TECHNICAL NOT

AIR LEAKAGE OF OFFICE BUILDINGS

I. N. POTTER
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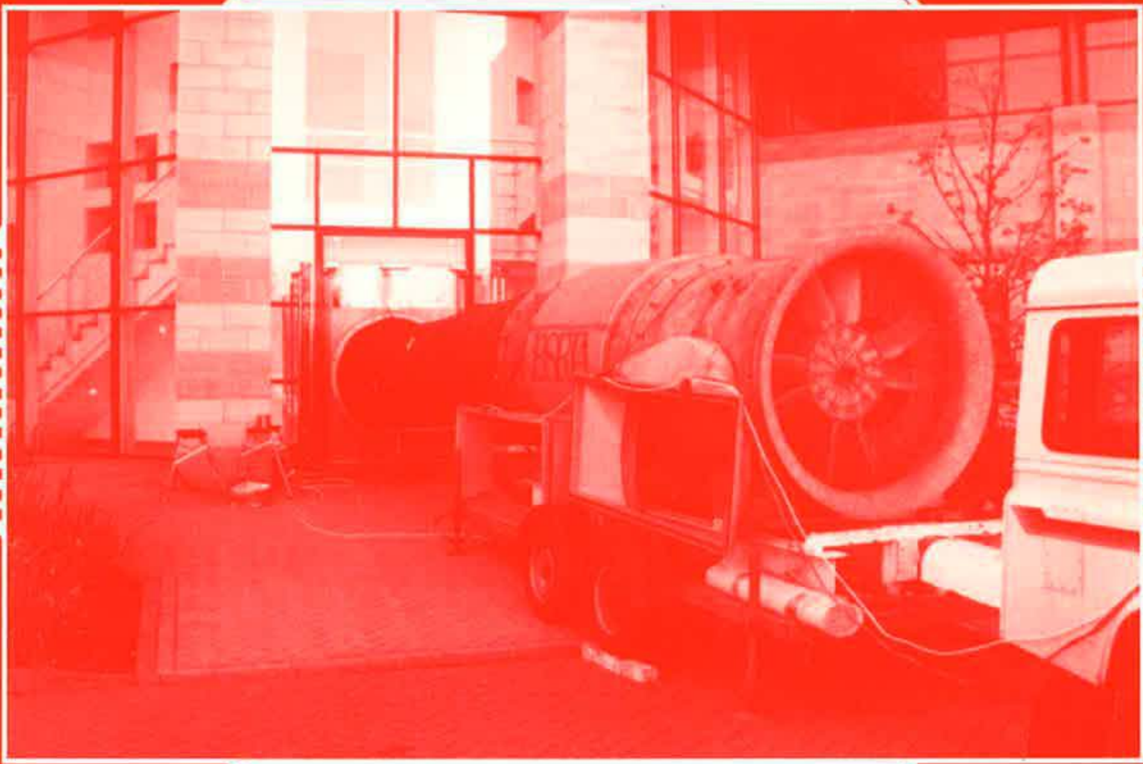

BSRIA

TECHNICAL NOTE TN8/95

AIR LEAKAGE OF OFFICE BUILDINGS

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SUMMARY

This Technical Note presents the results of measurements of the air leakage of twelve large office buildings. Various different construction types have been tested, with four of the buildings being naturally ventilated and the remainder air-conditioned.

Ideally air-conditioned buildings should have minimal air infiltration and naturally ventilated buildings should have air infiltration under occupant control. The results of this research indicate that for relatively large office buildings in the United Kingdom there are openings left in the structure which are on average equivalent to 5 square metres (54 square feet).

The average normalised leakage of these office buildings was 21.80 $m^3.hr^{-1}.m^{-2}$ at an envelope test pressure of 50 Pascals. The naturally ventilated buildings tended to be tighter than air-conditioned buildings and pre 1990 buildings tended to be tighter than post 1990 buildings. For comparison the average air leakage of large American office buildings is 8.25 $m^3.hr^{-1}.m^{-2}$ and large Canadian office buildings, post retrofit where applicable, is 6.76 $m^3.hr^{-1}.m^{-2}$. The average air leakage of UK factory/warehouse buildings is 35.86 $m^3.hr^{-1}.m^{-2}$ and the average air leakage of Swedish factory/warehouse buildings is 4.37 $m^3.hr^{-1}.m^{-2}$. BSRIA experience with buildings with an airtightness specification, has idicated that it is possible for UK office buildings to attain an air leakage less than 3.0 $m^3.hr^{-1}.m^{-2}$, superstores less than 3.0 $m^3.hr^{-1}.m^{-2}$, archival storage units less than 2.0 $m^3.hr^{-1}.m^{-2}$ and cold and chill stores less than 1.0 $m^3.hr^{-1}.m^{-2}$.

Whole building predicted infiltration rates exceed 1 air change per hour in nine of the buildings for wind speeds of 12.6 $m.s^{-1}$ ('Strong breeze' - Beaufort force 6) and above. In two buildings the air change rate is nearly three per hour for these wind speeds. Individual offices located on the windward side of such buildings will experience 'fresh' air change rates many times higher than those predicted for the entire building.

BSRIA recommends that all new buildings should have a maximum air leakage of 10 $m^3.hr^{-1}.m^{-2}$ and air-conditioned or low energy buildings should have a maximum air leakage of 5 $m^3.hr^{-1}.m^{-2}$ at a test pressure of 50 Pascals.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

This report presents the results of measurements of the air leakage of twelve large office buildings. Various different construction types have been tested, with four of the buildings being naturally ventilated and the remainder air-conditioned. The measurement protocol is presented in Section 2 and the details of the buildings tested are presented in Section 3. The results of the air leakage tests are given in Section 4.

The resultant ventilation rate has been predicted for all of the office buildings using a BSRIA air infiltration calculation model. The air infiltration rates have been calculated for all buildings tested at eight wind speeds, at three wind directions and for three internal/external temperature differences and the results are presented in Section 5.

The variation in air leakage characteristics of office buildings varies from marginally acceptable to worse than standard UK factory buildings. Therefore, for two similarly sized office buildings the predictive model was run for all anticipated wind speeds in increments of 1 $m.s^{-1}$ and all expected external temperatures in 1 deg C intervals to provide the ventilation heat loss of each building. The energy penalties for poorly constructed buildings in terms of airtightness are presented in Section 6.

2 MEASUREMENT PROTOCOL

The Ventilation & Special Projects Section designed the "Fan Rover" to assess the ventilation heat loss in factories and warehouses [1]. This same equipment was used to measure the air leakage characteristics of large office buildings in this project. This section describes the general method used, which is in accordance with the draft ISO standard (June 1990) for determination of building airtightness by the fan pressurisation method.

2.1 DESCRIPTION OF TEST PROCEDURE

The air leakage characteristics of the building were determined using an air pressurisation technique. This technique requires air to be supplied to the building at a variety of air flow rates, along with the measurements of the resulting pressure differential across the building. This pressure differential and measured air flow rate can be related by the equation:-

$$Q = k_*(dp)^n$$

Where:

Q	is the air flow rate supplied to the building	$m^3.s^{-1}$
dp	is the pressure differential across the building	Pa
k	is the air leakage coefficient	$m^3.s^{-1}.Pa^{-n}$
n	is an exponent normally between 0.5 and 1.0.	

BSRIA developed this pressurisation technique to assess the air leakage of large buildings using the "Fan Rover". This equipment consists of a mobile fan unit mounted on a trailer, and driven using the rear power take-off of a Land Rover, thus alleviating the need for any intrusion into a building's electrical system. The unit is designed to supply up to 30 $m^3.s^{-1}$, and has a lower measurable air flow rate of 5 $m^3.s^{-1}$ using the standard built-in flow grid. A special flow grid consisting of two tubes across the unit incorporates total pressure holes spaced at Log-Chebycheff intervals. The unit was calibrated at BSRIA using standard anemometric and tracer gas techniques. The pressure differential across the Flow Grid and the building are both measured using Furness Controls Type FC014 Micromanometers regularly calibrated by the manufacturers, augmented by regular calibration checks by BSRIA. Lower flow rates are measured by attaching a Wilson flow grid to the rear of the fan unit.

Throughout the test periods, air temperatures were measured using type UU thermistor probes connected to a Grant Squirrel data logger. All air temperatures were recorded at 2 minute intervals. The accuracy of these probes is better than ±/-0.2°C. The internal temperature was averaged for the period of each test to provide a mean internal air temperature. Similarly, the external temperature was averaged throughout the period of each test.

In addition, the local wind speed and direction was measured at a height of 10 m throughout the period of the tests, and recorded at intervals of 2 minutes and averaged for each test period. The wind speed and direction were measured with a Porton anemometer and windvane mounted on the top of a Clark telescopic mast which was secured to the rear of the Land Rover. If the local wind speed exceeds force 3 or 4, then it is not satisfactory to carry out the air leakage test.

All buildings were tested with all external doors and windows closed and with all internal doors wedged open. The test procedure was carried out with all mechanical ventilation openings sealed with polythene sheet and self-adhesive tape. Air inlets and outlets only were sealed and not smoke extract fans, grilles or flues.

2.2 DATA PROCESSING

The results of measurements directly associated with air leakage tests were initially verified 'on-site'. This consists of converting the pressure difference across the flow grid into an air flow rate using the required calibration. The pressure difference across the building versus the measured air flow rate were plotted on a lap-top computer, and the slope determined. This also provides confirmation that the relationship between these parameters was generally as expected and that a door or window had not opened during the tests. Provided that the envelope surface area was known, provisional results were determined on-site.

The data was further processed in the laboratory for two factors. The corrections applied to the air flow rates were firstly an air density correction, determined from the air temperature and barometric pressure of the flow grid. The second correction applied was for the change in air temperature as air enters the building, which results in a change in the air volume. For example, with pressurisation the outside air passes though the apparatus into the building, and mixes with the inside air. If the indoor air temperature is higher, the volume increases, and the volume flow out of the building envelope is slightly greater than the measured air flow rate. A regression analysis was carried out on the pressure differential across the building, and the corrected air flow rate to calculate values of 'k' and 'n'. The correlation coefficient was also calculated to indicate the 'fit' of the data to the calculated relationship. Using the calculated relationship, the air flow rate required to pressurise the building to 50 Pa was determined and included with the data presentation in the building report. The air flow rate required to pressurise the building to 50 Pascals was normalised with respect to the surface area (S) of the building, thus yielding values for Q_{50}/S ($m^3.hr^{-1}.m^{-2}$).

2.3 SMOKE TESTS

It is quite helpful to carry out smoke tests to determine the location of the air leakage paths. Not all buildings in this research programme were subject to a smoke test but whole building smoke tests can be undertaken for unoccupied buildings and partial smoke tests undertaken for occupied buildings.

Smoke generators utilising food grade polyglycols were used to identify air leakage paths. For whole building smoke tests five generators are used to fill up the entire building and the Fan Rover operated to displace the smoke through the air leakage paths in the structure. For occupied buildings, the Fan Rover would be operated to provide a suitable positive pressure within the building and smoke directed at particular candidate air leakage paths. Video recordings are usually taken of the smoke egress from outside the building and demonstrate quite clearly problem details.

2.4 ON-SITE REQUIREMENTS

The following outlines the requirements to complete the test programme on-site.

1. All mechanical ventilation openings are required to be sealed with polythene sheet and self-adhesive tape. Smoke extract fans grilles, etc. should not be sealed.

2. All exterior doors and windows need to be kept closed during the actual pressurisation tests.

3. Sufficient access to a door is required for the Fan Rover. The overall length, including ductwork is 15.5 m. A distance of a least 20 metres is therefore required to manoeuvre the facility into the required position and be normal to the access door. It is preferable to attach the unit to a roller shutter door or a double door, although we have the facility to attach the unit to a single door. The transformation to a single door means that the maximum flow rate is reduced by approximately 10%.

4. The actual test is usually completed in well under one hour. During this period no personnel should enter or exit the building. It is preferable if the building is unoccupied.

5. There should be no moveable objects near the fan unit inside the building, since they would be displaced by the air flow.

6. The integrity of the structure should be complete for the tests.

7. Envelope areas for the building need to be calculated. These are the areas of the roof and walls wherever the air sealed surface has been defined.

3 DESCRIPTION OF THE BUILDINGS TESTED

Building Number 1

Approximate date of construction 1970
Flat roof
Prefabricated panels fitted together using 'Clasp' construction
Single glazed windows, some openable
2 storey

Height of Building	:	6.10 m
Volume of Building	:	1,951 m^3
Footprint Area	:	308 m^2
Envelope Area	:	881.5 m^2

Building Number 2

Approximate construction date	:	Elizabethan (I)
Refurbished	:	Victorian

Pitched roof (49°)
Solid walls, outer skin brick
Leaded windows, openable
1, 2 and 3 storey

Height of Building	:	8.5 m
Volume of Building	:	14,109 m^3
Footprint Area	:	1,486 m^2
Envelope Area	:	5,131 m^2

Building Number 3

Approximate date of construction 1991
Flat roof with pitched mansard (45°)
Steel frame
Brick outer cladding wall
Pre-cast panels for inner wall
Metal framed double glazed windows, some openable
Full height central atrium
5 and 6 storey

Height of Building	:	18.85 m
Volume of Building	:	39,149.2 m^3
Footprint Area	:	2,268 m^2
Envelope Area	:	8,932.5 m^2

Building Number 4

Approximate date of construction 1985 and 1990
Pitched roof between ground and first floor
Flat roof with pitched mansard (40°)
Steel frame
Brick outer cladding wall
Blockwork and plasterboard inner cladding wall
Metal framed double glazed windows, fixed
1 and 2 storey

Height of Building	:	7.0 m
Volume of Building	:	14,855.5 m^3
Footprint Area	:	1,650.7 m^2
Envelope Area	:	4,457.0 m^2

Building Number 5

Approximate date of construction 1963
Flat roof
Pre-cast panels on frame
Metal openable windows with secondary glazing
5 storey with 7 storey central core between wings

Height of Building	:	14.5 m
Volume of Building	:	16,571.6 m^3
Footprint Area	:	1,111 m^2
Envelope Area	:	4,508.3 m^2

Building Number 6

Approximate date of construction 1991
Pitched roof (17°)
Steel frame
Brick - block cavity wall
Metal framed triple glazed windows, with encapsulated blinds
3 storey

Height of Building	:	10.28 m
Volume of Building	:	10,589.8 m^3
Footprint Area	:	1,031 m^2
Envelope Area	:	2,689.4 m^2

Figure 1 Normalised air leakage of offices

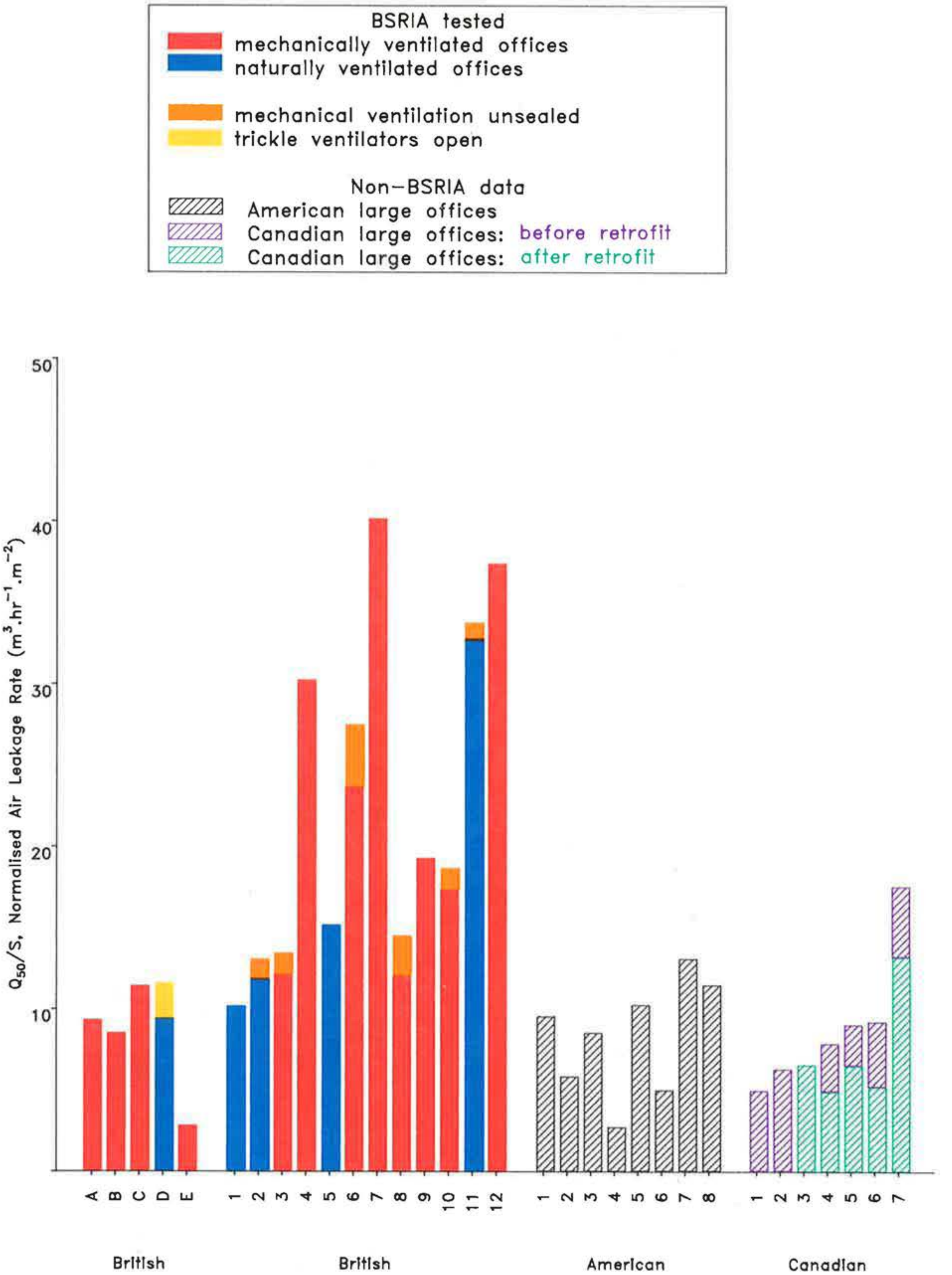


Figure 2 Predicted air change rates: based on actual leakage

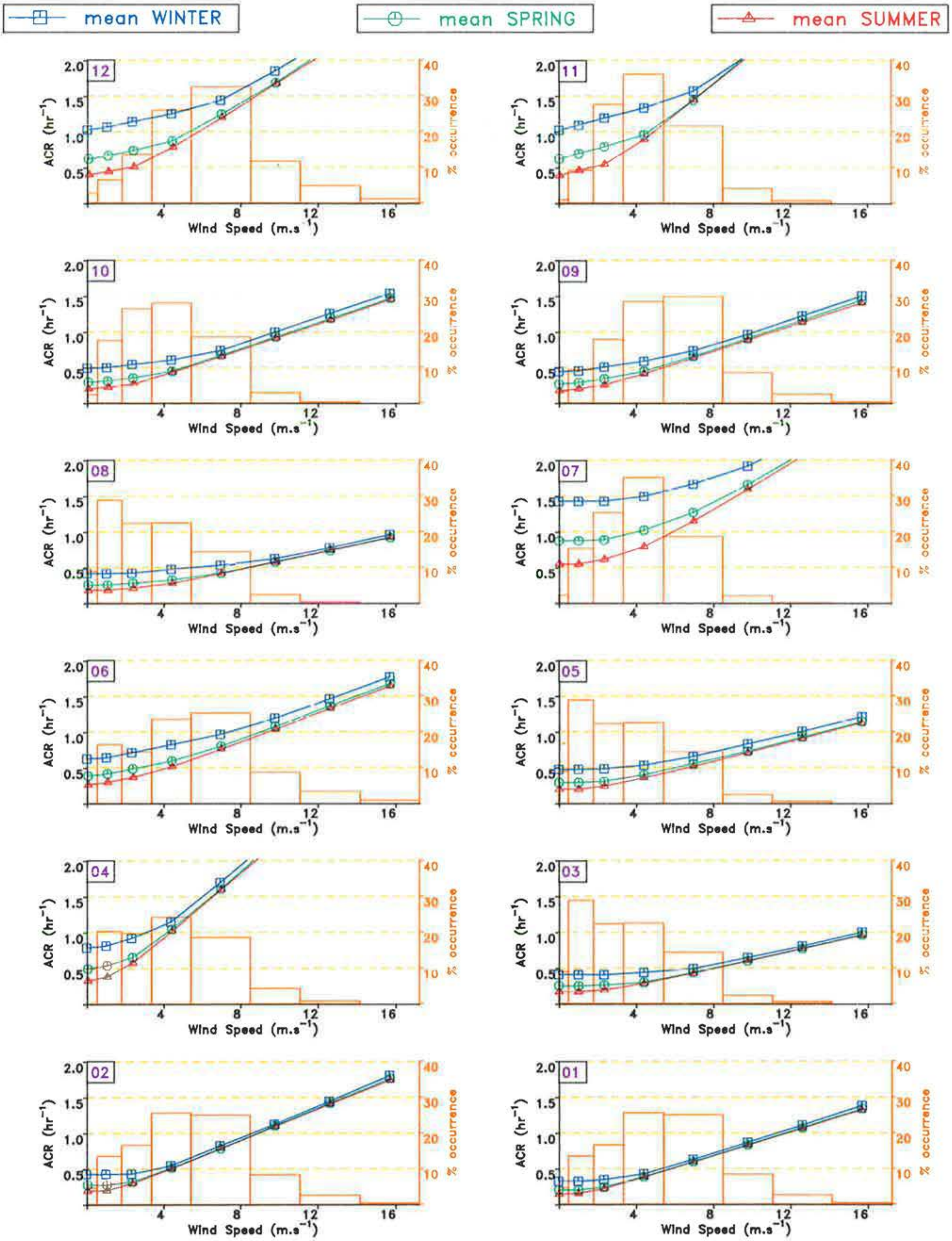


Figure 3 Average predicted ACR's for different air tightness targets

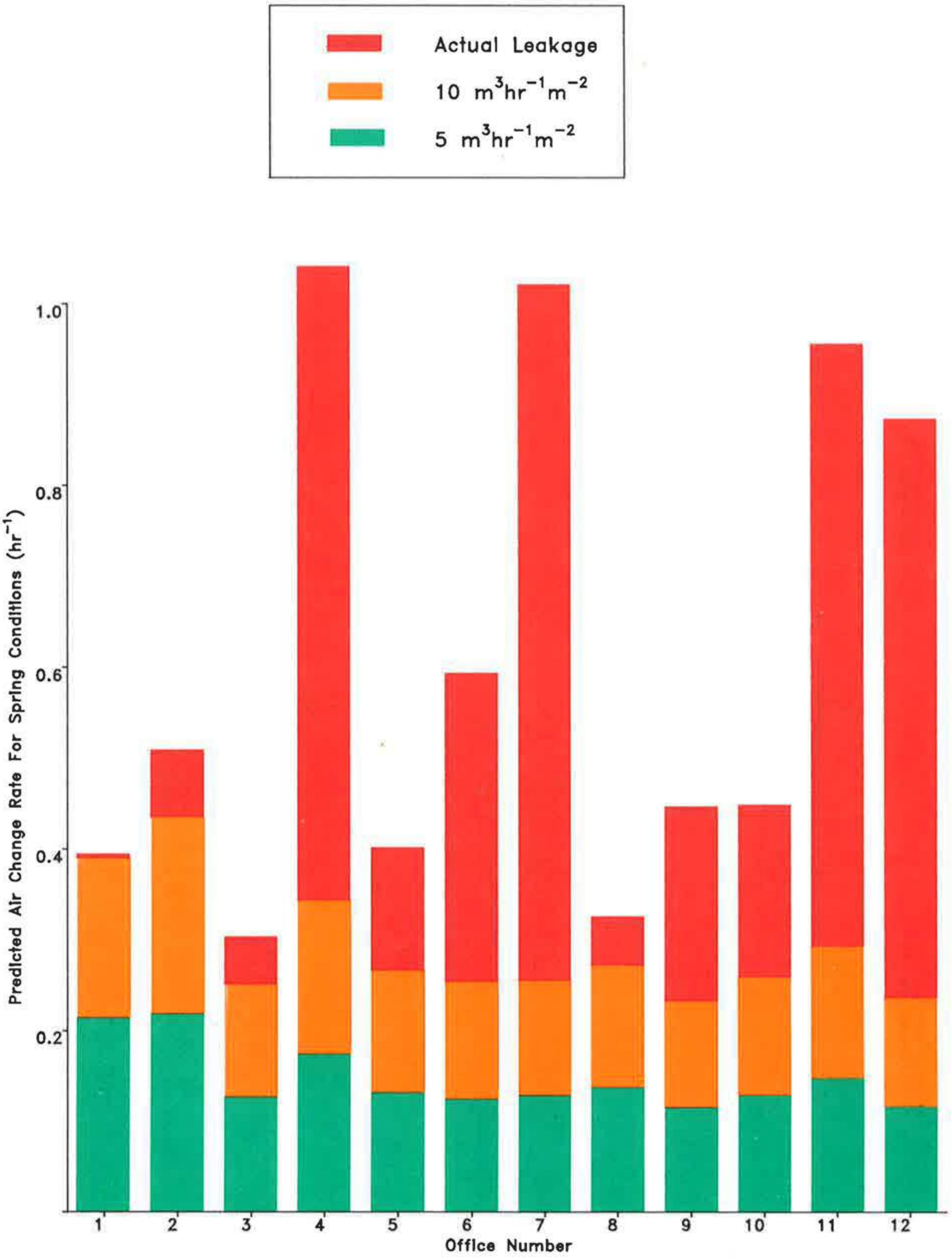
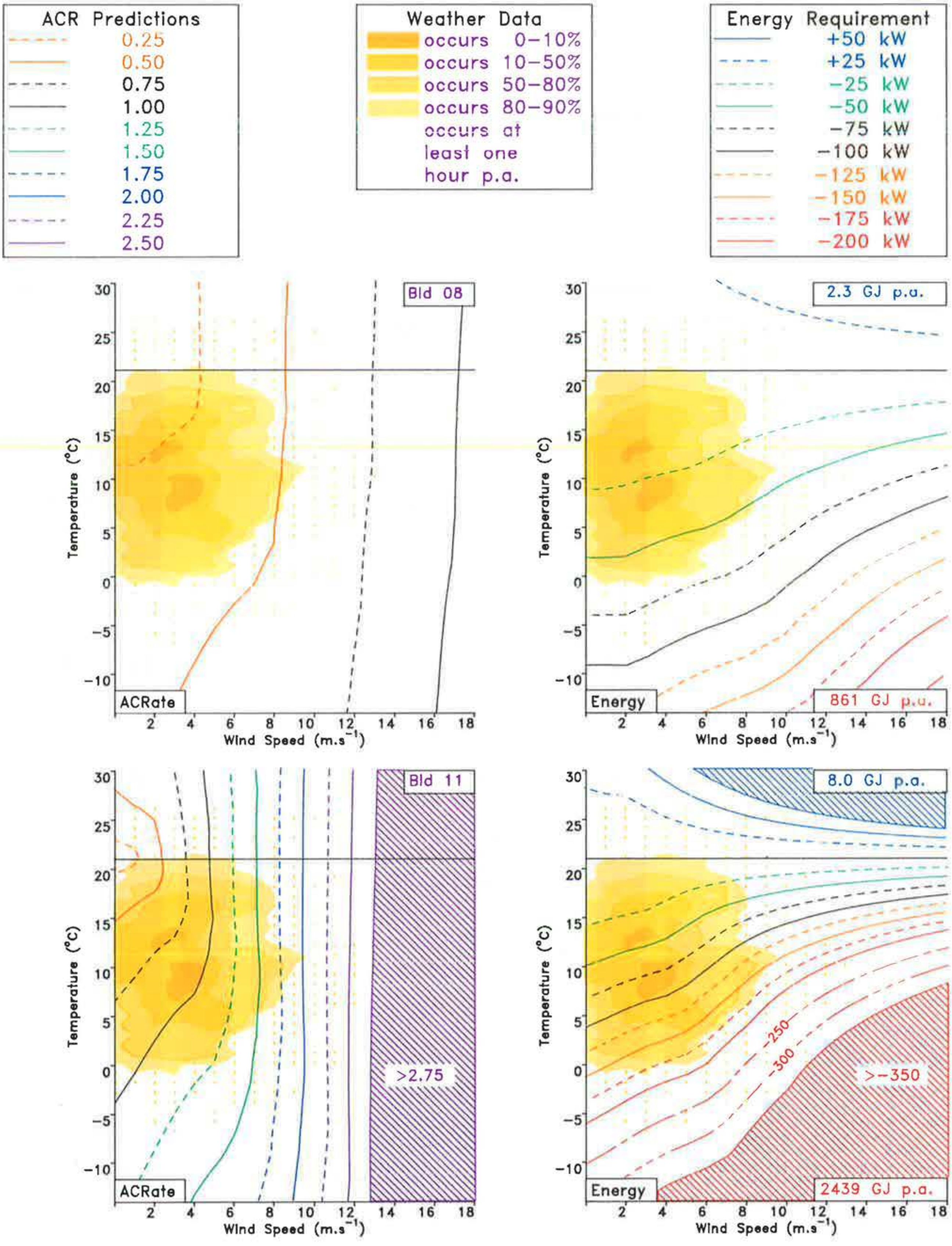


Figure 4 Comparison of two 20,000m³ office buildings



Building Number 7

Approximate date of construction 1986
Flat roof
Steel frame
Brick outer cladding
Blockwork inner wall
Metal framed windows double glazed
6 storey

Height of Building	:	20.0 m
Volume of Building	:	15,360 m^3
Footprint Area	:	814 m^2
Envelope Area	:	3,328 m^2

Building Number 8

Approximate date of construction 1989
Flat roof
Steel frame
Curtain walling on front protruding wings, brick outer cladding on remainder
Central full height atrium
Metal framed double glazed windows, all fixed
5 storey, diminishing floor area with height on front wings

Height of Building	:	18.30 m
Volume of Building	:	21,008 m^3
Footprint Area	:	1,375 m^2
Envelope Area	:	4,782.9 m^2

Building Number 9

Approximate date of construction 1991
Central section roof : in short pagoda style
Wings : pitched roof (30°)
Steel frame
Brick - block cavity wall
Full height central atrium
Metal framed windows, double glazed
1 and 3 storey

Height of Building	:	11.35 m
Volume of Building	:	44,335 m^3
Footprint Area	:	3,087 m^2
Envelope Area	:	8,810 m^2

Building Number 10

Approximate date of construction 1990
Pitched roof (30°)
Steel frame
Brick - blockwork cavity wall
Metal framed double glazed windows, some openable

Height of Building	:	10.1 m
Volume of Building	:	10,356.8 m^3
Footprint Area	:	1,047 m^2
Envelope Area	:	2,785.5 m^2

Building Number 11

Approximate date of construction 1992
Multi- blocks each with own section of pitched roof (22°)
Steel frame
Brick - block cavity wall with insulation fixed to inner skin

Double glazed metal windows : openable
Central atrium at entrance
2 and 3 storey

Height of Building	:	13.60 m
Volume of Building	:	20,379.3 m^3
Footprint Area	:	2,291 m^2
Envelope Area	:	5,504.4 m^2

Building Number 12

Approximate date of construction 1992
Pitched roof (23°)
Steel and concrete framed building
Outer cladding decorative blockwork/brick/curtain walling
Inner cladding blockwork
Full height atrium at entrance
Metal double glazed windows, some openable
2 and 3 storey

Height of Building	:	10.0 m
Volume of Building	:	17,576.8 m^3
Footprint Area	:	1,853 m^2
Envelope Area	:	4,723.9 m^2

4 RESULTS OF THE BUILDING TESTS

Various researchers nationally and internationally present the results of air pressurisation tests in different ways. The most commonly accepted method is to express the air leakage of the structure as the air flow rate required to pressurise the building to 50 Pascals (Q_{50}) divided by the envelope area (S). The results for the twelve office buildings tested in this project are presented as buildings 1 to 12 in the chart presented in Figure 1. The naturally ventilated buildings are denoted by solid blue bars and air-conditioned buildings or mechanically ventilated buildings by solid red bars. The orange 'hats' are the difference between the mechanical ventilation openings sealed and unsealed. The average air leakage for these twelve buildings is 21.80 $m^3.hr^{-1}.m^{-2}$. The naturally ventilated buildings (17.40 $m^3.hr^{-1}.m^{-2}$) tend to be tighter than air-conditioned buildings (23.98 $m^3.hr^{-1}.m^{-2}$). Pre 1990 buildings (17.81 $m^3.hr^{-1}.m^{-2}$) tend to be tighter than post 1990 buildings (24.62 $m^3.hr^{-1}.m^{-2}$). The overriding conclusion is that an office building can have an air leakage anywhere between 10 and 40 $m^3.hr^{-1}.m^{-2}$.

Other useful data on airtightness of office buildings are included in the chart. The data for buildings A, B and C are for fully glazed small air-conditioned buildings. The naturally ventilated building D was fitted with full window width trickle ventilators and the yellow 'hat' is the increased air leakage with all the trickle ventilators open. The yellow section, therefore, denotes the user control over the base air leakage rate. Ideally, the size of the blue and yellow sections should be reversed, such that the base air leakage is low and the user control high. Building E was a new air-conditioned building which had an airtightness specification target and accordingly tested for conformance. Office Building E is comparable to an average Swedish factory building.

Other international data is included in the chart for large American [2] and Canadian [3] office buildings and all average below 10 $m^3.hr^{-1}.m^{-2}$. Five of the Canadian buildings [4] were subjected to retrofits and the reduction in air leakage was apparent in four of the buildings as indicated by the green hatching compared with the original purple hatching. The retrofit had no impact on Canadian building number 3.

The resu'ts of the measurements are also presented in Table 1. The first two data columns present the air flow relationship between pressure and flow rate. Q_{25} and Q_{50} are the flow rates required to pressurize the building to the subscripted pressure in Pascals and N_{25} and N_{50} are the equivalent air change rates for the flow rates required to pressurise the building to the subscripted pressure difference (Pascals). The predicted average air change rate is also provided for an average wind speed of 4.38 $m.s^{-1}$, integrated over three wind directions with an external temperature of 11°C. The normalised air leakages of the building (Q_{25}/S and Q_{50}/S) are provided for test pressures of 25 and 50 Pascals, respectively. The last column indicates the area of holes left in the structure, which are given in square feet since most people can visualise this unit more easily. It is not difficult to conclude that 90 sq.ft. of holes left in an office building is unacceptable by any standard.

Table 1 Results of the Measurements carried out on the Office Buildings

Building Number	Leakage Coefficient	Flow Index	Q_{25}	Q_{50}	N_{25}	N_{50}	Predicted Average Air Change Rate	Q_{25}/S	Q_{50}/S	Area of Holes in Building sq.ft.
1	0.227	0.61	1.62	2.47	2.98	4.56	0.39	6.61	10.11	4.8
2	1.640	0.59	10.96	16.78	2.80	4.28	0.51	7.69	11.77	32.4
3	3.980	0.52	21.22	29.94	1.95	2.75	0.30	8.55	12.07	57.9
4	4.860	0.52	25.92	37.38	6.28	9.06	1.04	20.93	30.19	72.3
5	1.790	0.60	12.35	18.89	2.68	4.10	0.40	9.86	15.08	36.5
6	2.720	0.48	12.75	17.63	4.33	5.99	0.59	17.07	23.60	34.1
7	4.790	0.52	25.54	37.06	5.99	8.69	1.02	27.63	40.10	71.7
8	2.010	0.53	11.07	15.94	1.90	2.73	0.32	8.33	12.00	30.8
9	4.320	0.61	30.78	47.09	2.50	3.82	0.45	12.58	19.24	91.1
10	1.610	0.54	9.16	13.38	3.18	4.65	0.45	11.83	17.29	25.9
11	3.670	0.67	31.72	49.89	5.60	8.81	0.95	20.74	32.63	96.5
12	7.150	0.49	34.62	48.98	7.09	10.032	0.87	26.38	37.33	94.7

5 PREDICTION OF VENTILATION RATES

The natural ventilation rates have been predicted using the BSRIA designed and developed "CRKFLO" computer program [5], which calculates the flow rates between components, taking into account inside/outside temperature differences and wind effects on the building. The parameters which influence the natural ventilation performance of the building, wind effects and temperature difference, are described in this section, which also includes the results of the predictions.

5.1 WIND DATA

The first element in the prediction of natural ventilation rates is to establish the wind pressure coefficients for all the surfaces of the building structure. Each building was split up into twenty six external nodes of influence. The first twenty nodes characterize the external walls and nodes twenty one to twenty-six represent the roof sections. These are the node numbers for which a wind pressure coefficient needs to be assigned. Wind pressure coefficients are the fraction of the wind velocity pressure at building height. The data was established from an amalgam of data but principally from [6]. The wind velocity was varied between zero and 15.7 $m.s^{-1}$ in seven non equal steps. For these wind speeds various wind directions have also been incorporated into the predictions and an average taken of the three basic directions, ie 0°, 45°, 90°. The mean wind speed factors were derived using the Deaves and Harris model equation [7], which requires a Roughness Category for the terrain upwind of the building. Roughness Categories for the buildings varied according to location between 3, 4 and 5, which equate to open country, urban and city centre respectively. This Roughness Category establishes the aerodynamic roughness and zero-plane displacement values which are then used in the Deaves and Harris iterative model to calculate the basic friction velocity and gradient height. This does not hold true where the building height is less than the zero plane displacement, which does occur in city centre environments, in which case the CIBSE wind gradient data [8] has been used. Thus the basic mean wind speed measured over standard meteorological terrain at a height of ten metres can be translated to the friction velocity and gradient height upwind of the tested building, which are then used to derive the wind velocity at building height. The wind velocity at building height and the outside air temperature (density correction) are then used to calculate the velocity pressure. The wind pressure acting on a particular section of the building is simply the product of the velocity pressure and the pressure coefficient.

5.2 BUOYANCY PRESSURE

Under normal circumstances the buoyancy pressures (stack effect) acting between inside and outside of a building would be a simple function of the absolute temperature difference between inside and outside of the building. Without wind forces, and inside air temperatures greater than external air temperatures, air would infiltrate the lower sections of the building and exfiltrate at higher levels.

The buoyancy pressures have been calculated as a function of height of the building and used as a correction to the wind pressures calculated previously. The design internal temperature has been assumed to be 21°C for Spring and Winter conditions and 28°C for Summer conditions. The outside air temperature was set to -4°C for the Winter design condition, 11°C for the Spring condition and 24°C for the Summer design condition. For average wind speeds and above, the dominant pressures tend to be wind effects.

5.3 INPUT DATA

A special front end software package has been developed in order to provide comparability of results with relative ease and uses subroutines to undertake sensitivity studies more easily. The following parameters were then input into the model for each building:

Building volume
Height of building
Roughness category
Designated wind speeds
Internal temperatures
External temperatures
Envelope area
Measured air leakage characteristics of the building

The largest unknown in this study is the distribution of the air leakage paths. However the percentage air leakage through the roof sections does not in fact alter the overall air change rate particularly significantly. Wind direction is, however, quite a dominant factor.

5.4 RESULTS OF PREDICTIONS

The results of the predicted ventilation rates are presented in Figure 2. All twelve of the buildings are presented on the figure with building number twelve on the top left. The three curves present the predicted increase in ventilation rate with wind speed for the three temperature differentials used in the model and signified Winter, Spring and Summer. The orange histograms for each building present the percentage occurrence of wind speeds [9] at the location of the building (in practice the data applies to the nearest Meteorological Office anemograph station to the building). Building 12 is located in an exposed coastal region of South-East England and thus high wind speeds are more common than, for instance, building 4 which was located in Oxfordshire. Tall buildings and exposed locations lead to higher incidence of high wind speeds and therefore greater ventilation heat loss. It is therefore more critical to avoid high fabric air leakage rates in such circumstances. The five poorest buildings (4, 6, 7, 11 and 12) all exhibit high whole building air change rates at high wind speeds. It should be borne in mind that whilst the average air change rate appears low, these are the whole building air infiltration rates, which means that for a given wind direction, all of the infiltration load will be centred on the windward faces of the building and more particularly those offices which experience large air leakage paths. The air change rate in individual offices in such locations will be many times higher than the predicted values for the whole building. Equally 1.0 air change per hour in a building of 20,000 m^3 is still a significant infiltration flow rate at 5.6 $m^3.s^{-1}$.

Table 2 presents the predicted whole building air change rates for all the buildings tested for the range of expected wind speeds in the Spring temperature condition of 10°C external temperature and 21°C internal temperature. The predicted ventilation rates are based on the actual measured air leakage of the building and also with air tightness specifications of 10 $m^3.hr^{-1}.m^{-2}$ and 5 $m^3.hr^{-1}.m^{-2}$. The benefits of reduced fabric air leakage particularly under high wind speeds is indicated by the reduced predicted ventilation rates. Whole building predicted infiltration rates exceed 1 air change per hour in nine of the buildings for wind speeds of 12.6 $m.s^{-1}$ ('Strong breeze' - Beaufort force 6) and above. For building number 4, the air change rate is nearly three per hour for these wind speeds. Individual offices located on the windward side of the building coupled with large air leakage paths will experience 'fresh' air change rates many times higher than those predicted for the entire building.

Ventilation requirements for the occupants are only of significance in naturally ventilated buildings. Three of the four naturally ventilated buildings were quite good in terms of airtightness and satisfied the ventilation requirements of the occupants for average wind speeds and external temperature, based on 10 litres per second per person. Building 11 exceeded these ventilation requirements by a factor of five under the same weather conditions. It would be more appropriate from a design point of view to provide minimum ventilation under more severe weather conditions and leave the occupants to control the ventilation under less adverse conditions.

Figure 3 presents the predicted air change rates for different airtightness targets for *mean* wind speeds and Spring temperatures. The target for all buildings should be the top of the orange section at 10.0 $m^3.hr^{-1}.m^{-2}$. The target for air-conditioned or low energy buildings should be the top of the green section at 5.0 $m^3.hr^{-1}.m^{-2}$. If no specification is imposed on the building then the fabric air tightness is expected to be anywhere between 10 and 40.0 $m^3.hr^{-1}.m^{-2}$. The red bars present the actual air leakage of the buildings tested. The standard to which a building which is actually built is therefore quite variable. Building number 9 with an air leakage of 19.24 $m^3.hr^{-1}.m^{-2}$ is around the average for UK office buildings and the predicted whole building ventilation rate is 0.45 air changes per hour under average conditions. However, most of the air leakage paths in this building, as observed by smoke egress, were from the roof and roof/wall joints. This section of the building formed the supply plenum for the air-conditioning system on the First floor of the building. The location of the air leakage paths can therefore have a seriously detrimental effect on the performance of the HVAC system.

Table 2 Predicted ventilation rates during typical spring temperatures.

Office Number	Building Leakage $m^3hr^{-1}m^{-2}$	Wind Speed						
		1.02	2.34	4.38	6.95	9.78	12.6	15.7
1	Actual	0.20	0.24	0.39	0.60	0.84	1.08	1.35
	10	0.20	0.24	0.39	0.60	0.84	1.08	1.35
	5	0.11	0.13	0.21	0.33	0.46	0.59	0.74
2	Actual	0.26	0.31	0.51	0.78	1.10	1.42	1.76
	10	0.23	0.26	0.44	0.66	0.94	1.21	1.51
	5	0.11	0.13	0.22	0.33	0.47	0.61	0.75
3	Actual	0.25	0.26	0.30	0.44	0.61	0.78	0.97
	10	0.21	0.22	0.25	0.37	0.50	0.65	0.80
	5	0.11	0.13	0.13	0.18	0.25	0.33	0.40
4	Actual	0.53	0.65	1.04	1.60	2.27	2.92	3.63
	10	0.17	0.21	0.34	0.53	0.75	0.96	1.20
	5	0.09	0.11	0.17	0.27	0.38	0.49	0.60
5	Actual	0.29	0.31	0.40	0.56	0.73	0.93	1.15
	10	0.19	0.20	0.27	0.37	0.55	0.62	0.76
	5	0.10	0.10	0.13	0.18	0.24	0.30	0.37
6	Actual	0.41	0.48	0.59	0.80	1.07	1.36	1.68
	10	0.18	0.21	0.25	0.34	0.46	0.58	0.72
	5	0.09	0.10	0.12	0.17	0.22	0.28	0.35
7	Actual	0.87	0.88	1.02	1.27	1.66	2.10	2.60
	10	0.22	0.22	0.25	0.32	0.42	0.53	0.65
	5	0.11	0.11	0.13	0.16	0.21	0.26	0.33
8	Actual	0.25	0.28	0.32	0.42	0.58	0.74	0.92
	10	0.21	0.23	0.27	0.35	0.49	0.62	0.77
	5	0.11	0.12	0.14	0.18	0.24	0.31	0.39
9	Actual	0.29	0.34	0.45	0.66	0.91	1.16	1.44
	10	0.15	0.18	0.23	0.34	0.47	0.61	0.75
	5	0.07	0.09	0.12	0.17	0.23	0.30	0.37
10	Actual	0.31	0.35	0.45	0.68	0.93	1.19	1.47
	10	0.18	0.20	0.26	0.39	0.54	0.69	0.85
	5	0.09	0.10	0.13	0.19	0.27	0.34	0.42
11	Actual	0.69	0.79	0.95	1.44	2.07	2.68	3.36
	10	0.21	0.24	0.29	0.44	0.63	0.82	1.03
	5	0.11	0.12	0.15	0.22	0.32	0.41	0.52
12	Actual	0.67	0.74	0.87	1.25	1.68	2.19	2.73
	10	0.18	0.20	0.24	0.34	0.45	0.59	0.74
	5	0.09	0.10	0.12	0.17	0.22	0.29	0.36

6 PREDICTION OF VENTILATION HEAT LOSS

Two office buildings of similar size (20,000 m^3) were selected for more detailed predictive evaluation. Building 8 with a relatively low fabric air leakage rate of 12.0 $m^3.hr^{-1}.m^{-2}$ was compared with Building 11 which exhibited a relatively high fabric air leakage rate of 32.63 $m^3.hr^{-1}.m^{-2}$. The internal temperature of the buildings was fixed at 21°C and the infiltration model was run for all three wind directions, for all expected external temperatures in 1.0 deg C intervals and for all expected wind speeds in 1.0 $m.s^{-1}$ intervals. For this predictive exercise, both buildings were relocated to Kew for the climatic data set. The results are presented in Figure 4.

The top left hand graph presents the predicted air change rates for all expected temperatures and wind speeds for building number 8. The yellow shading presents the relative occurrence of such weather conditions. The yellow dots present occurrences outside the ninety percent of the time contour.

The bottom left hand graph presents the data for building number 11 and shows that high air change rates (greater than 1.0) cut through the section of high climatic occurrence. This is precisely what should be avoided. High fabric air leakage will mean that high and uncontrollable air change rates will occur for very significant proportions of the time.

These two buildings were selected because they were almost the same internal volume. An energy comparison could therefore be usefully determined as depicted by the right hand set of graphs in Figure 4. A ventilation heating load capacity of 100 kW (solid brown line), including people, lighting, small power and solar gain would be adequate for nearly all climatic occurrences for building number 8. A ventilation heating load capacity of nearly 300 kW (dashed red line) would be required for building 11. The infiltration load per annum has been calculated and printed in red in the lower right hand corner of each graph. For building 8 the infiltration load was 861 GJ per annum, whilst for building 11 this load rises to 2439 GJ per annum. The difference between these two buildings is therefore 1578 GJ per annum. This is not however a direct heating requirement since all internal gains need to be taken in to account but also this data assumes 24 hours a day, 365 days a year conditioning. However the difference in ventilation heat loss is not just a large energy wastage of several thousand pounds sterling per annum (based on gas heating costs) but there will be (and are) staff complaints in building 11 leading to wrangling between consultants, architects and builders, plus the additional expense of remedial action to correct the deficiencies. Excessive air leakage in occupied buildings is very expensive to correct.

7 AIR LEAKAGE PATHS IN NEW OFFICE BUILDINGS

In common with UK building practice, office buildings tend to be unique structures and as such the locations of the main air leakage paths vary considerably. It is entirely feasible and cost effective to specify new buildings with an air tightness specification which should be met before handover. Section 2 is a typical method statement for carrying out air tightness tests.

BSRIA has conducted airtightness and smoke tests on many buildings with air leakage specifications of 10 $m^3.hr^{-1}.m^{-2}$ or lower. This section provides some general guidance on minimisation of air leakage in office type buildings.

An airtight surface should be defined for the building and this is usually the inner surfaces of the structure so that ventilation of cavities and roof spaces is preserved.

Most modern windows are rarely a source of serious leakage. However the cills inadequately covering exposed cavities can be a significant air leakage path. Frames usually have a good mastic seal to the structure, but this should be checked, especially where recesses are involved. Large glazing systems are usually quite satisfactory but frame to frame and frame to structure details are sometimes deficient.

Perimeter heating pipes quite often run through a ventilated mullion cavity and these penetrations should be sealed. Equally all electrical, service and drain penetrations through the structure or into a cavity should be sealed. Particular cognisance should be taken of riser shafts and penetrations into and out of the shaft, which tend to terminate at ventilated roof level.

The major sources of air leakage however tend to be at roof level and roof to wall joints, especially where they tend to be hidden behind suspended ceilings. Offices with a concrete slab roof with or without a plant room above tend to be more airtight and easier to seal. Profiled metal decking type roof sections do leak, sometimes quite badly, and should be treated with an additional mastic seal on all end lap and longitudinal joints. Insulation filled plastic bags, tape sealed together should be avoided since they can rarely be adequately tape sealed at the perimeter of the structure. The life expectancy of the tape seal can be short since they can be subject to large temperature variations and mechanical damage can be easily sustained. Wall to roof section joints are typical major air leakage paths and these details should be designed with air sealing in mind. Changes in roof section also add to potential leakage through additional joints. It is also worth checking where the other end of Bison beams end up!

Lift shafts are quite normally vented to atmosphere, which in turn means that the lift shaft should be air sealed and good lift doors fitted with adequate seals.

Architects have a major role to play in designing out problem details, for instance, multiple steel beam joints at inner surface walls, multi level roofs (at air seal surface) with high joint lengths, etc. Quality assurance by the builder on site is singularly the most important factor. Sealing techniques which can be easily seen and therefore easily quality assured should be preferred and specified. Sub-contractors should also be aware of the airtightness requirements. For instance, well jointed blockwork and brickwork does not leak sufficiently to be of concern. Poorly jointed blockwork and brickwork can, and does, leak as do blocks left or knocked out for services. The use of unsurfaced treated mineral wool or glass fibre insulation to provide an air seal is wholly unsatisfactory and should be avoided.

Most of the above is covered by good building practice but envelope integrity is all too often overlooked during the design and build process.

8 CONCLUSIONS

Ideally air-conditioned buildings should have minimal air infiltration and naturally ventilated buildings should have air infiltration under occupant control.

The results of this research indicate that for relatively large office buildings in the United Kingdom there are openings left in the structure which are on average equivalent to 5 square metres (54 square feet).

The average normalised leakage of these office buildings was 21.80 $m^3.hr^{-1}.m^{-2}$ at an envelope test pressure of 50 Pascals. The naturally ventilated buildings tended to be tighter than air-conditioned buildings and pre-1990 buildings tended to be tighter than post 1990 buildings. The average air leakage of large American office buildings is 8.25 $m^3.hr^{-1}.m^{-2}$ and large Canadian office buildings, post retrofit where applicable, is 6.76 $m^3.hr^{-1}.m^{-2}$. The average air leakage of UK factory/warehouse buildings [1] is 35.86 $m^3.hr^{-1}.m^{-2}$ and the average air leakage of Swedish factory/warehouse buildings [10] is 4.37 $m^3.hr^{-1}.m^{-2}$.

Whole building predicted infiltration rates exceed 1 air change per hour in nine of the buildings for wind speeds of 12.6 $m.s^{-1}$ ('Strong breeze' - Beaufort force 6) and above. In two buildings the air change rate is nearly three per hour for these wind speeds. Individual offices located on the windward side of such buildings will experience 'fresh' air change rates many times higher than those predicted for the entire building.

It is quite clear that the air leakage of some UK office buildings is unacceptably high and leads to high predicted ventilation rates at all but low wind speeds. BSRIA experience with buildings with an airtightness specification, has indicated that it is possible for UK office buildings to attain an air leakage less than 3.0 $m^3.hr^{-1}.m^{-2}$, superstores less than 3.0 $m^3.hr^{-1}.m^{-2}$, archival storage units less than 2.0 $m^3.hr^{-1}.m^{-2}$ and cold and chill stores less than 1.0 $m^3.hr^{-1}.m^{-2}$.

BSRIA recommends that all new buildings should have a maximum air leakage of 10 $m^3.hr^{-1}.m^{-2}$ and air-conditioned or low energy buildings should have a maximum air leakage of 5 $m^3.hr^{-1}.m^{-2}$ at a test pressure of 50 Pascals.

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