TECHNICAL NOTE 7/92

# 6,142

# VENTILATION HEAT LOSS IN FACTORIES AND WAREHOUSES

I N Potter
T J Jones


BSRIA

TECHNICAL NOTE 7/92

# VENTILATION HEAT LOSS IN FACTORIES AND WAREHOUSES

I N Potter
T J Jones

**The Building Services Research and Information Association**
Old Bracknell Lane West,
Bracknell, Berkshire RG12 7AH UK
Tel: +44 (0) 1344 426511 Fax: +44 (0) 1344 487575
e-mail: bsria@bsria.co.uk web: www.bsria.co.uk

BSRIA

ISBN 0 86022 296 9

## CONTENTS


ACKNOWLEDGEMENTS 1

SUMMARY 2

1. INTRODUCTION 3

2. BACKGROUND 4

2.1 MEASUREMENTS INTO AIR LEAKAGE OF LARGE SINGLE CELL BUILDINGS 4

2.2 WORK CARRIED OUTSIDE THE UK 5

2.3 SUMMARY 5

3. DESIGN AND COMMISSIONING OF THE 'FAN ROVER' 8

3.1 TECHNICAL DIFFICULTIES 8

4. DESCRIPTION OF BUILDINGS TESTED 10

5. RESULTS OF THE BUILDINGS TESTED 4

6. PREDICTION OF NATURAL VENTILATION RATES 17

6.1 WIND DATA 17

6.2 BUOYANCY PRESSURES 17

6.3 INPUT DATA 18

6.4 RESULTS OF PREDICTIONS 18

7. ENERGY BENEFITS FOR BETTER SEALED STRUCTURES 20

8. REFERENCES 24

9. BIBLIOGRAPHY 26

## ACKNOWLEDGEMENTS

This project was jointly funded by:

British Coal

British Gas

The Building Services Research and Information Association

The Department of the Environment

The Electricity Council.

Munters Ltd.

The authors would also like to thank various organisations who assisted with providing permission to test their (or their clients) buildings. The order of these is purely alphabetical and does not relate to building number in any way:

Booker Property Developers Ltd.

Connell Wilson Ltd.

King and Co.

Lansdown Estates Group Ltd.

The Ministry of Defence

Munters Ltd.

Nigg Sheridan Properties Ltd.

Percy Bilton Estates Ltd.

Slough Estates

Tridionic Ltd.

Vail Williams Ltd.

## SUMMARY

The ventilation heat loss has been assesed for twelve factory/warehouse buildings covering a range of construction types. This has been achieved by the design and development of a new mobile test facility which can pressurise buildings up to and beyond 20,000 $m^3$, depending on their air leakage characteristics. The results of the measured air leakage characteristics have been translated into predicted air change rates for mean wind speeds and average internal/external temperature differences, from which the average ventilation heat loss has been calculated.

The CIBSE ventilation allowances given in Guide Book A Table A4.13 for various factory construction types are the rates of infiltration on which heat loss calculations for factories should be based where number of occupants is unknown. The predicted ventilation rates have been compared with CIBSE guidance data for these types of structures and in general there was not good agreement. There is quite clearly much scope for improvement in the energy efficiency for these types of buildings in terms of ventilation heat loss.

# 1. INTRODUCTION

This report describes the design and construction of a mobile test facility for measuring the air leakage characteristics of large single cell factory and warehouse units. Twelve factory units of various different construction types have been tested and the ventilation rate has been predicted for all of the factories using a BSRIA air infiltration calculation model. The air infiltration rates have been calculated for mean wind speeds at three wind directions and for a temperature difference of 10°C.

The results of the air infiltration rates have been further processed to provide the ventilation heat loss of each unit based on a normal five day working week and the results have been compared with the CIBSE guidance data. Additionally the results have been compared with what is considered to be readily achievable reductions in the ventilation of these buildings by careful attention to sealing the structures where air leakage paths through the structure are reasonably identifiable.

The main conclusion to be drawn from the results of this research project is that the CIBSE ventilation allowances are lower than are being realised in practice and that there is considerable scope for energy conservation by better sealing of these types of structures.

# 2. BACKGROUND

This section provides the background to the project and is a statement of the state of knowledge at the commencement of this research programme.

## 2.1 MEASUREMENTS INTO AIR LEAKAGE OF LARGE SINGLE CELL BUILDINGS

Within the field of air infiltration in large buildings the majority of the work has generally been directed towards the measurement of natural ventilation rates using a tracer gas technique. In the UK this type of work has been reported by a number of people[1,15,17,18,19,20]. Within this work a number have included investigations into the air leakage of large structures[1,18,19,20].

BSRIA[1] carried out measurements of air leakage on three factories using a fan with an output of up to 4.9 $m^3s^{-1}$. In all buildings tested, the maximum pressure differential this fan could develop was less than 4 Pa. This was on the smallest of the three factories investigated. On the other two factories the pressure difference across the factory was <1 Pa and 2.5 Pa. The size of the factories were 6700$m^3$ and 5700$m^3$.

British Gas have also carried out pressurization of large buildings both independently[18], and in cooperation with UWIST[20] and Coventry Polytechnic[19]. In carrying out this work they have used three types of air moving device, the first was a number of their Watson House domestic leakage testers in parallel, each capable of supplying up to 1.25 $m^3s^{-1}$ at a pressure of 50 Pa. The second device was a wind generator which could provide a flow rate of up to 5.6 $m^3s^{-1}$ at a pressure of 20 Pa. The results of the use of both of these pieces of equipment are reported in reference 15. The third device used was a wind tunnel fan[19].

British Gas have presented the results of investigations into the air leakage of five buildings ranging in size from 600 $m^3$ to 6000 $m^3$. After carrying out this work they came to a number of conclusions regarding the measurement of air leakage in industrial buildings.

a) To pressurize small industrial buildings up to 50 Pa requires flow rates of 18 $m^3s^{-1}$.

b) It is impractical to pressurize most industrial buildings larger than 5000-10000 $m^3$ to 50 Pa.

c) If a standard for air leakage is required then a lower standard value than 50 Pa may be required to alleviate inaccuracies resulting from extrapolation.

d) For large or excessively leaky buildings an alternate method of assessing the air leakage may be required.

The paper concludes that they have now constructed a purpose built fan system capable of delivering 40 $m^3s^{-1}$ @ 50 Pa, but no results seem to have yet been published.

## 2.2 WORK CARRIED OUTSIDE THE U.K.

Within Europe L.Lundin[5] has designed and tested equipment to determine the air leakage of industrial buildings. The fan capable of 20 $m^3s^{-1}$ @ 60 Pa has been used to test 9 buildings, the flow rate of the fan being determined by a tracer gas dilution technique. The factories were located in Sweden, the largest being >61000 $m^3$. The factories were either a concrete frame with lightweight pre-cast concrete cladding or steel frame with steel panel cladding. Given the Swedish reputation for the air tightness of their buildings it is probably feasible for this type of testing to take place using a fan of relatively small size.

In America measurements have been carried out to determine the air leakage of a number of different types of buildings. These have been either office buildings[22,23] or schools[16]. In some cases these have used the fans of the installed air conditioning system, while others have used separate fans.

Retrotec of Canada have designs for a development of their blower door (normally used in domestic situations) for use in light commercial buildings, however no further mention of the success (or failure) of this type of equipment has been found.

## 2.3 SUMMARY

A summary of the results of various tests on the air leakage of factories in the U.K. is presented in the following table:

**Summary of air leakage tests (U.K. building stock only)**

| Reference No. | Building volume $m^3$ | Flow Rate at a pressure difference of 50Pa $m^3s^{-1}$ | |
|---|---|---|---|
| 18 | 660 | 9.7 | |
| | 1300 | 18.0* | |
| | 810 | 9.7* | |
| | 6000 | 11.1* | low energy factory units |
| | 6000 | 9.7* | low energy factory units |
| 1 | 2380 | 21.7* | |
| | 5690 | 35.4* | |
| | 6780 | 65.0* | |

*NB * - indicates that this value is an extrapolation of the results*

This limited survey of air leakage characteristics of large buildings indicates the variation that exists within the building stock of single cell buildings. It also provides a first indication of the magnitude of air flow rates required to obtain suitable pressure differences across this type of building.

This tends to reinforce the conclusions that British Gas arrived at, in that to use this pressurization technique to compare the air tightness of large factories a lower standard pressure difference across the building is required or alternative methods of comparing the air leakage of different large buildings are required. It was concluded that a more realistic value of universally applied pressure difference should be 25 or 30 Pa.

If a comparison is drawn between the air leakage of these factory/warehouse units with those tested in Sweden, then the quality of build is graphically demonstrated as provided in Figure 2.1. Thus from previous, albeit extrapolated, data the air leakage of Swedish buildings is shown to be substantially less than those in the United Kingdom.

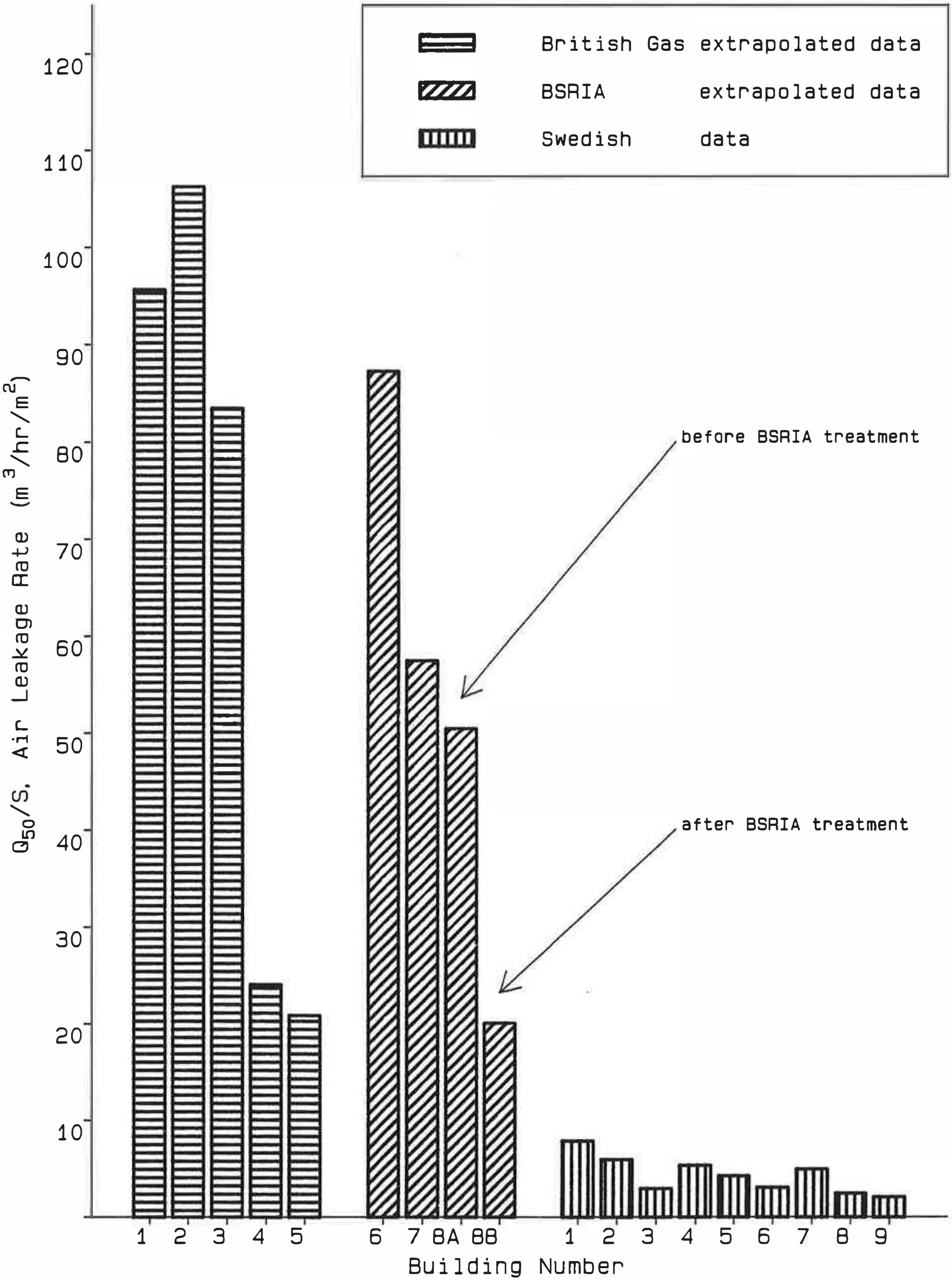


*Fig 2.1: Comparison of UK and Swedish Industrial Buildings*

# 3. DESIGN AND COMMISSIONING OF THE 'FAN ROVER'

Previous experience with the pressurisation of factory and warehouse units (ref 1) indicated that flow rates of at least 30 $m^3/s$ would be required and that intrusion into the three phase electrical circuits of a factory unit would be impracticable. A facility was required which was self powered, easily transported, easy to set up, reliable in operation and capable of pressurising building envelopes with a variety of flow rates between approximately 3 - 30 $m^3/s$. The size and weight of a fan unit with silencer if mounted on a trailer would always require a substantial vehicle to tow it and the concept of using the engine power of a Land Rover to drive the fan was therefore a logical solution.

From the power requirements of up to 80 kilowatts to provide the required air flow rate, a 3.5 litre petrol driven engine was the only choice out of the standard Land Rover options. The next choice was whether to hydraulically drive the fan from a centre power take off or to directly drive the fan via a propeller shaft directly from the gear box. The former would have been practical, but the size of reservoir required for the hydraulics and the cooling requirements would have been substantial. The direct drive option was preferred and ordered as a special directly from Land Rover, since the chassis requires special holes in it to accommodate the drive shaft, which since it is effectively a rear power take off, the petrol tank and battery had to be relocated. Other than a hand throttle control, rev counter and special cooling alarms, the rest of the vehicle was standard, other than the gear ratios in the transfer box.

It was originally conceived that a variable speed fan would be more easily controlled, particularly for fine tuning and so a special variable speed drive fan was ordered with a bell entry, mesh guard, downstream guide vane, silencer, spacer duct, spigot and anti-vibration mounts. A 2.5 ton load capacity twin axle trailer was also required to mount the fan unit and a propeller shaft to directly link the Land Rover to the trailer. A special 1.2m diameter flexible duct was also acquired to link the output of the fan directly to factory units via a spigot mounted onto a square board to wedge in roller or sliding shutter doors. Extra aluminium sheets of various sizes were made to fill in the rest of the gap in the door and mounted in hardwood slotted sections for rigidity on site.

The flow rate is measured using a special device some diameters downstream of the fan. A pair of crossed tubes were installed into the unit with small diameter holes drilled into a stainless steel tubes at Log Chebycheff intervals. A piezometer ring was also incorporated into the unit to facilitate direct measurement of the integrated velocity pressure. The system was calibrated using standard anemometric techniques and tracer gas techniques. Portable calibrated micromanometers are used to measure the air flow rates into and the pressure difference across the building under test.

## 3.1 TECHNICAL DIFFICULTIES

The concept of direct drive introduced by Land Rover were more attuned to driving lawn mowers around local parks and did not expect the full potential of a 3.5 litre engine to be required down the power take off. The power train had therefore to be upgraded including larger universal joints. A different manufacturer had to be found which provided high power rating universal joints and which would still penetrate the purpose provided holes in the chassis.

It was originally intended to utilize standard tractor power take off transmission shafts and safety covers, but since these were not rated above 500 rpm, special transmission drives and safety covers were made to accommodate power being transmitted up to 2000 rpm.

The fan unit, when ready for collection, had the downstream guide vane on the inlet and the direction of rotation reversed. When these items were changed and the fan unit had been lowered onto the trailer, it was immediately obvious that the anti-vibration mounts would not have stopped the fan ending up in the back of the Land Rover after braking nor was the weight distribution quite right. After putting the trailer unit on to a weigh bridge it was found that the weight of the fan was approximately 500 kg heavier than quoted by the manufacturer. Eight special anti-vibration mounts were ordered which were tuned to the weight of the unit and expected range of speeds. The position of the fan was changed on the trailer which involved unwelding the cross beams on the RSJ's and the wheels moved to provide the correct balance.

The height of the driven shaft on the fan was also not quite to specification and so another transfer box was required to keep the propeller shaft within five degrees of straight (there is quite a drop off in transmitted power for universal joints operated at angles above 5 degrees).

During operation there are no real difficulties, except for keeping an eye on the engine cooling system and oil temperature at high output (The entire exhaust system has been known to glow cherry red from manifold to discharge, even during very cold weather conditions). The flexible duct incorporated sewn in steel rings at 300 mm spacings and these rings are occasionally discharged into the factory unit, especially at full engine power. This duct has subsequently been replaced by a different design.

## 4. DESCRIPTION OF THE BUILDINGS TESTED

**Building Number 1**

| | | | |
|---|---|---|---|
| Frame type: | Monitor Roof | | |
| Cladding - walls: | Brick/Block cavity filled with ureaformaldhyde | | |
| - roof: | Asbestos panels, lined | | |
| Number of roller doors: | None (1 sliding door) | | |
| Height of building: | 6.74 m | Volume of building: | 3276 $m^3$ |
| Footprint area: | 645 $m^2$ | Envelope area: | 1262 $m^2$ |
| CIBSE ventilation allowance - | occupied: | 0.5 | air changes per hour |
| - | unoccupied: | 0.25 | air changes per hour |

**Building Number 1a**

| | | | |
|---|---|---|---|
| Frame type: | Monitor Roof | | |
| Cladding - walls: | Brick/Block cavity filled with ureaformaldhyde | | |
| - roof: | Asbestos panels, lined | | |
| Number of roller doors: | None (1 sliding door) | | |
| Height of building: | 6.74 m | Volume of building: | 7033 $m^3$ |
| Footprint area: | 1373 $m^2$ | Envelope area: | 2351 $m^2$ |
| CIBSE ventilation allowance - | occupied: | 0.5 | air changes per hour |
| - | unoccupied: | 0.25 | air changes per hour |

**Building Number 2**

| | | | |
|---|---|---|---|
| Frame type: | Portal frame | | |
| Cladding - walls: | Profiled metal sheet with insulated lining, internal blockwork up to 1 metre | | |
| - roof: | Profiled metal sheet with insulated lining | | |
| Number of roller doors: | One | | |
| Height of building: | 8.75 m | Volume of building: | 10686 $m^3$ |
| Footprint area: | 1363 $m^2$ | Envelope area: | 2449 $m^2$ |
| CIBSE ventilation allowance - | occupied: | 0.5 | air changes per hour |
| - | unoccupied: | 0.25 | air changes per hour |

**Building Number 3**

| | | | |
|---|---|---|---|
| Frame type: | Portal frame | | |
| Cladding - walls: | Profiled metal sheet with insulated lining, internal blockwork up to 1 metre | | |
| - roof: | Profiled metal sheet with insulated lining | | |
| Number of roller doors: | One | | |
| Height of building: | 8.75 m | Volume of building: | 10380 $m^3$ |
| Footprint area: | 1319 $m^2$ | Envelope area: | 2351 $m^2$ |
| CIBSE ventilation allowance - | occupied: | 0.5 | air changes per hour |
| - | unoccupied: | 0.25 | air changes per hour |

**Building Number 4**

| | | | |
|---|---|---|---|
| Frame type: | Fink truss | | |
| Cladding - walls: | Flat metals panels with insulated lining | | |
| - roof: | Profiled metal sheet including openable roof lights | | |
| Number of roller doors: | One | | |
| Height of building: | 16.0 m | Volume of building: | 19513 $m^3$ |
| Footprint area: | 1501 $m^2$ | Envelope area: | 3734 $m^2$ |
| CIBSE ventilation allowance - | occupied: | 0.5 air changes per hour | |
| - | unoccupied: | 0.25 air changes per hour | |

**Building Number 5**

| | | | |
|---|---|---|---|
| Frame type: | Portal frame | | |
| Cladding - walls: | Brick infil | | |
| - roof: | Profiled metal sheet with lining and internal gutters | | |
| Number of roller doors: | Four | | |
| Height of building: | 6.6 m | Volume of building: | 30007 $m^3$ |
| Footprint area: | 4617 $m^2$ | Envelope area: | 6763 $m^2$ |
| CIBSE ventilation allowance - | occupied: | 0.25 air changes per hour | |
| - | unoccupied: | 0.125 air changes per hour | |

**Building Number 6**

| | | | |
|---|---|---|---|
| Frame type: | Portal frame | | |
| Cladding - walls: | Brick infil | | |
| - roof: | Profiled metal sheet with lining and internal gutters | | |
| Number of roller doors: | Two | | |
| Height of building: | 6.6 m | Volume of building: | 15364 $m^3$ |
| Footprint area: | 2364 $m^2$ | Envelope area: | 3641 $m^2$ |
| CIBSE ventilation allowance - | occupied: | 0.25 air changes per hour | |
| - | unoccupied: | 0.125 air changes per hour | |

**Building Number 7**

| | | | |
|---|---|---|---|
| Frame type: | Portal frame | | |
| Cladding - walls: | Front and rear - profiled metal, insulated lining sides - blockwork | | |
| - roof: | Profiled metal sheet with insulated lining | | |
| Number of roller doors: | One | | |
| Height of building: | 8.5 m | Volume of building: | 3467 $m^3$ |
| Footprint area: | 447 $m^2$ | Envelope area: | 1089 $m^2$ |
| CIBSE ventilation allowance - | occupied: | 0.5 air changes per hour | |
| - | unoccupied: | 0.25 air changes per hour | |

**Building Number 8**

| | | | |
|---|---|---|---|
| Frame type: | Cambered lattice truss, single axis | | |
| Cladding - walls: | Profiled metal sheet (traditional corrugated sheet) | | |
| - roof: | Corrugated asbestos | | |
| Number of roller doors: | Four | | |
| Height of building: | 6.1 m | Volume of building: | 4909 $m^3$ |
| Footprint area: | 848 $m^2$ | Envelope area: | 1506 $m^2$ |
| CIBSE ventilation allowance - | occupied: | 1.0 | air changes per hour |
| - | unoccupied: | 0.5 | air changes per hour |

**Building Number 9**

| | | | |
|---|---|---|---|
| Frame type: | Fink truss on masonry frame | | |
| Cladding - walls: | Concrete blocks | | |
| - roof: | Corrugated asbestos | | |
| Number of roller doors: | One plus four large sliding doors | | |
| Height of building: | 6.8 m | Volume of building: | 10399 $m^3$ |
| Footprint area: | 1747 $m^2$ | Envelope area: | 2685 $m^2$ |
| CIBSE ventilation allowance - | occupied: | 0.25 | air changes per hour |
| - | unoccupied: | 0.125 | air changes per hour |

**Building Number 10**

| | | | |
|---|---|---|---|
| Frame type: | Portal frame | | |
| Cladding - walls: | Profiled metal sheet with insulated lining windows in one wall, one plasterboard wall | | |
| - roof: | Profiled metal sheet with insulated lining | | |
| Number of roller doors: | One | | |
| Height of building: | 8.0 m | Volume of building: | 6787 $m^3$ |
| Footprint area: | 972 $m^2$ | Envelope area: | 1771 $m^2$ |
| CIBSE ventilation allowance - | occupied: | 0.75 | air changes per hour |
| - | unoccupied: | 0.375 | air changes per hour |

**Building Number 10a**

| | | | |
|---|---|---|---|
| Frame type: | Portal frame | | |
| Cladding - walls: | Profiled metal sheet with insulated lining windows in one wall | | |
| - roof: | Profiled metal sheet with insulated lining | | |
| Number of roller doors: | Two | | |
| Height of building: | 8.0 m | Volume of building: | 14569 $m^3$ |
| Footprint area: | 2081 $m^2$ | Envelope area: | 3235 $m^2$ |
| CIBSE ventilation allowance - | occupied: | 0.5 | air changes per hour |
| - | unoccupied: | 0.25 | air changes per hour |

**Building Number 11**

| | | | |
|---|---|---|---|
| Frame type: | Cambered truss on metal frame - single axis | | |
| Cladding - walls: | Front and rear - bottom 2 metres, brick remainder - profiled metal sheet with lining side walls - brick | | |
| - roof: | Profiled metal sheet with lining | | |
| Number of roller doors: | One | | |
| Height of building: | 7.0 m | Volume of building: | 2088 $m^3$ |
| Footprint area: | 318 $m^2$ | Envelope area: | 757 $m^2$ |
| CIBSE ventilation allowance - | occupied: | 1.0 | air changes per hour |
| - | unoccupied: | 0.5 | air changes per hour |

**Building Number 12**

| | | | |
|---|---|---|---|
| Frame type: | Space frame with perpendicular cambered truss | | |
| Cladding - walls: | Lower 2 metres - block/brickwork, remiander profiled metal sheet with lining on three walls, fourth wall all blockwork | | |
| - roof: | Profiled metal sheet and lining | | |
| Number of roller doors: | Two | | |
| Height of building: | 9.75 m | Volume of building: | 17599 $m^3$ |
| Footprint area: | 1983 $m^2$ | Envelope area: | 3471 $m^2$ |
| CIBSE ventilation allowance - | occupied: | 0.5 | air changes per hour |
| - | unoccupied: | 0.25 | air changes per hour |

## 5. RESULTS OF THE BUILDINGS TESTED

For each building tested the air flow rate was measured along with the pressure differential achieved across the building. The air flow rate was varied for each building to generate a range of pressure differentials. A regression analysis was undertaken for each configuration and these values were plotted on log-log scales. The regression analysis produces an air leakage characteristic and a flow index for the building. One building was tested with and without the roller shutter door sealed, but the results of this exercise were such that the roller shutter door air leakage was small compared with the overall air leakage of the building fabric. There was nevertheless a wide variation in the quality of the roller shutter doors and this should not be neglected when assessing the quality of the structure.

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 pressurize the building to 50 Pascals ($Q_{50}$) divided by the envelope area (S). The results of all of BSRIA's activities for large factory and warehouse type buildings are presented as a bar chart in Figure 5.1. It is quite likely that the extrapolated data (reproduced from Figure 2.1) is an overestimate of the actual normalised envelope air leakage, but is useful for comparison. A factory unit tested in a joint BRE/EEC contract (ref 1) illustrates that factory units can be treated with mastic, etc. to reduce the air infiltration loss as illustrated by the before and after BSRIA treatment air leakage figures. There is clearly quite considerable scope for reducing the air leakage of nearly all the buildings tested.

The results of the measurements are also presented in Table 5.1. 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 when the building is pressurized to the subscripted pressure difference.

The predicted air change rate will be dealt with in section 6, but as a rule of thumb the pressure required to pressurize the building to equate with the mean predicted ventilation rate is also given and the average is 0.4 Pascals. Thus on average using the measured air flow pressure characteristics for the building and using a pressure difference of 0.4 Pascals would, as a rule of thumb, generate the predicted mean air change rate.

As a comparison the predicted air change rate is expressed as a percentage of the CIBSE guidance data (unoccupied case) in the last column of the table and simply serves to demonstrate that current guidance data are generally well below that being achieved in practice.

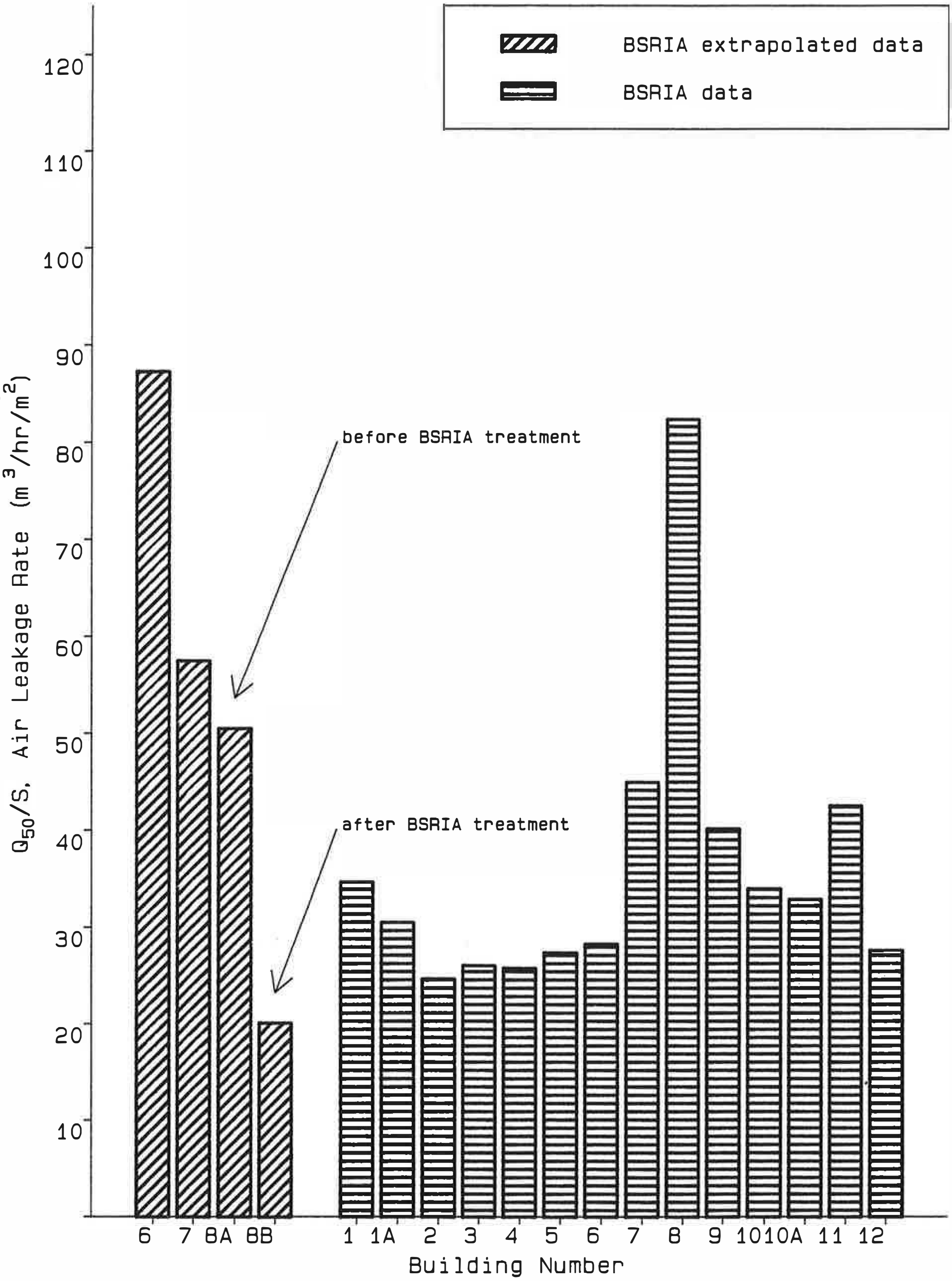


*Fig. 5.1: Comparison of UK Industrial Buildings*

*Table 5.1: Results of the tests carried out on the factory buildings*

| Building number | Leakage coefficient | Flow index | $Q_{25}$ $m^3 . s^{-1}$ | $Q_{50}$ $m^3 . s^{-1}$ | $N_{25}$ $hr^{-1}$ | $N_{50}$ $hr^{-1}$ | Predicted air change rate $hr^{-1}$ | Pressure to achieve air change rate Pa | $Q_{25}/S$ $m^3hr^{-1}m^{-2}$ | $Q_{50}/S$ $m^3hr^{-1}m^{-2}$ | Percent of CIBSE (unocc.) data |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.72 | 0.50 | 8.60 | 12.16 | 9.45 | 13.36 | 1.04 | 0.3 | 24.53 | 34.69 | 416% |
| 1a | 3.05 | 0.48 | 14.30 | 19.94 | 7.32 | 10.21 | 0.85 | 0.3 | 21.90 | 30.53 | 340% |
| 2 | 1.22 | 0.67 | 10.54 | 16.78 | 3.55 | 5.65 | 0.29 | 0.6 | 15.49 | 24.67 | 116% |
| 3 | 1.83 | 0.57 | 11.46 | 17.02 | 3.97 | 5.90 | 0.41 | 0.4 | 17.55 | 26.06 | 164% |
| 4 | 2.46 | 0.61 | 17.53 | 26.75 | 3.23 | 4.94 | 0.36* | 0.7 | 16.90 | 25.79 | 144% |
| 5 | 8.51 | 0.46 | 37.41 | 51.46 | 4.49 | 6.17 | 0.55 | 0.3 | 19.91 | 27.39 | 440% |
| 6 | 3.74 | 0.52 | 19.94 | 28.60 | 4.67 | 6.70 | 0.48 | 0.3 | 19.72 | 28.28 | 384% |
| 7 | 1.07 | 0.65 | 8.67 | 13.61 | 9.00 | 14.13 | 0.76 | 0.5 | 28.66 | 44.99 | 304% |
| 8 | 5.70 | 0.46 | 25.06 | 34.47 | 18.38 | 25.28 | 2.18 | 0.3 | 59.90 | 82.40 | 436% |
| 9 | 3.92 | 0.52 | 20.90 | 29.97 | 7.23 | 10.38 | 0.75 | 0.3 | 28.02 | 40.18 | 600% |
| 10 | 1.73 | 0.58 | 11.19 | 16.73 | 5.94 | 8.87 | 0.57 | 0.4 | 22.75 | 34.01 | 152% |
| 10a | 3.18 | 0.57 | 19.92 | 29.57 | 4.92 | 7.31 | 0.48 | 0.4 | 22.16 | 32.90 | 192% |
| 11 | 1.60 | 0.44 | 6.59 | 8.95 | 11.36 | 15.43 | 1.53 | 0.3 | 31.34 | 42.56 | 306% |
| 12 | 2.65 | 0.59 | 17.70 | 26.64 | 3.62 | 5.45 | 0.37 | 0.5 | 18.36 | 27.63 | 148% |

*Exposed site (urban prediction = 0.31 air changes per hour).

# 6. PREDICTION OF NATURAL VENTILATION RATES

The natural ventilation rates have been predicted using the BSRIA designed and developed "CRKFLO" computer program (ref 2), 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.

## 6.1 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. The building was split up into twenty-six external nodes of influence. The first ten nodes characterize the lower external levels, nodes eleven to twenty represent the upper external levels and nodes twenty-one to twenty-six represent the roof sections. These are the node numbers for which a wind pressure coefficient need 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 in References 4, 7, 9 and 10.

The wind velocity has been fixed as the average value over a ten year period at Kew and is 4.1 metres/second ( 9.2 m.p.h.). For this wind speed various wind directions have also been incorporated into the sensitivity study and an average taken of the three basic directions, i.e. 0°, 45°, 90°.

The mean wind speed factors were derived using the Deaves and Harris model equation (ref 4), which requires a Roughness Category for the land upwind of the building. For all wind directions used, a Roughness Category (RC) of 4 was assumed which is equivalent to an urban environment, except for one building which was located in open country and assigned a value of RC = 3. 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. 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 pressure acting on a particular section of the building is simply the product of the velocity pressure and the pressure coefficient.

## 6.2 BUOYANCY PRESSURES

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 17°C and has been fixed at that temperature. The outside air temperature has been fixed at 7°C for these sensitivity studies. For average wind speeds and above, the dominant pressures tend to be wind effects.

## 6.3 INPUT DATA

A special front end software package was developed for this project in order to provide comparability of results with relative ease and also develop subroutines to undertake sensitivity studies more easily. Each building was treated as though it had a plan aspect ratio of 2:1 and all elevations open to the effects of wind pressures. The following parameters were then input into the model for each building:

- Building height
- Building volume
- Whether the roof was pitched (>25°)
- Roughness category
- Design wind speed
- Internal temperature
- External temperature
- Envelope area
- Percentage air leakage through the roof
- Measured air leakage characteristics of the building

The largest unknown in this study is the distribution of the air leakage paths. An estimate was therefore made of the relative contribution the roof had on the overall air leakage of the building. The software then calculated the air leakage for individual parts of the facade of the building such that the overall air leakage of the building equalled the measured value. The measured flow index was used for all nodes in the network. It transpired however that the percentage air leakage through the roof sections did not in fact alter the overall air change rate particularly significantly. Wind direction was however quite a dominant factor. The computer program was therefore run for the three primary wind directions of 0°, 45° and 90° and an average of the predicted ventilation rates taken.

## 6.4 RESULTS OF PREDICTIONS

The results of the predicted ventilation rates (unoccupied) are presented in Table 6.1 and compared with the CIBSE ventilation allowance (unoccupied). These are both based on mean wind speeds and do not cater for high wind speeds. Since there is scope for improvement of the air leakage of the majority of the buildings tested an estimate was made of the likely reduction in air leakage that could be achieved relatively easily using various mastics and draught excluding techniques. The results of these estimates are also presented in Table 6.1. When compared with Swedish buildings these reductions are clearly extremely modest.

| | | Air Changes per hour (unoccupied) | | |
|---|---|---|---|---|
| Building number | volume $m^3$ | Predicted | Achievable | CIBSE |
| 1 | 3276 | 1.04 | 0.52 | 0.25 |
| 1A | 7033 | 0.85 | 0.43 | 0.25 |
| 2 | 10686 | 0.29 | 0.20 | 0.25 |
| 3 | 10380 | 0.41 | 0.20 | 0.25 |
| 4 | 19513 | 0.36 | 0.25 | 0.25 |
| 5 | 30007 | 0.55 | 0.28 | 0.13 |
| 6 | 15364 | 0.48 | 0.24 | 0.13 |
| 7 | 3467 | 0.76 | 0.38 | 0.25 |
| 8 | 4909 | 2.18 | 1.09 | 0.50 |
| 9 | 10399 | 0.75 | 0.38 | 0.13 |
| 10 | 6782 | 0.57 | 0.29 | 0.38 |
| 10A | 14569 | 0.48 | 0.24 | 0.25 |
| 11 | 2088 | 1.53 | 0.77 | 0.50 |
| 12 | 17599 | 0.37 | 0.20 | 0.25 |

*Table 6.1: Summary of the results of the predictions compared with the achievable reductions and CIBSE guidance*

## 7. ENERGY BENEFITS FOR BETTER SEALED STRUCTURES

The benefits derived from reduced air infiltration have been calculated with respect to a base ventilation energy input and the differences accrued by reducing the ventilation rate. It has been necessary therefore to try to ignore the heating of the structure. In this respect some broad assumptions have to be made. It has been assumed that for occupant satisfaction the building would be heated to, on average 17°C, between 8:00 am and 6:00 pm for five days a week and that the heating would come on where necessary at 6:00 am. The degree hours have been calculated, using standard CIBSE weather years for the five main areas in the UK and the external air temperature noted at 6:00 am. The energy required to compensate for the predicted air infiltration rate has been calculated for the occupancy period plus an allowance to heat up the air in the building at 6:00 am to the required base temperature. Since we do not know the evolution of the internal air temperature overnight, it has been assumed that the internal air temperature would evolve to being half way between the design internal temperature of 17°C and the external air temperature at 6:00 am, as a first order approximation.

For comparative purposes the ventilation heat loss has been calculated for all of the factories tested, based on the CIBSE ventilation allowance, the predicted ventilation heat loss and the effect of reducing the ventilation rate by better sealing or construction techniques. This latter case is seen as being eminently feasible in the majority of cases and already demonstrated in a previous BSRIA project. The data is presented in the form of annual ventilation energy consumption in Table 7.1 and normalised for unit area in Table 7.2 and for volume in Table 7.3.

The most graphic demonstration of the results is however presented in Figure 7.1, where the annual energy consumption for each building are provided for the three cases, along with the carbon dioxide output based on the use of gas appliances at an efficiency of 70%. The top graph illustrates the total ventilation energy consumption for each case, whilst the lower two graphs illustrate the difference between CIBSE guidance and predicted along with the potential savings by better sealing of the structures.

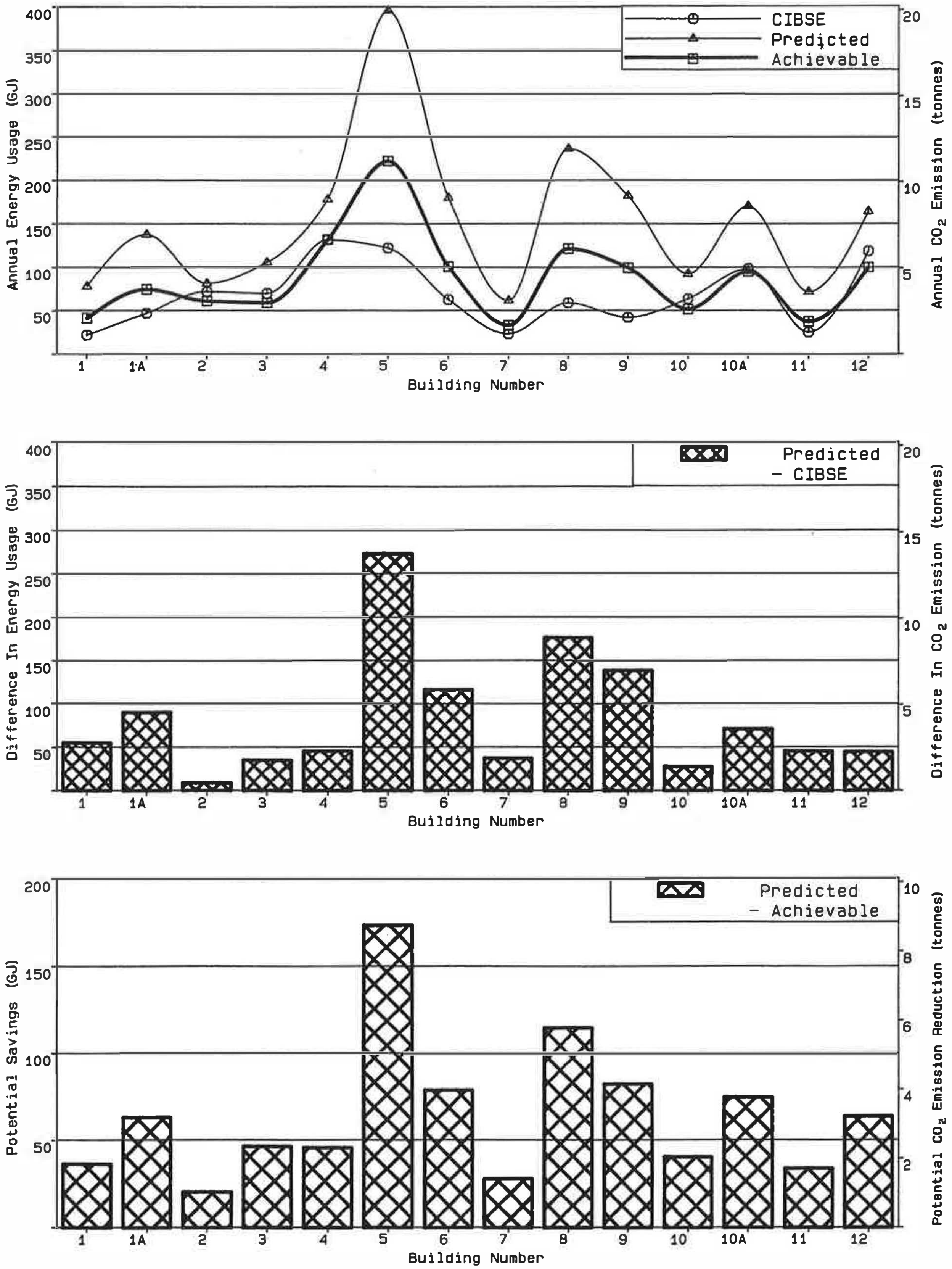


*Figure 7.1: Comparison of energy costs*

| Building number | Predicted ventilation heat loss | Achievable ventilation loss | CIBSE ventilation allowance |
|---|---|---|---|
| | *Energy GJ* | *Energy GJ* | *Energy GJ* |
| 1 | 77 | 41 | 22 |
| 1a | 137 | 74 | 47 |
| 2 | 81 | 60 | 72 |
| 3 | 105 | 59 | 70 |
| 4 | 177 | 131 | 131 |
| 5 | 395 | 222 | 122 |
| 6 | 179 | 100 | 62 |
| 7 | 61 | 33 | 23 |
| 8 | 236 | 121 | 59 |
| 9 | 181 | 99 | 42 |
| 10 | 92 | 51 | 63 |
| 10a | 170 | 95 | 98 |
| 11 | 71 | 37 | 25 |
| 12 | 164 | 100 | 118 |

*Table 7.1 : Annual ventilation energy consumption*

| | | **Energy (MJ) per m³** | | |
|---|---|---|---|---|
| Building number | Volume m³ | Predicted | Achievable | CIBSE |
| 1 | 3276 | 23.7 | 12.5 | 6.8 |
| 1A | 7033 | 19.6 | 10.6 | 6.8 |
| 2 | 10686 | 7.6 | 5.7 | 6.8 |
| 3 | 10380 | 10.2 | 5.7 | 6.8 |
| 4 | 19513 | 9.1 | 6.8 | 6.8 |
| 5 | 30007 | 13.2 | 7.4 | 4.1 |
| 6 | 15364 | 11.7 | 6.5 | 4.1 |
| 7 | 3467 | 17.1 | 9.5 | 6.8 |
| 8 | 4909 | 48.1 | 24.8 | 12.1 |
| 9 | 10399 | 17.5 | 9.5 | 4.1 |
| 10 | 6782 | 13.6 | 7.6 | 9.4 |
| 10A | 14569 | 11.7 | 6.5 | 6.8 |
| 11 | 2088 | 34.2 | 17.9 | 12.1 |
| 12 | 17599 | 9.3 | 5.7 | 6.8 |

*Table 7.2: Energy consumption comparison per unit volume*

| | | Energy (MJ) per m² | | |
|---|---|---|---|---|
| Building number | Area m² | Predicted | Achievable | CIBSE |
| 1 | 645 | 120 | 64 | 34 |
| 1A | 1372 | 100 | 54 | 35 |
| 2 | 1362 | 60 | 45 | 53 |
| 3 | 1318 | 80 | 45 | 53 |
| 4 | 1501 | 118 | 88 | 88 |
| 5 | 4616 | 86 | 48 | 27 |
| 6 | 2363 | 76 | 43 | 27 |
| 7 | 447 | 137 | 74 | 52 |
| 8 | 848 | 278 | 143 | 70 |
| 9 | 1747 | 104 | 57 | 24 |
| 10 | 972 | 95 | 53 | 66 |
| 10A | 2080 | 82 | 46 | 47 |
| 11 | 318 | 224 | 117 | 79 |
| 12 | 1983 | 83 | 50 | 60 |

*Table 7.3: Annual energy consumption comparison per unit area*

## 8. REFERENCES


1. DEWSBURY, J., JONES, T. J., POTTER, I. N. Measurement of air infiltration rates in large enclosures and buildings. BSRIA, March 1986.

2. POTTER, I. N. Operating manual for the 'CRKFLO' computer program for predicting natural ventilation rates in buildings. *Confidential report.* BSRIA, August 1976.

3. POTTER, I. N. Effect of fluctuating wind pressures on natural ventilation rates. In: *ASHRAE Transactions*, 1979, Vol. 85, No. 2, 445–457.

4. COOK, N. J. Background, drainage survey, wind data and structural classification. In: *The designers guide to wind loading of buildings and structures – Part 1*. Building Research Establishment/Butterworth Heineman. ISBN 0 40800 870 9, 1986, 352pp.

5. Measured air leakage of buildings. In: *Symposium sponsored by ASTM Committee E-6, Philadelphia.* April, 1984.

6. Tariffs Public electricity suppliers. In: *Engineering Services Management.* January/February 1991, Vol. 5, No. 1, 26–32.

7. COOK, N. J. Static structures. In: *The designers guide to wind loading of buildings and structures – Part 2*. Building Research Establishment/Butterworth Heineman. ISBN 0 40800 871 7, 1990, 600pp.

8. LIDDAMENT, M. W. Air infiltration calculation techniques – an application guide. Air Infiltration and Ventilation Centre, 1986.

9. BS 5925: 1991 Ventilation principles and designing for natural ventilation. British Standards Institute.

10. Code of basic data for the design of buildings – Part 2 wind loads. CP3 Chapter V, British Standards Institute, 1972.

11. BARRITT, C. M. H. Advanced Building Construction, Vol. 2, Longman, 0 58201 970 2, 1988, 244pp.

12. DRURY, J. Factories – Planning, design and modernisation. Architectural Press, ISBN 0 85139 302 0, 1981.

13. BROOKES, A. J., GRECH, C. The building envelope. Construction Press, ISBN 0 40850 030 1, 1990.

14. Joints between concrete wall panels, open drained joints. *BRE Digest No. 85*, Building Research Establishment, 1967.

15. LILLY, J. P. et al. Air infiltration reduction in existing buildings. In: *Proceedings of 4th Air Infiltration and Ventilation Centre Concerence.* 24–28 September, 1983, 5.1–5.14.

16. SHAW, C. Y. Air infiltration reduction in existing buildings. In: *Proceedings of 4th Air Infiltration and Ventilation Centre Conference*. 24–28 September, 1983, 8.1–8.8.

17. LAWRENCE, G. V. et al. Ventilation technology research and application. In: *Proceedings of 8th Air Infiltration and Ventilation Centre Conference*. 21–24 September, 1987, 2.1–2.18.

18. LILLY, J. P. Ventilation technology – Research and applications. In: *Proceedings of 8th Air Infiltration and Ventilation Centre Conference*. 21–24 September 1987, 18.1–18.11.

19. LILLY, J. P. Ventilation strategies and measurement techniques. In: *Proceedings of 6th Air Infiltration and Ventilation Centre Conference*. 16–19 September, 1985.

20. ETHERIDGE, D. W. et al. Ventilation of factories. In: *Proceedings of 6th Air Infiltration and Ventilation Centre Conference*. 16–29 September, 1985.

21. PERERA, M. D. A. S. et al. Use of BREFAN to measure the airtightness of non-domestic buildings. *BRE Information paper 6/89*. Building Research Establishment, 1989.

22. HUNT, C. H. Induced pressure measurements in high rise office buildings. In: *STP 904*, ASTM, 1986.

23. GROT, R. A. Pressurisation testing of federal buildings. In: *STP 904*. ASTM, 1980.

# 9. BIBLIOGRAPHY


1. Retrotec. In: *Retrotec Bulletin*, 1985.

2. JENSON, L. Determination of leakage in the building envelope using pressurisation test method. In: *Air Infiltration Review*. Vol. 7, No. 4, August 1986, 6–8.

3. THOMPSON, C. A review of building air tightness and ventilation standards. In - *Technical Note, No. 14*. Air Infiltration and Ventilation Centre, February 1984.

4. GADSBY, K. J., HARRJE, D. T. Fan pressurisation of buildings - standards, calibration, and field experience. In: *ASHRAE Transations*. Vol. 1, Part 2B, 1985, 95–104.

5. FERGUSON, J. E. Air Infiltration in warehousing and light industrial buildings. In: *BETT Publication No. 82.06*. Energy Mines and Resources, Canada, 1982.

6. SHIPP, M. P. Results of on site examination of some pressurisation installations in buildings. In: *Fire Surveyor, Vol. 9, No. 3*. June 1980, 42–48.

7. ADAN, O. C. G., HENDRIKS, L. W. S. L. Appliance of infra-red thermography in examining air leakage of buildings. In: *Ventilation Technology – Research and Application, Proceedings of 8th Air Infiltration and Ventilation Centre Conference*, 21–24 September 1987, 5.1–5.18.