The Role of Ventilation
15th AIVC Conference, Buxton, Great Britain
27-30 September 1994

Reducing Air Infiltration Losses in Naturally Ventilated Industrial Buildings

P J Jones, G Powell

The Welsh School of Architecture, University of Wales, Cardiff, Bute Building, King Edward VII Ave, Cardiff CF1 3AP

SYNOPSIS

The UK factory stock is predominantly naturally ventilated. Measurements performed in this class of building have indicated that air infiltration rates in factories are usually excessive in relation to occupants' requirements for health and safety, resulting in an energy penalty.

As part of a project to investigate construction options for energy efficient industrial buildings, three factories of different cladding construction types were designed and then built at Aberaman, South Wales. One of the primary aims of the project was to reduce air infiltration losses and increase air tightness. Attention has been paid to design details in order to achieve these aims. The construction process was observed in order to monitor site practice and workmanship.

Tracer gas tests (primarily constant concentration) tests and air leakage (fan pressurisation) tests have been performed to determine the air infiltration rate and air leakage performance of the factories. A thermographic survey was used to assist the identification of the major air leakage sites. The results have shown that air infiltration rates have been reduced by the order of 40% for the three 'conventional' cladding constructions. Air leakage rates measured at 50 Pa are the lowest achieved in this class of building in the UK, based on published data. The major site for air leakage was found to be the eaves detail.

1.0 INTRODUCTION

Modern factories are predominantly naturally ventilated. In winter, ventilation is mainly provided by natural leakage through the construction. In summer this is often supplemented when necessary by mechanically operated roof ventilators.

Measurements carried out by The Welsh School of Architecture (WSA) in Welsh Development Agency, (WDA) factories [1], have indicated that natural ventilation rates over a range of factories are usually excessive in relation to occupants' requirements for health and safety, resulting in an energy penalty. The potential therefore exists for reducing ventilation rates whilst still maintaining adequate fresh air levels.

Thermographic investigations have indicated that the major locations for air infiltration occur at the various construction details around components, such as roof ventilators, doors, flues, etc. In particular, the eaves and wall details are often major sources of air leakage. Earlier work [2] used a zonal ventilation model to estimate that ventilation rates could be reduced by about half as a result of better sealing of construction details, whilst still maintaining adequate fresh air levels for occupancy.

This paper describes the ventilation performance of three new factories, each of a different cladding construction, that were designed to have 'reduced' air infiltration rates. The three factories, Units 40, 41 and 42, were constructed at Aberaman Industrial Estate, South Wales by the WDA.

2.0 CONSTRUCTION TYPES AND DESIGN DETAILS

In each factory the eaves height was 5m and the ridge height 7m. Units 40 and 41 had a production space floor area of 840 m^2 whereas Unit 42 was smaller, having a production space floor area of 720 m^2. Rooflights were linear eaves to ridge and of a double skin construction. Each of the three factories had external 'wrap around' office space and a low level (1m high) masonry perimeter wall. The three constructions are described below.

2.1 Sandwich (Lining Panel) Cladding System (Unit 40).

The sandwich construction is detailed in Figure 1. It can be summarised as follows:

> An outer liner sheet of coated steel of thickness 0.55 mm. A breather paper, to separate the ventilation path in the air gap of the external profile from the insulation layer. 80 mm of rock-fibre quilt insulation of density 33 kgm^{-3} and k-value 0.034 $Wm^{-2}K^{-1}$. A vapour barrier on the warm side of the insulation to reduce the risk of interstitial condensation. An inner liner sheet of coated steel of thickness 0.4 mm.
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> Fixing was by means of Z-spacers onto the cladding rails and purlins, with an adhesive thermal barrier tape (density 175 kgm^{-3}) separating the Z-spacer from the external liner sheet. Ventilated profile fillers were used to control ventilation on the 'cold side' of the insulation between the breather paper and the outer cladding sheet. The design U-value was 0.40 $Wm^{-2}K^{-1}$.

The main disadvantage with this construction is that unless there is a high standard of site supervision, it is potentially more prone to problems of poor workmanship. However, it is a relatively inexpensive system in its construction costs.

2.2 Liner Tray Cladding System (Unit 41)

The liner tray construction is detailed in Figure 2. It can be summarised as follows:

> An outer liner sheet of coated steel of thickness 0.55 mm. A breather paper, to separate the ventilation path in the external profile from the insulation layer. 80 mm of rock-fibre insulation batt of density 33 kgm^{-3} and k-value 0.034 $Wm^{-2}K^{-1}$, fitted into the liner tray. The structural liner tray of steel with a thickness of 1.0 mm, with a tray width of 450 mm and a depth of 80 mm.
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> Fixing of the external liner sheet to the liner tray was by means a top hat section with a rock-fibre adhesive thermal barrier tape (density 175 kgm^{-3}) separating the top-hat

section from the external liner sheet. The liner trays were fixed to the cladding rails and purlins. A mastic sealant strip was stuck to the side of each tray prior to fixing to prevent air infiltration between adjacent trays. The design U-value was 0.40 $Wm^{-2}K^{-1}$.

This construction was similar to the sandwich cladding system above except that the inner liner sheet and vapour barrier had been replaced by a structural liner tray. This offered the advantage over the sandwich construction that there was less risk of interstitial condensation, as the liner tray itself acted as a vapour barrier. However, there was the disadvantage that each joint offered a potential cold bridge and infiltration path if not properly detailed.

2.3 Composite Cladding System (Unit 42)

The composite construction is detailed in Figure 3. It can be summarised as follows :

The composite panel was 450 mm width and was supplied in lengths of 6 m. The panel incorporated a coated steel of 0.6 mm outer skin and 0.7 mm inner skin. It contained 80 mm of a rock-fibre lamella insulation of density 120 kgm^{-3} and k-value 0.037 $Wm^{-2}K^{-1}$

The U-value for this construction was 0.45 $Wm^{-2}K^{-1}$ which complied with current building regulations.

3.0 AIR INFILTRATION RATE PERFORMANCE

3.1 Introduction

Air infiltration rates were measured using a 10 channel automated tracer gas system developed at WSA. The majority of data was collected under constant concentration although some tracer decay tests were performed. Nitrous Oxide (N_2O) was used as the tracer gas. The continuous measurements were carried out for between 1 and 2 weeks for each factory.

In addition to factory 'as-built' air infiltration rate measurements, further experiments were performed to evaluate the ventilation performance of door opening of the installed summer time cooling fans. There has been concern that cooling or extract fans are not achieving design extraction rates as buildings have become more air tight as insufficient make-up air is allowed to infiltrate through the envelope. This was of particular relevance to the project factories as increased air tightness was one of the primary aims of the exercise.

3.2 Results

The mean values and ranges of measured air infiltration rate are given in Table 1. The effect of door opening and ventilation fans operating either separately or in combination is presented in Table 2.

Table 1: Summary of mean air infiltration rates, wind speed and stack (ranges given in brackets).

Unit Number	Air Infiltration Rate (ach^{-1})	Wind Speed (ms^{-1})	Stack (°C½)
40	0.16 (0.05-0.41)	1.8 (0-5.7)	3.6 (2.6-4.4)
41	0.15 (0.07-0.33)	2.4 (0-6.7)	2.6 (1.0-3.4)
42	0.16 (0.04-0.45)	3.2 (0-8.8)	2.3 (0.6-3.4)

Table 2: Summary of mean ventilation rates, wind speed and stack (ranges given in brackets).

Unit Number	Door Open (ach^{-1})	Door Open and Fans On (ach^{-1})	Door Closed and Fans On (ach^{-1})
40	1.2	2.9	2.7
41	1.3	3.7	2.0
42	1.3	1.9*	1.5*

* only one of two fans in operation

3.3 Discussion

The three factories had very similar average air infiltration rates, being 0.16 ach^{-1}, 0.15 ach^{-1} and 0.16 ach^{-1} for Units 40, 41 and 42 respectively. On the recommended basis [3] that 8 ls^{-1} of fresh air per person should be provided in a factory environment, these air infiltration rates would give safe occupancy levels of 28, 26 and 24 people respectively for Units 40, 41 and 42.

Comparison with the results from modelling [2] which indicated that infiltration rates could be reduced to 0.15 ach^{-1} for this type of factory was good. Maximum measured air infiltration rates (corresponding to wind speeds of 7 ms^{-1}) have been reduced from a predicted level of 0.8 ach^{-1} to 0.4 ach^{-1}.

Opening the loading door increased the ventilation rate to either 1.2 or 1.3 ach^{-1}.

Operating the summer time ventilation fans increased the ventilation rate to 2.7, 2.0 and 1.5 ach^{-1} for Units 40, 41 and 42 respectively. In Unit 42 only one fan was operational. The design air change rate of 4 ach^{-1} was not being achieved. Opening the loading door increased the ventilation rate to 2.9, 3.7 and 1.9 ach^{-1} for Units 40, 41 and 42 respectively which provided some indication that there was not sufficient make up air in the factories as-built due to their relatively low air leakage. Opening the door could enable the fans to achieve the design extraction rate if wind conditions were suitable, which implied that directional effects were also present. It would seem likely that the installed fan capacity was not sufficient to provide the design extraction rate under all conditions.

4.0 AIR LEAKAGE PERFORMANCE

4.1 Introduction

Air leakage tests were performed using a fan pressurisation test rig developed at WSA. Each of the tests were performed using a single variable speed fan that had a maximum flow rate of 8.6 m^3s^{-1}.

The main component areas of interest were loading bay doors and roof ventilators. In these cases during the experiment the component was sealed using polythene sheeting and the tests repeated under different levels of sealing, i.e. door only sealed, doors and vents sealed. This enabled the potential for reductions in ventilation losses by the use of high performance components to be estimated.

4.2 Results

The air leakage characteristic curves for each unit are shown in Figures 4, 5 and 6 respectively. The data was fitted to a curve of the following form:

$$Q = C\Delta P^n \quad m^3s^{-1}$$

where:

$Q =$ Air leakage Rate (m^3s^{-1})
$C =$ Flow Coefficient
$\Delta P =$ Internal To External Static Pressure Difference (Pa)
$n =$ Flow Exponent

The unknowns C and n were found from the curve fitting exercise. Then, by putting ΔP equal to 50 Pa the air leakage rate at 50 Pa was be deduced. Table 3 below presents the results obtained at a pressure difference of 50 Pa for each of the factories. The normalised air leakage rate is the absolute air leakage rate at 50 Pa divided by the external envelope area (excluding the floor) of each factory. The experimental error for the fan pressurisation technique was estimated to be of the order of 8%.

Table 3: Absolute and Normalised Air Leakage Rates at 50 Pa

Unit No:		Door And Vents Sealed	Door Only Sealed	As-Built
40	m^3s^{-1}	7.10	7.67	7.72
	$m^3h^{-1}m^{-2}$	13.86	14.94	15.05
41	m^3s^{-1}	7.44	8.15	8.17
	$m^3h^{-1}m^{-2}$	14.51	15.88	15.95
42	m^3s^{-1}	6.21	6.77	6.75
	$m^3h^{-1}m^{-2}$	13.54	14.76	14.72

The air leakage rates measured for each of the factories with roof ventilators and loading door sealed gave a measure of the air leakage performance of the fabric only. From the normalised air leakage rates given in Table 3 above it can be seen that Unit 42 (composite panel) was tightest followed by Unit 40 (conventional sandwich) and finally Unit 41 (liner tray). The difference in normalised air leakage rate performance across construction types was only small. Unit 40 was 2.4% more leaky than Unit 42 and Unit 41 was 7.2% more leaky than Unit 42. It was considered that the liner tray construction was most leaky due to leakage through the butt joints between adjacent panels.

The factory as-built tests show that the same rank ordering of constructions occur even after the addition of components. The percentage differences in normalised air leakage performance are Unit 40 was 2.2% more leaky than Unit 42, Unit 41 was 8.4% more leaky than Unit 42. These relative differences were similar to the relative differences obtained for the factory sealed cases above, showing that the leakage effects of components was similar for each of the three constructions.

Removing the sealing on the roof ventilators increased the absolute air leakage rates for each of the factories. The percentage increases were 8.0%, 9.5% and 9.0% for Units 40, 41 and 42 respectively. These results show that fitting the roof vents into the envelope increased the air leakage by between 8% and 9%. The close agreement of the measured increases in air leakage showed that the leakage effects of roof vents was the same for each of the constructions. A visual inspection of the roof ventilators showed that air leakage could occur around each of the roof ventilators as well as through the closed louvers within the component.

Removing the sealing on each of the loading doors resulted in increases in air leakage rate of 0.65%, 0.25% and -0.003% for Units 40, 41 and 42 respectively. These results implied that there was no real measurable air leakage increase as a result of fitting a loading door in each of the constructions. A greater increase may have been measured if the door sealing had been removed before the roof vent sealing. Time constraints, however, prevented this strategy from being tested.

4.3 Comparison with other UK Factory Data

BSRIA have published work [4] concerning the measurement of air leakage rates in factories. Two of the buildings were of similar construction (cladding sandwich) and size (1300 m^2 floor area) to those at Aberaman.

A bar chart showing the measured air leakage rate for the Aberaman factories and the BSRIA factories is given in Figure 7 using the building code key shown below in Table 4.

Table 4: Building Code Key

Code Number	Building	Sealing Level	Leakage At 50 Pa ($m^3h^{-1}m^{-2}$)
1	BSRIA Building #2	As-Built	24.5
2	BSRIA Building #3	As-Built	26
3	Aberaman Unit 40	As-Built	15.05
4	Aberaman Unit 40	Sealed	13.86
5	Aberaman Unit 41	As-Built	15.95
6	Aberaman Unit 41	Sealed	14.51
7	Aberaman Unit 42	As-Built	14.72
8	Aberaman Unit 42	Sealed	13.54

From the air leakage rates presented above in Table 4 and from Figure 7 it can be seen that the buildings at Aberaman were considerably 'tighter' than similar buildings in terms of air leakage rates. A comparison of the Aberaman factories' recorded air leakage results with results from the authors' unpublished results for a range of factories has shown these constructions to be the most air tight UK factories, based on available data.

5.0 IDENTIFICATION OF AIR INFILTRATION SITES USING THERMOGRAPHIC SURVEYS

The main purpose of a thermographic survey has been to assess the standard of installation of insulation. However, the thermographic equipment can also be used for leakage detection. Leakage detection is assisted if the survey is carried out in conjunction with the fan pressurisation test equipment.

An internal thermographic survey to assess the standard of installation of insulation of each factory had indicated that for the liner tray construction (Unit 41) there were some examples of air infiltrating along the joint between adjacent trays and at the eaves detail for all units.

External thermographic surveys of each factory were carried out in order to locate the main air leakage sites on the external faces of the building envelope. First the survey was performed without the pressurisation fans switched on. The pressurisation fans were then switched on (causing the factories to be pressurised with respect to outside) and the survey repeated. The assumption was that pressurisation would force warm air through the leakage sites, hence exaggerating the effect that would occur under normal ventilation (infiltration) processes and thereby making the detection of air leakage more pronounced.

For all units, the thermograms indicated that infiltration occurred at the eaves, the verge, around the fire exit door and around the main loading door. As an example, Figures 8 and 9 show air leakage at the eaves of Unit 42, as-built and under pressurisation respectively. Switching on the pressurisation fan exaggerated the heating effect of the air leakage. However, switching on the fan has not identified any new air leakage sites

6.0 CONCLUSIONS

The average infiltration rates of the three factories were measured to be similar at between 0.15 and 0.16 ach^{-1} over the prevailing wind and temperature conditions. This was considered to be about half the average air infiltration rate for typical factories of this size and construction. The average air infiltration rates would give safe occupancy levels of 28, 26 and 24 people for Units 40, 41 and 42 respectively, based on a fresh air requirement of 8 ls^{-1} per person. The results indicated that ventilation rates can be significantly reduced in factories offering the potential for large energy savings. However, at the same time care must be taken to ensure adequate fresh air ventilation for occupants.

Significant increases in ventilation rate were recorded during loading door opening, with ventilation rates increasing to about 1.3 ach^{-1}. The use of summertime roof ventilation fans gave ventilation rates between 2.0 to 2.7 ach^{-1}, and opening the loading doors whilst running the roof ventilators resulted in ventilation rates between 2.9 and 3.7 ach^{-1}. The WDA design for summertime ventilation is 4.0 ach^{-1}, with doors closed. It is likely that the increased sealing measures have resulted in difficulty in providing make-up air through infiltration.

The difference in air leakage performance between the three different constructions was less than 10%, with the composite panel being the most air tight, the conventional lining panel second and the liner tray third. It was considered that the liner tray construction was the most leaky due to leakage through the butt joints between adjacent panels.

The air leakage performance of the three units with doors and vents sealed was 13.86, 14.51 and 13.54 $m^3h^{-1}m^{-2}$ for Units 40, 41 and 42 respectively. Compared with available data from other air leakage measurements performed in the UK, these factories have the lowest recorded air leakage rates.

Incorporation of roof ventilators into the building envelope increased the air leakage rates by 8% - 9% in each case. There was no measurable increase in air leakage attributed to around the closed loading doors.

The thermographic surveys indicated that the main leakage sites identified in this test were at the eaves. Combining thermographic surveys with pressurisation resulted in a more pronounced thermographic view of air leakage. However, even without pressurisation the major sites were identified. A thermographic survey is therefore appropriate for qualitatively assessing the air leakage as well as the integrity of the insulation.

The main source of air leakage was identified to occur at the eaves detail. This proved to be the most difficult detail to design and construct in relation to air leakage and also to thermal cold bridging. Achieving an airtight eaves detail in all construction types is difficult in practice, due to the angle the roof makes with the wall, the structural penetration of the eaves for gutters, overhangs, and the difficulty in inspecting the workmanship. This is therefore an area that needs to be addressed if further air tightness is required.

This work has demonstrated that low air infiltration rates can be achieved in practice. However, there is also the need to maintain good air quality for the health and safety of the workforce. The ventilation design of factories should be examined, including any provision for summertime ventilation cooling, to ensure that in addition to achieving a good thermal performance, good air quality for occupants must be ensured.

ACKNOWLEDGEMENTS

The work has been funded by the Welsh Development Agency and Rockwool (UK) Ltd.

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"Ventilation Heat Loss in Factories and Warehouses, Technical Note 7/92" The Building Services Research and Information Association. BSRIA 1992. ISBN 0 86022 2969.

Figure 1: Lining Panel (Sandwich) Construction

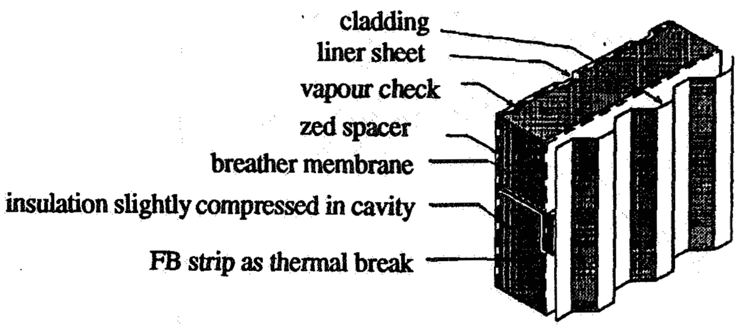

Figure 2: Liner Tray Construction

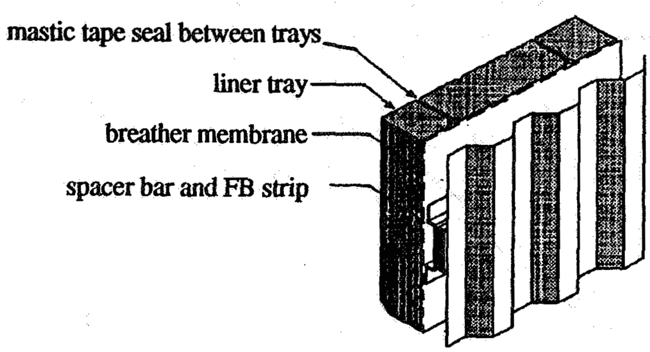

Figure 3: Composite Panel Construction

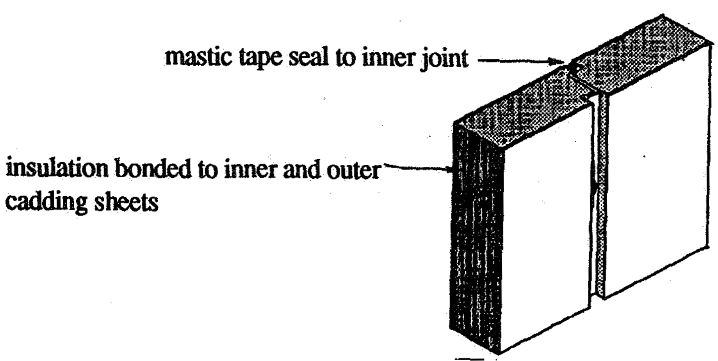

Figure 4: Air Leakage Curve For Unit 40 - Sandwich Construction

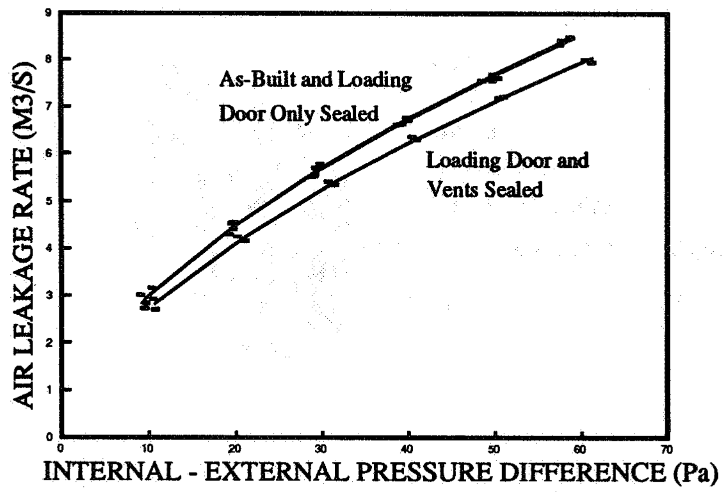

Figure 5: Air Leakage Curves For Unit 41 - Liner Tray Construction

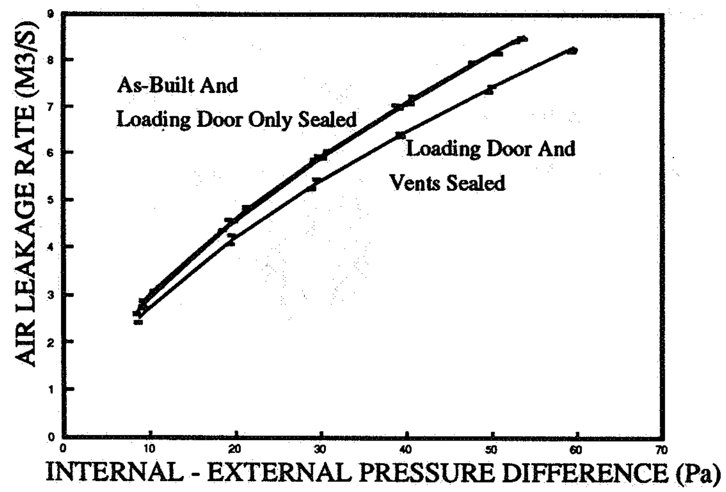

Figure 6: Air Leakage Curve For Unit 42 - Composite Panel Construction

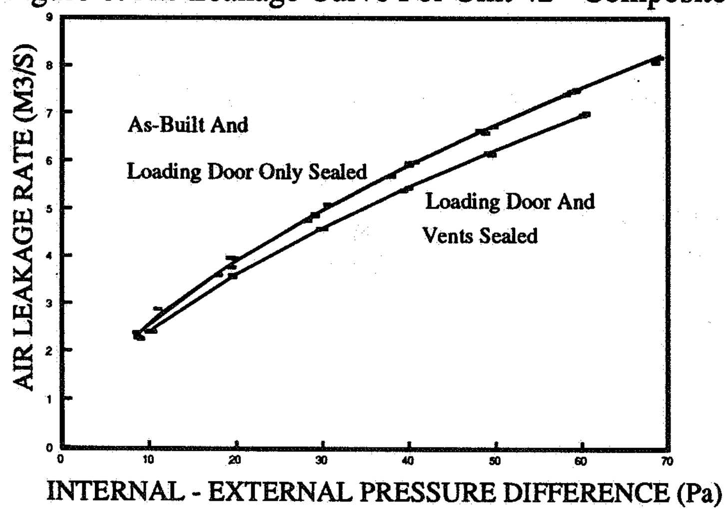

Figure 7: Comparison of Aberaman Air Leakage with Published Data.

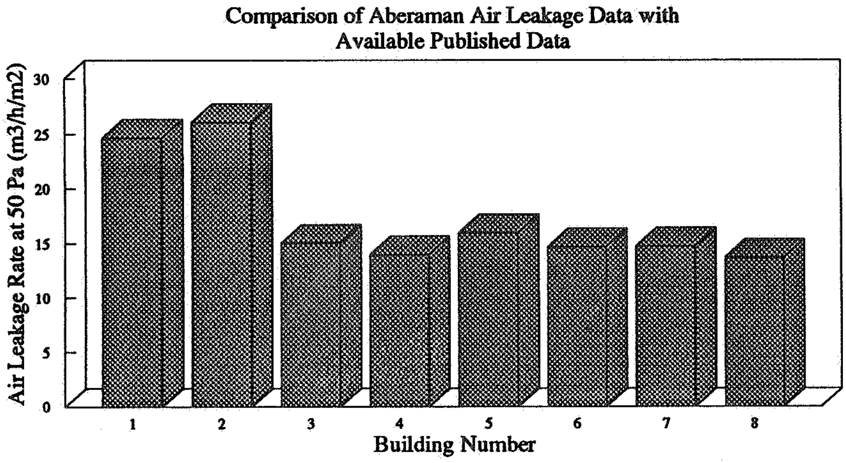

Figure 8: Thermogram of Eaves, Unit 42, Factory Not Pressurised.

Figure 9: Thermogram of Eaves, Unit 42, Factory Pressurised.