, which are very common in Norway. During the last years we have had an increasing number of cases where smoke has come into the room. The problem may, however, be solved at some extra cost, e.g. by means of separate air ducts to the fireplace.

10.2 Air quality

The indoor air quality is dependent on the air change rate of the single rooms and of the building. In older leaky houses air leakages must be considered as an integral part of the ventilation system, and the risk of having a too low air change rate has been minimal. In new airtight houses planning and construction of an adequate ventilation system and the use of the building is of vital importance for the indoor air quality. At the same time we have an increasing number of new materials involving volatile and hazardous gases in building components and furniture.

In buildings with a balanced ventilation system all extra air infiltration is undesirable, and air leakages should be kept as low as possible. An air outlet or inlet should be placed in each room.

In buildings with extract ventilation an air tightness level lower than building regulation requirements would have little influence on the average air change rate.

In buildings with only natural ventilation the air change rate will vary with outside temperatures and wind. To achieve a good ventilation it will be necessary to extensive open and close vents according to the weather conditions. At times one must expect that outlets function as inlets. In summer and partly also spring and autumn it will be necessary to ventilate through windows and doors in order to achieve the generally recommended air change rate of 0,5 m3/m3h. In these buildings air leakages may be considered as desirable, but even very leaky houses will have too low air change rates during most of the year if windows and doors are closed.

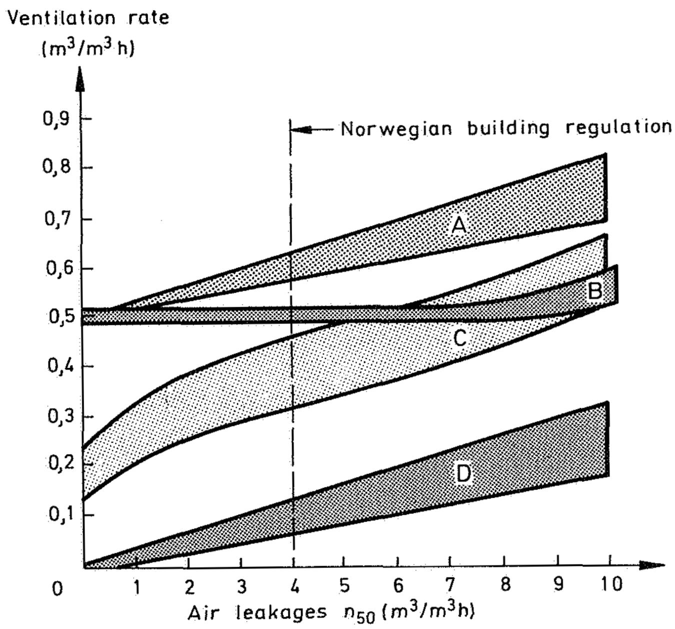

Figure 4. Calculated air change rates in a 2 storey detached house by + 10 oC outside temperature and no wind.

A: Balanced ventilation
B: Extract ventilation with open air inlets
C: Natural ventilation with open outlets and inlets according to building regulations minimum requirements.
D: Air infiltration only, all vents closed.

11. COMPARISON OF POSITIVE AND NEGATIVE CONSEQUENCES

Due to the lack of reliable information, only building costs and energy savings as a result of air infiltration reduction are compared. Costs are based on mean values from chapter 8 and the following assumptions:

. investment	1000 NOK
. life time of construction	30 years
. interest	7 %
. annual energy saving	1200 kWh
. energy price	0,30 NOK/kWh
. detached or row house, floor area	120 m2

	Annual amount (NOK)	Years	Dis-counting factor	Now-value (NOK) Positive	Negative
Direct consequences:					
1. Investment	1000	1	1		1000
2. Energy	360	30	12,34	4450	
Indirect consequences:					
Information not available					
Balance				+3450	

Because of Norwegian tax rules in connection with bank loans and interests, the private profitability of investments should be better than shown above. If other indirect consequences also were taken into account, the result would probably be even more positive.

12. COMPARATIVE ANALYSIS

The consequence of alternative building regulation requirements is not evaluated.

13. ERROR ANALYSIS

There are involved large areas of uncertainty in the assumptions. The table below indicates the amount of uncertainties and their consequences for the calculations. The limits of the total balance is calculated for each parameter, while the other parameters are left constant.

Parameter	Assumption	Uncertainty	Limits	Now-value Balance (NOK)
Extra cost	-1000 NOK	+1000 NOK	0 NOK	+4500
		-1000 NOK	-2000 NOK	+2500
Energy cost	360 NOK/year	+ 100 NOK/year	460 NOK/year	+4700
		- 100 NOK/year	260 NOK/year	+2200
Energy price	0,30 NOK/year	+0,05 NOK/kWh	0,35 NOK/kWh	+4200
		-0,05 NOK/kWh	0,25 NOK/kWh	+2700
Life time	30 years	+10 years	40 years	+3800
		- 5 years	25 years	+3200
Interest	7 %	+ 2 %	9 %	+2700
		- 2 %	5 %	+4500
		- 4 %	3 %	+6000

14. CONCLUSION

New building regulation requirements from 1.1. 1981 concerning air leakages are quantified and in principle controllable. Because of limitations in testing methods and available testing equipment it is possible to control only small buildings in situ and building components only in laboratories.

The economical consequences are calculated only for dwellings. The new air tightness requirements should give insignificant change in building practice for new apartment buildings, and thus modest economical consequences. For new detached and row houses extra costs are estimated to less than NOK 1000 per dwelling in average. This extra cost is compensated by a wide margin by energy savings estimated to a now value of NOK 4350 in average.

Better air tightness will lead to less complaints due to draught problems, less moisture damages and a tendency to increasing numbers of mechanical ventilation systems.

The risk of getting low air change rates and reduced indoor air quality in certain periods of the year will increase with better air tightness of the buildings. One storey houses with natural ventilation only will be especially vulnerable. Appropriate mechanical ventilation systems will eliminate these problems.

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THE IMPLEMENTATION AND EFFECTIVENESS OF AIR INFILTRATION STANDARDS IN BUILDINGS

5th AIC Conference, October 1-4 1984, Reno, Nevada, USA

PAPER 15

MEASURED AND BUILDING CODE VALUES OF AIR CHANGE RATES IN RESIDENTIAL BUILDINGS

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SYNOPSIS

Since 1970 measurements of air change rate have been carried out in about one thousand buildings by the Swedish Institute for Building Research (SIB). In this paper we present results from these measurements.

The studied buildings are of various design and have ventilation systems of different types, natural as well as mechanical. The buildings include single family houses, row houses, and multi family residential buildings, erected between 1900 and 1982.

The measurements have then been carried out using tracer gas (decay) techniques to determine the rate of air exchange. Other collected data include building geometry, building design, and meteorological conditions at the time of the measurement. The outdoor conditions have varied.

In the analysis the buildings have been divided into groups according to the year of construction, building design, and type of ventilation system. The measured rate of air change is compared to that required by the Code for each group of buildings.

In many cases measurements have been carried out before and after retrofits aiming at saving energy. For a lot of buildings pressurization measurements as well as tracer gas measurements have been done simultaneously. In these cases we have also estimated the airtightness of different building categories.

1. INTRODUCTION

In this paper we report results from an analysis of data on the rate of air change in residential buildings. The data have been collected by the field measurement unit of the Swedish Institute for Building Research (SIB) between 1974 and to 1983. These data have been collected for various research projects, having different purposes, like determination of the energy status of buildings, assessment of the indoor air quality in buildings, investigation of buildings with radon content in the air, diagnosis of building damages caused by moisture, etc.

The results given here are based on data from 600 buildings, representing one- and two storey detached homes, two storey row-houses, and multi storey apartment buildings, situated in different parts of Sweden. However, it should be noted that the collection of buildings does not constitute a true statistical sample from the Swedish building stock. Buildings from Mideastern and Northern Sweden are overrepresented.

During the measurements climate variables like the indoor and outdoor air temperature, the wind speed and direction at the building site, etc., have been recorded. The measurements have been rather equally distributed throughout the heating season.

The rate of air change has been determined, in accordance with common Swedish practice, by measurement of the decay of tracer gas (N_2O) concentration in the air[1], from an initial concentration of 30- 100 ppm. Fans have been placed in every room of the house, or the apartment, to ensure mixing of the air.

The measured air change rate can be compared to that required by the Swedish Building Code. For many years this Code has prescribed a minimal ventilation rate of 0.5 ACH (air changes per hour) for hygienic resons. In practice this limit has also become an upper limit, which should not be exceeded in new buildings and in retrofitted old buildings in order to save energy.

2. RESULTS

Some preliminary results of the analysis of the data considered here, including a determination of the effective leakage area of buildings, have already been presented[2].

In Fig. 1- 4 we present the measured rate of air change for flats in multi- family residential buildings, detached houses, and row-houses equipped with an exhaust air ventilation system or with a natural ventilation system.

For apartments with an exhaust air system, the average air change rate is not too far from 0.5 ACH, but the scatter around this average is 30 or 40 % (Fig. 1 and 2).

For apartments with a natural ventilation system, the rate of air change seldom exceeds 0.5 ACH, for new detached houses and row-houses it is in most cases substantially lower than 0.5 ACH. The scatter around the average value is between 40 and 50 % (see Fig. 3).

For detached houses and row- houses there is a difference between houses built before and after 1970, the average rate of air exchange being 0.33 and 0.23 ACH, respectively (see Fig. 4). This reflects the fact that buildings were made more airtight after the energy crisis, but only seldom measures were taken to counteract the resulting decrease of the air change rate. This was the case also for houses equipped with an exhaust air system. When this effect was noted, it became more common to supply houses with inlets.

Half the sample of detached houses and row- houses erected before 1970 is from Mideastern and Northern Sweden, which means that this building category is overrepresented in the sample. Another investigation[3] indicates an average value closer to 0.5 ACH than the value of 0.33 ACH found in this investigation. This may reflect different local building traditions for older buildings.

We have also investigated the scatter of the air change rate between apartments in the same building, relative to the average air change rate for that building, for some buildings equipped with an exhaust air ventilation system. In Fig. 5 we give the results from three buildings, where the rate of air change has been measured in about twenty apartments in each building. The scatter around the average is about 20 %. Taking into account a measurement error of about 10 %, the real scatter should then be about 15 %.

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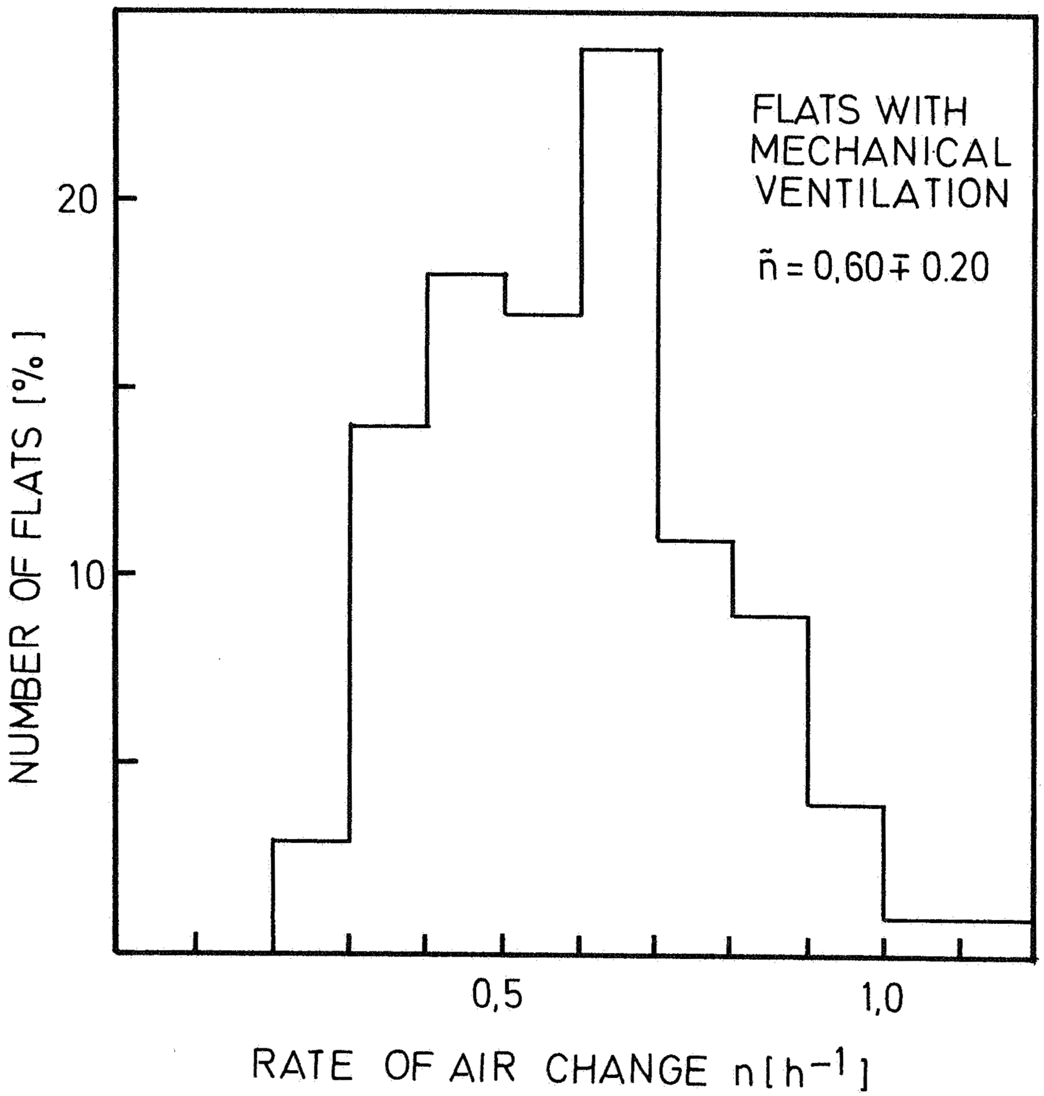

Fig 1 The distribution function of the rate of air changes, n, for flats in 3-8 storey multi-family residential buildings with an exhaust air ventilation system

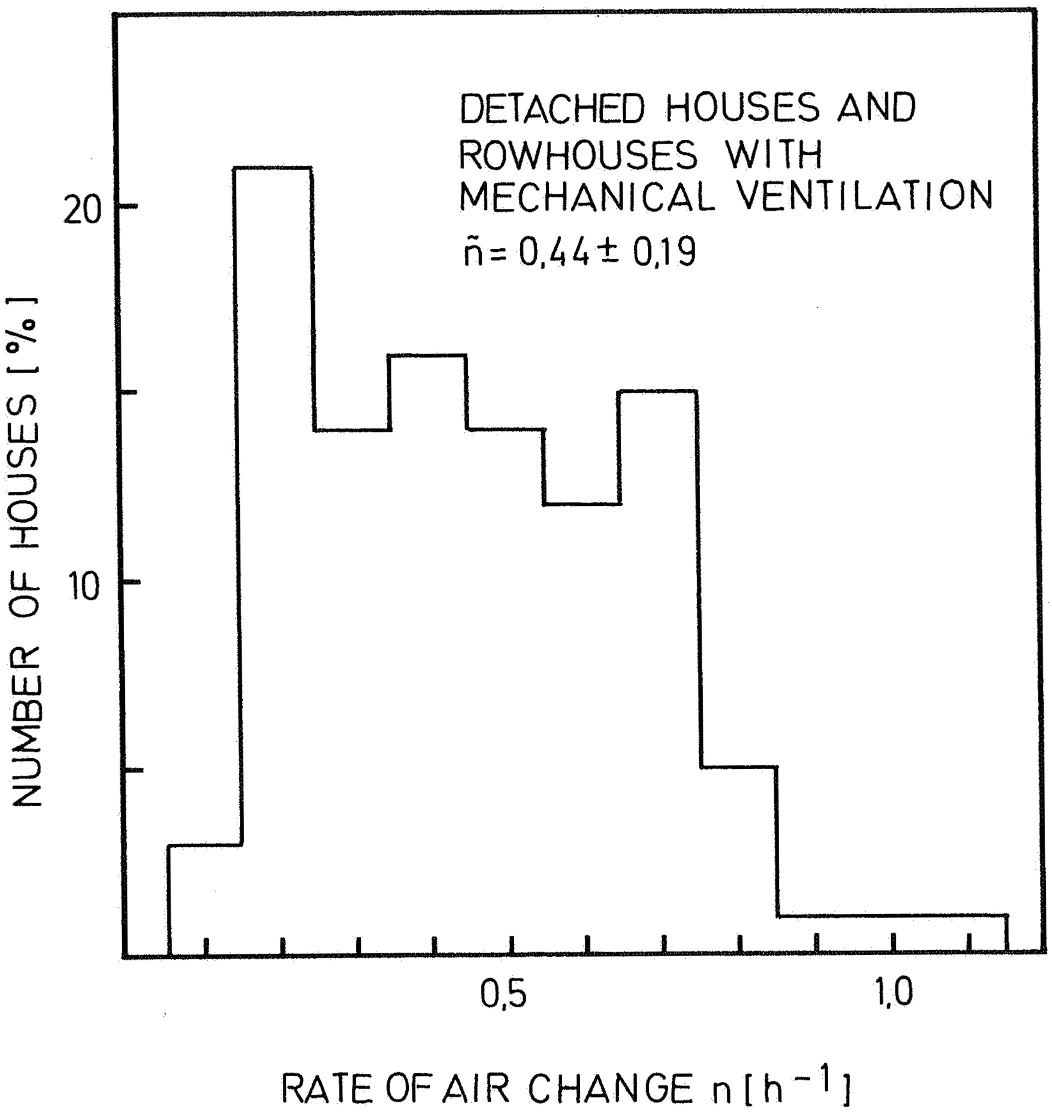

Fig 2 The distribution function of the rate of air changes, n, for one and two storey detached houses and row-houses with an exhaust air ventilation system

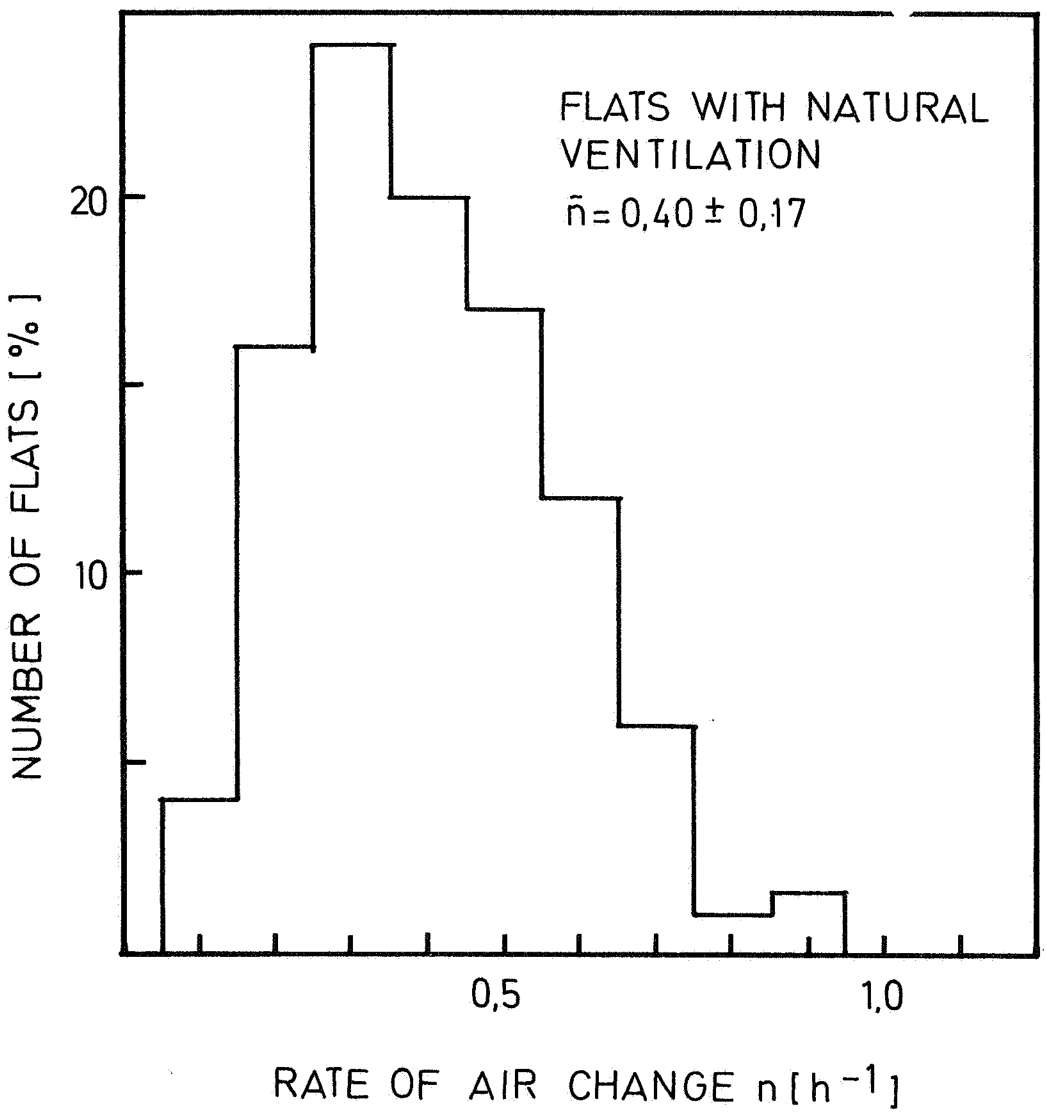

Fig 3 The distribution function of the rate of air change, n, for flats in 3-storey multi-family residential buildings with a natural ventilation system

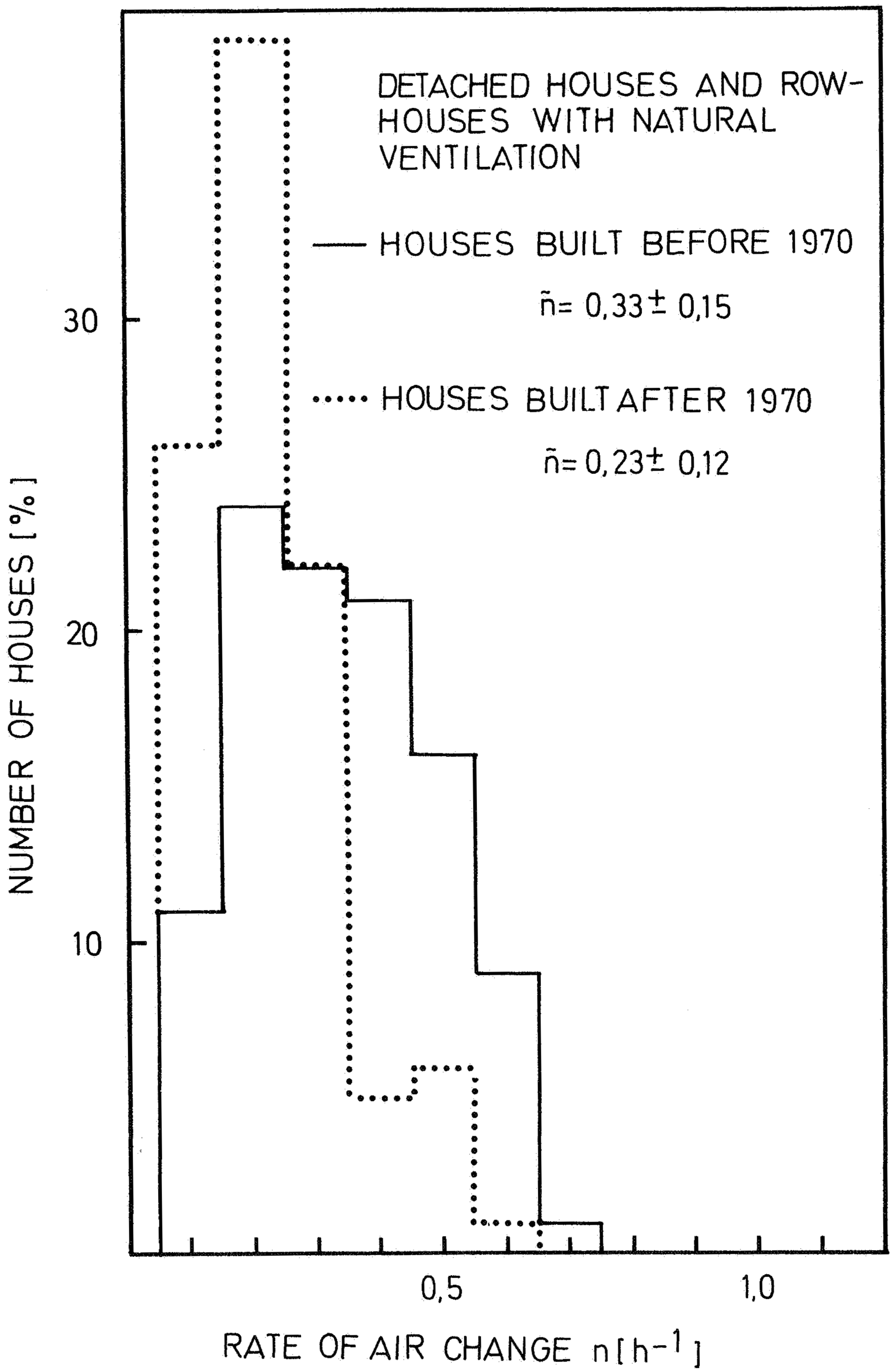

Fig 4 The distribution function of the rate of air change, n, for 1- and 2-storey detached houses and row-houses with a natural ventilation system. The houses have been divided into two groups according to the year of construction

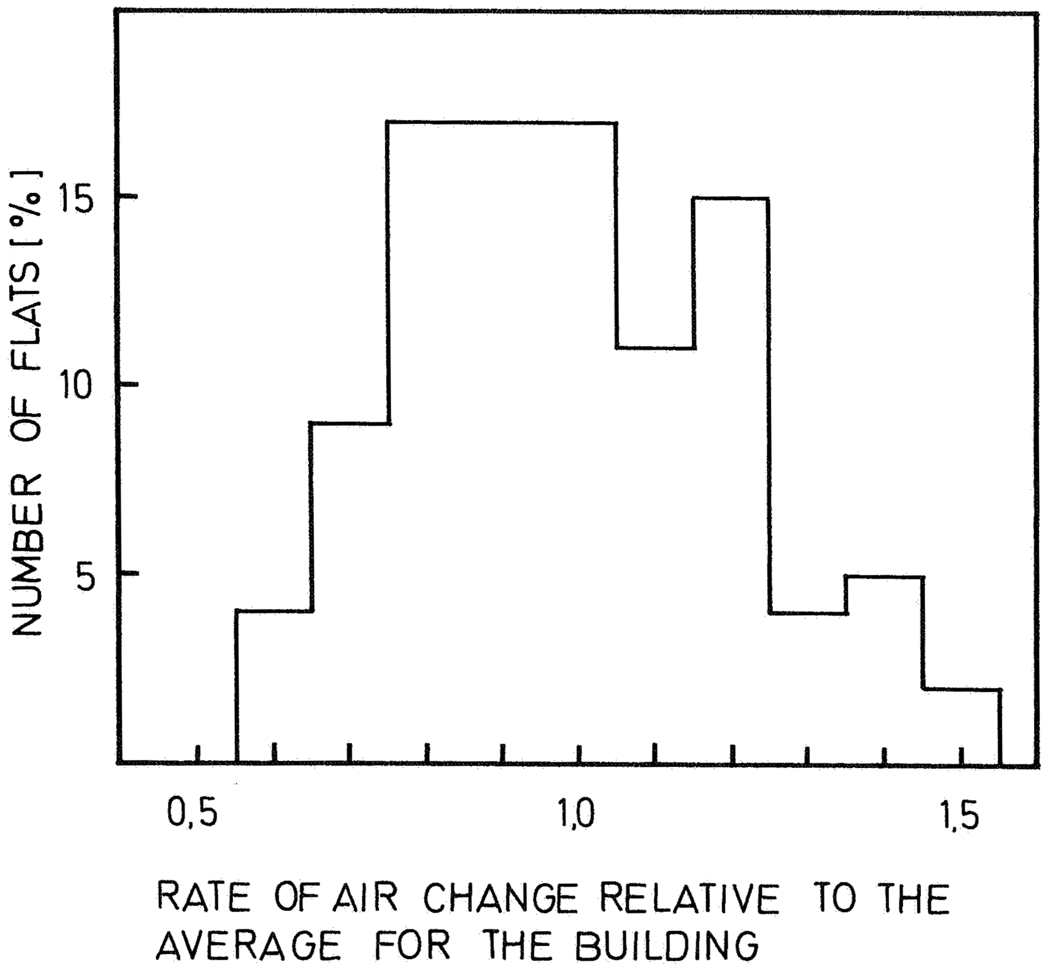

Fig 5 The distribution of the rate of air change for apartments in the same building for buildings with an exhaust air ventilation system (average value = 1.0). Data from 3 apartment buildings. The scatter is 22 %

THE IMPLEMENTATION AND EFFECTIVENESS OF AIR INFILTRATION STANDARDS IN BUILDINGS

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PAPER 16

CONSTANCY OF AIR TIGHTNESS IN BUILDINGS

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SYNOPSIS

In a pre-project the air tightness of 15 detached houses has been measured firstly immediately after erection, secondly after a period of 1.5 to 4.5 years. All the houses were timberframed ones, equipped with mechanical ventilation system. Only two houses out of the 15 tested show clear changes in air tightness. Thus, the air tightness behaviour of the houses seems to be fairly constant.

1. BACKGROUND

The aim of the project - the first part of which is reported in this paper - is to determine whether there are any considerable changes in the air tightness of newer onefamily houses during the first years after erection.

The degree of change of the air tightness is investigated by means of the pressurization/depressurization technique.

In this pre-investigation 15 houses were tested 1.5-4.5 years after erection (and first pressurization/depressurization test).

2. FIELD INVESTIGATION

2.1 Investigation objects

The objects were chosen from a total number of some hundreds of earlier test results. It was settled that the houses should fulfill the following demands:

- The houses should have been pressurized/depressurized in accordance with a standardized procedure (SS 02 15 51).
- Not more than five years should have elapsed since the first measurements.
- The first measurement should have been done immediately after the erection of the house.
- A low value of n_{50} ($\leq$3.0 ac/h) at the first measurement.
- No air-tightening or other measures should have been undertaken after the first measurement.
- The houses should be detached ones.

The 15 houses tested hitherto are all timber framed and equipped with exhaust fan ventilation system. 7 of the houses (no. 1, 2, 8, 11, 12, 13, 14) were prefabricated as volume elements, while the others were site-built or prefabricated as surface elements. 6 of the houses are 1 1/2 floor houses (no. 4, 5, 6, 7, 8, 10); the others are 1 floor houses.

2.2 Method

The investigation is a typical comparative one. This involves some statistical approach to determine whether two measurement values with certain inaccuracies differ from each other to a statistically significant degree or not.

The inaccuracy of the measurement procedure was estimated to ±5% in n_{50}, (Kronvall[1]). Using the assumption that a single measurement value has a normal distribution round the mean, statistical theory, e.g. Sachs[2], gives the degree of difference in n_{50} between the two measurement values needed for statistical significance. Figure 1.

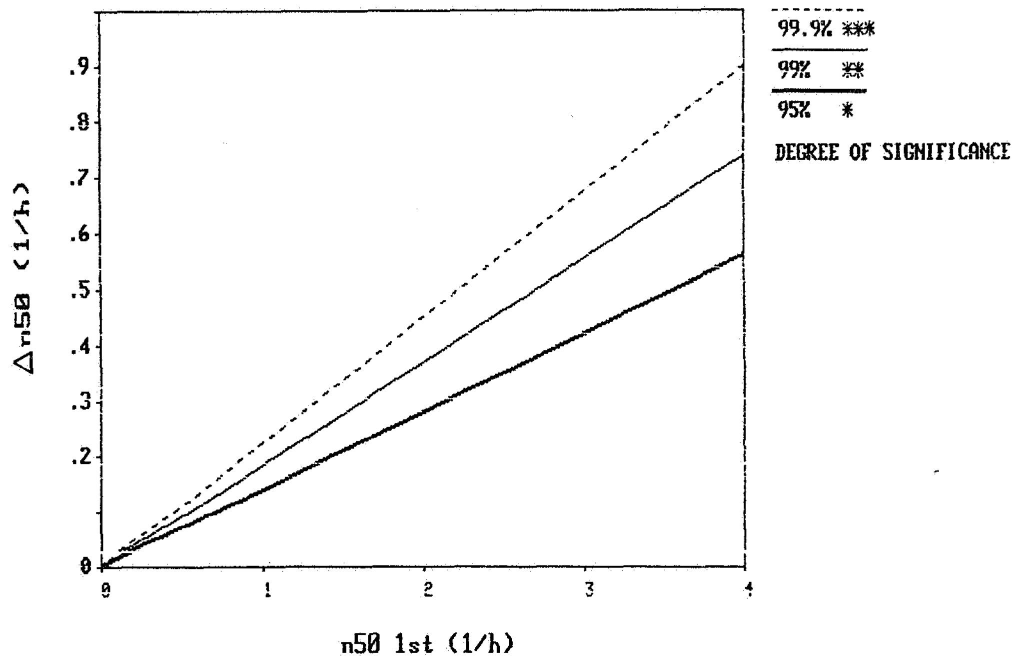


Figure 1. Required difference in n_{50} between two measurement values for different degrees of significance.

2.3 Results

The results are summarized in table 1.

The leakage characteristics of the houses tested are shown in figure 6. (Pressurization/depressurization data at 10, 20, 30, 40, 45, 50, 55 Pa fitted to a power-expression).

The coefficent, A, and the exponent B in the power expression

$$q_v = A \cdot \Delta p^B \qquad (1)$$

are given in table 1.

OBJECT NUMBER	TIME BETWEEN 1st and 2nd MEASUREMENT (year)	TEST MONTH 1st	TEST MONTH 2nd	n_{50} (1/h) 1st	n_{50} (1/h) 2nd	A FLOW COEFFICIENT ($m^3/(h \cdot p^B)$) 1st	A FLOW COEFFICIENT ($m^3/(h \cdot p^B)$) 2nd	B FLOW EXPONENT (-) 1 st	B FLOW EXPONENT (-) 2nd	A_{eq} EQUIVALENT LEAKAGE AREA AT 4 Pa (cm^2) 1st	A_{eq} EQUIVALENT LEAKAGE AREA AT 4 Pa (cm^2) 2nd
1	3.5	12	5	1.4	1.5	33	33	0.73	0.74	1.7	1.7
2	2.5	12	5	2.4	2.1	41	35	0.78	0.78	2.2	1.9
3	2.5	1	5	1.7	1.6	71	26	0.59	0.78	2.9	1.4
4	2.5	1	5	2.1	2.1	32	35	0.76	0.72	1.7	1.8
5	2.5	1	6	1.9	1.3	56	27	0.58	0.67	2.3	1.2
6	2	3	5	1.4	1.3	46	11	0.54	0.89	1.8	0.7
7	2	3	5	0.9	1.3	8	7	0.90	1.00	0.5	0.5
8	3.5	2	6	2.5	2.5	82	62	0.59	0.67	3.4	2.9
9	1.5	2	6	2.2	2.3	38	84	0.78	0.58	2.1	3.4
10	1.5	2	6	1.6	1.7	28	25	0.69	0.73	1.3	1.2
11	4.5	1	6	2.5	2.9	27	79	0.92	0.69	1.8	3.8
12	4.5	1	6	2.4	2.5	72	91	0.66	0.61	3.3	3.9
13	4.5	1	6	2.4	2.8	76	64	0.65	0.73	3.4	3.3
14	1.5	11	6	2.4	2.6	119	91	0.50	0.59	4.4	3.8
15	1.5	2	6	1.6	1.7	35	33	0.74	0.77	1.8	1.7

Table 1.

For comparative reasons the equivalent leakage area at a pressure difference of 4 Pa (Δp_{ref}) was calculated too.

$$Aeq = \frac{1}{C_d \sqrt{\frac{2}{\rho}}} \cdot \frac{q_v(\Delta p_{ref})}{\sqrt{\Delta p_{ref}}} \qquad (2)$$

C_d (coefficient of discharge) = 0.6

ρ = density of air, kg/m^3

The relationship between n_{50} and Aeq at 4 Pa is shown in figure 2.

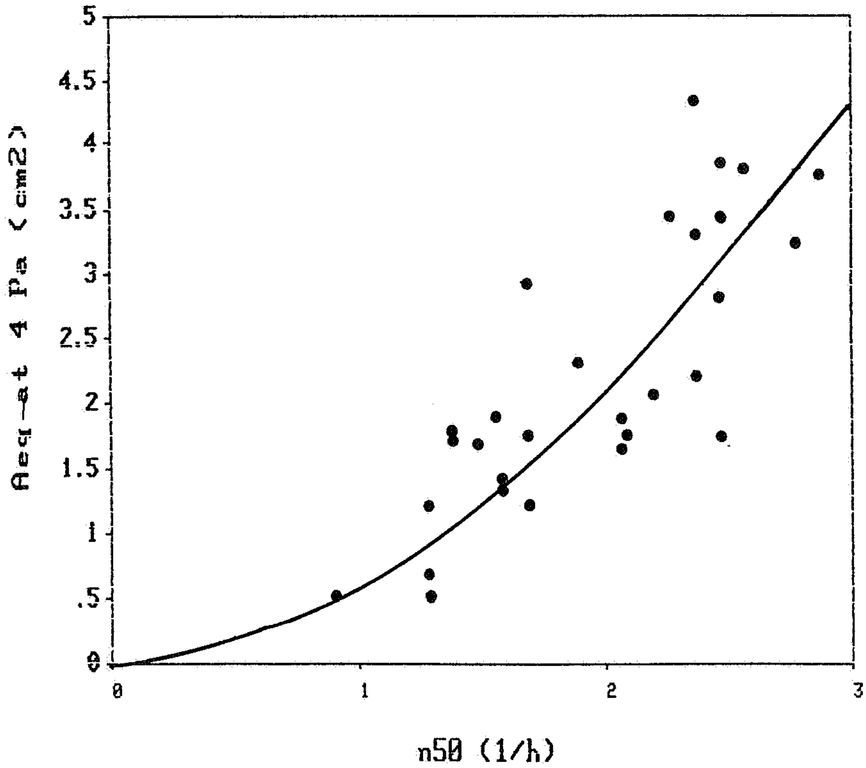


Figure 2. The equivalent leakage area, Aeq, at 4 Pa vs. n_{50}. The curve origins from data fitted by means of the least square method:

$Aeq = 0.66 \cdot n_{50}^{1.69}$, $r^2 = 0.72$

The results of the first and the second measurement are shown in figure 3, (n_{50}), and figure 4, (Aeq).

The result of a curve fit to a straight line is:
$n_{50}^{2nd} = 0.063 + 0.995\, n_{50}^{1st}$, $r^2 = 0.78$.

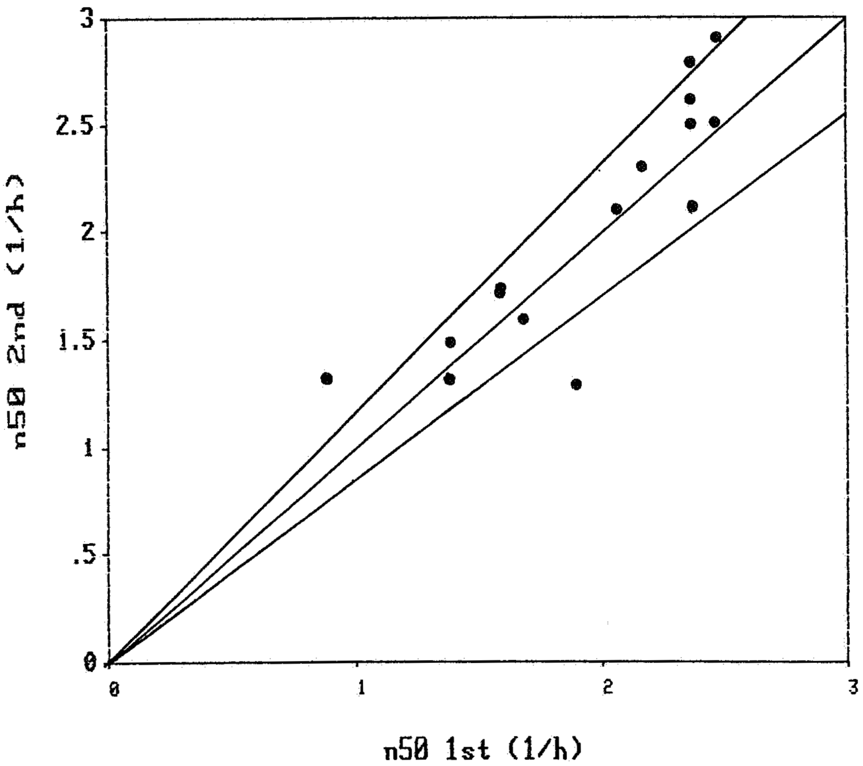


Figure 3. n_{50} at the first and the second measurement. The area between the lines symmetric around the line y = x illustrates the field within which there is no significant (95% level) difference between the two measurement values.

In figure 4 the results of the measurements expressed as equivalent leakage area at 4 Pa are shown.

The result of a curve fit to a straight line is:

$Aeq^{2nd} = 0.430 + 0.775\ Aeq^{1st}$, $r^2 = 0.44$.

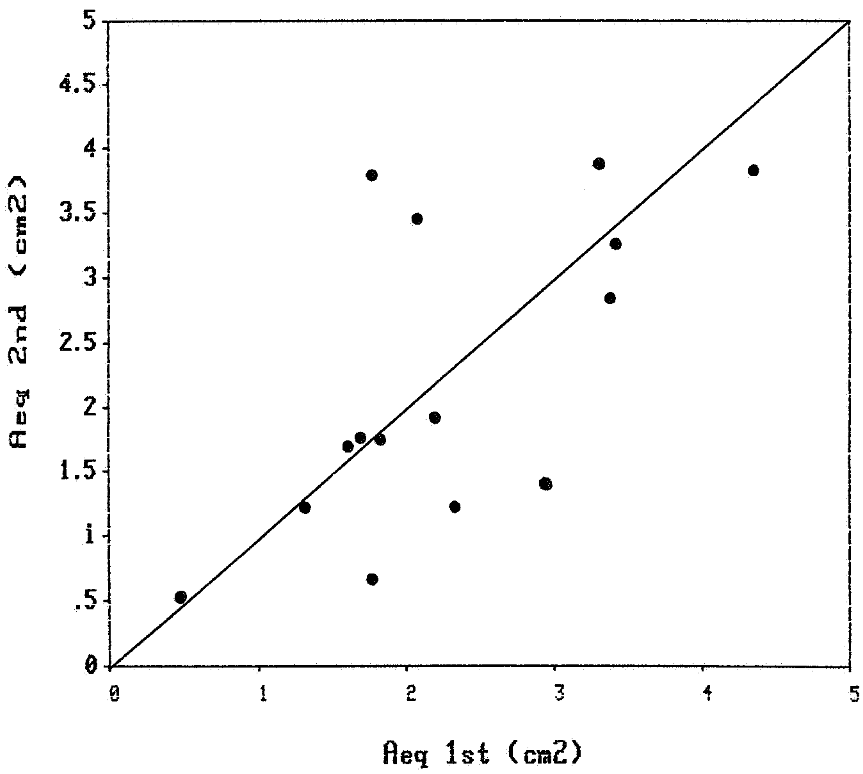


Figure 4. Aeq at 4 Pa at the first and the second measurement.

The alterations in n_{50} and Aeq are plotted versus each other in figure 5.

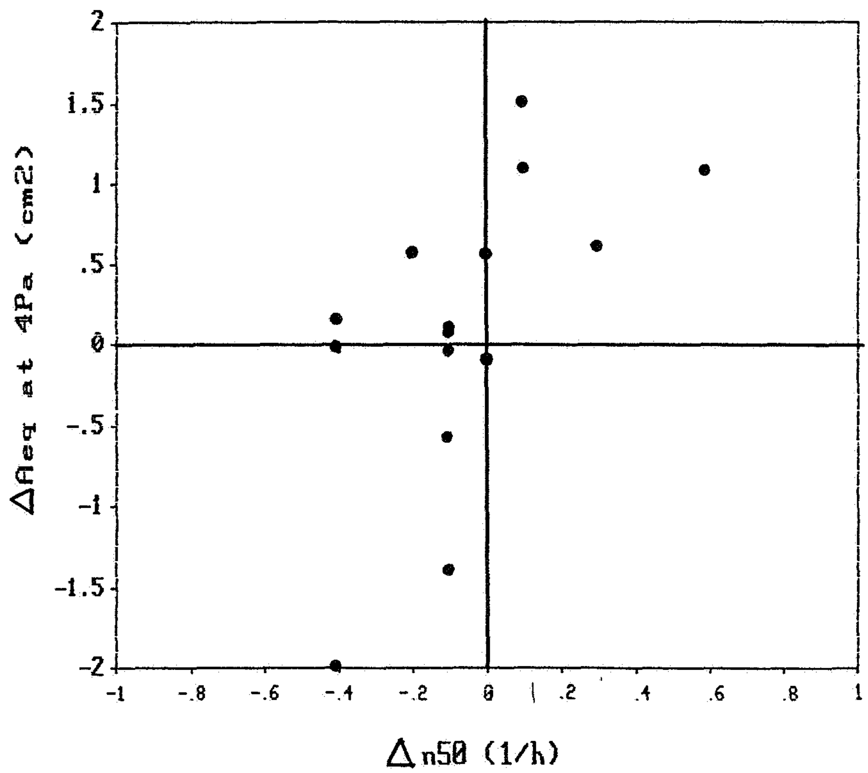
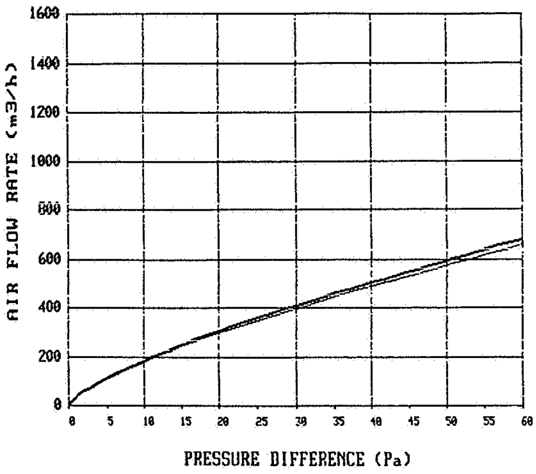


Figure 5. Alterations in n_{50} and Aeq. Negative values stand for deteriorated air tightness (higher n_{50} and Aeq at the second measurement compared to the first one).

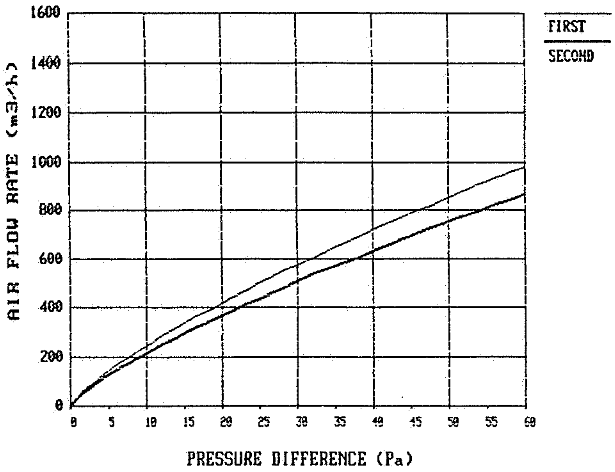
2.4 Discussion

If n_{50}-values from two measurements are compared to each other (figure 3), only four objects out of the investigated 15 ones show significant differences. The air tightness according to n_{50} has deteriorated in three cases (clearly in one case), and improved in one case.

The results indicate that the air tightness behaviour of the houses seems to be fairly constant.



House 1



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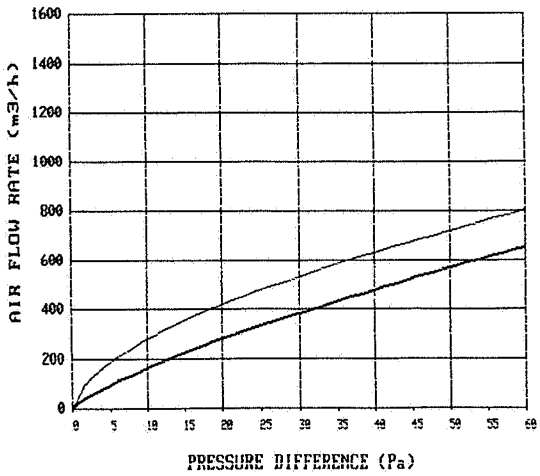

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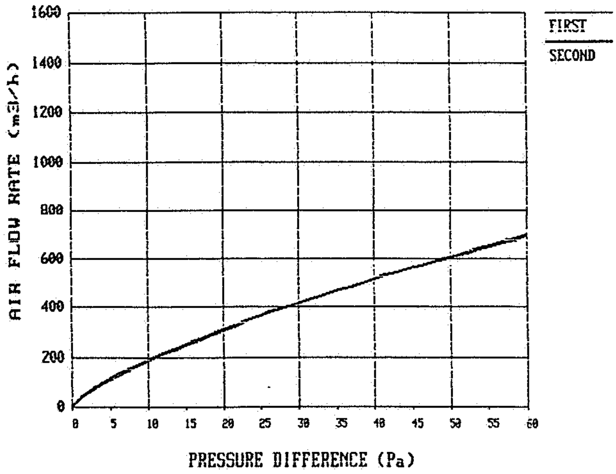

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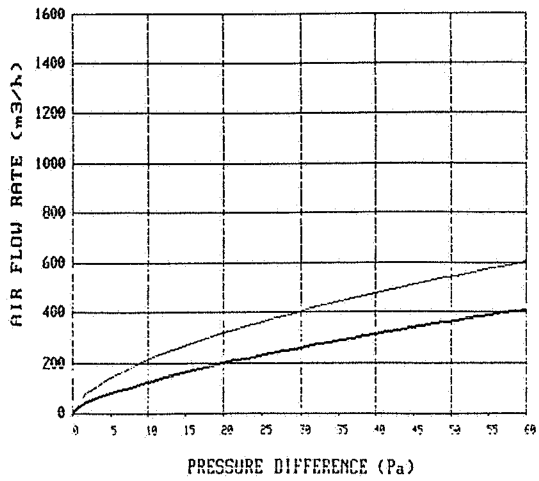
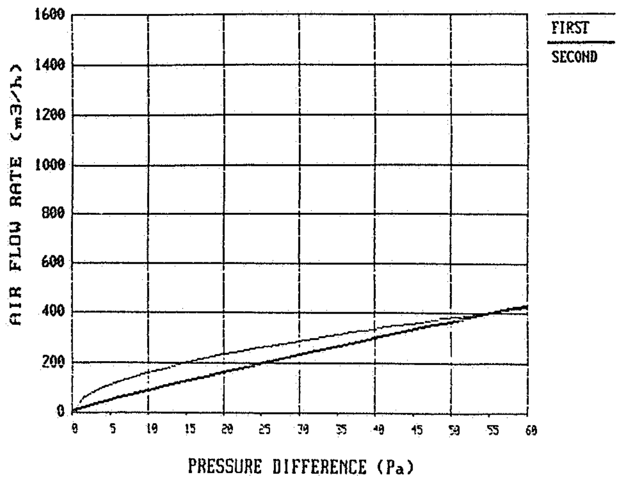
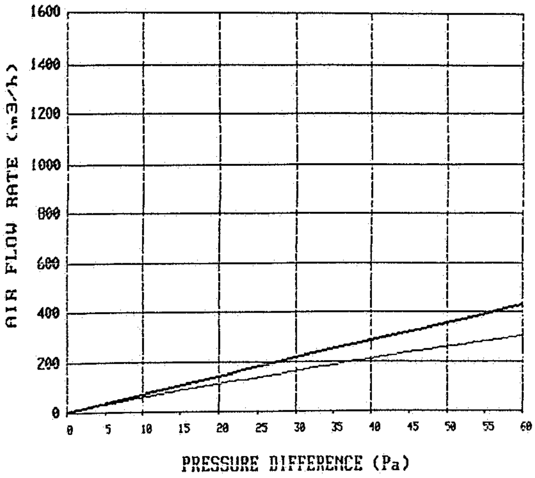


House 5



House 6

Figure 6 (cont)



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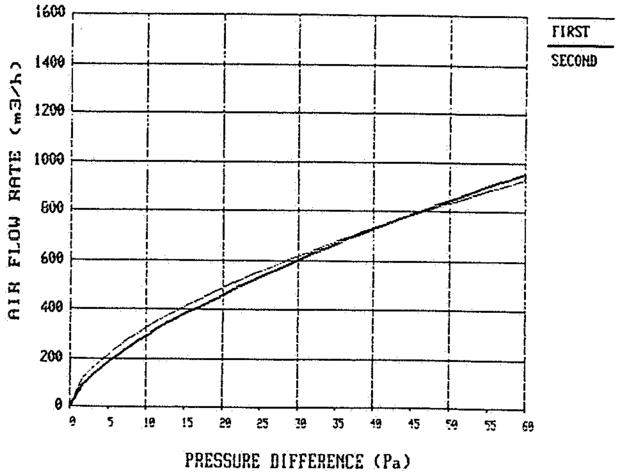

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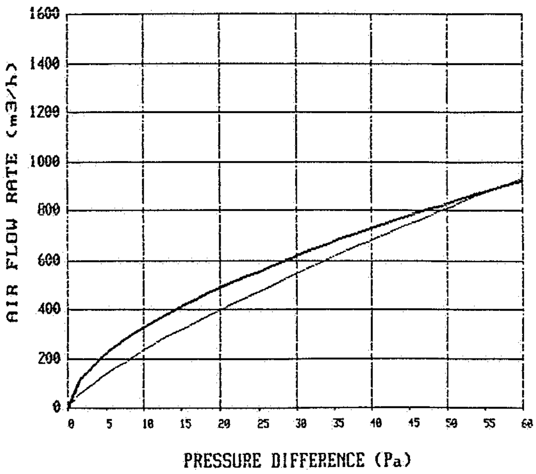

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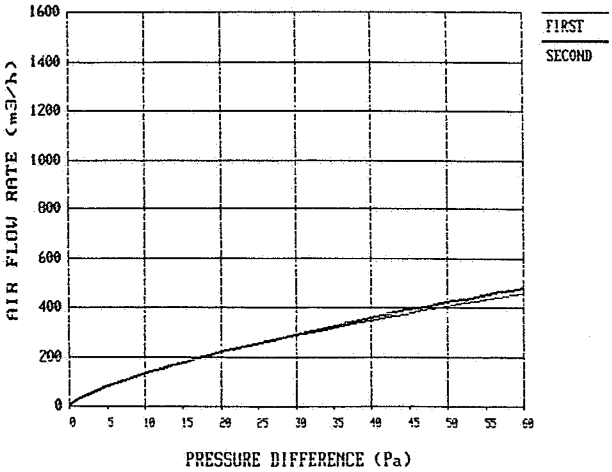

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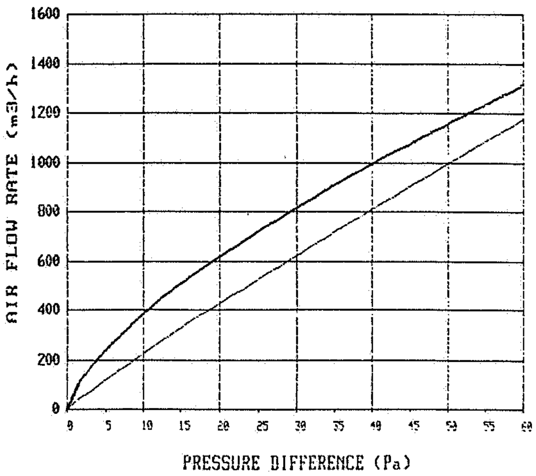
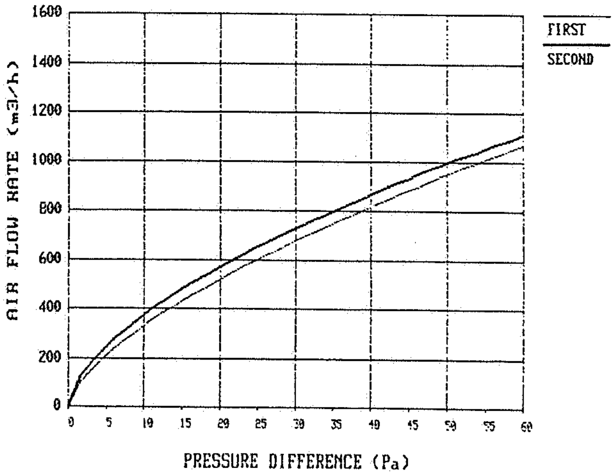
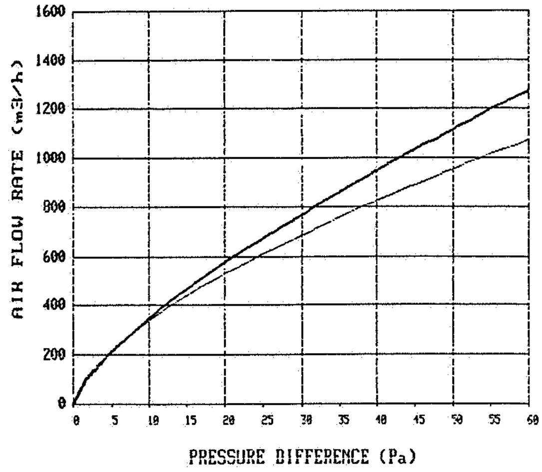


House 11

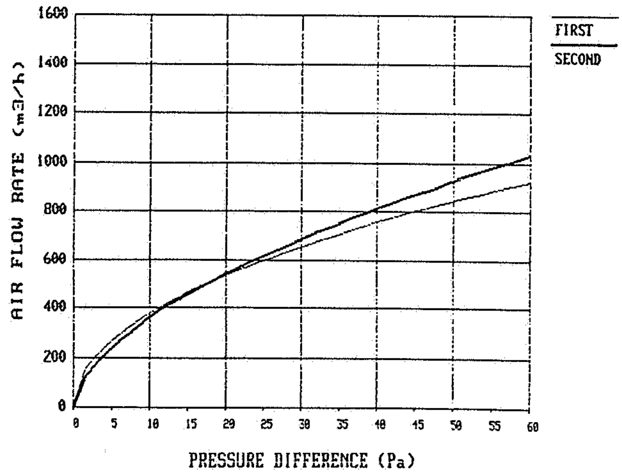


House 12

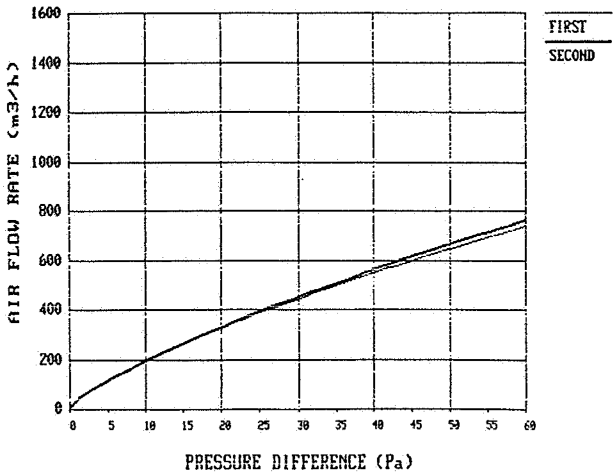
Figure 6 (cont)



House 13



House 14



House 15

Figure 6

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THE IMPLEMENTATION AND EFFECTIVENESS OF AIR INFILTRATION STANDARDS IN BUILDINGS

5th AIC Conference, October 1-4 1984, Reno, Nevada, USA

PAPER 17

BASELINE DATA: HEALTH AND COMFORT IN MODERN OFFICE BUILDINGS

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SYNOPSIS

Reduction of fresh air ventilation is becoming the major means of energy conservation in office buildings. Simultaneously, health and comfort problems experienced by occupants are often suspected to be a direct result of reduced fresh air ventilation. However, there is little data available on health and comfort problems experienced by occupants of buildings operated under normal ventilation rates.

Baseline data needed to compare occupant health and comfort complaints in buildings with reduced ventilation to complaints in "normal buildings" was provided by a survey of 1106 members of the New York local of the Office and Professional Employees International Union in nine office buildings with no prior history of complaints from occupants of health and comfort problems. Buildings were screened for energy conserving retrofits and architectural and ventilation factors.

1. INTRODUCTION

New modes of design, construction, ventilation and energy management have had profound effects on the manner in which pollutants are generated, entrapped or eliminated in buildings. A number of extensive reviews have now documented that sealed, air conditioned buildings, especially modern office buildings, contain a wide variety of pollutants often exceeding levels found outdoors.[1 2 3 4 5] Occupants of these same buildings often also suffer from a complex of symptoms including headaches, burning eyes, irritation of the respiratory system, drowsiness, fatigue and general malaise, now termed Building Illness or Tight Building Syndrome.[6 7] Many public health authorities believe building illness may be reaching epidemic proportions in sealed, air conditioned buildings.

The acceleration of fuel costs in the 1970's placed immediate pressures to conserve energy on the building sector. Building construction, maintenance and service practices and standards were altered to allow energy reduction. Ventilation was drastically decreased and occupant control over ventilation and lighting was reduced. New ventilation standards proposed by the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) and the U.S. Department of Energy recommend and permit a reduction of ventilation air by up to 90%.[8 9] For example, the previous ASHRAE "Standard for Natural and Mechanical Ventilation" recommended 25 cubic feet per minute (CFM) per person of fresh air ventilation in general office areas of air conditioned office buildings.[10] However, the new ASHRAE standard, "Ventilation for Acceptable Indoor Air Quality" requires only 5 CFM per person of fresh outside air providing smoking is either not allowed or restricted to designated areas.[8] Similar decreased ventilation standards are also being adopted in other countries.

Problems experienced by occupants are often suspected to be a direct result of reduced fresh air ventilation. Without comparative data it is difficult to determine whether the situation experienced by occupants under reduced ventilation conditions is better or worse than under previous conditions. However, baseline data needed to compare occupant health and comfort complaints in buildings with reduced ventilation to complaints in "normal buildings" is now available from a detailed survey of 1106 members of the New York local of the Office and Professional Employees International Union in 9 "normal" office buildings.

2. METHOD

A self-administered Work Environment Survey questionnaire designed to collect perceptions of environmental conditions and prevalence of Building Illness symptoms among office occupants was administered to 1106 office workers in greater New York City (45% men and 55% women). As far as was determined, there was no prior history of health and comfort complaints among the study group, no prior investigations of the office environment, and no major energy conservation retrofits.

The work environment survey questionnaire requested information about:

Environmental conditions: air movement, air quality, lighting, glare, unpleasant odors, temperature, humidity, seating.

Lighting type: fluorescent ceiling light, fluorescent table light, incandescent ceiling light, incandescent table light, natural window light.

Health related symptoms: headache, dizziness, fatigue, sleepiness, nausea, skin rashes, ringing in ears, nose irritation, breathing difficulty, chest pain or tightness, blurred vision, eye irritation, sore throat or cold symptoms.

Control over environmental conditions: windows, illumination, heating, ventilation, air conditioning, smoking.

Questions were so constructed that they could be scored on a 3 point scale, with a 1 indicating a favorable, 2 an intermediate and 3 an unfavorable response. The distribution of responses for health and environment related questions were evaluated by constructing comprehensive indices which combined related and nonconflicting questions.

Table 1 shows the indices used to assess overall effects of working conditions on health related symptoms (visual, cardiorespiratory, musculoskeletal and neurophysiological systems, symptoms common among outbreaks of Building Illness in general, absenteeism and the use of medication) and environmental conditions (lighting, ventilation, temperature, humidity and odor).

Health and environment indices were cross tabulated with responses to individual questions about control of environment (such as opening windows). Cross tabulations were also tested for independence by use of Chi Square statistics.

3. RESULTS

Table 2 presents the percent distribution of complaints about environmental conditions. Seventy-five percent of office workers reported too little air movement as opposed to only 35% reporting too much air movement "Sometime or Often". Unpleasant odor, often used as an indicator of inadequate ventilation, was reported by 40% of respondents as occurring at least "Sometimes" and by 14% as occurring "Often or Always". Temperature was a consistent problem with 77% reporting conditions too cold and 72% reporting conditions too hot "Sometimes or Often". Although 44% of respondents complained of smoky air in the workplace, 74% reported stuffy conditions. These results seem to indicate a need for more appropriate regulations or control by office workers of conditions affecting temperature and air quality. Current air quality regulations[8] are based on restriction of tobacco smoke, however from the survey results it would appear that "stuffy air" rather than "smoky air" would be a better indicator of overall air quality.

Lighting conditions were considered satisfactory. However, responses indicated that brightness and glare could be improved. Fourty-three percent reported that lighting was too dim and 45% reported glare on work surfaces "Sometimes or Often". Lighting conditions are not now a significant problem among office workers, however, with illumination levels and window area being reduced to conserve energy, future problems could result.

Table 3 presents the distribution of Building Illness symptoms commonly reported in the indoor air pollution literature. Headache, fatigue, nose irritation and eye irritation (symptoms indicating general discomfort with environmental conditions) were reported most frequently. Thirty-seven percent of office workers reported headaches, 52% reported fatigue, 32% reported nasal irritation and 37% reported eye irritation more than once a week. Twenty-one percent of respondents reported sore throat or cold symptoms once a week or more.

3.1 Ventilation

Results of the cross tabulation between answers to the question, "In your primary work area do you feel that there is too little air movement?" and the Building Illness Index are shown in Table 4 and the association between "Too Much Air Movement" and Building Illness is shown in Table 5. Table 4 demonstrates a highly significant relation between Building Illness symptoms and insufficient air movement. ($\chi^2 = 52.72$ and $p \leqq .001$). This is also shown by the approximately four times as many respondents in the insufficient as in the sufficient air movement group who scored "poor" on Building Illness. On the other hand, the responses of "Too much air movement" do not show a significant association to Building Illness (Table 5, $\chi^2 = 7.41$, the value of p is omitted in all tables when the test falls short of reasonable statistical significance). Again this lack of relationship is made obvious by the comparison of the almost equal proportion of respondents in the group that scored low and high on this question. While movement of air by itself does not ensure better fresh air ventilation, it seems to be so perceived and in fact may be the case in buildings that are better ventilated.

Table 6 shows the association between conditions of ventilation in the work place and Building Illness symptoms. There is a highly significant relation between poor ventilation and building illness ($\chi^2 = 44.72$ and $p \leqq .001$). Fourty-four point six percent of office workers with good ventilation as compared to 32.9% with poor ventilation did not complain of Building Illness (i.e. ranked as "good"). As fewer occupants of well ventilated buildings complain of Building Illness symptoms, air movement and quality of ventilation appear to be major determinants of health and comfort among office workers.

3.2 Lighting

Table 7 shows the association between office lighting conditions and Building Illness symptoms. There is a highly significant relation between poor lighting and Building Illness ($\chi^2 = 45.63$ and $p \leqq .001$). Twenty-five point two percent of office workers with poor lighting ranked "poor" on Building Illness while only 10.3% with good lighting did so. Table 8 shows the association between lighting conditions and visual health. Again, the relationship is significant and substantial ($\chi^2 = 74.82$ and $p \leqq .001$). Eighteen point four percent of office workers with poor lighting also had poor visual health while only 6.4% with good lighting did so.

3.3 Effects Of Smoking

Some of the workers surveyed smoked (57%) and some of them did not (43%). Some of them worked in places where smoking was permitted, some in places where smoking was prohibited, and some in places where smoking was restricted.

Thus a number of groups were constructed for comparison:

- Nonsmokers working in places where smoking was permitted.
- Nonsmokers working in places where smoking was restricted.
- Nonsmokers working in places where smoking was prohibited.

- Smokers working in places where smoking was permitted.
- Smokers working in places where smoking was restricted.
- Smokers working in places where smoking was prohibited.

As responses to questions were almost identical for places where smoking was restricted and where it was prohibited, we combined workplaces where smoking was restricted or prohibited into a single category.

The effect of smoking on nonsmoking office workers is reviewed in the next two tables. Tables 9 and 10 show that there is no significant association between smoking at work and either Building Illness or Visual Health among office workers who either smoke or do not smoke.

Table 11 shows the association between Smoking at Work and the Odor Index. There is no significant difference in the perception of unpleasant odors among nonsmokers or smokers regardless of whether smoking was or was not permitted.

3.4 Control Over Environment

In most modern office buildings, but not in all of them, control of air conditioning and lighting is centralized and thus removed from office occupants. Tables 12 and 13 show the association between control by occupants of air conditioning and lighting on the Building Illness Index. Air conditioning is used here as a generic term referring to the heating, ventilation and air conditioning (HVAC) system. Table 12 shows a significant relationship between control of air conditioning and incidence of Building Illness ($\chi^2 = 12.17$ and $p \leq .005$). Fifteen point nine percent of office workers with no control of air conditioning scored "poor" on the Building Illness Index compared to 4.8% of office workers with control of air conditioning. Table 13 shows a significant relationship between control of lighting and incidence of Building Illness ($\chi^2 = 8.80$ and $p \leq .05$). Fifteen point nine percent of office workers who had no control of lighting scored poor on the "Building Illness Index" compared to 6.7% who had control of lighting conditions. In both cases (Tables 12 and 13) respondents who had control over conditions were approximately three times less likely to suffer symptoms of building illness than those with no control.

4. DISCUSSION

The results indicate that even among occupants of buildings operated under normal ventilation and lighting conditions, there exist problems with environmental conditions as well as a relatively high level of health and comfort complaints. There is a consistent pattern of association of factors relating both ventilation and lighting with frequency of reported illness symptoms. Office workers judging their ventilation and lighting environments as poor were more likely to have health complaints than those who considered ventilation and lighting to be good. Office workers with control over environmental and lifestyle factors such as controlling air conditioning, opening and closing windows, switching on and off lighting and smoking had fewer complaints about health and stress symptoms than did office workers with no control over environmental and lifestyle factors.

Very interesting is the lack of significant association between Building Illness, Visual Health and Odor indices and either active or passive smoking. That passive smoking is a known irritant for many nonsmokers is well known. The findings here however do not relate to irritation due to smoking but to the association of smoking to perceived health and/or comfort levels. This lack of association probably is due to two reasons. First, pollutant patterns depend heavily on ventilation factors while, at the same time, byproducts of combustion infiltrate or are generated and entrapped in a building from many sources. In fact, exhaustive reviews of the literature[3] and review of pollutants levels reported in 143 buildings by NIOSH, CDC and other investigators[11] fail to find differences in pollution concentration or patterns in offices with and without smoking restrictions. Second, the manner of administering the questionnaire avoided calling attention to smoking (or any other) factors, besides including questions pertaining to them. It is especially interesting that there were no differences in perception of odors between locations with and without smoking rules (Table 11).

This Work Environment Survey, though limited to office workers in greater New York City, provides some measure of human health and comfort with environmental conditions provided by contemporary office buildings. However, the majority of office buildings may now be designed and built to reduced environmental standards in order to achieve energy conservation goals. Also, many existing contemporary office buildings are being renovated and operated to reduce the amount of energy used. The human costs that may result from reduced environmental standards for energy conservation in office buildings are still unclear. This study presents baseline data showing the relation of environmental parameters to health and comfort of office workers in buildings prior to energy conserving adjustments or modifications. These questionnaire survey results can be used for comparison with similar data collected from occupants of energy conserving office buildings to provide background for prudent standards to ensure that energy efficient buildings are designed, built and operated to provide conditions acceptable for human occupation.

ACKNOWLEDGEMENTS

The study was made possible by the cooperation and support of leaders and members of Local 153, Office and Professional Employees International Union in greater New York City. We are indebted to Diana Hartel-Kobayashi of the Columbia University School of Public Health for help with design, layout and administration of the Work Environment Questionnaire.

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Health Indices	Environment Indices
Visual . blurred vision . eye irritation . split or double vision . trouble focusing eyes	Lighting . lighting too bright . lighting too dim . glare on work surface
Cardiorespiratory . nose irritation . breathing difficulty . chest pain or tightness . racing heart	Ventilation . too little air movement . too much air movement . air too stuffy
Musculoskeletal . neck ache . sore arms, hands, wrists . backache	Temperature . too cold . too hot
Neurophysiological . headache . dizziness . fatigue . sleepiness . moodiness . depression . lightheadedness . confusion	Humidity . too dry . too moist
Building Illness . headache . fatigue . nose irritation . eye irritation . sore throat or cold symptoms	Odor . unpleasant odor . too smoky
Absenteeism . days absent during past six months . days left work due to illness in past six months	
Medication . aspirin . stomach or digestive aids . cough, cold or sinus medication . stimulants (pep pills) . prescription medicine . laxatives . depressants . sleep inducing aids	

Table 1 - Groups of questions used to construct health and environmental indices

Environmental Condition	Never or Rarely	Sometimes	Often or Always	Total %
Too Little Air Movement	25	39	36	100
Too Much Air Movement	65	29	6	100
Lighting Too Bright	77	15	8	100
Lighting Too Dim	57	28	15	100
Glare on Work Surfaces	55	30	15	100
Unpleasant Odors	46	40	14	100
Temperature Too Cold	23	54	23	100
Temperature Too Hot	28	56	16	100
Air Too Dry	35	43	21	100
Air Too Moist	73	25	3	100*
Air Too Smoky	56	31	13	100
Air Too Stuffy	26	47	27	100

* error due to rounding

Table 2 - Percent distribution of complaints about environmental conditions

Symptoms	Once a Month or Less	Once a Week	Once a Week or More	Total %
Headache	63	16	21	100
Fatigue	49	24	28	100
Nose Irritation	68	13	19	100
Eye Irritation	63	20	17	100
Sore Throat or Cold	79	13	8	100

Table 3 - Percent distribution of symptoms commonly associated with building illness

BUILDING ILLNESS INDEX	Never	Sometimes	Often	Number of Cases
Good	52.9	45.3	31.1	453
Average	40.8	42.2	46.2	465
Poor	6.3	12.4	22.7	156
Total	100%	100%*	100%	
Number of Cases	272	419	383	
$\chi^2 = 52.72$	$p \leq .001$			

Table 4 - Too little air movement

BUILDING ILLNESS INDEX	Never	Sometimes	Often	Number of Cases
Good	42.8	42.7	43.8	440
Average	41.3	47.0	37.5	439
Poor	16.0	10.3	18.8	149
Total	100%*	100%	100%*	
Number of Cases	664	300	64	
$\chi^2 = 7.41$				

Table 5 - Too much air movement

BUILDING ILLNESS INDEX	Good	Average	Poor	Number of Cases
Good	44.6	50.0	32.9	445
Average	44.6	41.4	45.2	461
Poor	10.8	8.6	21.9	153
Total	100%	100%	100%	
Number of Cases	195	430	434	
$\chi^2 = 44.72$	$p \leq .001$			

Table 6 - Ventilation index

BUILDING ILLNESS INDEX	Good	Average	Poor	Number of Cases
Good	46.7	43.9	30.5	443
Average	42.9	43.9	44.3	459
Poor	10.3	12.1	25.2	156
Total	100%*	100%*	100%	
Number of Cases	687	66	305	

$\chi^2 = 45.63 \quad p \leq .001$

Table 7 - Lighting index

VISUAL HEALTH INDEX	Good	Average	Poor	Number of Cases
Good	78.0	62.1	51.5	734
Average	15.6	25.8	30.2	216
Poor	6.4	12.1	18.4	108
Total	100%	100%	100%*	
Number of Cases	687	66	305	

$\chi^2 = 74.82 \quad p \leq .001$

Table 8 - Lighting index

BUILDING ILLNESS INDEX	Non Smoker No Smoking Work Zone	Non Smoker Smoking Work Zone	Smoker No Smoking Work Zone	Smoker Smoking Work Zone	Number of Cases
Good	37.9	43.1	43.0	38.9	312
Average	51.5	38.7	44.4	46.5	349
Poor	10.6	18.2	12.6	14.6	112
Total	100%	100%	100%	100%	
Number of Cases	66	137	151	419	

$\chi^2 = 5.30$

Table 9 - Smoking at work

VISUAL HEALTH INDEX	Non Smoker No Smoking Work Zone	Non Smoker Smoking Work Zone	Smoker No Smoking Work Zone	Smoker Smoking Work Zone	Number of Cases
Good	66.7	68.6	70.9	68.3	531
Average	24.2	16.1	17.9	20.5	151
Poor	9.1	15.3	11.3	11.2	91
Total	100%	100%	100%*	100%	
Number of Cases	66	137	151	419	

$\chi^2 = 4.19$

Table 10 - Smoking at work

ODOR INDEX	Non Smoker No Smoking Work Zone	Non Smoker Smoking Work Zone	Smoker No Smoking Work Zone	Smoker Smoking Work Zone	Number of Cases
Good	28.6	37.9	37.1	33.8	255
Average	58.7	47.7	56.6	53.3	392
Poor	12.7	14.4	6.3	12.9	87
Total	100%	100%	100%	100%	
Number of Cases	63	132	143	396	

$\chi^2 = 7.63$

Table 11 - Smoking at work

BUILDING ILLNESS INDEX	Yes	No	Number of Cases
Good	51.6	40.9	447
Average	43.5	43.2	458
Poor	4.8	15.9	155
Total	100%	100%	
Number of Cases	124	936	

$\chi^2 = 12.17 \quad p \leq .005$

Table 12 - Control air conditioning

BUILDING ILLNESS INDEX	Yes	No	Number of Cases
Good	46.0	41.3	449
Average	47.3	42.8	464
Poor	6.7	15.9	156
Total	100%	100%	
Number of Cases	150	919	

$\chi^2 = 8.80 \quad p \leq .05$

Table 13 - Control lighting

THE IMPLEMENTATION AND EFFECTIVENESS OF AIR INFILTRATION
STANDARDS IN BUILDINGS

5th AIC Conference, October 1-4 1984, Reno, Nevada, USA

PAPER 18

FIRST-PHASE OCCUPANT REACTION TO WELL-SEALED INDOOR ENVIRONMENTS.

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ABSTRACT

Possible health effects and changes in sensation of comfort among tenants after replacement of single glass windows in leaky frames with double glass windows in airtight frames have been studied. The study design was observational, and included a study group and a corresponding control group. The results indicate essential improvements of the indoor climate and of the health status of the tenants after replacement of the windows (i.e. positive effects on temperature conditions, lowering of noise, fewer symptoms related to mucosal surfaces, fewer rheumatic symptoms, and possibly fewer headaches). Significant changes in complaints or health effects which could be related to reduced air quality caused by the air-tightening were not found. This study cannot give any evidence of inconveniences that may occur later if the apartments become too airtight.

INTRODUCTION

Increased energy costs have brought efforts to reduce ventilation and infiltration in indoor spaces.

The air quality in an indoor space, and more specifically the concentration of a given inhaled pollutant indoors, depends on the outdoor air quality, on the presence and strength of emissions from indoor sources, on the ventilation rate and ventilation efficiency, and the presence and effectiveness of other elimination procedures such as adsorption, sedimentation, or neutralization.

The pollutants to be considered will generally be tobacco smoke (passive smoking), NO_2, CO_2, CO (from combustion), formaldehyde, asbestos, mineral fibres, organics, and radon (from materials and consumer products), odours, moisture, and microorganisms (from occupancy). Some pollutants can more specifically be listed as allergens.

It has been realized that the knowledge of exposure effect relationship, especially with regard to delayed effects of chronic exposure is inadequate, while the knowledge of complaints on acute discomfort by occupants in some buildings is well established (1).

The aim of this study was to measure the possible health effects among tenants after certain energy conservation measures had been taken in their dwellings i.e. replacement of windows in leaky frames with double glass windows in airtight frames.

In addition to health effects, changes in sensation of comfort/-discomfort related to indoor climate, including the thermal and acoustic environment, were also included.

The study has been designed as an observational study with two groups; a study group and a corresponding control group not exposed to environmental changes in their homes.

MATERIALS AND METHODS

The majority of apartment houses in central urban areas, which have been weatherproofed in recent years, are owned by building societies. Thirty-three of the largest building societies in Denmark were invited to participate in the study. Twenty-four building societies accepted, and 8 of these owned apartment houses that fulfilled the criteria for participation:

Study group:	Houses 2-5 stories high, with untight windows having one layer of glass. Windows were replaced during the period from September 1981 to November 1981.
Control group:	Houses 2-5 stories high with untight windows that were not replaced in the study period.

Personal data (name, address, age and sex) were collected from the Central Person Register using the addresses supplied by the building societies.

All residents over 18 years of age received a questionnaire in August 1981 before replacement (if any) of windows. The persons who answered the questionnaire and thereby indicated that they were willing to participate in the study received new questionnaires in December, January and February. In the study group the replacement of windows took place in the period between the first and the second questionnaire. The winter period was chosen because changes in indoor climate are maximal at this time of year (Korsgaard, 2).

Questionnaires were each month sent to all persons who had answered the previous questionnaire. The response rates are given in Table 1, i.e. the number of valid answers in percent of the number of distributed questionnaires, but corrected for the number of persons who had moved.

Table 1 shows that a large number did not respond in August. This number was smaller in December and very small in January and February , thus indicating that the group of persons that participated in the study gradually stabilized.

The persons who had answered all four times and whose apartments fit the criteria for participation are included in the analysis of data.

This group consists of 641 persons, where 106 are in the study group and 535 are in the control group, see table 2. The reduction from 1013 to 641 was caused by the building societies´ change of plans for the replacement of windows.

The age distribution in the group of persons who were invited to participate in the study was: 28% 18-40 years, 51% 41-70 years and 21% over 70 years. The age distribution in the group of persons who responded was, 30% 18-40 years, 52% 41-70 years and 18% over 70 years. Women constituted 59% of the original group and 60% of the group of responders. Thus, the response rate was not related to age or sex.

The questionnaires consisted of the same questions on all four occasions, except the questions regarding the characteristics of the apartment (number of rooms etc.) which were only included in the first questionnaire.

The questionnaire included questions about number of rooms, number of persons under and over 18 years in the household, number of smokers in the household and type of windows.

In addition to the questions related to the characteristics of the apartment, the questionnaire included a number of questions concerning the person´s wellbeing and health status. There were questions about the number of days with inconvenience in the previous month (0, 1-2, 3-8 and more than 8 days per month).

The questions related to well-being and inconvenience could be divided into five groups: Temperature, Noise, Symptoms related to mucosal surfaces, Rheumatic symptoms, and General symptoms.

The study was carried out in a period with temperatures below normal. The average temperature in December 1981 was -4,3^{o}C - the lowest average temperature in Denmark ever measured.

STATISTICAL METHODS

In the statistical analysis was used contingency tables. Correlation between retrofitting and symptoms was expressed with odds-ratios.

Example, odds-ratios in August:

Study group: a persons with symptom X in August
b persons without symptom X in August

Odds for X in the study group: a/b

Control group: c persons with symptom X in August
d persons without symptom X in August

Odds for X in the control group: c/d

$$\text{Odds-ratio for X} = \frac{a/b}{c/d} = \frac{a \cdot d}{b \cdot c}$$

Odds-ratios were calculated separately for each month and normalized with respect to August (odds-ratio for August = 1). The odds-ratios for December, January and February were thus compared with the odds-ratios for August. A x^2-test in a log-linear model is used for significance testing. The p-values indicate the probabilities that the odds-ratios in August, December, January and February are equal.

RESULTS

Apart from the replacement of the windows, there exist certain background variables which affect the registered inconveniencies, e.g. the time per day spent in the apartment and the participants´ age.

About 40% of the residents either live by her/himself , or only one person from the apartment answered. This applies to the study group as well as to the control group.

The persons in the control group tend to be away from the apartment for a longer time than the persons in the study group. This is related to the fact that there are more persons over 60 years in the study group: 56% in the control group and 41% in the study group. Smoking habits are similar in the two groups, see table 2.

The questions related to well-being and inconvenience were originally divided into four categories. However, the results show that the answers were concentrated in category 1 (0 days per month) and category 4 (more than 8 days per month). Taking this into account, the categories were combined so that only two categories of answers are considered: 0-2 days and more than two days per month. It was tested for all results whether age had any effect on the results. Results on symptoms on which age had effect are described in the text. The frequency of symptoms was not observed to be related to the person´s sex.

Information related to temperature is collected from four questions. The questions concerned draught, cold floor, too low temperatures and too high temperatures, see Fig. 1. In August, 22% of the participants in the control group and 33% in the study group reported that they experienced inconvenience from draught in the apartments. In all three months during the winter season more participants in the control group and less in the study group reported draught inconvenience. The same pattern was observed with regard to cold floor, which bothered 20% of the participants in August and with regard to low temperature which bothered 10% of the participants in August.

Table 3 shows the results of the normalized odds-ratios on temperature. The effects of weatherproofing on draught, cold floor, and low temperature are significant ($p = 0.000$, $p = 0.000$ and $p = 0.007$ respectively). Weatherproofing had no effect on inconveniences from high temperatures.

Almost 40% of the participants were bothered by outdoor noise and about 20% of the participants were bothered by noise originating from inside the building, see Fig 1. The frequency of noise nuisance is apparently constant in the following months in the control group, whereas there is a dramatic drop in the study group. Outdoor noise almost disappears after weather proofing ($p = 0.000$) but with regard to the noise from the building the effect is less pronounced ($p = 0.06$), see Table 3.

Smarting or irritation of the eyes is reported by more than 10% of the residents in August, but the frequency of disturbances drops dramatically in the following months in both groups, see Fig. 2. Throat complaints were reported by 8% of the participants in August, see Fig. 2. In the following months throat complaints were reported by 20% of the participants in the control group and by 10-15% in the study group. For both of these symptoms related to mucosal surfaces it is noted that the tendencies towards improvements in the study group observed in Fig. 2 are not significant ($p = 0.2$ and $p = 0.4$, respectively).

Further analysis of the impact of flu and cold, age and smoking habits showed that correction for these background variables did not change the calculated odds-ratios substantially.

Rheumatic symptoms are included in questions concerning knee and hip joints, pains in the neck and upper part of the back and intake of analgesics for each of these two conditions (salicylic acid and like substances). The frequency of pains are seen in Fig 2.

The calculation of odds-ratios for rheumatic symptoms shows that weatherproofing had a pronounced effect. However, this effect is not manifest until January and February. The effect on joint pains and neck/back pains is significant ($p = 0.04$ and $p = 0.000$). The effects on intake of analgesics are also significant ($p = 0.02$ and $p = 0.001$), see Table 3.

The rheumatic symptoms mentioned previously increase in frequency with age, especially for persons over 60. The results were therefore divided into two age groups: less than 60 years/over 60 years.

This analysis showed that the effect on joint pains was most pronounced for persons over 60 years. The neck and back pains were affected in both age groups but the effect was most pronounced in the age group over 60 years. The same tendencies were observed for the intake of analgesics for both age groups for joint pains and neck and back pains, respectively.

Fig. 2 indicates that weather proofing apparently had a positive effect on the frequency of headaches and the frequency of the intake of analgesics for headaches. However, this effect is not significant ($p = 0.5$).

Apparently there was a minor effect of weatherproofing on the symptoms "one´s head feels heavy". However, this effect was not significant ($p = 0.096$).

Additional analyses were carried out for these symptoms in order to make corrections for age and sex, but these corrections had only minor influence on p-values and odds-ratios.

Cases of flu and cold had also a very limited influence on the frequency of symptoms.

Habits with regard to airing were investigated in order to test any relationship to weatherproofing and age. However, there was not found any relationship between these two variables. Smoking was the only variable which had pronounced effect on airing: smokers aired more than non-smokers.

In addition, it was investigated whether mould growth and damages due to moisture in the apartment were related to airing habits and drying of clothes in the apartment. Only drying of clothes was found to be related to signs of mould.

DISCUSSION

The response rate from the first questionnaire was 54% which might seem low. The persons who participate in an epidemiological study like this will not benefit directly or personally. Thus they are not greatly motivated to participate. In addition, we assume that the low response rate to some extent is due to the fact that the questionnaire had a rather computer-like design, - in order to facilitate analysis of data. Furthermore, the participants have felt obliged to answer the following three questionnaires if they had answered the first one.

The only information available for all participating persons included sex, age and address (Capital, Provincial towns). There was apparently no selection with regard to these three factors.

Originally the study group was supposed to be as large as the control group. The observed reduction is not due to loss of participants only, but is mainly the result of the building societies´ change of plans for the replacement of windows.

The results of this study are rather clearcut. Even though the reduction in participants was large, the nonparticipants had to be very different from the participants to influence the results in an opposite direction. The effects are registered for the same participants before and after the "experiment" i.e. the results are intrapersonnel variations. We therefore conclude that the magnitude of the effects must be interpreted with some caution whereas the trends are very clear.

Furthermore, it should be emphasized that all the measured effects are acute or subacute effects. This study cannot give any evidence of inconveniences that may occur later if the apartments become too airtight.

The dramatic improvement in the indoor climate with regard to temperature and noise may have influenced the answers to the questions about symptoms, which are not directly related to low temperatures and draught.

The results of this study therefore show that it would be desirable to conduct similar studies under different climatic conditions and for other types of buildings, but with the same methodology so that the studies would be comparable.

This study has been part of a number of projects, which the Department of Energy, Copenhagen has given the Institute of Hygiene, University of Aarhus, comprising indoor pollutant source control (3) as well as changes in housedust mite populations related to moisture changes in retrofitted dwellings (2,4).

The concept of combining different methodological studies like this is based on the experience from other fields of environmental health studies in that they generally should include both field measurements and observational health studies, as well as controlled exposure studies, to be conclusive.

The conclusion so far has been that insulation and retrofitting in flats seems to have predominantly positive acute effects regarding to votes on comfort and well-being. Possible long term consequenses, of a very low ventilation rate, with negative health effects cannot be excluded from this study and will have to be observed in the future.

The environmental changes which took place in the buildings concerned in this study were not physically monitored. This has to be done in studies in continuation.

Acknowledgements

The authors wish to thank Professor, dr.med. Johs. Ipsen, Aarhus, for many valuable discussions during this work.

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Table 1 Number of reponses and response rates

	August	December	January	February
Number of distributed questionnaires	3309	1739	1268	1112
Number of answered questionnaires	1922	1306	1148	1043
Number of valid answers	1739	1268	1112	1013
Response rate	53.6	73.9	88.5	92.8

Table 2 Follow-up group: Distribution of background variables in percent

		August	December	January	February
Periods away from apartment ≤ 4 hours	control group	18.3	57.1	61.5	57.5
	study group	24.2	69.5	67.9	67.0
Smokers	control group	51.8	52.0	51.1	51.7
	study group	51.7	51.8	53.6	54.1
Total number of answers	control group	535	535	535	535
	study group	141	141	141	141

Table 3. Normalized odds-ratios for disturbances and symptoms

	August	December	January	February
Temperature				
Draught	1	0.07	0.08	0.06
Cold floor	1	0.15	0.16	0.18
High temperatures	1	1.32	1.22	0.79
Low temperatures	1	0.15	0.14	0.17
Noise				
Outdoor noise	1	0.04	0.02	0.03
Noise from the building	1	0.33	0.26	0.35
Symptoms related to mucosal surfaces				
Smarting or irritation of the eyes	1	0.33	0.00	0.00
Dryness of the throat	1	0.44	0.52	0.67
Rheumatic symptoms				
Joint pains	1	0.79	0.41	0.28
Analgesics for joint pains	1	1.30	0.37	0.32
Neck/back pains	1	0.38	0.11	0.18
Analgesics for back pains	1	0.73	0.11	0.19
General symptoms				
Heaviness of the head	1	0.64	0.25	0.35
Headache	1	0.45	0.63	0.72

Fig. 1 Frequencies of disturbances

C = control group
S = study group

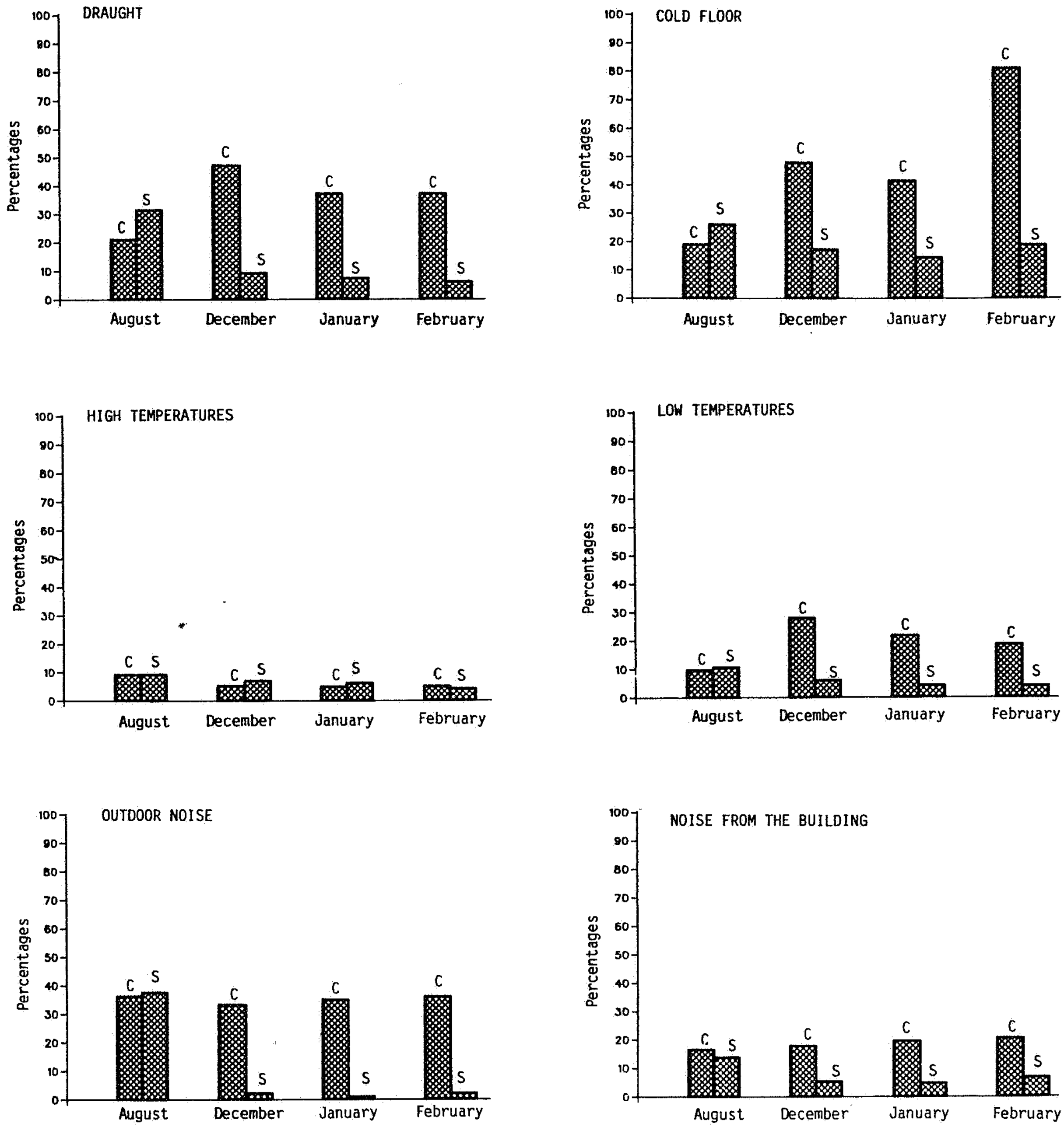
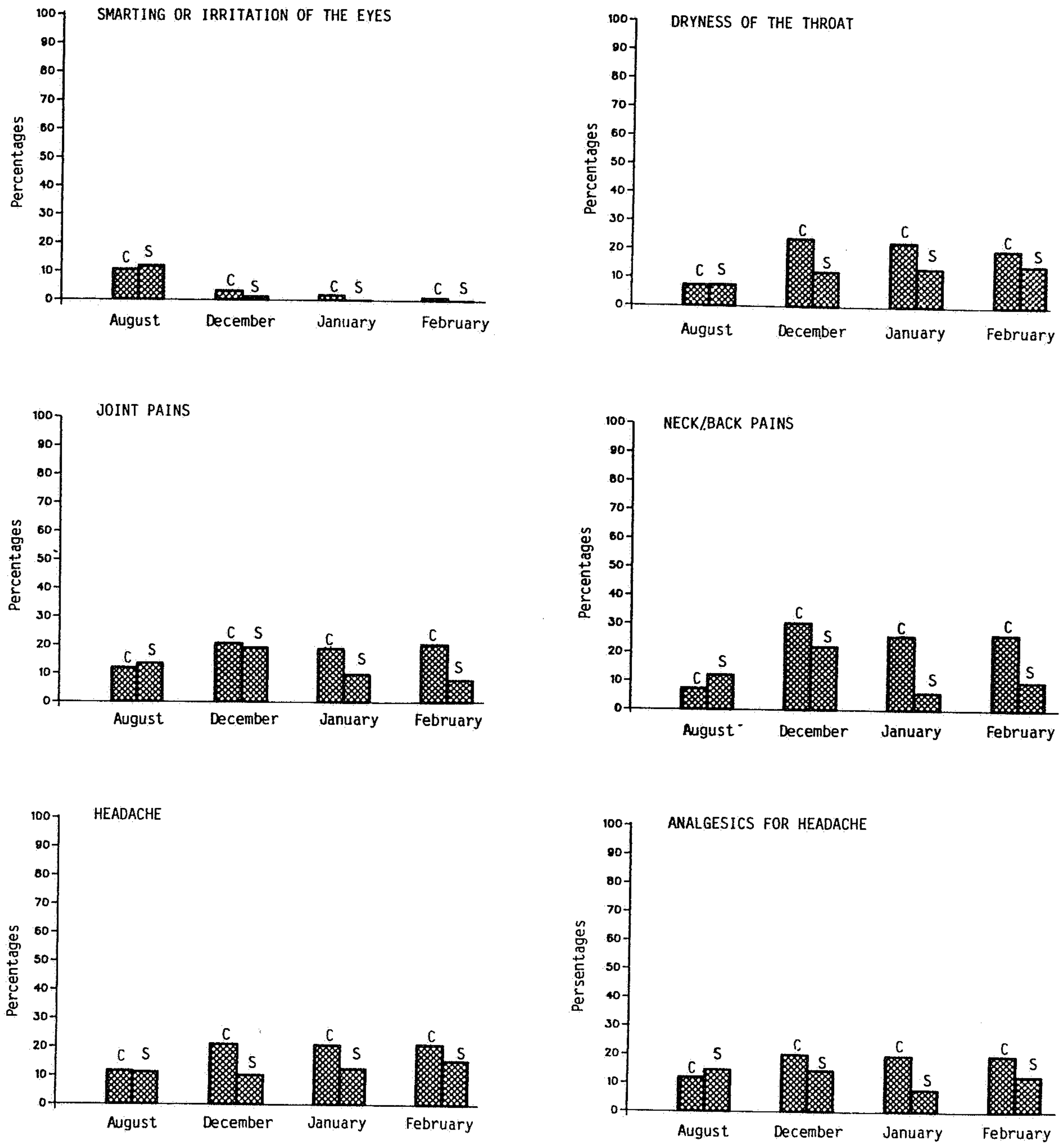


Fig. 2 Frequencies of symptoms

C = control group
S = study group



THE IMPLEMENTATION AND EFFECTIVENESS OF AIR INFILTRATION STANDARDS IN BUILDINGS

5th AIC Conference, October 1-4 1984, Reno, Nevada, USA

PAPER 19

CONTAMINANT BUILD-UP IN HOUSES

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SYNOPSIS

The relation between air infiltration rate and indoor concentrations of radon gas, radon daughters, and formaldehyde has been investigated for both summer and winter conditions in a number of Toronto houses with low rates of natural ventilation. Air infiltration rates obtained by the fan depressurization method and the sulfur hexafluoride tracer gas dilution method are compared. Formaldehyde levels were monitored using both the revised NIOSH impinger sampling method and badge dosimeters. Levels of radon gas and daughters were determined by a grab sampling technique and by film dosimeter as well for radon daughters.

Average air change rates in air-conditioned houses were lower over the summer months (0.12 - 0.40 ach) than over the winter period (0.21 - 0.66 ach). The average summer indoor formaldehyde concentration for air-conditioned houses was 0.076 ppm as compared with an average of 0.038 ppm in winter. The average radon and radon daughter concentrations for air-conditioned houses were higher by 44% and 32%, respectively, during the summer months than during the winter months.

1. INTRODUCTION

Prolonged exposure to low concentrations of indoor air contaminants can under certain circumstances be a serious threat to the health of building occupants. In recent years considerable attention has been focussed on formaldehyde gas emissions from urea formaldehyde foam insulation and, in areas of high natural radioactivity, on particulate airborne radioactivity (radon daughters) resulting from radioactive decay of radon gas. With the increasing demand for improvement in air-tightness of the building envelope as an energy conservation measure, the potential for such contaminants to be present at an unacceptable level, even in the absence of significant sources, has increased. Formaldehyde gas, for example, can be traced to sources such as synthetic fabrics, wood products, and products of combustion. Radon gas, a decay product of naturally-occurring nuclide radium-226, can be found to some extent in most soils throughout the world. Radon emanates from earth-derived building materials and can enter a building by transport from surrounding soil through cracks and openings in foundations.

This paper presents a summary of the results of a monitoring program designed to examine the relation between infiltration rate and indoor concentrations of radon, radon daughters and formaldehyde in houses having relatively low rates of natural ventilation. It also compares air infiltration data obtained by the fan depressurization and tracer gas dilution methods. Twelve houses in Metropolitan Toronto were tested weekly during the winter heating season from November to March 1982. Ten of them were tested also during the summer from July to September 1982; eight of the ten used their central air-conditioning systems extensively.

2. DESCRIPTION OF TEST HOUSES

Electrically heated houses with forced warm-air systems were selected for the test program because their air exchange is not augmented by a furnace chimney. Two-storey, single-family dwellings with basements and no urea formaldehyde foam insulation were studied; their volumes, including basements, ranged from 555 to 948 m^3. All were frame construction with brick siding, ten years old or less, with central air-conditioning and fireplaces.

Selection of the twelve test houses from a pool of eighteen was based on low natural ventilation rate, characterized by the overall air leakage properties assessed by the fan depressurization method (CGSB Interim Standard 149-GP-10, "Determination of Air Tightness of Buildings by the Fan Depressurization Method"). It gives the tightness of a building enclosure by exhausting air from the structure and measuring the airflow rate and corresponding pressure difference across the enclosure. A portable commercial exhaust fan unit developed by Orr and Figley[1] was used.

3. MONITORING AND ANALYTICAL TECHNIQUES

Weekly air sampling consisted of taking grab samples for radon/radon daughters and formaldehyde analysis and concurrent measurements of air exchange rate using the tracer gas dilution method. Thermohygrographs were installed in the living room to measure indoor temperature and relative humidity. Outdoor environmental conditions, including temperature, relative humidity, wind speed and direction, and atmospheric pressure were recorded at the time of sampling. Door and window openings and occupant activities (vacuuming, smoking, etc.) were noted for each sampling period.

3.1 Air Infiltration

In the tracer gas dilution method the infiltration rate can be determined from the exponential decay rate of the tracer gas concentration with respect to time. If the natural logarithm of the concentration is plotted against time, the measurements should fall on a straight line provided the air change rate remains constant. A scatter of points is expected and a straight line best fit can be calculated using the least squares method.

The air change rate is given by

$$S = \frac{\ln C_1 - \ln C_2}{t_2 - t_1}$$

where

C_1 = concentration of tracer gas at time t_1
C_2 = concentration of tracer gas at time t_2
S = air change rate per unit time.

In each of the test houses 50 cc of SF_6 (as a tracer gas) was injected upstream of the fan into the return-air plenum of the forced-air heating system. Samples were drawn at the same location for subsequent analysis of SF_6 concentration 30, 45, 60 and 75 min after injection. During the sampling period the furnace fan was switched to manual mode in order to achieve thorough and continuous mixing of air within the structure. Connecting doors, closet doors, registers, etc., were opened to allow free circulation of air. Windows, exterior doors and fireplace dampers were closed.

Tracer gas injection and sample extraction from the return-air pleneum was achieved using a hypodermic syringe. The transfer of SF_6 from a gas cylinder to the 50-cc syringe was accomplished outside and downwind of the test house. A clean 50-cc syringe and needle were used to draw sample air from the return-air plenum for injection into a 20-mL evacuated glass tube for temporary storage and subsequent analysis in the laboratory with an electron-capture dectector/chromatograph.[2]

3.2 Formaldehyde

Formaldehyde levels were monitored following the revised NIOSH (National Institute for Occupational Safety and Health) impinger sampling method developed by R.R. Miksch at the University of California, and using a 1-h sampling period. Samples were taken in the living room or dining room of each house, with the sampling train located approximately 1 m above floor level. A calibrated constant-flow pump was used to draw air at 1 L/min through a midget impinger containing sodium bisulfite absorbing solution for subsequent analysis in a spectrophotometer.

For comparison, formaldehyde badge dosimeters containing sodium bisulfite solution were used to collect samples over a seven-day period. Badges were suspended approximately 1 m above the floor in the living room and in one of the bedrooms in each house.

3.3 Radon/Radon Daughters

Simultaneous radon/radon daughter samples were collected from the basement area of each house using a grab sampling technique. All measurements were taken approximately 1 m above the floor. For radon gas sampling, several changes of basement room air were drawn through a zinc sulphide-coated flow-through scintillation cell after passing a glass fibre filter to exclude daughter particles. The radon gas collected inside the cell was allowed to decay for approximately 4 h (seven half-lives of short-lived daughter chain), at which time the daughters were virtually at equilibrium with the parent radon. The cell was then placed inside a light-tight castle containing a photomultiplier tube connected to a scaler/counter. The alpha particles resulting from radioactive decay interact with the zinc sulphide coating of the cell to produce the scintillations observed by the counting system. Calibration of each cell counter system against a known radon source yields a count per minute to pico curie per litre (pCi/L) conversion after subtracting the predetermined background count for the cell.

Radon daughter concentrations were determined by means of the modified Kusnetz method.[3] A high-volume air pump with a capacity of 30 L/min was used to draw air through a glass fibre filter for 10 min. The particulate radon daughters collected on the filter were then counted with a portable alpha counter incorporating a photomultiplier tube detector.

For comparison with grab sampling data, three radon dosimeters were exposed in each house (two in the basement, one on the main floor) over a four-month sampling period. Alpha particles from the decay of radon gas and daughters bombarding an alpha-sensitive plastic film detector (mounted on a card) leave radiation tracks. Analysis of the dosimeters was carried out by the manufacturer.

4. DATA ANALYSIS

4.1 Air Infiltration

Figure 1 shows the average air change of each house for both winter and summer months, obtained by the tracer gas dilution method and the air change rate for each house; this ranged from 3.9 to 7.9 air changes per hour (ach), obtained by the fan depressurization method at a pressure difference across the building envelope of 50 Pa. From a best fit line drawn through the points, the ratio of air infiltration rates measured by the tracer gas method and fan depressurization method was 1/14 for winter and 1/20 for summer.

Figure 2 shows the average infiltration rate of each house, determined by the SF_6 tracer gas method for both periods of

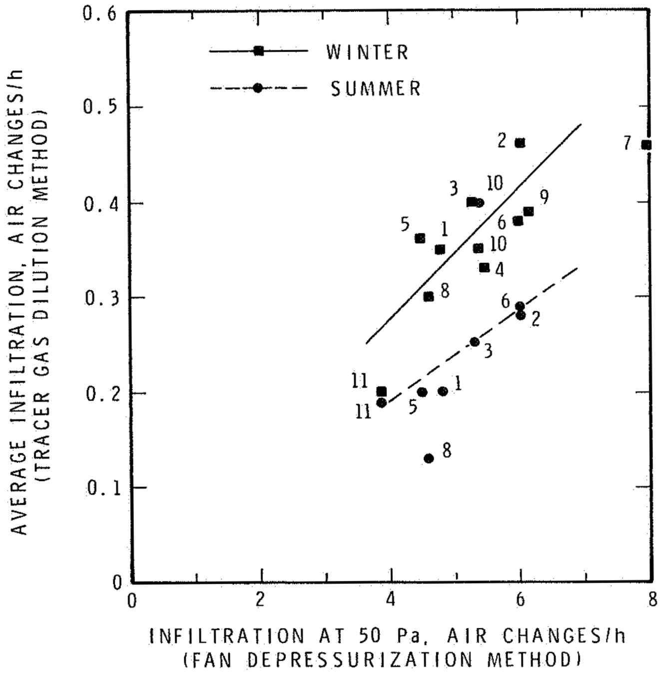

Figure 1 Comparison of air infiltration rates determined by the tracer gas dilution and the fan depressurization methods

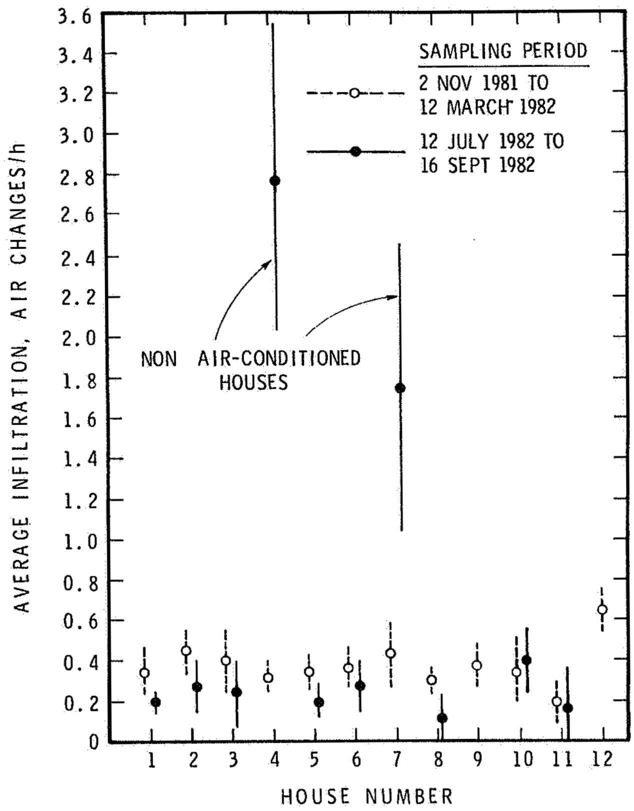

Figure 2 Average air infiltration rates (tracer gas dilution method) (with range of two standard deviations)

testing. Infiltration rates for air-conditioned houses over the summer months (0.12 - 0.40 ach) were lower than those over the winter period (0.21 - 0.66 ach). In two houses in which air conditioners were not used and windows were open the air change rates were much higher (1.75 ach for House No. 7, and 2.78 ach for House No. 4). The apparent relatively high air change rate in House No. 10 in summer may be related to air circulation, inasmuch as only one of two furnace fans is used for circulation of cooling air in summer. The gradual diffusion of SF_6 into uncirculated areas would give the effect of more rapid decay of tracer gas concentration, resulting in an incorrectly high apparent air exchange rate.

Figure 3 presents average air changes, wind speeds, and heating/cooling degree-days for eight air-conditioned houses in the summer months and for twelve houses in the previous winter. Air change rates were significantly less in the summer months than in the winter months when there are greater indoor/outdoor temperature differentials.

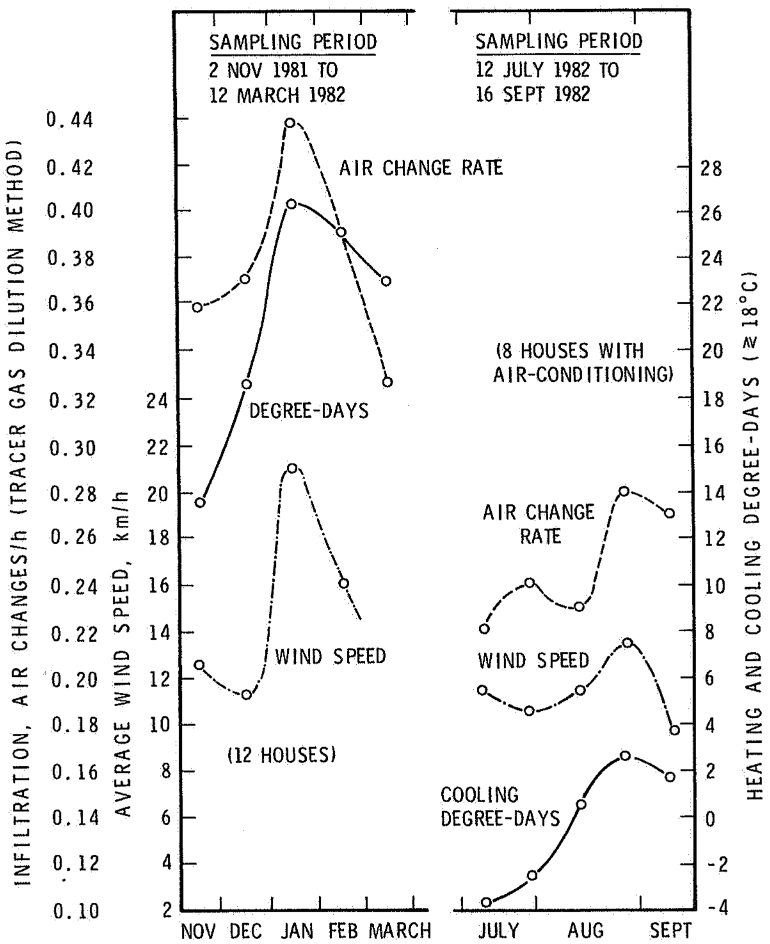

Figure 3 Average period air infiltration rate, wind speed and degree-days

It is expected that during the summer when the temperature differentials are low the air change rate will be due mainly to wind. There appears to be a positive correlation between air change rate and wind speed for several of the eight air-conditioned houses. Increased indoor relative humidity causes increased air tightness during the summer months and may also be a factor in the decreased air change rate[4]; winter averages of relative humidity ranged from 34 to 47%, and summer averages ranged from 56 to 65%.

4.2 Formaldehyde

The mean indoor formaldehyde concentrations obtained from 1-h NIOSH measurements in each of the houses are shown on Figure 4. In general, there was good agreement between the weekly dosimeter (7-day exposure) and 1-h NIOSH results over the winter sampling period, as shown graphically in Figure 5. Agreement was poor when they were compared on a weekly basis for each house. The higher indoor formaldehyde levels in air-conditioned houses appear to be related to a lower air change rate during the summer months. The average indoor concentration for the air-conditioned houses was 0.076 ppm, which is twice the winter average of 0.038 ppm. The levels of formaldehyde concentration indoors appear to be affected, as well, by those outdoors. Measurements during the summer tests indicated that outdoor levels near a highway and a major road (distance of 25 to 120 m) varied from 0.014 to 0.022 ppm, and near minor roads from 0.006 to 0.008 ppm. Outdoor levels are affected by traffic density since automobile exhaust contains significant concentrations of formaldehyde and other aldehydes.

At present the accepted indoor level of formaldehyde is 0.10 ppm (ASHRAE Standard 62-81, Ventilation for Acceptable Indoor Air Quality). In three of the test houses this level was exceeded in 70% of the indoor measurements made during the summer months. Over the winter months the same three houses also had the highest formaldehyde concentrations, but the maximum acceptable concentration was exceeded in less than 10% of the measurements.

4.3 Radon/Radon Daughters

Figure 6 shows averaged radon concentrations and Figure 7 averaged radon daughter concentrations for the two measurement periods. Average radon concentrations over the winter period ranged from 0.3 to 2.2 pCi/L; over the summer period they ranged from 0.37 to 2.26 pCi/L. Average radon daughter concentrations over the winter period ranged from 0.0007 to 0.0065 working level (WL); corresponding summer data ranged from 0.0011 to 0.007 WL. Comparison of summer and winter data for the eight air-conditioned houses shows that, on average, the radon gas and radon daughter

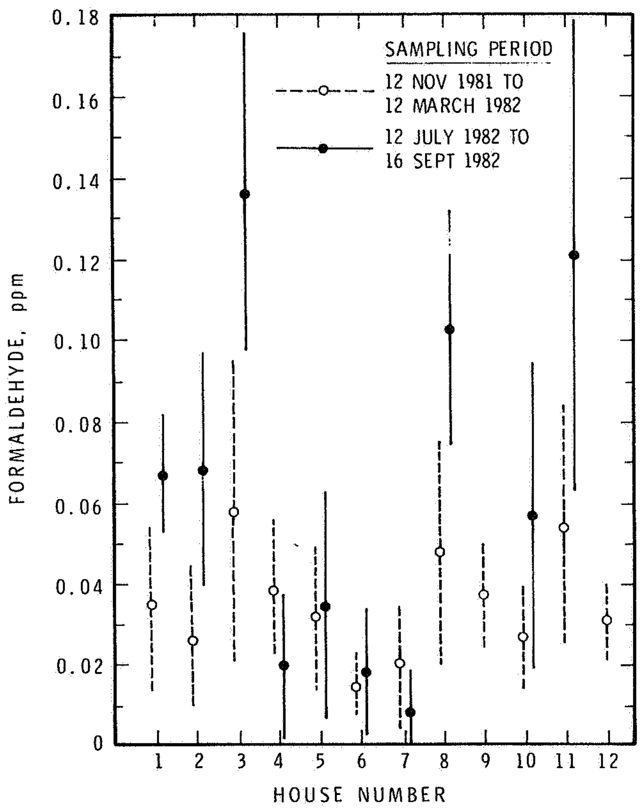

Figure 4 Average 1-h NIOSH formaldehyde concentrations (interior) (with range of two standard deviations)

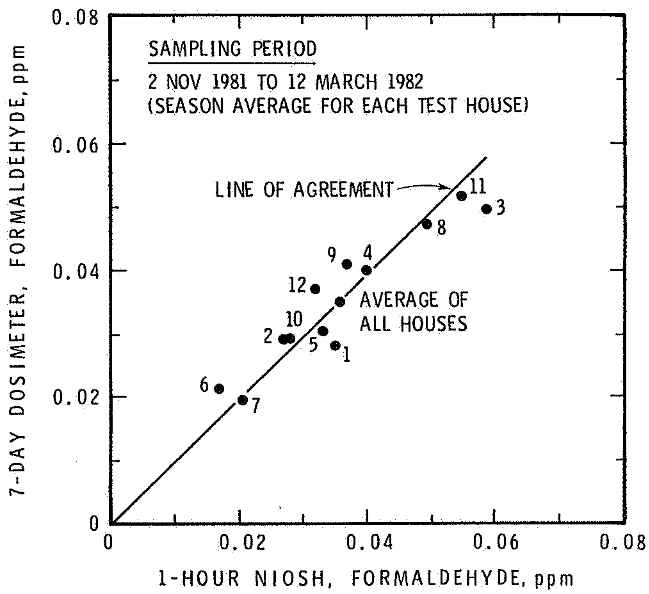

Figure 5 Comparison of average 1-h NIOSH and 7-day dosimeter formaldehyde measurements

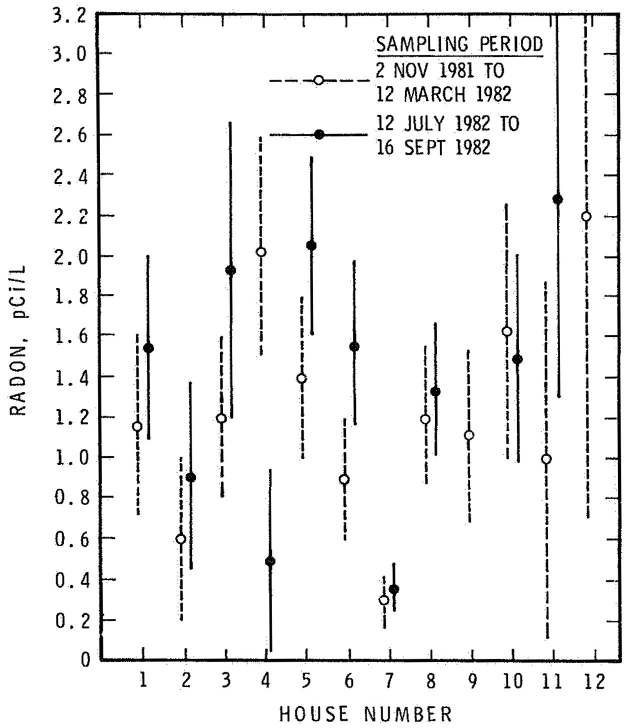

Figure 6 Average daily radon concentration (with range of two standard deviations)

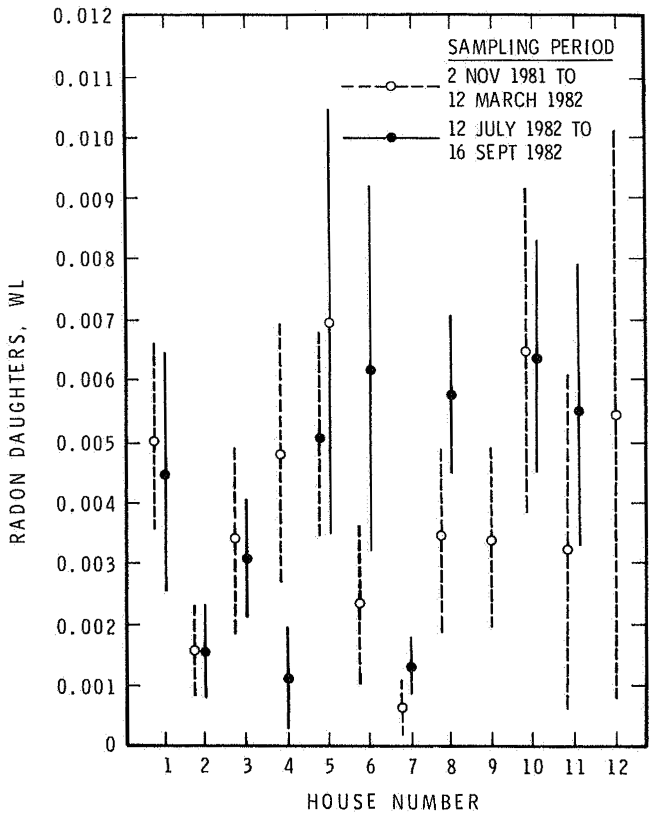

Figure 7 Average daily radon daughter concentrations (with range of two standard deviations)

concentrations were greater for the summer months than for the winter months by 44 and 32%, respectively. The acceptable limit for radon daughters is 0.01 WL (ASHRAE Standard 62-81). The radon/radon daughter data showed expected variations in individual samples taken at the same house on different sampling days. It can be explained, at least in part, by the effects of various meteorological factors shown in other studies to be statistically significant in affecting the emission rate of radon gas from soil. These include barometric pressure, air and soil temperature, relative humidity, and wind speed.

The average equilibrium factor (the ratio of measured radon daughters to the potential radon daughter concentration that could occur when in complete equilibrium with the parent radon) did not change significantly from winter (0.33) to summer (0.30) in the eight air-conditioned houses. Figure 8 provides a comparison of average radon and radon daughter measurements for each house, using a grab sampling technique with data obtained from the film dosimeters exposed over the winter sampling period. Agreement between the two sets of data can be considered fairly good. Figure 9 suggests that concentrations of both formaldehyde and radon gas tend to decrease as the air change rate increases and vice versa.

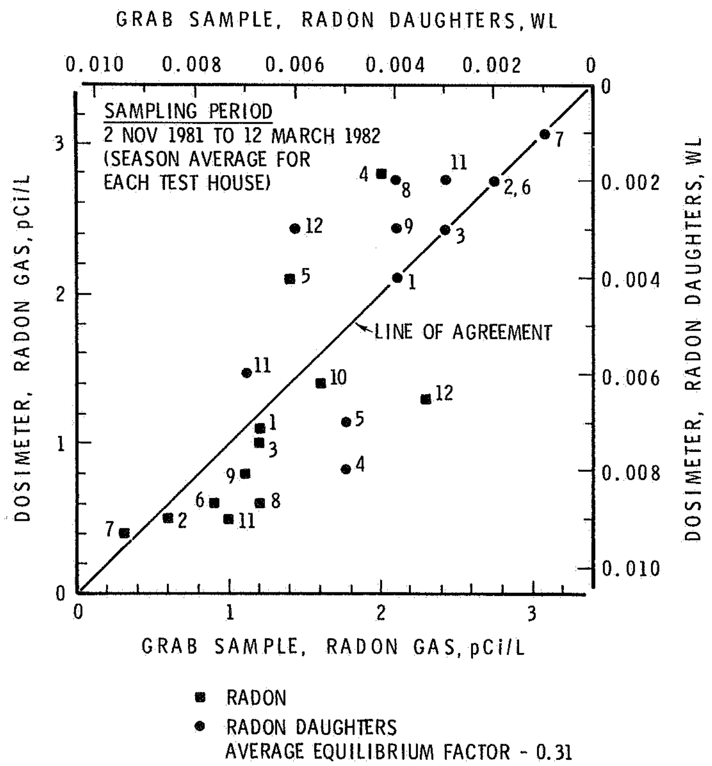

Figure 8 Comparison of grab sample and film dosimeter measurements of radon and radon daughter concentrations

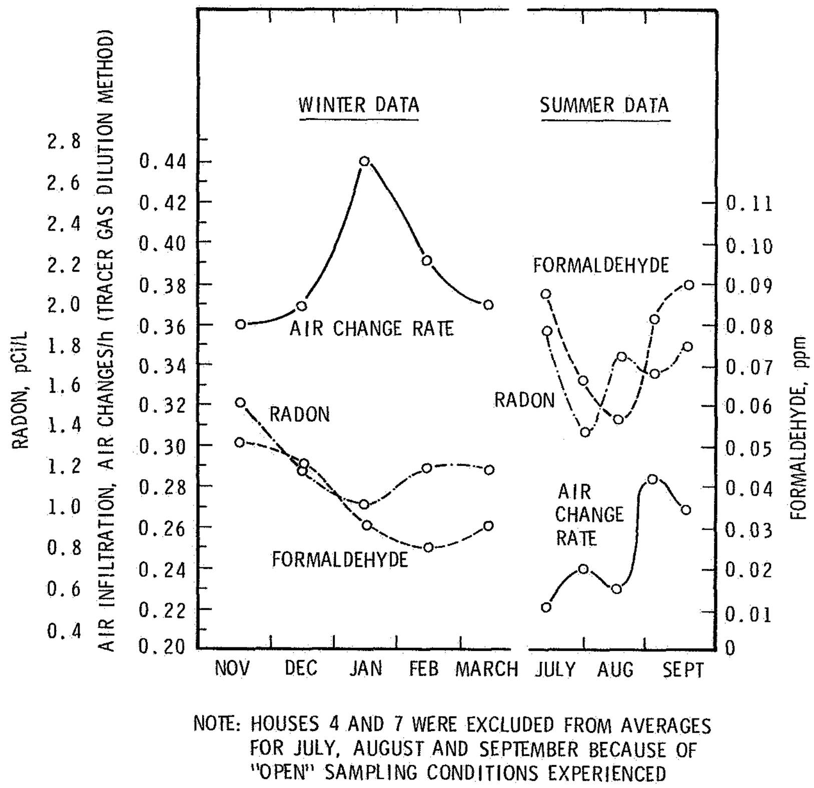

Figure 9 Average monthly air infiltration rate and formaldehyde and radon concentrations

5. SUMMARY

The possible correlation between air infiltration rate and indoor concentrations of radon, radon daughters, and formaldehyde in houses having relatively low rates of natural ventilation has been examined.

1. Air change rates measured by the fan depressurization method varied from 3.9 to 7.9 air changes per hour at a pressure difference of 50 Pa. Averaged infiltration rates obtained by tracer gas measurements over the summer study period (for air-conditioned houses) ranged from 0.12 to 0.40 air changes per hour; over the winter months the rates were higher at 0.21 to 0.66 air changes per hour. These measurements represent 1/20 and 1/14, respectively, of the air change rates as measured by the fan depressurization method at a pressure difference of 50 Pa.

2. The averaged indoor concentration of formaldehyde for all air-conditioned houses, as measured by the 1-h NIOSH method, was 0.076 ppm (ranging from 0.019 to 0.136 ppm) during the summer months, and 0.038 ppm (ranging from 0.015 to 0.059 ppm) for the winter months.

3. The averaged radon gas concentrations for all air-conditioned houses during the summer months ranged from 0.37 to 2.26 pCi/L; for the winter months they ranged from 0.30 to 2.2 pCi/L. The averaged radon daughter concentrations for all air-conditioned houses during the summer months ranged from 0.0011 to 0.007 WL; for the winter months they ranged from 0.0007 to 0.0065 WL.

4. Measurements indicate that concentrations of formaldehyde, radon, and radon daughters are affected by infiltration rate.

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THE IMPLEMENTATION AND EFFECTIVENESS OF AIR INFILTRATION
STANDARDS IN BUILDINGS

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PAPER 20

VERIFICATION OF CALCULATION MODELS OF AIR INFILTRATION USING THREE TYPES OF TEST HOUSES

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SYNOPSIS

In order to verify the calculation models of air infiltration using three wooden test houses which have the same type of construction but have different leakage distributions, airtightness of building components of these three houses were measured by means of the fan pressurization method, and then air infiltration was measured twenty-two times by CO_2 concentration decay technique. Some of the leaks were sealed so that total leakage of each of the three houses was equal, but the leakage distribution was different between House A and House B, and the amount of total leakage of House C was twice that of House A and of House B.

Secondly, air infiltration was calculated by means of the LBL model and the BRE model. The values as calculated by the LBL model were unexpectedly two to three times the values of measurement. The values as calculated by the BRE model were in the range of one to two times the values of measurement.

Thirdly, calculation by means of the JCV model widely used in Japan was done under the assumption of there being five types of leakage distribution in order to clarify the effect of leakage distribution on the accuracy of estimation. With the JCV model the internal pressure and the air infiltration are calculated by the Newton Raphson method using an equation in which the total infiltration is zero. Before this calculation, the pressure difference due to the combination of the wind and stack effects is introduced into the leakage equation for each leak.

As a result, the best estimation is yielded by the uniform distribution as opposed to the other distributions. So, it can be said that the assumption of uniform distribution of leakage can be accepted in the case of a house which is not so much airtight.

LIST OF SYMBOLS

n' : Predicted value of air infiltration ratio, 1/h

n : Measured value of air infiltration ratio, 1/h
or flow exponent used in leakage air flow equation

v : Wind velocity, m/s

ΔT : Indoor-outdoor temperature difference, °C

T : Indoor temperature, °C

g : Gravity acceleration, m/s^2

ρ_r : Indoor air density, kg/m^3

ρ_o : Outdoor air density, kg/m^3

Δp : Pressure difference across a leakage, Pa

Δp_o : Indoor-outdoor base pressure difference, Pa

p_r : Indoor pressure at the floor level, Pa

A_o, A_c, A_f: Equivalent leakage area of the envelope, the ceiling, and the floor, respectively, cm^2

A_i : Wall area of i, m^2

H : Ceiling height, m

h : Height from the floor level, m

Q : Air infiltration rate or leakage flow rate, m^3/h

Q_o : Leakage flow rate for $\Delta p = \Delta p_o$, m^3/h

Q_i, Q_c, Q_f: Leakage flow rates through wall i, ceiling and floor, respectively, m^3/h

Q_w : Air infiltration rate due to the wind effect, m^3/h

Q_s : Air infiltration rate due to the stack effect, m^3/h

C_i : Wind pressure coefficient on wall i

C_r : Indoor pressure coefficient

a_i, a_c, a_f: Wind pressure coefficients of wall i, ceiling and floor as based on indoor pressure, respectively

$A_r = T \cdot g \cdot H/((t+273) \cdot v^2)$

$Z = h/H$

$B = 2 \cdot A_r$

ϕ : Wind direction

a, b ,c : Regression coefficients

1. INTRODUCTION

It is very important to precisely predict the air infiltration of a house for the purpose of estimating the heating load and the indoor air quality. As more attention is being paid to thermal insulation and airtightness of residential buildings from the viewpoint of energy conservation, this subject is becoming more and more important. One reason is that the ratio of heating loss due to air infiltration increases with thermal insulating of a house, in comparison to the ratio of heat loss through the walls. Another reason is that the indoor air is easily polluted with various contaminants when a house is made airtight; further study of this contamination is becoming necessary due to the above mentioned improvement.

However, the method for precisely predicting air infiltration has not been developed because of the following reasons:

a) Air leakage of a building can be found not only around doors and windows but also at the following parts of the building:

1) holes for wall pipes,
2) electric outlets,
3) joints between the wall and the window frames,
4) interfaces between the ceiling and walls,
5) interfaces between the floor and walls,
6) wall surfaces and ceiling surfaces themselves.

These leakages cannot be identified at the planning stage.

b) The airtightness of windows installed in walls is often different from the catalog data. This is affected by the quality of construction. The measured values are generally greater than those data listed in a catalog.

c) As there is little data on wind pressure coefficients, it is difficult to estimate the appropriate coefficient for each house.

d) Wind velocity and wind direction is always fluctuating. Evaluation of the effect of this fluctuation on air infiltration has not been possible up to now.

e) It is difficult to estimate air infiltration when window and doors are opened and closed.

Problems a) and b) mentioned above are dependent on the quality of construction; therefore, airtightness should be measured. Items c), d) and e) are major areas needing further research.

In this paper, as the first stage in the development of a method for predicting air infiltration, attention is focused on verification of air infiltration in single-room-calculation models. Wind pressure on the envelope and indoor-outdoor temperature differences were measured for three types of test houses for which airtightness data had already been obtained.

Three prediction models, the LBL model[1], the BRE model[2] and the JCV model[3] were evaluated. The JCV model, which is explained later, is the model widely used in Japan for calculation of ventilation.

Some of leaks of three test houses were sealed so that the total leakage of House A and of House B was equal, but the leakage distribution of House A and House B differed, and the total leakage of House C was twice that of House A and of House B.

2. MEASUREMENT OF AIRTIGHTNESS AND AIR INFILTRATION OF TEST HOUSES

2.1 Test houses and their surroundings

The photograph of the three test houses and their plan are shown in Fig.1 and Fig.2, respectively. Each of these wooden houses has a single room with windows in all four walls and also have attic space and crawl space except for House C which has no crawl space, because the wooden floor is constructed directly on the concrete slab which is directly on top of the ground. The attic space and the crawl space have ventilation inlets. Floor area is 23.7 m^2. Room air volume is 60 m^3.

The test houses were constructed in the courtyard of a factory in Yamagata Prefecture. The surroundings of the houses are shown in Fig.3. The main factory building is northwest of the houses. On the southeast is an orchard. There is no obstacle blocking the wind from the south. Wind direction varied between ENE and ESE during the first year of measurement. During the measurement period in the second year, wind was from the east and also from other directions; however the measured data was only analysed with regard to wind from the east.

2.2 Airtightness of houses

2.2.1 Method for obtaining airtightness

After a duct with an attached fan was installed in the hole previously opened for the ventilation fan, airtightness of the houses was measured by means of the fan pressurization method. The range of indoor-outdoor pressure difference was 3 to 50 Pa. Pressure was measured by a capacitance manometer. Speed of flow at the center of the duct was measured using a thermistor anemometer, and airflow rate was estimated based on previously obtained data as to the relationship between the wind speed at the center and the airflow rate.

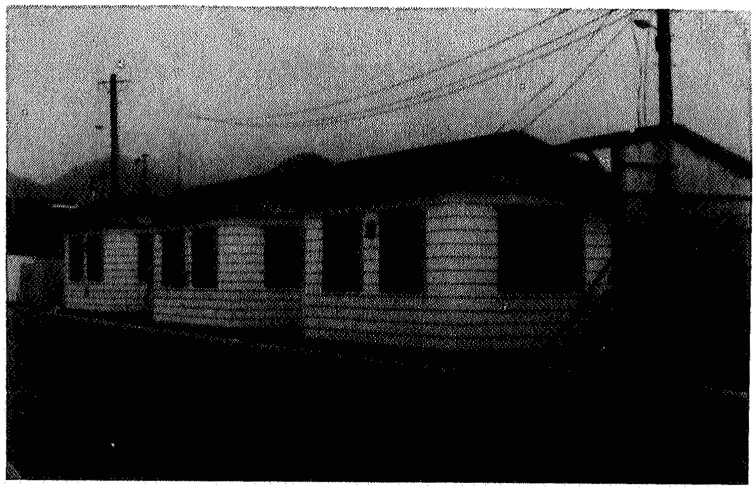


Fig.1 View of the test houses from the west

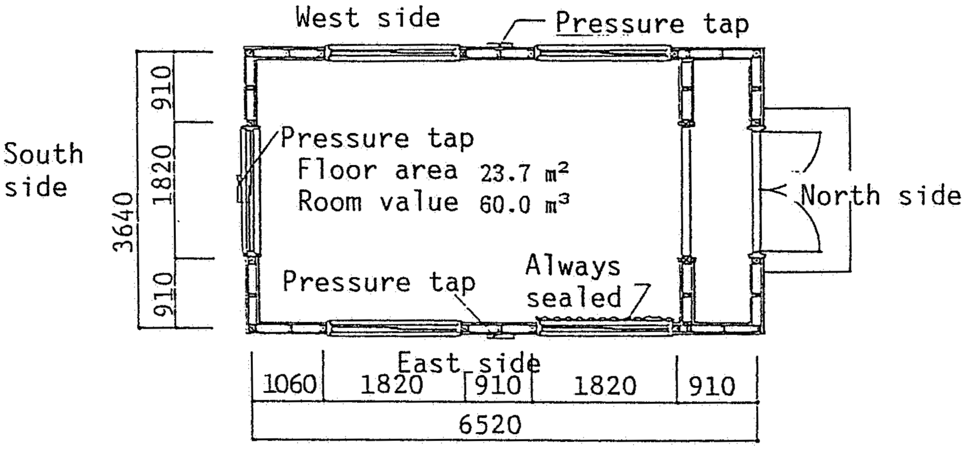


Fig.2 Plan of the test houses

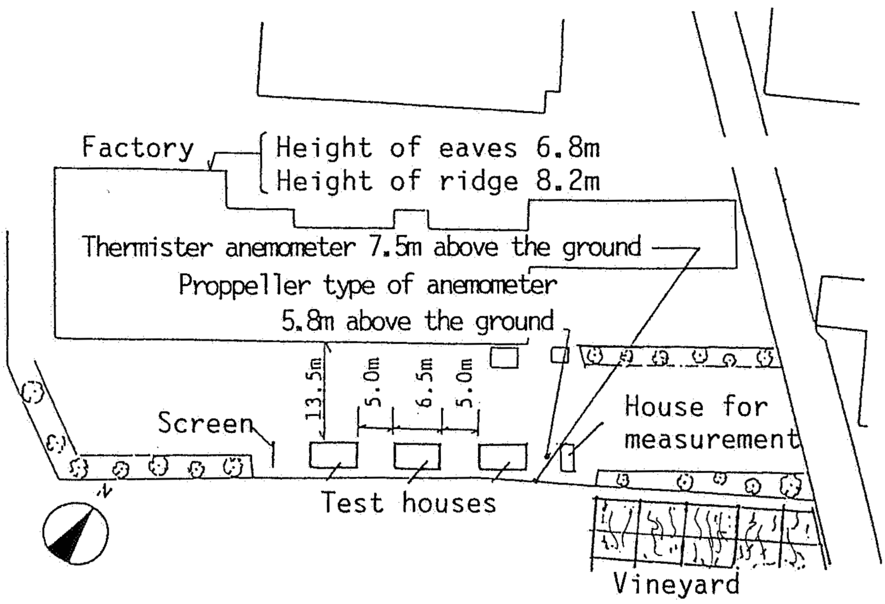


Fig.3 Site plan of the test houses

2.2.2 Measured results

The measured results of airtightness of the building elements are shown in Fig.4. If the relationship between the indoor-outdoor pressure difference, Δp, and the flow rate, Q, is shown by equation (1), the flow rate, Qo, for Δpo=10 Pa and the flow component, n, of each leakage can be indicated as in Table 1.

$$Q = Q_o(\Delta p/\Delta p_o)^{1/n} \qquad \text{------(1)}$$

In House A, the interface between the floor and walls and the southern window were sealed with vinyl sheeting. In House B, the eastern window, the southern windows and the northern windows except for one of the northern windows were sealed. But in House C no leaks were sealed. The equivalent leakage area per floor area (specific leakage area) of a whole house can be calculated by

$$A_o = 2.78\sqrt{\rho/2}\,Q_o \qquad \text{-----(2)}$$

Specific leakage areas of House A, B and C are 7.6, 8.1 and 14.7 cm^2/m^2, respectively. These values fall between Airtightness Rank 4 and 5 as shown in Ref.4. This means that the airtightness of the test houses is equivalent to that of popular prefabricated houses in Japan.

As a result of sealing some leaks, the total leakage of House A and House B was equal, but the leakage of the western window of House A and the interface between floor and walls of House B were comparatively great. The total leakage of House C was 1.9 and 1.8 times greater than that of House A and of House B, respectively. The western window of House C was especially leaky.

At the beginning of the second year, the airtightness of the three houses was tested by the fan pressurization method after the same leaks as had been sealed in the first year were once again sealed. The results are shown in the lower part of Table 1. Qo of House A in the second year was nearly equal to that of House A measured in the first year. However, the values of Qo of House B and House C were 19 % and 13% smaller, respectively, than the values obtained in the first year. These differences may be due to changes in outdoor temperature and humidity, changes of building material characteristics, differences in the method of sealing, etc. The average outdoor temperature and humidity during the period of measurement, including the 5 days before measurement, were 26.5°C and 80.4 % in the first year and 25.2°C and 61.8 % in the second year. The humidity in the first year was more than that in second year. If humidity affects airtightness, then a difference in airtightness of House A should have been obserbed between the first year and the second year, and also, Houses B and C should have been more airtight during the more humid first year. Therefore, the difference does not seem to be due to the effect of humidity. Other possible reasons were not investigated.

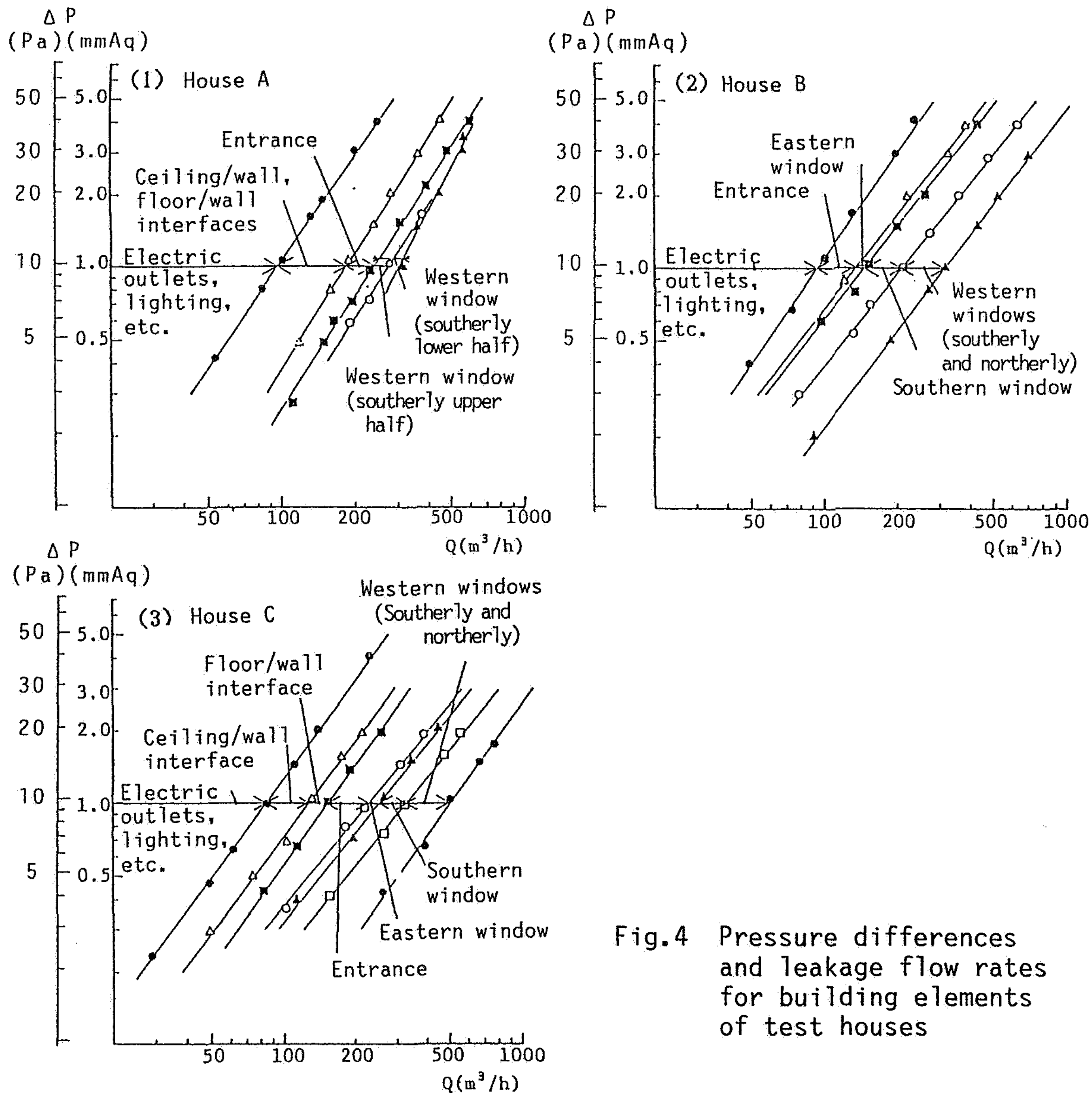


Fig.4 Pressure differences and leakage flow rates for building elements of test houses

Table 1 Effective leakage areas of building elements

	House A		House B		House C	
	Q_0(m^3/h)	n	Q_0(m^3/h)	n	Q_0(m^3/h)	n
Entrance	51.2	1.34 [1]	52.6	1.21	74.6	1.09
Eastern window	9.6	1.0(0.97)		—	24.4	1.08
Southern window		—		—	74.2	1.29
Western window	107.0	1.43	35.3	1.13	177.5	1.67
Floor/wall interface		—	92.7	1.93	24.8	2.0(2.14)
Other obscure leakages	94.9	1.5	99.6	1.57	① 43.6 [2]	1.22
					② 86.5	1.36
Total First year	262.7	1.31	280.2	1.47	505.6	1.36
Total Second year	252.5	1.37	226.8	1.49	438.9	1.47

1) The values in parentheses were obtained by measurement. Because the flow component n varies between 1 and 2, n=1 when n<1, n=2 when n>2 in later calculation.
2) The values of ① and ② are for ceiling/wall interfaces and "other obscure leakages", respectively.

2.2.3 Height of the neutral level

After the indoor-outdoor temperature difference was stabilized at around 20°C by means of the method described later, the indoor-outdoor pressure difference at a point 2.1 m above the floor, was measured under calm outdoor conditions. In Houses A, B and C, the measured pressure differences were 0.9, 0.8 and 0.4 Pa, and the neutral levels were calculated to be 1.21, 1.30 and 1.69 m above the floor, respectively. The ceiling height was 2.42 m. The neutral level was nearly equal between House A and House B, while that of House C was slightly higher.

2.3 Measurement of air infiltration

2.3.1 Methods of measurement

Methods of measurement of air infiltration ratio, pressure, temperature, etc. is outlined in Table 2.

(1) Air infiltration ratio

The infiltration ratio was measured by the CO_2 concentration decay technique. While the air in the room was being circulated by two fans, the air at the center of the room was absorbed through rubber pipe into a CO_2 interferential concentration meter. The interval between measurements was 10 minutes for Houses A and B, and 5 minutes in the case of House C.

(2) Pressure and temperature

During the first year, the pressures were measured only on the building envelope of House A. On the basis of the pressure at the level of 2.1 m above the floor, the surface pressures on the four outer walls at the same level and the pressures in the attic and crawl spaces were measured by means of two pressure transducers which were switched every two minutes. During the second year, in order to find the pressure distribution among the three test houses, the surface pressure on the outer walls of House B and C were measured with the corresponding surface pressure of House A being used as a reference point.

Indoor temperatures were measured 1 m above floor level at the center of the room by a thermocouple and a multi digital recorder after acertaining that there was no vertical temperature difference.

(3) Outdoor environment

Wind velocity was measured by a thermistor anemometer standing 7.5 m above ground level, and the wind direction was measured by the propeller type of the anemometer 5.8 m above ground level.

Table 2 Techniques for measurement of infiltration rates,etc.

	Measurement techniques	Instruments
Infiltration rates	CO_2 concentration decay	CO_2 interferometer
Indoor-outdoor pressure difference	Pressure are measured at the outsides of four walls, in the attic and in the crawl space,on the basis of the indoor pressure at a level 2.1m above the floor.(The surface pressure on the outer walls of Houses B and C were measured on the basis of wall surface pressure of House A corresponding to those of the other houses.)	Capacitance-type of pressure transducer
Room temperature	Measured at the center of each room 1.0m above the floor.	Thermo-couples and electric degital recorder
Air temperature	Measured in the screen	Thermo-couples
Wind speed and direction	Wind speed at a height of 7.5m and wind direction at a height of 5.5m.	Thermistor anemometer & propeller type of anemometer

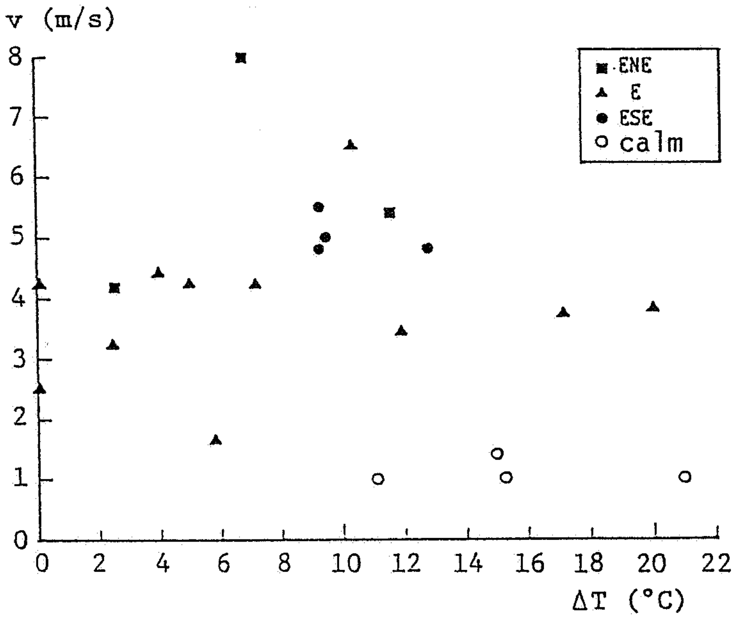


Fig.5 Experimental condition (Relationship between wind speed and indoor-outdoor temperature difference)

Outdoor temperature was measured by a thermocouple mounted in a screen.

2.3.2 Conditions of measurement

Indoor temperature was controlled in the range of ±1°C by heaters which automatically switched on and off. Relationship of the indoor-outdoor temperature difference and the wind speed is shown in Fig.5. Wind velocity was distributed between 0 and 8 m/s, and temperature difference was 0 to 21°C. Wind direction was ENE to ESE.

2.3.3 Measurement results

(1) Relationship of air infiltration ratio between three test houses

Table 3 shows the measured results. No.21 and No.22 were measured during the second year. The average infiltration ratios excluding No.6 of House A, B and C were 0.30, 0.31 and 0.76 1/h, respectively. The difference of leakage distribution between House A and House B had no influence on the infiltration ratio. While the leakage area of House C was twice that of both House A and House B, the infiltration ratio of House C was about 2.5 times that of House A and House B. This means that the infiltration ratio didn't rise in proportion to the increase of the total leakage.

Fig.6 shows the relationship of air infiltration between House A and House B or between House A and House C. The relationship varied according to the direction of wind. In the cases of Houses B and C, the air infiltration ratios were relatively great when the wind direction was ESE. When wind direction was ENE or E, these ratios were relatively small. This may be because Houses A and B prevented Houses B and C from exposure to wind from the E and ENE.

(2) Factors influencing air infiltration ratio

Fig.7 shows the relationship between the wind velocity and the infiltration ratio. The infiltration ratio rose with an increase in wind velocity. This tendency is especially evident in the case of House C. The infiltration ratio increased slightly when the indoor-outdoor temperature difference became greater under a constant wind velocity.

(3) Regression analysis of the relationship between infiltration ratio and factors affecting this ratio

Bahnfleth et al.[5] show that the infiltration ratio, Q, can be expressed by a linear equation (3) which includes the indoor-outdoor temperature difference, T, and the wind velocity, v, as variables.

Table 3 Experimental results

Exp. No.	Wind direc.	Wind Speed (m/sec)	Outdoor temp. (℃)	Indoor temp. (℃) House A	Indoor temp. (℃) House B	Indoor temp. (℃) House C	Wind pressure coeff. (House A) East	South	West	North	In ceiling	Below floor	Measured infilt. ratios (1/h) House A	House B	House C
1	ENE	8.0	23.8	30.3	30.8	30.7	0.16	-0.05	-0.10	0.02	0.08	0.02	0.57	0.50	1.25
2	E	6.5	21.1	31.4	31.0	32.0	0.19	-0.01	-0.06	0.10	0.06	0.02	0.49	0.50	1.16
3	ESE	4.8	27.3	40.4	39.9	39.9	0.25	-0.08	-0.13	-0.04	0.06	0.02	0.37	0.41	1.06
4	ESE	5.5	25.8	35.1	35.1	35.1	0.34	-0.08	-0.12	0.05	0.06	0.02	0.49	0.60	1.46
5	ESE	5.0	25.1	35.1	34.4	34.3	0.38	-0.12	-0.12	0.07	0.06	0.02	0.43	0.46	1.21
6	ESE	4.8	23.1	32.9	32.4	—	0.37	-0.04	-0.10	0.12	0.06	0.02	0.41	0.50	—
7	E	4.4	20.3	24.0	24.2	24.6	0.37	-0.14	-0.14	0.15	0.06	0.02	0.36	0.34	0.98
8	E	3.4	19.0	30.9	30.5	31.2	0.34	-0.24	-0.13	0.08	0.06	0.02	0.28	0.28	0.71
9	E	3.7	18.5	35.6	35.7	35.4	0.44	-0.12	-0.18	0.17	0.06	0.02	0.37	0.37	0.34
10	E	3.7	18.6	38.4	38.5	39.1	0.32	-0.13	-0.15	0.26	0.06	0.02	0.43	0.36	0.86
11	ENE	4.2	24.4	26.8	26.6	27.5	0.21	-0.06	-0.15	0.34	0.06	0.02	0.31	0.29	0.68
12	E	3.2	25.7	28.0	27.8	28.8	0.21	0.02	-0.19	0.25	0.06	0.02	0.13	0.20	0.45
13	ENE	5.4	24.7	35.7	36.8	36.5	0.20	-0.08	-0.16	0.32	0.06	0.02	0.50	0.45	1.05
14	E	4.2	21.2	26.0	26.1	26.5	0.23	-0.13	-0.16	0.34	0.06	0.02	0.38	0.30	0.86
15	E	4.2	20.6	28.1	27.5	27.9	0.23	-0.11	-0.18	0.31	0.06	0.02	0.39	0.30	0.89
16	0	1.0	19.6	31.0	30.2	31.0	0.0	0.0	0.0	0.0	0.0	0.0	0.09	0.13	0.27
17	0	1.0	18.8	33.9	34.6	33.9	0.0	0.0	0.0	0.0	0.0	0.0	0.10	0.20	0.31
18	0	1.4	20.7	35.9	36.0	35.3	0.0	0.0	0.0	0.0	0.0	0.0	0.11	0.17	0.32
19	E	1.6	19.3	25.4	24.9	25.0	0.25	0.00	-0.06	0.25	0.06	0.02	0.10	0.08	0.24
20	0	1.0	19.9	41.2	41.0	40.5	0.0	0.0	0.0	0.0	0.0	0.0	0.17	0.23	0.44
21	E	4.2	29.2	29.4	27.4	28.9	0.09	-0.08	-0.10	0.10	0.02	0.00	0.16	0.19	0.59
22	E	2.5	20.9	21.0	21.6	20.8	0.24	-0.03	-0.17	0.24	0.10	0.10	0.15	0.15	0.33
												Average	0.31	0.32	0.76

No.1∿No.20 were measured in the first year.
No.21 and No.22 were measured in the second year.

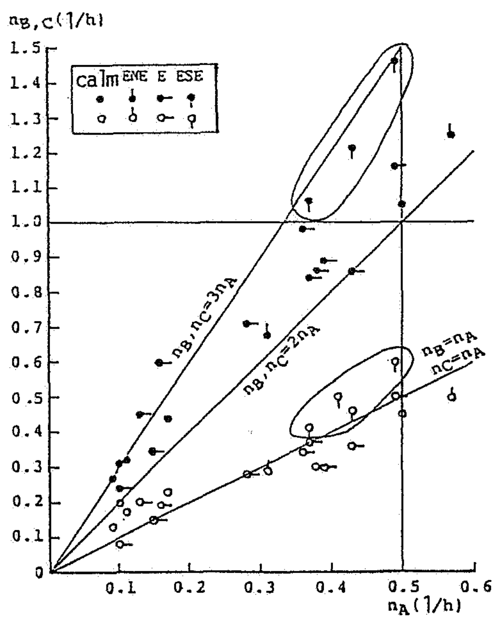


Fig.6 Comparison of infiltration ratios between Houses A, B and C

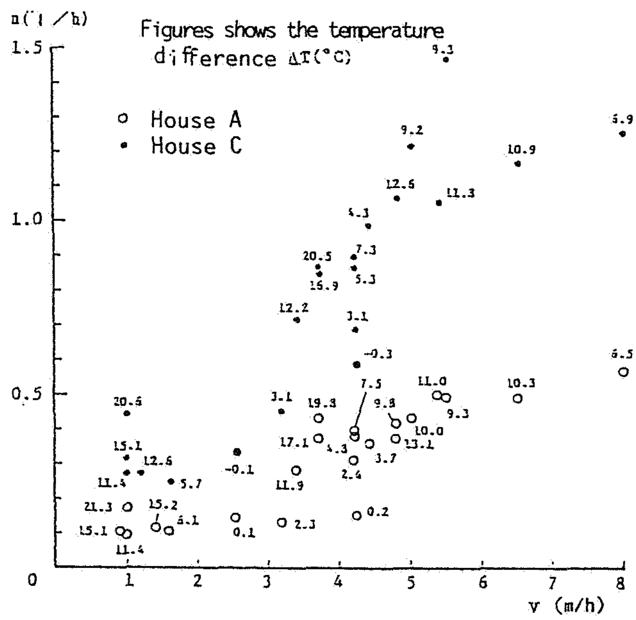


Fig.7 Measured infiltration ratios of Houses A and C

Table 4 Average wind pressure coefficient

Wind direc.	East	South	West	North
ENE	0.19	-0.06	-0.14	0.23
E	0.26	-0.09	-0.14	0.20
ESE	0.34	-0.08	-0.12	0.05

$$Q = a + b\,\Delta T + c\,v \qquad \text{------ (3)}$$

On the basis of the measured results, the regression equations obtained which predict the infiltration ratio, n', are:

$$\begin{aligned} &\text{House A:} \quad n' = -0.0904 + 0.0087\,\Delta T + 0.0831\,v \\ &\text{House B:} \quad n' = -0.0490 + 0.0096\,\Delta T + 0.0729\,v \qquad \text{------(4)} \\ &\text{House C:} \quad n' = -0.0987 + 0.0162\,\Delta T + 0.1873\,v \end{aligned}$$

The correlation coefficients of the predicted value, n', obtained by Eq.(4) and the measured value, n, are as high as 0.95, 0.92 and 0.93 in cases of Houses A, B and C, respectively. The partial regression coefficient of ΔT is remarkably smaller than that of v. In the case of C, the coefficients of ΔT and v are larger than those of Houses A and B, corresponding to the relatively high level of total leakage of House C.

2.4 Pressure distribution around the building envelope

Table 3 includes the wind pressure coefficient of House A based on wind velocity 7.5 m above ground level as obtained by Eq.(5). The stack effect due to indoor-outdoor temperature difference is not included.

$$C = (p_i - p_r)/(\rho v^2/2) \qquad \text{----- (5)}$$

As the wind was mainly from the east, the pressure on the surface of the east wall was usually plus and that on the west wall was minus. Table 4 shows the mean wind pressure coefficient for each wind direction.

In the second year, the distribution of the wind pressure coefficents for Houses A, B and C were measured when the wind was from the east. Fig.8 shows the wind pressure coefficients of various points as based on the indoor pressure in House A. The values for the north wall of House B and C were smaller than that for House A due to wind being blocked by the adjacent test houses. This is related to the results shown in Fig.6 in that the infiltration ratio is rather small in the case of wind from the east.

The wind pressure coefficient of the wall surface 1 m above ground level is much smaller for the east and north walls and larger for the west wall, which is to be expected.

The wind pressure coefficient of Houses B and C used in Chapter 3 for the evaluation of the calculation model is the same value as that of House A for a wind direction of ESE. Coefficients in the case of wind from the E or ENE are also given as based on the pressure coefficient of House A in view of the difference as shown in Fig.8. The pressure difference between the upper and lower parts of the wall as measured for House A was taken into consideration to calculate the mean pressure for each wall. The pressure coefficients of the attic space and the crawl space are given as the mean value of tests No.21 and No.22.

3. VERIFICATION OF CALCULATION MODELS

3.1 LBL model

3.1.1 Model

Air flow rate through leakage is assumed to be given by Eq.(6) in the range of Δp=2 to 10 Pa.

$$Q = A_o\sqrt{(\rho/2)\Delta p} \qquad \text{----- (6)}$$

Based on the result of the pressurization test, the effective leakage area, Ao, is calculated for Δp= 4 Pa. Air infiltration rates, Qw and Qs, which depend on the wind effect and the stack effect are respectively expressed by

$$Q_w = 3600\ f_w\ A_o\ v \qquad \text{------ (7)}$$

$$Q_s = 3600\ f_s\ A_o\ \sqrt{gH\{\Delta T/(T+273)\}} \qquad \text{------ (8)}$$

where

$$f_w = C'(1 - R)^{1/3} \qquad \text{---- (9)}$$

$$f_s = 1/3\ (1 + R/2)\ \{1 - X^2/(2 - R)^2\}^{3/2} \qquad \text{---- (10)}$$

and

$$C' = 1/2\ (\sqrt{|C_i - C_r|}) \qquad \text{----- (11)}$$

$$R = (A_c + A_f)/A_o \qquad \text{----- (12)}$$

$$X = (A_c - A_f)/A_o \qquad \text{----- (13)}$$

When the wind effect and the stack effect act simultaneously, these two effects can be combined as:

$$Q = \sqrt{Q_w^2 + Q_s^2} \qquad \text{----- (14)}$$

These equations are based on the following assumptions:

a)leakage is uniformly distributed on each wall, ceiling and floor;

b)the air flow through leakage is turbulent;

c)wind pressure coefficients of the ceiling and the floor are zero, and

d)prevailing wind direction can not be ascertained.

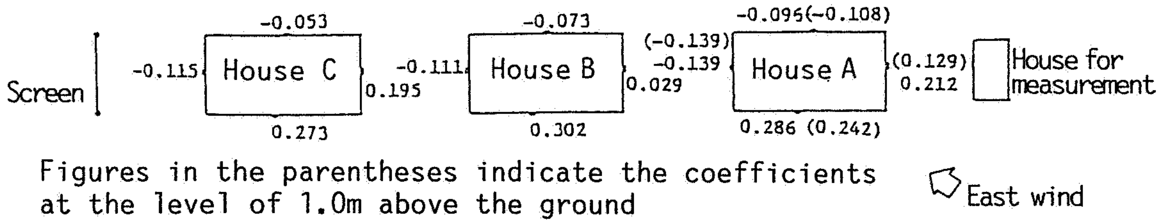


Fig.8 Measured wind pressure coefficients of test houses (East wind)

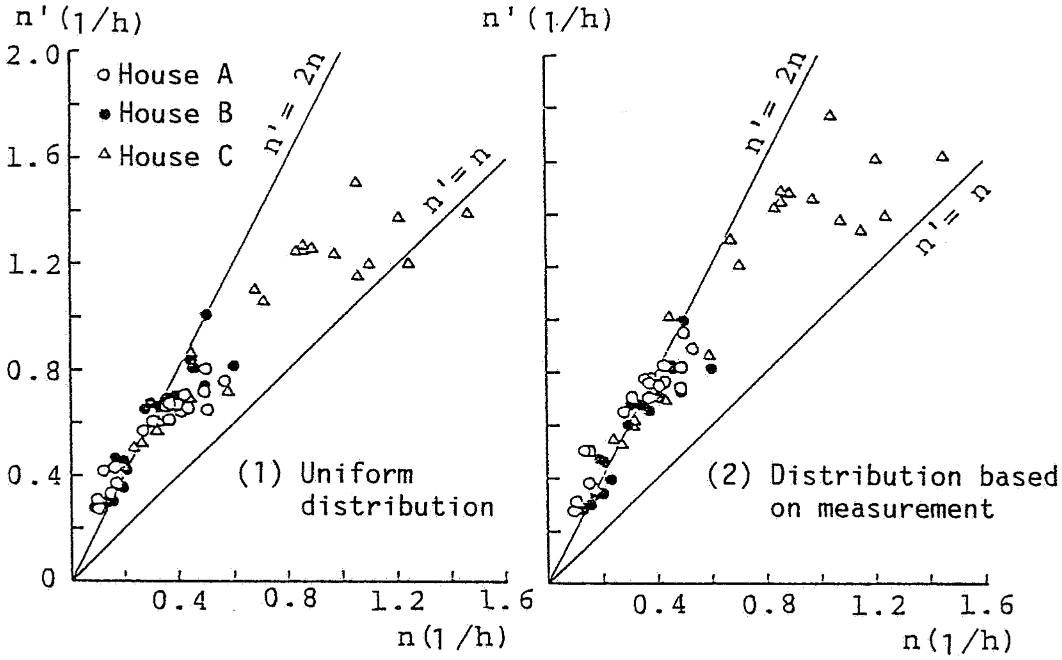


Fig.9 Relationship of infiltration ratios between measurement and calculation with LBL model

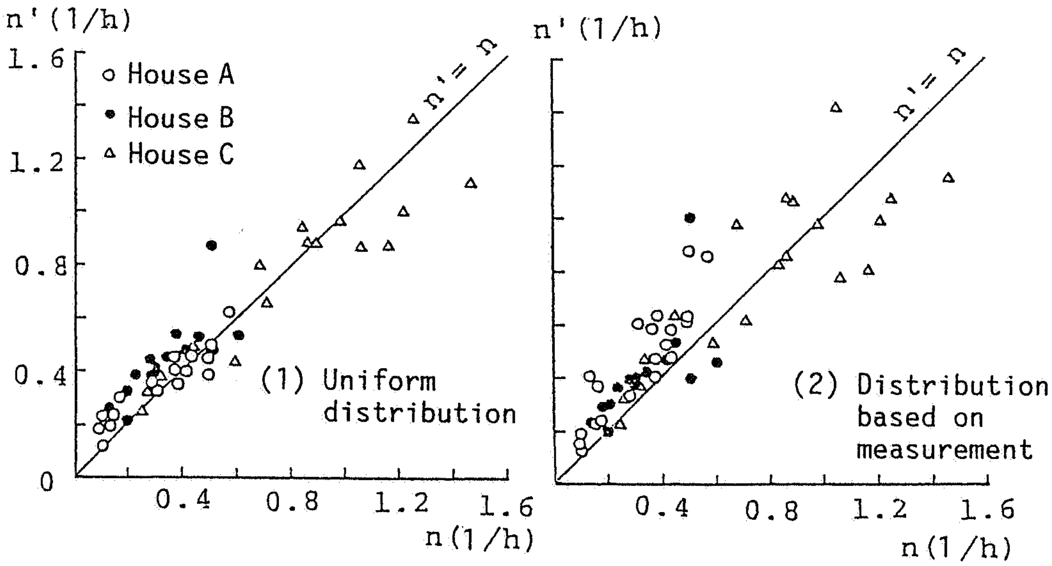


Fig.10 Relationship of infiltration ratios between measurement and calculation with BRE model

3.1.2 Calculated result

Fig.9 shows the relationship between the predicted values and the measured values. The coefficient C' is given by

$$C' = 1/2\ (\sqrt{|a_i|}) \qquad \text{----- (15)}$$

where a_i is estimated using the measured pressures of House A based on the pressure distribution as shown in Fig.8. Fig.9-(1) is an example of leakage uniformly distributed over the building envelope, while Fig.9-(2) is an example of the leakage uniformly distributed on each wall, ceiling and floor.

The calculated infiltration rates are overestimated in both cases. The predicted values of Houses A and B are twice the measured values, while those of House C are one to two times the measured values. This is probably because with the LBL model infiltration rate is calculated under the assumption that the wind effect and the stack effect act independently, when in fact, these two different effects are often related.

3.2 BRE Model

3.2.1 Model

The values Qo and n are calculated by means of Eq.(1) using the result of the pressurization test. The indoor-outdoor pressure difference, Δp_j, acting on the wall i at a height above the floor of Z is given by Eq.(16) which combines the wind and stack effects.

$$\Delta p_j = \rho v^2\ (a_i - BZ)/2 \qquad \text{----- (16)}$$

where

$$\begin{aligned} a_i &= C_i - C_r \\ B &= 2\ TgH/(T+273) = 2\ A_r \qquad \text{----- (17)} \\ Z &= h/H \end{aligned}$$

Under the assumption that leakage is uniformly distributed on each wall, the air flow rate, ΔQ_j, through the part j of wall i is given by

$$dQ_j = (dh/H)\ Q_{oi}(|\Delta p_j|/\Delta p_o)^n\ \mathrm{sign}(\Delta p_j) \qquad \text{----- (18)}$$

After Eq.(16) is incorporated into Eq.(18), the air flow rate, Qi, can be obtained by integrating Eq.(18) by Z between 0 and 1. The flow rates through the ceiling and the floor are obtained in the same manner. The indoor pressure, C , is ditermined by the iterative calculation method using the following equation.

$$\Sigma Qi + Qc + Qf = 0 \qquad \text{---- (19)}$$

Consequently, the air infiltration rate is expressed as

$$Q = Q_o(\rho v^2 \Delta p_o/2)^{1/n} F(A_r, \phi) \qquad \text{----- (20)}$$

where,

$$F(A_r, \phi) = [1/\{2B(1/n+1)\}] \Sigma[(Q_i/Q_o)\{(|a_i|)^{1/n}\text{sign}(a_i) -(|a_i-B|)^{1/n}\text{sign}(a_i-B)\}] +(Q_f/Q_o)(|a_i|)^{1/n}+(Q_c/Q_o)(|a_c-B|)^{1/n} \quad (21)$$

If the wind effect or the stack effect acts independently, the infiltration rate can be determined by an equation similar to Eq.(21), after slight modification of Eq.(15).

3.2.2 Calculated results

Fig.10-(1) shows the results in the case of uniform leakage distribution over the envelope, while Fig.10-(2) shows results for the case of uniform distribution on each wall. The predicted values of Houses A and B are slightly overestimated, one to two times the measured values. The predicted values of House C are plotted in the range from 0.8 to 1.5 times the measured values. The predicted result for House C under the assumption of uniform distribution, yields a good estimation.

3.3 JCV model

3.3.1 Method of Calculating air infiltration

The indoor-outdoor pressure difference through leakage j at a height h above the floor is expressed by Eq.(22), which combines the wind effect and the stack effect.

$$\Delta p_j = C_j \frac{\rho}{2} v^2 - p_r + h_j(\rho_r - \rho_o) \qquad \text{----- (22)}$$

The air flow rate, Qj, through leakage j is determined by

$$Q_j = Q_{oj}(\Delta p_j)^{1/n_j} \qquad \text{----- (23)}$$

Eq.(22) is introduced into Eq.(23), and then Qj is introduced into Eq.(24). Consequently, the total infiltration rate or air exfiltration rate is equal to zero.

$$\Sigma Q_j = 0 \qquad \text{----- (24)}$$

The indoor pressure and the air flow rate of each leakage can be obtained by means of Eq.(24) using the Newton-Raphson iterative calculation method.

Although Eq.(16) and Eq.(22) are expressed differently, they yield the same result.

3.3.2 Leakage distributions for calculation

Air infiltration was calculated under the assumption of there being five types of leakage distributions as shown in Table 5 as estimated by the fan pressurization test. No.1 to No.3 are cases in which leakage characteristics of each building element as shown in Table 1 are used for calculation. However, in the cases of No.2 and No.3, the flow exponent, n, for each element is assumed to be equal to the value obtained by the fan pressurization test for a whole house. This is because the flow exponent of each leakage, as shown in Table 1, is scattered.

The other leakage is assumed to be uniformly distributed over the envelope in the cases of No.1 and No.2, and is also uniformly distributed along the interfaces between the ceiling and the walls and between the walls. In the case of No.4, the leakage is uniformly distributed over the building envelope only. In the case of No.5, the leakage is concentrated at the entrance and the window.

The longitudinal leakage and the uniformly distributed leakage are divided into ten parts. It is assumed that the divided leakage is concentrated at the center of each part. In House C, there is no leakage through the floor because the floor is constructed on a concrete slab which is directly on the ground.

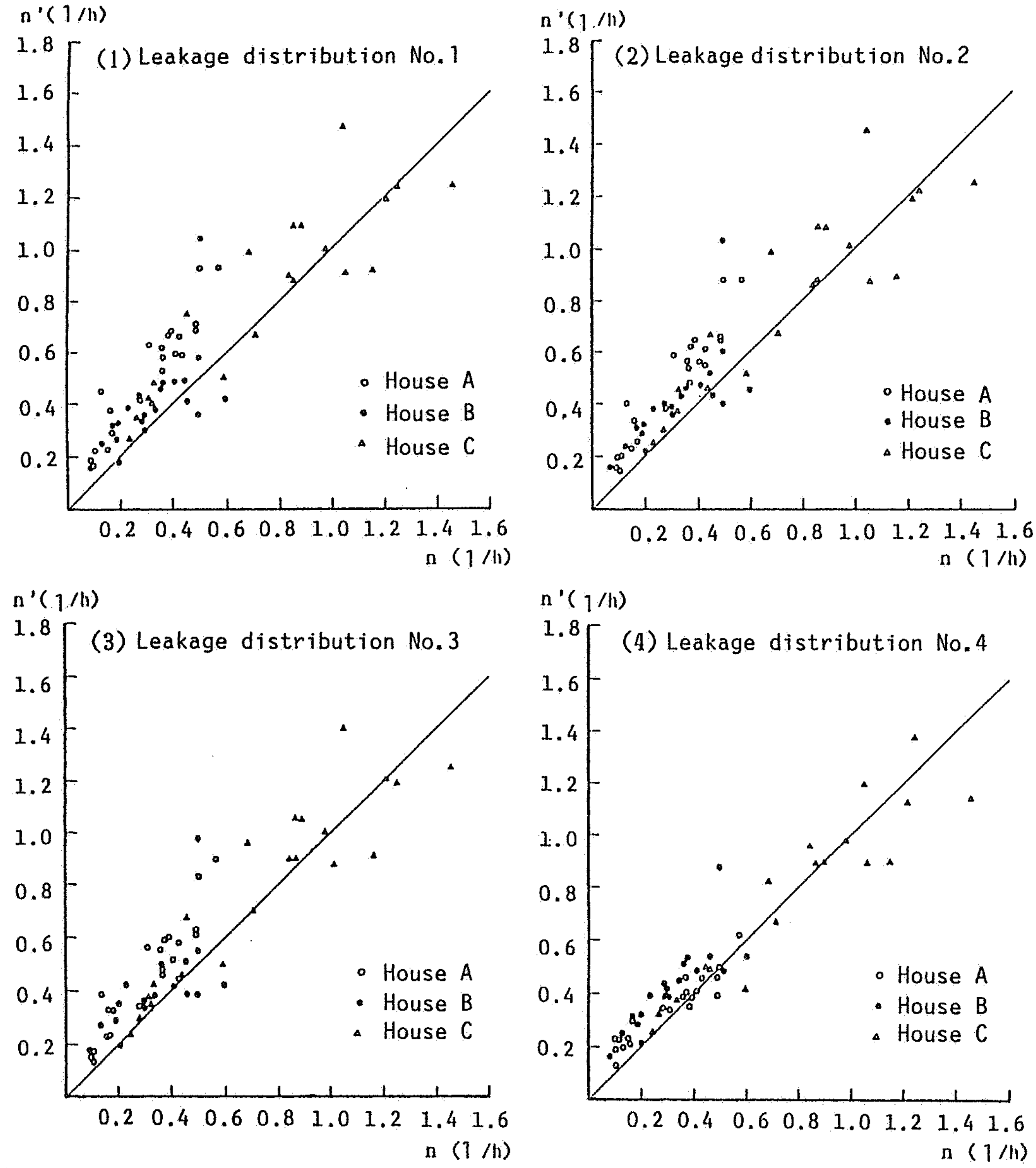
The neutral level of the house having varied leakage distribution can be calculated as shown in Table 6. No.4 is similar to the measured value.

3.3.3 Comparison between calculation and measurement

Fig.11 shows the relationship between the predicted values and the measured values. Table 7 indicates the standard deviation of errors of the predicted values from the measured values divided by the mean of the measured values. This table includes the results calculated by means of the LBL model and the BRE model.

The values predicted under the condition of different leakage distributions differ greatly. But the predicted infiltration rates under the leakage distributions of No.1, No.2 and No.3 have almost equal values, because these three leakage distributions are similar. The scattering of the predicted values under distribution No.4 is smallest, while that calculated under distribution No.5 is largest.

In the case of House A, all of the predicted values overestimate



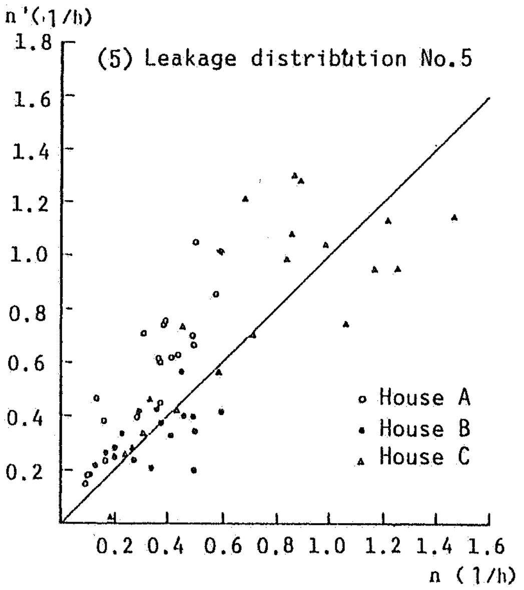


Fig.11 Relationship of infiltration ratios between calculation using JCV model and measurement

Table 5 Leakage distribution and contents

Variation	Contents
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.

Table 6 Variation of distribution and height of neutral level (height above the floor : m)

		House A	House B	House C
Measured height of neutral level		1.21	1.30	1.69
Leakage distribution	No. 1	1.42	0.72	1.67
	No. 2	1.42	0.72	1.67
	No. 3	1.42	0.72	1.67
	No. 4	1.22	1.22	1.71
	No. 5	1.37	1.04	1.43

Table 7 The ratio of the standard deviation of error to the average of measured values

Variation of calculation	Variation of leakage distribution	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

the measured values. Among the three houses, the degree of error from the measured values is greatest for House A except for distribution No.4. In the case of House B, almost all of the predicted values also overestimate the measured values except for distribution No.5. In the case of House C, the calculated results give relatively good estimations under all five distributions. This is probably because the leakage area of House C is great and the leaks are distributed over the envelope.

The reason that uniform distribution No.4 gives a good estimation for all three houses, is that the obscure leaks other than the leaks found around the windows and the entrance make up 36%, 69% and 31% of the total leakage of House A, B and C, respectively; these leaks play an important role in air infiltration by connecting the outdoors and indoors.

The result obtained by distribution No.4 is the same as the result of the BRE model, assuming uniform distribution over the envelope. The difference between the two methods is either due to integration of the air flow along the longitudinal leak or summation of the air flow through the divided leaks.

4. CONCLUSIONS

Calculation models of air infiltration in a single room were verified by measuring the airtightness and the air infiltration in three test houses. The results can be summarized as follows:

1) While the ratio of the total leakage of House A, B and C was 1:1.1:1.9, the relation of the mean air infiltration ratio of the three houses was 1:1:2.5. Therefore, the infiltration ratio is not proportionate to the total leakage.

2) The air infiltration ratio was expressed by the indoor-outdoor temperature difference and the wind velocity using the linear equation by Bahnfleth, et al. The correlation coefficient between the predicted values obtained by this equation and the measured values was more than 0.9.

3) The predicted values found with the LBL model were two times the measured values in the cases of House A and B, and one to two times in the case of House C. This overestimation is probably due to the calculation method under the assumption that the wind effect and the stack effect act independently.

4) The predicted values found with the BRE model were one to two times the measured values. However, the calculation for House C under conditions of uniform distribution over the envelope gave a good estimation.

5) The accuracy of prediction of the calculation method widely used in Japan, was investigated as to the effects of five types of leakage distributions assumed on the basis of the fan

pressurization test. It was found that the assumption of uniform distribution over the envelope gave the best estimation. This was as expected because the obscure leaks played an important role in air infiltration by connecting the indoors and outdoors.

Therefore, it can be said that in the case of a wooden house which is not particularly airtight, air infiltration can be estimated by the usual calculation method based on the result of the airtightness test for a whole house without measuring the airtightness of every building element.

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THE IMPLEMENTATION AND EFFECTIVENESS OF AIR INFILTRATION STANDARDS IN BUILDINGS

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PAPER 21

AIR FLOW CALIBRATION OF BUILDING PRESSURIZATION DEVICES

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SYNOPSIS

Whole building pressurization devices, or blower doors, have been used to quantify building airtightness and to determine compliance with airtightness standards. Using pressurization testing in airtightness standards requires knowledge of the accuracy of the air flow rate measurement techniques employed by blower doors. The quantitative accuracy of existing air flow calibrations are not known and have been questioned. The blower doors considered in this report employ calibration formula relating the air flow rate through the door to the fan speed and the pressure difference across the door. Such fan speed calibrations must be done accurately over a wide range of fan speed/pressure difference combinations and in a physical setting that closely approximates the manner in which the blower doors are used in the field.

In order to obtain an accurate and well-documented calibration of pressurization devices, a facility was designed and constructed at the U.S. National Bureau of Standards. The calibration facility discussed in this work was built to accurately determine the flow rate through the fan as a function of fan speed, air density and pressure difference across the fan. This report describes the calibration facility and the rationale for its particular design. Results from the calibration of one blower door are presented. The effect of the form of the calibration equation on the accuracy of the air flow rate determination is also discussed.

1. INTRODUCTION

There are two basic uses of whole-house pressurization devices, diagnostics for the location of air leakage paths and quantification of the airtightness of buildings. When used as a diagnostic tool, the pressure differences induced by blower doors accentuate the air flow through leakage paths, thereby making their detection easier[1]. Such leakage detection is further enhanced by using smoke and/or infrared thermography in conjunction with pressurization. Blower doors can also be used to quantify the airtightness of buildings by measuring the air flow rate required to induce and sustain a given inside-outside pressure difference[2,3]. It is this second use of pressurization which concerns us here.

Quantification of building airtightness is useful for the determination of space conditioning loads and the maintainance of indoor air quality. While actual infiltration measurement can fulfill these needs as well as, or perhaps better than, pressurization testing, the characterization of a building's airtightness requires infiltration measurements over a wide range of weather conditions, and is an expensive and time consuming procedure. Pressurization testing requires only a single measurement which takes roughly one hour and is relatively inexpensive. Airtightness measurement through pressurization can be used for measuring the effectiveness of shell tightening retrofits, comparing homes to each other and determining compliance with building tightness standards. Sweden, in fact, requires new homes to achieve a specific tightness level as measured by pressurization[3], and the American Society of Heating, Refrigerating and Air Conditioning Engineers is formulating an airtightness standard for U.S. homes. The use of pressurization testing for airtightness evaluation implies a relation between pressurization and weather induced infiltration. This relation has been studied extensively[4-10], however the ability to predict infiltration from pressurization is limited.

In order to use blower doors as quantitative tools, one must know the accuracy of the measurements. Previous work has shown pressurization test results to be reproducible within about 2% over periods of a few weeks[11]. The absolute accuracy of air flow rate measurement of many pressurization devices has not been well established, especially for devices which employ fan speed calibrations for determining the air flow rate. Some devices have been calibrated by their manufacturers and other researchers[12], but the accuracy of these calibrations has not been carefully examined. In this report, pressurization equipment is discussed briefly, along with general calibration requirements. Several calibration strategies are reviewed and the particular technique used at NBS is described in detail. The formulation of these flow calibrations are also discussed. Finally, preliminary results obtained at the NBS facility are presented.

2. PRESSURIZATION EQUIPMENT

There are basically two types of blower doors, those which measure air flow directly using nozzle or orifice meters, and those which use a calibration formula to relate the air flow rate to the fan speed and the inside-outside pressure difference. Direct flow measurement techniques are based on relations between the air flow rate through a nozzle or orifice and the pressure drop across such a constriction. Flow rate measurement with orifices and nozzles is a well documented technique[14-19], but the existence of these constrictions decreases the flow capacity of a fan. In addition, orifice and nozzle meters require ducting and flow straighteners to condition the flow before it passes through the constriction, and this further decreases the flow capacity and makes the device more bulky. For reasons of portability and expense, many designers have developed "calibrated" blower doors in which the air flow rate is given by a general function

$$q = f(\omega, \Delta p) \tag{1}$$

where

q = air flow rate, m^3/s
ω = fan speed, s^{-1}
Δp = inside-outside pressure difference, Pa.

The fan speed ω is the number of revolutions per second of the fan blade and not the blade tip speed. Calibrated blower doors will be the topic of discussion in the remainder of this report, however the material on calibration also applies to blower doors which employ direct air flow rate measurement.

3. CALIBRATION TECHNIQUES AND FORMULATONS

3.1 Calibration Requirements

The technique of pressurization testing leads to specific requirements on the calibration of blower doors. When pressure testing a building, one induces several inside-outside pressure differences generally ranging from 10 to 70 Pa in increments of about 10 Pa[13]. One notes the fan speed required to induce each pressure difference, and using calibration formula, calculates the air flow rate at that pressure difference.

Blower doors must be able to induce a wide range of air flow rates to enable testing of homes ranging from small and tight to large and leaky. At each pressure difference, one must be able to induce and measure reliably a wide range of air flow rates. One may determine a desirable range of air flow rates for a blower door by considering a small, tight house (180 m^3, 2.5 exchanges/hr at 50 Pa) and a large, leaky house (600 m^3, 15 exchanges/hr at 50 Pa). By considering pressurization test data that would correspond to these limiting cases, we calculated the maximum and minimum air flow rates for several pressure differences. Table 1 shows the results of these calculations. At each pressure difference the maximum flow rate is twenty times the minimum, with the maximum flow rate at 75 Pa about 64 times the minimum flow rate at 12.5 Pa. This table gives desirable air flow rate capacities for a blower door, however not all doors are able to cover this range of flow rates.

Table 1. Range of Blower Door Flow Rates

Inside-Outside Pressure Difference (Pa)	Small, Tight House* Flow Rate (m^3/s)	Large, Leaky House* Flow Rate (m^3/s)
12.5	0.051	1.015
25.0	0.080	1.593
37.5	0.104	2.074
50.0	0.125	2.500
62.5	0.145	2.890
75.0	0.163	3.254

* The flow exponent for both houses is assumed to be 0.65.

In addition, blower door calibration formulas must deal with the effects of air density on the air flow rate. Air density varies with air pressure, temperature and relative humidity, and therefore blower door tests are conducted at different air densities, depending on the ambient conditions. At constant air pressure and relative humidity, air density changes by about 7% for a 20°C change in temperature. A change in air pressure corresponding to a 500 m change in altitude changes the air density by about 6%. Changes in air temperature and pressure can combine to cause 10% variations in air density. Blower doors are generally calibrated at a single air density of about 1.2 kg/m^3 (corresponding to an air temperature of 20°C and atmospheric air pressure), and the question exists of how to adjust the calibration to account for measurements at other air densities. We know the air flow rate for a given density, fan speed and pressure difference, and want to know the air flow rate for the same values of fan speed and pressure difference but different air density. While fan laws exist to deal with some analogous situations, these particular circumstances are not amenable to fan laws[14].

Standards exist for testing the performance of fans[15,16]. ASHRAE standard 51-75 describes several physical arrangements for the fans and flow rate measuring equipment[15]. In general, the fans are either mounted in a duct of a diameter similar to that of the fan or installed in a large plenum (see fig. 1). In most cases an exhaust system is required to control the back pressure against which the fan blows. The calibration of blower doors should be carried out in a physical setting that closely approximates the manner in which such devices are used in the field. When blower doors are used to test a house, they are installed in a doorway. The fan, in effect, is mounted in a vertical plane. Having a fan mounted in a duct will affect the characteristics of the air flow through it, and therefore a calibration obtained with a fan in a duct will not apply to the same fan used in a blower door. Thus, blower doors should be calibrated with the device mounted in a large chamber into which the fan blows air. Such a chamber allows the air to "settle" or reach an approximately static condition. A simple schematic of such a chamber is shown in figure 1. The air flow rate measurement device must be appropriate to the magnitude of the air flow rates and the air flow/pressure difference combinations in table 1. Several measurement techniques are discussed in the following section.

3.2 Air Flow Rate Measurement

There are several options for measuring the air flow rate out of the calibration chamber including devices such as orifice plates, nozzles, and pitot tube arrays. Each alternative has advantages and disadvantages, and several options are discussed below, concluding with the flow rate measurement technique used in the NBS calibration facility. The use of orifice plates and nozzles installed in pipes is a well documented procedure for measuring fluid flow rates[17-19]. The references listed provide specifications for orifice design, lengths of pipe upstream and downstream from the metering section, flow straighteners and other aspects of design, installation and use. When the appropriate specifications are followed, the uncertainty of the air flow rate measurement is well determined. The basic problem with such meters is the significant pressure drop caused by the pipe lengths, flow straighteners and the orifice or nozzle. The pressure drop is generally too large to obtain the air flow/pressure difference combinations in table 1. Therefore, one requires a large capacity, variable exhaust system to control the back pressure. Also, several different sized orifices and nozzles are required to cover the wide range of flow rates of interest.

To avoid the large pressure drops associated with orifices in pipes, several researchers have used orifices mounted in the walls of plenums or settling chambers[12,13]. This technique is indeed much simpler than using orifices in pipes, but it is not well documented, nor is there a statement of uncertainty associated with the measurements. No discussion of this technique is found in the three basic handbooks of orifice metering referred to earlier[17-19]. A text on air flow measurement by Ower and Pankhurst[20] does mention the technique, but not in detail. The authors refer to reference 18 as a source of discharge coefficients for such orifices, but Ower and Pankhurst appear to have derived these coefficients from extrapolating data for orifices in large pipes. A practical handbook of fan engineering[21] also provides discharge coefficients for such a situation but does not provide the source of the values. This lack of documentation of discharge coefficients is one problem with this technique. The value of the discharge coefficient may not be as significant a source of error as the characteristics of the flow impinging on the orifice. The theory of orifice meters is based on conditions of fully developed, turbulent flow upstream of the constriction. Ower and Pankhurst[20] mention that these conditions may not be met for flow discharging from a chamber through an orifice and refer to the need to eliminate flow disturbances such as drafts. The existence of such drafts and the lack of fully developed flow impinging on the constriction may induce unknown measurement errors when using this flow measurement technique. The indeterminant accuracy and the lack of documentation of the technique lead us not to use it nor to recommend its use.

Several commercial flow measurement devices exist, such as a multi-point pitot tube traverse station combined with a flow straightener. The flow measurement is based on the difference between the total and static pressures of the flow. Based on the magnitude of the flow rates of interest and the size of the devices, the pressure differences (total minus static) which must be measured are quite small, in some cases on the order of 1 Pa. It is difficult and expensive to measure such small pressure differences accurately. Also, pitot tubes are generally inaccurate for the small flow rates of interest here. In addition, these pitot tube arrays should be calibrated, and this presents the same problem we are trying to solve. Another commercially available device is referred to as a laminar flow element which channels the air flow through a large number of narrow, parallel passages. These channels are sufficiently narrow that the flow through them is laminar, and the magnitude of the air flow rate is related straightforwardly to the pressure drop across the channels. These devices are expensive and several would be required to cover the range of flow rates of interest. In addition, the pressure drop through the devices is extremely large. Other devices exist but none satisfactorily combine cost, minimal pressure drop and accuracy.

The flow measurement technique used in the NBS calibration facility is a constant flow, tracer gas injection scheme[22]. Tracer gas (sulfur hexafluoride, SF_6) is injected at a constant and known rate into the air stream, and the concentration is measured as far downstream from the injection point as possible (see fig. 2). Under conditions of good mixing of the tracer and the air flow, the air flow rate can be determined from the SF_6 injection rate and the measured concentration according to

$$q = i/c, \tag{2}$$

where

i = SF_6 injection rate, m^3/s
c = SF_6 concentration, ppm.

The SF_6 injection rate is measured and controlled with individually calibrated variable-area float-type rotameters. The accuracy of these devices is ±1% of full scale and four different meters are used, providing injection flow rates from 10 to 2500 ml/min. The SF_6 concentration downstream of the injection is measured with an infrared gas analyzer with a 1.5 m path length operating at 10.7 μm. The tracer gas injection rate is adjusted such that the downstream concentration is 25 ppm. The gas analyzer is calibrated with a 25 ppm gas mixture prepared by a gas distributor to an accuracy of ±1%. This air flow rate measurement system has a minimal pressure drop through it. To obtain the desired air flow/pressure difference combinations, we still must use constrictions and a variable exhaust fan in the exit duct.

A schematic of the NBS calibration chamber is shown in figure 2. The chamber is used in the large environmental test facility at the Center for Building Technology at NBS, which enables control of air temperature and humidity, and therefore air density. The calibration chamber has a square base with 3.66 m sides and is 1.83 m high. Air is drawn into the calibration chamber from the larger environmental enclosure through the blower door being tested. The air is exhausted to the outside of the large enclosure through a 4.88 m long exit duct. The SF_6 is injected at the upstream end of the exit duct and the concentration measured at the downstream end. The exhaust fan and constriction locations are shown in figure 2. The details of data recording and preliminary results are discussed later in this report.

3.3 Calibration Formulation

Calibrations of blower doors have generally been expressed as linear relations between air flow rate and fan speed for each inside-outside pressure difference[12,13]. These linear relations are the result of applying linear regressions to the calibration data. While such formulas are straightforward to use, they are not physically correct and no indication is given of how to account for density effects. In addition, as will be shown later, such a linear approximation breaks down at low fan speeds. A physically correct calibration formulation has been presented previously which involves nondimensionalization of the air flow rate q and the pressure difference Δp[4,11]. The nondimensional air flow rate is expressed as

$$\alpha = q/\omega d^3 \tag{3}$$

and the nondimensional pressure difference as

$$\beta = \Delta p/\rho(\omega d)^2, \tag{4}$$

where

ρ = air density, kg/m^3
d = fan diameter, m.

A fan's characteristics are described by a relation between α and β, expressed in general as

$$\alpha = g(\beta). \tag{5}$$

The data we collected, and the values of α and β derived from other calibration formulas[4,11], fit well to an equation of the form

$$\alpha = A_1 \exp(A_2\beta), \tag{6}$$

where A_1 and A_2 are constants. By substituting eq (3) and (4) into eq (6) one obtains the following expression for q,

$$q = A_1'\omega \exp(A_2' \Delta p/\rho\omega^2), \tag{7}$$

where A_1' and A_2' are constants obtained by absorbing the constant fan diameter d into A_1 and A_2. Thus, for Δp=0 a linear relationship between q and ω is appropriate. For nonzero pressure differences, the exponential factor causes a deviation from a straight line, particularly at low fan speeds. This deviation from linearity and its significance will be discussed in the next section.

This nondimensional calibration formulation leads to a straightforward correction for air density, and explains the inappropriateness of fan laws for such a correction[14]. Fan laws are obtained by holding β, and therefore α, constant. A constant value of these nondimensional quantities implies certain relations between the physical quantities from which they are constituted. For our situation in which Δp and ω are constant, but the density ρ is variable, one sees that α and β change and therefore fan laws are not appropriate.

4. TEST RESULTS

This section describes preliminary results obtained in the NBS blower door calibration facility. Only one door, referred to as Blower Door A, was tested in the counter-clockwise direction of fan rotation. Blower Door A consists of a 0.46 m diameter axial fan coupled by a belt drive system to an electrically reversible, variable speed constant-torque DC motor.

4.1 Experimental Procedure

The most important factor in the tracer gas flow rate measurement technique is the mixing of the tracer gas with the air in the exit duct. The tracer gas must be well-mixed for eq (2) to apply. Good mixing is obtained by injecting SF_6 at several vertically coplanar points immediately upstream of the exhaust fan shown in figure 2. Under this injection scheme the downstream SF_6 concentration is constant in time and location in the duct within about $\pm$0.25 ppm of the 25 ppm concentration setting. In addition to good mixing, this flow rate measurement technique assumes that the SF_6 concentration in the air flowing through the blower door into the calibration chamber is 0 ppm. This assumption is checked after every other flow rate measurement by turning off the SF_6 injection and making sure the SF_6 concentration in the exit duct returns to 0 ppm. If the SF_6 concentration in the outgoing flow returns to 0 ppm, then there is no SF_6 in the air flowing through the blower door into the calibration chamber.

The desired air flow/pressure difference combinations are obtained by using the exhaust fan or installing constrictions in the exit duct. A high speed setting on the exhaust fan corresponds to testing large, leaky homes, i.e. low resistance to air flow. Constrictions in the exit duct correspond to smaller, tighter homes with a higher resistance to air flow. The measured ranges of fan speed and air flow rate for each pressure difference are in table 2. The air flow rates range from about 0.05 to 1.10 m^3/s. This is smaller than the range of interest given in table 1, due primarily to the limited flow capacity of our exhaust fan.

Table 2. Range of NBS Calibration

Inside-Outside Pressure Difference (Pa)	Fan Speed (s^{-1})	Air Flow (m^3/s)
12.5	7.50-23.33	0.050-0.725
25.0	10.83-30.00	0.075-0.950
37.5	12.50-35.83	0.075-1.050
50.0	14.17-38.33	0.075-1.050
62.5	15.83-38.33	0.075-0.975

For each calibration point, the fan speed, pressure difference across the chamber wall and the air density are also measured. The fan speed for this blower door is measured in the field with a digital tachometer employing a magnetic transducer and a toothed gear interrupter which was found to agree within 0.02 s^{-1} with a digital stroboscope/tachometer with an accuracy of $\pm 0.02\ s^{-1}$. The pressure difference across the calibration chamber wall was measured in four locations with magnetic linkage type pressure gauges individually calibrated against an inclined manometer. The four measured pressure differences agree within the range of uncertainty of the pressure gauge calibration, and the average pressure difference across the chamber walls is known within $\pm$ 0.6 Pa. The air density was determined by measuring the air temperature, relative humidity and barometric pressure, and calculating the density using the appropriate formulas. Based on the uncertainties in the measurements of temperature, humidity and pressure, the air density determination has an uncertainty of $\pm$ 0.02 kg/m^3. We then calculated α and β using eq (3) and (4). Based on the uncertainties in q, Δp, ω, and ρ, α and β are determined within about $\pm 6\%$.

4.2 Presentation of Results

Figure 3 is a plot of α versus β for counter-clockwise fan rotation for Blower Door A as determined in the NBS calibration facility. Fitting a curve of the form of eq (6) to the data yields

$$\alpha = 0.368 \exp(-1.72\beta). \tag{8}$$

The coefficient of determination r^2 has a value of 0.9928, and the standard error of the estimate of α is roughly $\pm 4\%$ of its mean value.

Equation (8) can be expressed as a relation between flow rate q and fan speed ω, pressure difference Δp and air density ρ as

$$q = \omega(3.52 \times 10^{-2}) \exp(-8.23\Delta p/\rho\omega^2). \quad (9)$$

As discussed earlier, eq (9) is not a linear relation between flow rate and fan speed, however the deviation from linearity is small except at low fan speeds. Figure 4 shows several lines relating flow rate to fan speed derived from eq (9), each for a different pressure difference. The solid portion of each line corresponds to the fan speed range for which calibration data was actually collected. The dashed portions extend beyond the measured range. The measured range of fan speed for each value of pressure difference are given in table 2. The dotted lines extending to the lower left in figure 4 are straight line fits to the calibration data. The straight line fits are indistinguishable from the actual calibration lines except at low fan speeds where the deviation can be significant. Past calibration formulations have employed straight lines, corresponding to these dotted lines[12,13]. We see that the use of such straight lines will lead to erroneously low estimates of air flow rates at low fan speeds. Table 3 shows air flow rates at Δp = 50 Pa for a range of fan speeds derived from eq (9) and from a straight line fit to the calibration data. The errors are large for the lower fan speeds, which implies that if straight line fits are used, then tight or small houses will be reported as tighter than they actually are.

Table 3. Comparison of 50 Pa Flows from Equation (9) and a Straight Line Fit to the Calibration Data

Fan Speed (s^{-1})	Air Flow Rate (m^3/s) Eq (9)	Air Flow Rate (m^3/s) Straight Line	% Error of Straight Line
13.33	0.068	0.031	-54%
14.17	0.090	0.065	-28%
15.00	0.115	0.099	-14%
15.83	0.142	0.134	- 6%
16.67	0.171	0.169	- 1%
17.50	0.201	0.203	+ 1%
18.33	0.233	0.238	+ 2%

Table 4 shows the results of applying both eq (9) and straight line calibration formulas to a sample of pressurization data for a small, tight house. The fan speed is given for each pressure difference, along with the corresponding air flow rates as calculated using eq (9) and a straight line fit to the calibration data. The air flow rates determined using the straight line are all lower than the flow rates calculated from eq (9). Curves are fit to the data, as is often done in analyzing pressurization test results from the field, and two common building tightness measures are calculated, the flow rates at 4 and 50 Pa. The 4 Pa air flow rate from the straight line fit is 24% lower than the 4 Pa rate from eq (9). The 50 Pa flow rate from the straight lines is 10% lower. Thus, we see the potential for error when using straight line calibration formulas to analyze blower door data.

Table 4. Comparison of Pressurization Test Results Using Equation (9) and Straight Line Fits to Calibration Data

Pressure Difference (Pa)	Fan Speed (s^{-1})	Air Flow Rate (m^3/s) Eq (9)	Straight Line	% Error of Straight Line
12.5	7.33	0.053	0.043	-19%
25.0	10.50	0.078	0.066	-15%
37.5	13.17	0.105	0.093	-11%
50.0	15.33	0.126	0.113	-10%
62.5	17.33	0.146	0.135	-8%
75.0	19.00	0.161	0.148	-8%

Curve Fits

Equation (9)	$Q = 0.0104\,\Delta p^{0.637}$	Q(4) = 0.025	Q(50) = 0.126
Straight Line	$Q = 0.0070\,\Delta p^{0.712}$	Q(4) = 0.019	Q(50) = 0.113
% Error of Straight Line		Q(4): -24%	Q(50): -10%

4.3 Comparison to Other Calibrations and Discussion

Figures 5 and 6 show calibration data for Blower Door B, which was built by the same manufacturer as the door tested in the NBS facility. The data on Blower Door B were obtained by the manufacturer by measuring air flow rates with an orifice plate in the wall of a settling chamber as described earlier. The individual "bunches" of points correspond to the different orifices used in the air flow rate measurements. There are fewer data points and more scatter than in the NBS calibrations shown in figure 3. The manufacturer fit the counter-clockwise fan rotation calibration data to the following expression

$$Q = 234 - 355\sqrt{\Delta p} + 178\omega \; . \tag{10}$$

Q is air flow in m^3/hr. Besides being physically incorrect, eq (10) predicts a nonzero air flow rate for zero Δp and ω. Fitting the NBS calibration data to a curve of the same form yields

$$Q = -1 - 265\sqrt{\Delta p} + 149\ \omega. \qquad (11)$$

While eq (11) still leads to errors at low fan speeds, it does predict essentially zero air flow for Δp and ω equal to zero. While eq (9) is physically correct and more accurate than the linear formulations in eq (10) and (11), it is also more complex and questions have been raised concerning misuse by field personnel[23]. Equation (11) could be used as a substitute without much loss of accuracy, but only for a limited range of fan speed.

Figure 7 shows a comparison of the curve fit to our calibration of Blower Door A and the measurements made on Blower Door A by the manufacturer (counter-clockwise fan rotation). The manufacturer's calibration data for Blower Door B are also included in the figure. The manufacturer tested Blower Door A using only a single orifice, and therefore all the points are close together. These data are about 25% greater than the curve fit to our calibration of the same door. The manufacturer obtained more data on Blower Door B, and these data are above our curve fit to Blower Door A, about 0.02 higher on the α scale. This difference corresponds to about 50% of α for high values of β and 6% for low values. There are a few manufacturer's points, with α equal to about 0.45, which lie much farther from our line. These points are very different from a curve fit to the other manufacturer's points, and this difference is obvious in the nondimensional presentation of the data. The reason for the otherwise consistant difference between the manufacturer's calibration of Blower Door B and our calibration of Blower Door A is not clear. The difference could be due to sight differences in the blower doors.

5. CONCLUSIONS

This report has presented the problem of calibrating blower doors and the techniques used in the NBS calibration facility. The NBS facility was used to calibrate one blower door, and a physically appropriate calibration formulation was applied to the data. Previous calibrations have used linear relations between air flow rate and fan speed which can lead to errors in flow determination at low fan speeds. It is pointed out that such errors can lead to tight or small houses being reported as more airtight than they actually are if the straight line fits are used. Such straight line calibrations can be used if the range of fan speed is appropriately limited. In addition, our calibration formulation allows for straightforward density corrections. Other blower doors, including those which employ direct air flow rate measurement, may be tested in the facility in the future.

6. ACKNOWLEDGMENTS

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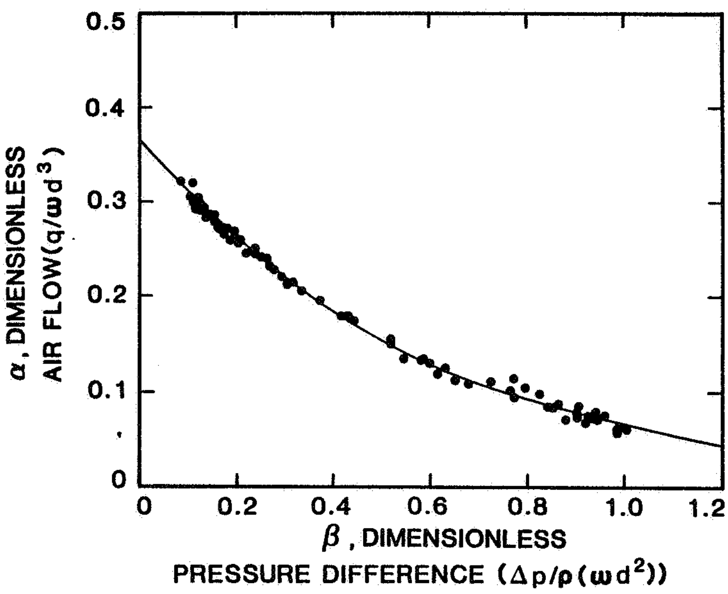

Figure 3 Dimensionless Flow Rate vs Dimensionless Pressure Difference, Counter-Clockwise Fan Rotation, NBS Calibration of Blower Door A

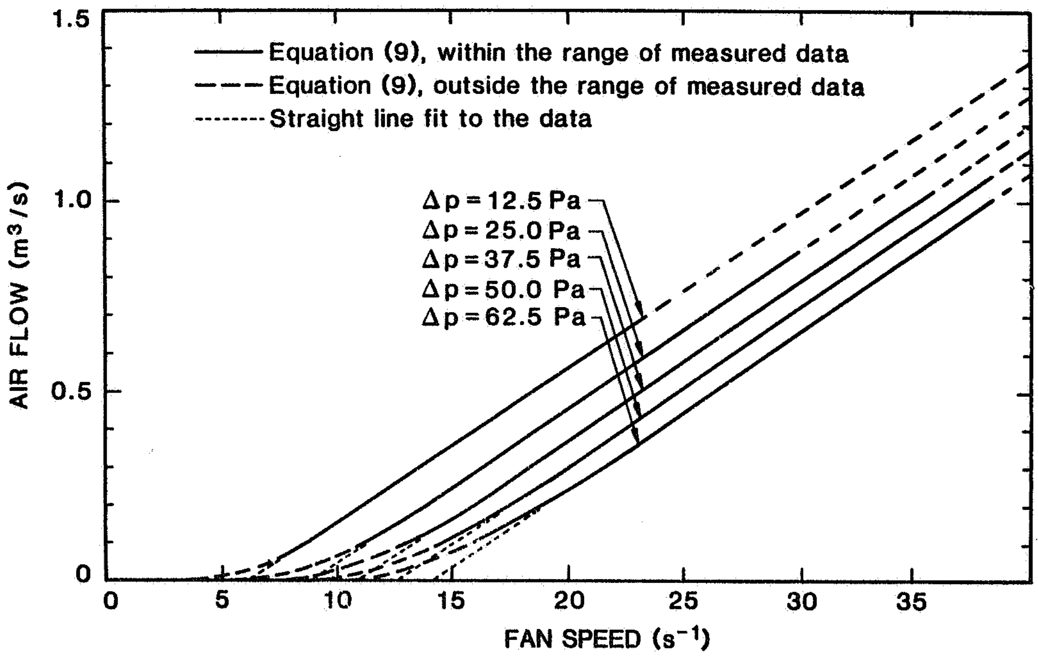

Figure 4 Air Flow Rate vs Fan Speed at Several Pressure Differences

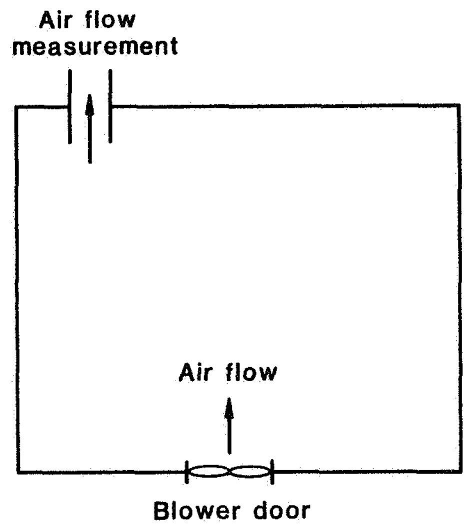

Figure 1 Simple Schematic of General Calibration Chamber

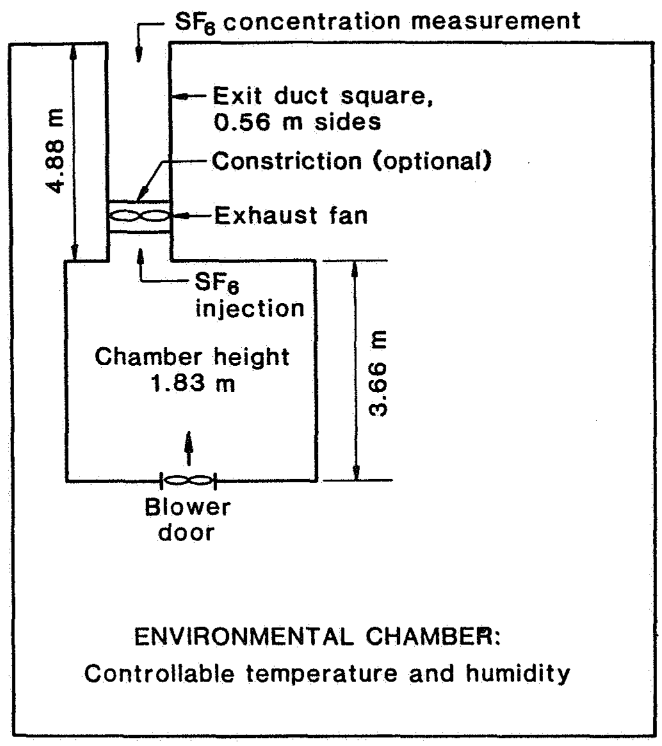

Figure 2 Schematic of NBS Calibration Facility

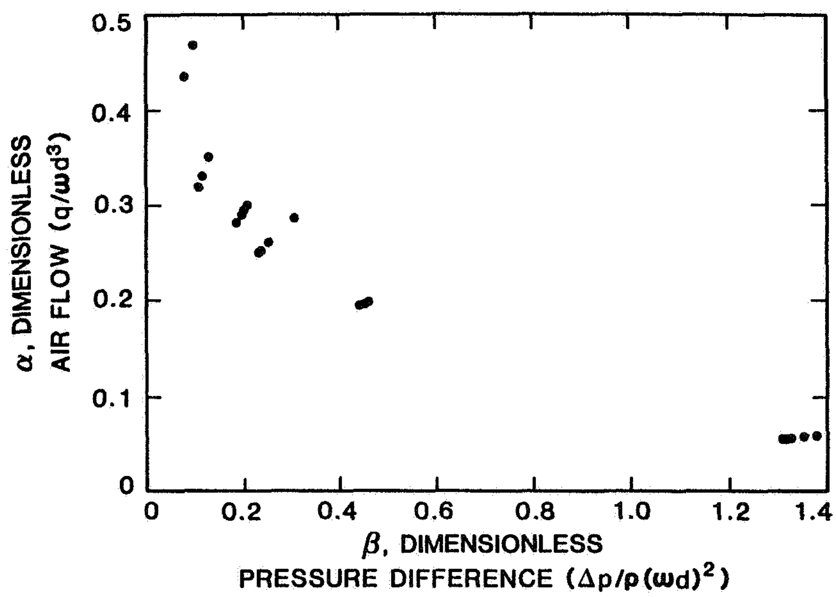

Figure 5 Dimemsionless Flow Rate vs Dimensionless Pressure Difference, Counter-Clockwise Fan Rotation, Manufacturer's Calibration of Blower Door B

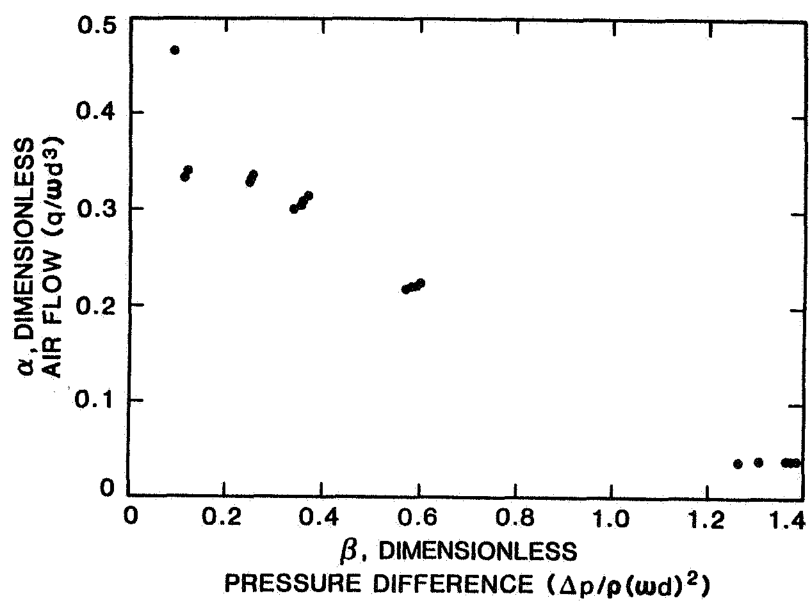

Figure 6 Dimensionless Flow Rate vs Dimensionless Pressure Difference, Clockwise Fan Rotation, Manufacturer's Calibration of Blower Door B

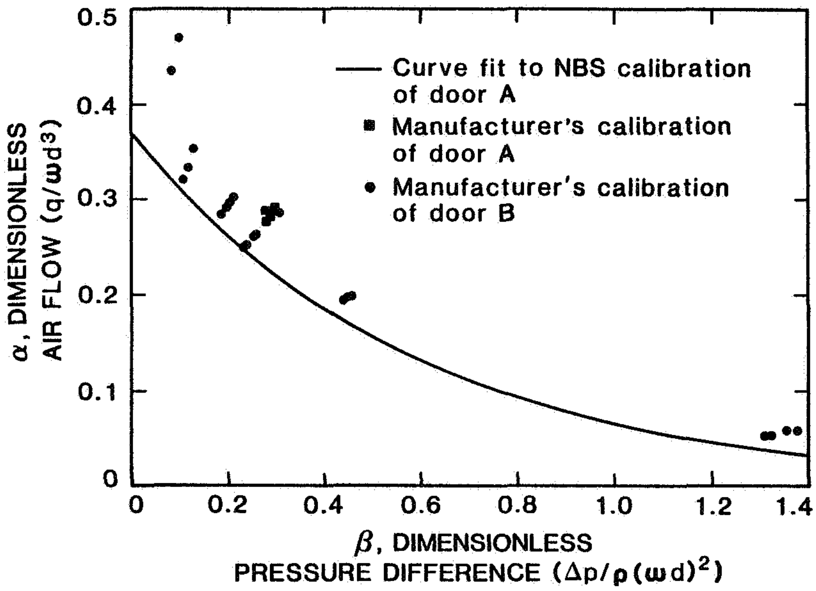

Figure 7 Comparison of Calibrations of Blower Doors A and B

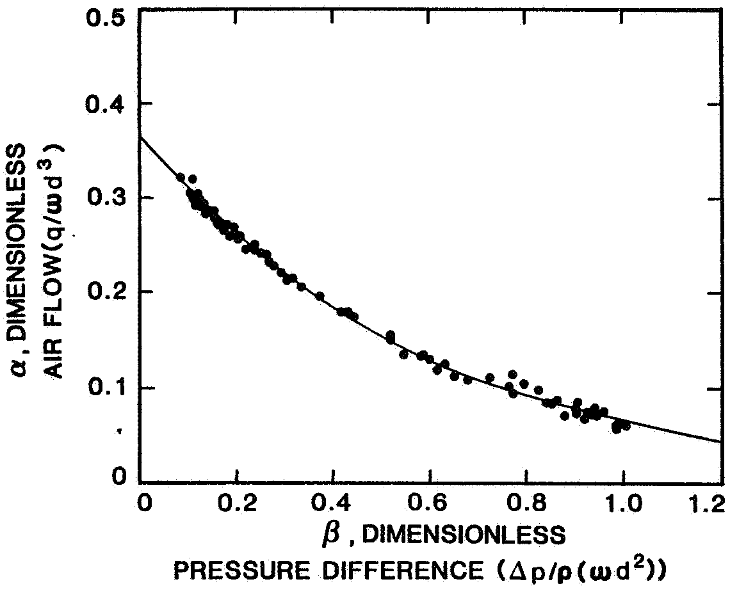

Figure 3 Dimensionless Flow Rate vs Dimensionless Pressure Difference, Counter-Clockwise Fan Rotation, NBS Calibration of Blower Door A

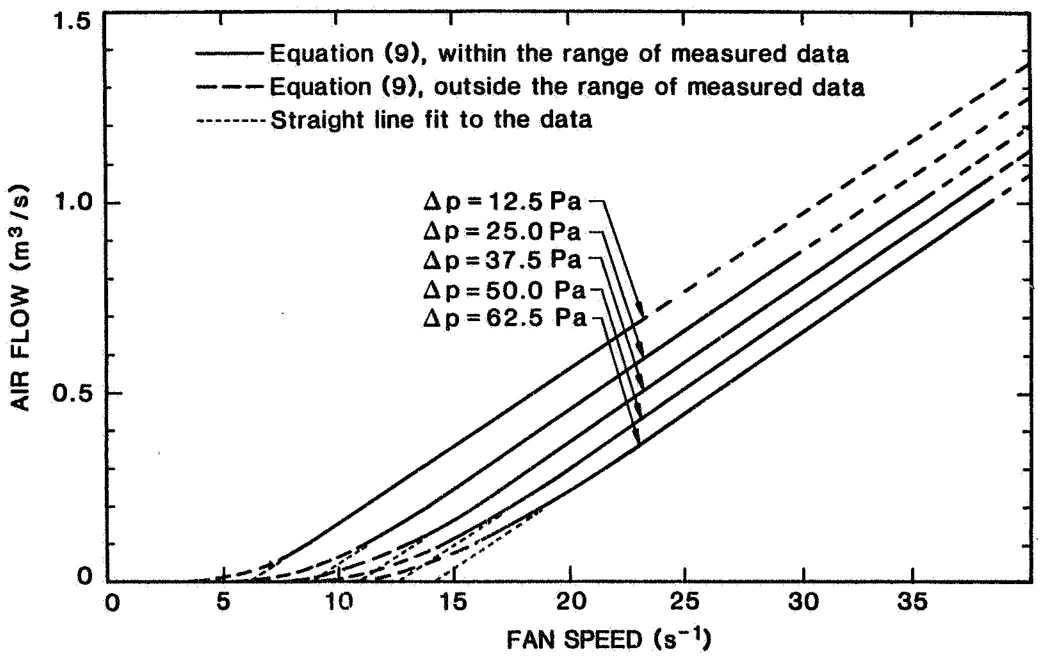

Figure 4 Air Flow Rate vs Fan Speed at Several Pressure Differences

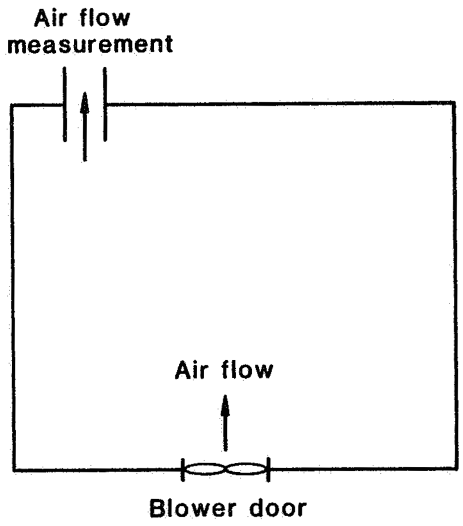

Figure 1 Simple Schematic of General Calibration Chamber

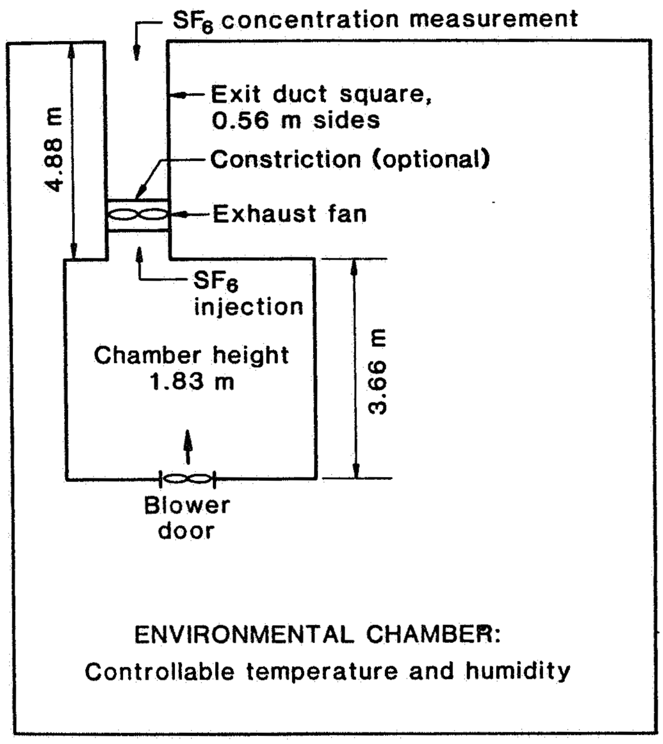

Figure 2 Schematic of NBS Calibration Facility

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