PROGRESS AND TRENDS IN AIR INFILTRATION
AND VENTILATION RESEARCH

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Poster 10

COMPARISON OF AIR INFILTRATION RATE AND AIR LEAKAGE TESTS UNDER REDUCTIVE SEALING FOR AN INDUSTRIAL BUILDING

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1. SYNOPSIS

The paper compares air infiltration rate measurements with air leakage measurements in a modern industrial building. In each case the tests have been performed firstly with the building 'as-built', and then with the major leakage components sealed.

The building investigated was of a cladding wall construction with U-values of 0.6 $W.m^{-2}.K^{-1}$ for both the walls and roof. It had a floor area of 466 m^2. The volume was 3050 m^3.

Tracer decay tests and constant concentration methods (both using N_2O) were performed in the building to establish the air infiltration rates. The air leakage of the building was determined by the fan pressurisation method.

The paper presents the results of the measurements and the discussion focuses on the variations of the air infiltration rate due to changes in internal and external conditions. The results from the three different techniques used are compared.

The results show that there was good agreement between the tracer decay and constant concentration methods when determining the air infiltration rate. There was also good agreement under reductive sealing between the reductions in measured air infiltration rate and measured air leakages.

The paper is a result from research work funded by the Building Research Establishment to investigate air infiltration rates and air leakage rates in Industrial Buildings.

2. INTRODUCTION

This paper describes the air infiltration and air leakage tests carried out in a modern lightweight industrial unit constructed in approximately 1986.

The main aims of the investigation were:

(i) To carry out tracer decay and constant concentration experiments to determine the air infiltration rate and its variation with wind velocity and internal-external air temperature difference.

(ii) To determine the air leakage rate at an induced internal-external static pressure difference up to 50 Pa.

(iii) To repeat (i) and (ii) above having carried out sealing measures to the loading door and roof ventilators.

The factory had a production space floor area of 466 m^2 and a production space volume of 3050 m^3. The factory walls had an inner leaf of masonry with a cladding external leaf. The roof was of a metal cladding construction with an inner leaf of fibreboard. Both constructions incorporated glass fibre quilt insulation to give a U-value of 0.6 $W.m^{-2}.K^{-1}$. The factory was built on a concrete slab base. There was an office space which was partitioned off from the production area.

There was 7.5%, by area, of glazing in the walls (all double glazed and tinted) and approximately 10% skylights in the roof. There were 4 louvered ventilators fitted in the roof, each of area 1.56 m^2. These were electrically operated by means of a single switch which controlled all four vents simultaneously.

The factory was fitted with a single standard roller shutter loading door of approximate area 16 m^2. The loading bay door faced north, the factory being orientated on an east-west axis.

Figure 1 contains a floor plan and section of the factory.

For factories of this size and construction, the recommended[1] design air infiltration rate for the purpose of design heat loss calculations is quoted at 1 $ac.h^{-1}$.

3. METHOD

3.1 Tracer Gas Test Equipment

Tracer gas tests were performed using the Autovent System developed and marketed by British Gas plc.

The system comprised of a gas analyser, 2 injection units each having 7 injection channels (6 for the primary tracer and one for the secondary tracer) and a 12 channel sample unit. The equipment was controlled by a personal computer via an interface. In addition there was the facility to monitor 12 internal air temperatures, the external air temperature, the wind speed and wind direction.

The gas analyser used was a Binos infra-red twin channel analyser that measured sulphur hexafluoride (SF_6) and nitrous oxide (N_2O) on dedicated channels and in the range 0 - 200 ppm. The analyser was fitted with an optical filter which prevented the N_2O measurement being affected by cross-sensitivity to water vapour. In addition to the two display meters (one each to display the measurements for SF_6 and N_2O), there was also an output signal 0-1 Volt dc that corresponded to the measurement range 0 - 200 ppm.

A Rexagan interface was used as the interface between the controlling computer and the sample/injection units. An IBM-XT personal computer was used as the controlling computer with an Epson FX-100 printer which permitted summary information in the form of tables to be printed out during the course of a run after a user-specified time interval.

The Autovent logging program permitted a constant concentration experiment to be run using the primary tracer gas (ie injecting on channels 1 to 12). In addition, 10 pairs of injection and release times could be entered for each of the two remaining channels (Channels 13 and 14). This permitted the running of a simultaneous decay experiment using a second tracer gas.

The tracer decay tests described in this paper were performed by preparing a program disc beforehand that set up the channels as sample only (ie no injection required). The factory was then brought up to target concentration in the usual way. Once a uniform concentration was achieved, the constant concentration run was aborted and the subsequent decay recorded using the sample only program disc.

Both the constant concentration tests and the tracer decay tests were performed using pure nitrous oxide (N_2O) as the tracer gas. An initial target concentration of 75 ppm N_2O was used for the tracer decay experiments. A target concentration of 50 ppm was used for the constant concentration experiments. The calibration of the gas analyser performed at the start of each test was achieved using a cylinder of 50 ppm N_2O in N_2.

Tracer decay tests were performed using a 120 second cycle time (ie the time taken to sample channels 1 to 12 inclusive). Subsequent data analysis was based on half hourly average readings.

Constant concentration tests CC01 – CC03 were performed using a 120 second cycle time. The remaining constant concentration tests (CC04 – CC08) were performed using a 360 second cycle time. Again, subsequent data analysis was based on a half hourly time base.

3.2 Air Leakage Test Equipment

The pressurisation unit employed for the tests at this factory was a modular system based on two fans of nominal diameter 24", namely a Woods 24 JL and a Eurofoil CA635. The unit was arranged such that the Eurofoil unit was mounted on top of the Woods unit and the whole arrangement fitted into a standard sized fire exit. The door exit was sealed by means of a plywood blanking plate fitted with bell mouthed inlets on the external face and flanges on the internal face. The fan system was offered up to the fire exit and linked to the flanges by means of flexible connectors.

The two fan ducts were each of 3m length. The volume flow rate through the ducts was measured using Wilson Flow Grids. Flow straighteners were fitted to eliminate swirl within the region of the Flow Grids.

Volume flow rate control was by means of speed controllers fitted to each fan. The Woods unit had a two speed controller whereas the Eurofoil fan unit had a five speed control unit.

The fans on maximum speed delivered 4.1 $m^3.s^{-1}$ and 4.3 $m^3.s^{-1}$ for the Woods and Eurofoil units respectively.

A schematic drawing of the fan pressurisation system is illustrated in Figure 2.

3.3 Work Programme

Air infiltration (tracer decay and constant concentration) and air leakage (fan pressurisation) experiments were carried out during July/August 1988.

The work programme for this study is shown in Table 3.1 below.

Table 3.1: Work Programme

Test	Configuration
Tracer Decay	
D01 and D02	As built
D03	As built. Vents open
Constant Concentration	
CC01 - CC06	As built
CC07	Loading door sealed
CC08	Loading door and roof vents sealed
Air Leakage	
P01 (a)	Loading door sealed
P01 (b)	Loading door sealed. Vents open
P02	Loading door and vents sealed
P03	As built

4. RESULTS

The results for the tracer decay, constant concentration and air leakage tests are summarised below.

The wind speed during the experimental period, averaged using a 30 minute time base, was recorded in the range from 0 to 7 $m.s^{-1}$. The wind direction was predominantly south and south west. External temperatures were recorded in the range 11 to 21 °C.

4.1 Tracer Decay

The tracer decay curves for the three experiments, namely Tests D01, D02 and D03, are shown in Figure 3. The corresponding log-linear transformations are shown in Figure 4. A half hourly averaging time base has been used in all cases.

The results of each test are summarised in Table 4.1 below.

Table 4.1 : Summary of Tracer Decay Tests

Test	Ventilation Rate $ac.h^{-1}$	$m^3.s^{-1}$	Wind Speed $m.s^{-1}$	Wind Direction	Stack $(°C)^{1/2}$	Configuration
D01	0.30	0.25	Low*	--	1.60	As-built
D02	0.39	0.33	4.1	SW	1.83	As-Built
D03	2.12	1.80	3.7	SW	1.89	As-built; Roof vents open.

* Although the windspeed and wind direction monitoring equipment was not operating for the duration of this test, on site observations noted that the windspeed decreased from moderate to very light during the course of the test. Examination of Figure 4, ie the log-linear plot of the concentration decays, suggests that after an elapsed time of four hours the infiltration rate changes. The tracer decay curve appears to consist of two distinct parts. The mean air infiltration rates were found to be 0.53 $ac.h^{-1}$ (0.45 $m^3.s^{-1}$) for the first part of the run (moderate windspeed) and 0.19 $ac.h^{-1}$ (0.16 $m^3.s^{-1}$) for the latter part of the run (light windspeed).

4.2 Constant Concentration

Constant concentration experiments were carried out for three factory configurations, namely as-built, loading door only sealed and loading door plus roof vents sealed.

The average values for each test are presented in Table 4.2 below.

Table 4.2 : Summary of Constant Concentration Tests

Test	Ventilation Rate $ac.h^{-1}$	$m^3.s^{-1}$	Wind Speed $m.s^{-1}$	Wind Direction	Stack $(^\circ C)^{1/2}$	Configuration
CC01	0.27	0.23	2.4	S,SW	1.9	As built
CC02	0.32	0.27	2.5	S	1.7	As built
CC03	0.42	0.36	3.0	S	2.9	As built and heating on
CC04	0.50	0.42	4.6	S	2.2	As built
CC05	0.48	0.41	3.7	S,SW	2.6	As built
	2.44	2.07	3.7		1.9	Roof vents open
CC06	0.33	0.28	2.4	S,SW	2.6	As built
CC07	0.27	0.23	0.9	S,SW	4.2	Door sealed and heating on
CC08	0.31	0.26	3.2	S,SW	2.9	Door and ventilators sealed

The data from Tests CC01-CC06 inclusive was amalgamated to form a single data set comprising of factory as-built data. The relationship of air infiltration rate with windspeed was examined for the factory as-built and factory with loading door plus roof vents sealed configurations. The windspeed range for the factory with door only sealed was too small to warrant any investigation of the relationship of air infiltration rate with windspeed. The analysis firstly considered all recorded wind directions together and then considered subsets of each data file by separating out the data into separate wind direction components, namely south and southwest directions for both factory configurations, there being little data recorded for any other directions.

Figures 5 to 7 inclusive show the air infiltration rate versus windspeed for both factory configurations for all wind directions, south winds and southwest winds respectively.

As the air infiltration rate appeared to be highly correlated with windspeed, a linear regression was performed on each set of data. A relationship of the following form was assumed to exist.

$$I = C_1 \cdot (WS) + C_2$$

Where
I = air infiltration rate ($ac.h^{-1}$)
WS = windspeed ($m.s^{-1}$)
C_1, C_2 = coefficients to be found from the regression analysis

The regression coefficients obtained are presented in Table 4.3 below together with the standard error of estimating the air infiltration rate, the correlation coefficient of the regression, (R^2) and the number of observations (N_{obs}). These regression are shown in Figures 8 to 10 inclusive.

Table 4.3: Regression Data For Air Infiltration Rate As A Function Of Windspeed Only.

Wind Direction	C_1	C_2	Standard Error	R^2	N_{obs}
As-Built					
All Directions	0.096	0.100	0.069	80.5%	375
South	0.076	0.145	0.063	65.7%	211
Southwest	0.110	0.056	0.063	88.4%	144
Loading Door Only Sealed					
All Directions	−0.003	0.274	0.039	0.3%	29
South	−0.057	0.308	0.041	17.5%	15
Southwest	−0.003	0.281	0.037	0.6%	10
Loading Door And Vents Sealed					
All Directions	0.062	0.110	0.053	67.8%	138
South	0.046	0.142	0.042	57.0%	91
Southwest	0.061	0.144	0.055	62.1%	47

To investigate the relationship of air infiltration rate with climate further, the stack effect was considered.

The measured air infiltration rates were normalised with respect to the stack and plotted against the windspeed normalised with respect to stack. Figures 11 to 13 inclusive show plots of (air infiltration rate ÷ stack) versus (windspeed ÷ stack) for the two factory configurations under study for all wind directions, south wind and south west wind components respectively.

A regression analysis was performed that took into account the stack effect. A relationship of the form;

$$I = C_3 \cdot WS + C_4 \cdot S \quad (ac.h^{-1})$$

was assumed where

I = air infiltration rate ($ac.h^{-1}$)
WS = Windspeed ($m.s^{-1}$)
S = Stack ($^{\circ}C^{1/2}$)
C_3, C_4 = Coefficients to be found from the regression analysis.

The data obtained from the linear regressions performed are presented below in Table 4.4.

Table 4.4: Air Infiltration Rate As A Function Of Windspeed And Stack.

Wind Direction	C_3	C_4	Standard Error	R^2	N_{obs}
As-Built					
All Directions	0.093	0.046	0.061	84.4%	375
South	0.081	0.055	0.056	72.8%	211
Southwest	0.104	0.032	0.059	90.0%	144
Loading Door Sealed					
All	0.018	0.061	0.036	13.4%	29
South	−0.028	0.069	0.037	34.8%	15
Southwest	0.022	0.060	0.036	75.2%	10
Loading Door And Vents Sealed					
All	0.066	0.033	0.054	66.8%	138
South	0.059	0.036	0.047	45.6%	91
Southwest	0.069	0.035	0.060	54.8%	47

The above regression fits were applied to the factory as-built and factory with door plus vents sealed configurations to determine the reductions in air infiltration rate effected by sealing. The air infiltration rate has been shown versus windspeed (using the regression equations obtained for all wind directions) and for two values of stack, namely 1 and 3 $^{\circ}C^{1/2}$ in Figures 14 and 15 respectively.

The potential reductions at these stack values are summarised in Tables 4.5 and 4.6 for two values of windspeed, namely 2 $m.s^{-1}$ and 5 $m.s^{-1}$.

Table 4.5: Predicted Air Infiltration Rates At Stack = $1^{\circ}C^{1/2}$.

Configuration	Windspeed 2 $m.s^{-1}$	5 $m.s^{-1}$
As-built	0.232	0.511
Door And Vents Sealed	0.165	0.363
Reduction	28.9%	29.0%

Table 4.6: Predicted Air Infiltration Rates At Stack = $3^{\circ}C^{1/2}$.

Configuration	Windspeed 2 $m.s^{-1}$	5 $m.s^{-1}$
As-built	0.324	0.603
Door And Vents Sealed	0.231	0.429
Reduction	28.7%	28.9%

4.3 Air Leakage

Three air leakage experiments, namely Tests P01, P02 and P03, were performed as detailed in the work programme, Table 3.1 for the loading door sealed, loading door plus roof vents sealed and factory as-built configurations respectively. In addition, for the loading bay door sealed configuration (Test P01), the roof vents were opened but a maximum internal-external static pressure difference of only 4 Pa was achieved (fan flow rate = 8.3 $m^3.s^{-1}$).

The air leakage plots for the three factory configurations are shown in Figure 16 together with an experimental line fit to the data in each case.

The curve fits to the experimental data shown were found by assuming a relationship of the form:

$$Q = C \cdot (\delta P)^n \quad (m^3.s^{-1})$$

Logarithmic transformation of the variables was then performed to find the flow coefficient, C, and the exponent, n.

The resulting equations for each factory configuration are given below.

Test P01 (Door Sealed)

$$Q = 0.446 \cdot (\delta P)^{0.667}$$

R-sq = 99.6% (7 data points)

Test P02 (Door and Vents sealed)

$$Q = 0.539 \cdot (\delta P)^{0.608}$$

R-sq = 99.4% (6 data points)

Test P03 (Factory as-built)

$$Q = 1.052\ (\delta P)^{0.540}$$

R-sq = 99.1% (7 data points)

A summary of the air leakage rates at 50 Pa internal-external static pressure difference (ie Q_{50}) is presented in Table 4.7 below together with the Q_{50} air leakage normalised with respect to the envelope area of the factory.

The air leakage at 50 Pa quoted for the factory as-built case was an extrapolated value obtained from regression analysis performed on the logarithmically transformed variables. The extrapolation is considered valid[2] as the regression coefficient is greater than 99.0% and the flow exponent, n, has a value between 0.5 and 0.7.

The leakages at 50 Pa for the other two cases were also calculated from the regression fits, and can be checked graphically from the experimental data since pressure differences of up to 75 Pa were achieved.

Table 4.7: Summary of Air Leakage Tests

Test	Q_{50} ($m^3.s^{-1}$)	($m^3.s^{-1}.m^{-2}$)*	Configuration
P01	6.06	0.056	door sealed
P02	5.83	0.054	door and vents sealed
P03	8.70	0.079	'as built'

* The envelope area of the factory was estimated to be 1100 m^2. The area of the loading door was taken to be 16 m^2. There were 4 ventilators, each of area 1.56 m^2.

5. DISCUSSION

The tracer decay results show an increase in infiltration rate from 0.30 $ac.h^{-1}$ (0.25 $m^3.s^{-1}$) to 0.39 $ac.h^{-1}$ (0.33 $m^3.s^{-1}$) with increasing wind speed, from low to moderate. Opening the roof vents increased the ventilation rate to 2.12 $ac.h^{-1}$ (1.80 $m^3.s^{-1}$).

The constant concentration results show that for all wind speeds there was a good correlation of infiltration rate with wind speed (wind direction was almost without exception from the south/south west). This data is presented in Figures 5, 6 and 7. At low wind speeds (less than 1 $m.s^{-1}$) the infiltration rate was approximately 0.2 $ac.h^{-1}$ (0.17 $m^3.s^{-1}$). The correlation with stack was second order, as demonstrated by the strong correlation of air infiltration rate with windspeed (Figures 5, 6 and 7) and the relative magnitude of the windspeed and stack coefficients in the regression equations (Table 4.4). For the 'as built' configuration, including the stack in the regression improved the goodness of fit (ie. R-squared). However, for the sealed configuration there is a slight decrease in the goodness of fit, from 67.8% to 66.8%, when stack is included. Figures 11, 12 and 13 show air infiltration rate normalised with respect to stack versus windspeed normalised with respect to stack.

From the regression equations relating air infiltration rate to windspeed (all directions) and stack for the factory as-built and factory with door plus roof vents sealed, sealing the loading door and roof ventilators reduced the infiltration rate by approximately 28% (refer to Figures 14 and 15, Tables 4.5 and 4.6).

Comparing constant concentration runs with tracer decay for low and moderate wind speeds gave good agreement as shown in Table 5.1 below.

Opening the roof vents increased the infiltration rate to 2.44 $ac.h^{-1}$ (2.07 $m^3.s^{-1}$) as measured by the constant concentration method. This again agrees well with tracer decay results for roof vents open, (air infiltration rate 2.12 $ac.h^{-1}$), as summarised in Table 5.1 below.

Table 5.1 : Comparison of Tracer Decay with Constant Concentration Tests

	Tracer Decay			Constant Concentration		
	($ac.h^{-1}$)	($m^3.s^{-1}$)		($ac.h^{-1}$)	($m^3.s^{-1}$)	
Low Wind	0.30	0.25	(D01)	0.27	0.23	(CC01)
Moderate Wind	0.39	0.33	(D02)	0.48	0.41	(CC05)
Roof Vents open	2.12	1.78	(D03)	2.44	2.07	(CC05)

At moderate windspeeds, the mean air infiltration rate as determined by the constant concentration experiment (0.48 $ac.h^{-1}$) was higher than that determined by the tracer decay experiment (0.39 $ac.h^{-1}$). This was due to the mean value of the stack being higher for the constant concentration test (2.6 $^\circ C^{1/2}$) than for the tracer decay test (1.8 $^\circ C^{1/2}$) (refer to the Appendix, Tables A2 and A8).

The air leakage results show a decrease in air leakage rate with increasing sealing, from 8.70 $m^3.s^{-1}$ (0.079 $m^3.s^{-1}.m^{-2}$) (extrapolated value) to 6.06 $m^3.s^{-1}$ (0.056 $m^3.s^{-1}.m^{-2}$) to 5.83 $m^3.s^{-1}$ (0.054 $m^3.s^{-1}.m^{-2}$), for the 'as built', door sealed and door and vents sealed cases respectively. This represents a reduction in air leakage of 23% achieved by sealing the loading door, and a total reduction in air leakage of 33% achieved by sealing both the loading door and the roof vents.

The percentage reduction (33%) in air leakage effected by sealing the loading door and roof vents agrees reasonably well with the reduction in air infiltration rate (28%) as measured by the constant concentration experiments.

6. CONCLUSIONS

Infiltration rates were well correlated with windspeed for the wind directions (south and south west) under which measurements were taken. There was good agreement between the tracer decay and constant concentration tests results. This would imply that both methods are suitable for air infiltration measurements in this size of building.

On average, the air infiltration rate was measured to be 0.4 $ac.h^{-1}$ (0.34 $m^3.s^{-1}$). This is well below the CIBSE[1] design value of 1 $ac.h^{-1}$ for this size and construction factory.

Averaging the results obtained from tracer decay and constant concentration experiments showed that opening the roof vents provided a ventilation rate of 2.3 $ac.h^{-1}$ (1.95 $m^3.s^{-1}$).

The air leakage rate was 8.7 $m^3.s^{-1}$ (0.079 $m^3.s^{-1}.m^{-2}$) at 50 Pa static pressure difference (extrapolated value). On opening the roof vents with the loading door sealed, a maximum flow rate of 8.3 $m^3.s^{-1}$ produced an internal – external static pressure difference of 4 Pa.

Sealing the roof ventilators and loading door reduced the air infiltration rate by 28% as determined by the constant concentration method. This compares well with a reduction in air leakage of 33% at 50 Pa static pressure difference as measured by the fan pressurisation method.

The major component for air leakage as identified by the air leakage tests was the loading door. Sealing the loading door reduced the air leakage at 50 Pa by 23%.

7. ACKNOWLEDGEMENTS

The work described here formed part of a program of work funded by the Building Research Establishment (BRE) that is still in progress. The paper describes interim results and does not necessarily represent the views of the BRE.

We would like to acknowledge the help of the Welsh Development Agency in making the factory available for our tests.

8. REFERENCES

1. CIBSE Guide A4. Table A13, p A4 – 15
The Chartered Institute Of Building Services Engineers, London.

2 Determining the airtightness of buildings by the fan pressurisation method: BRE recommended procedure. p8.
R. K. Stephen BSc.

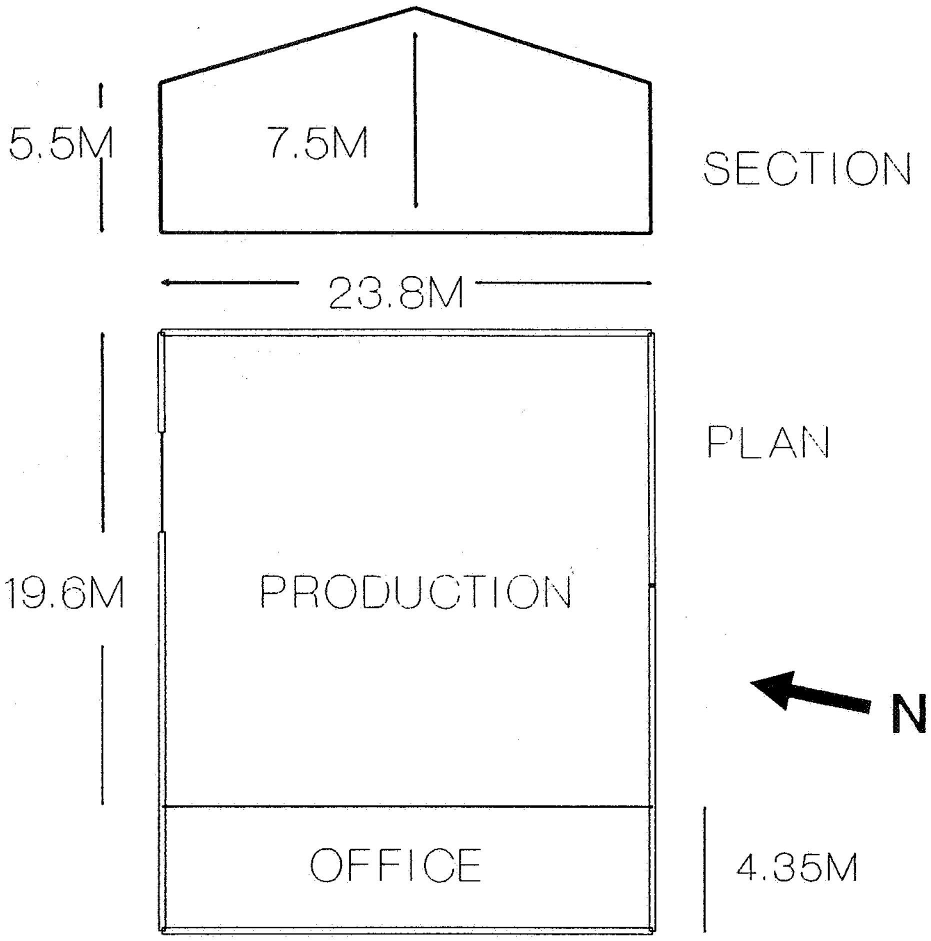

Figure 1: Section And Plan Of Factory

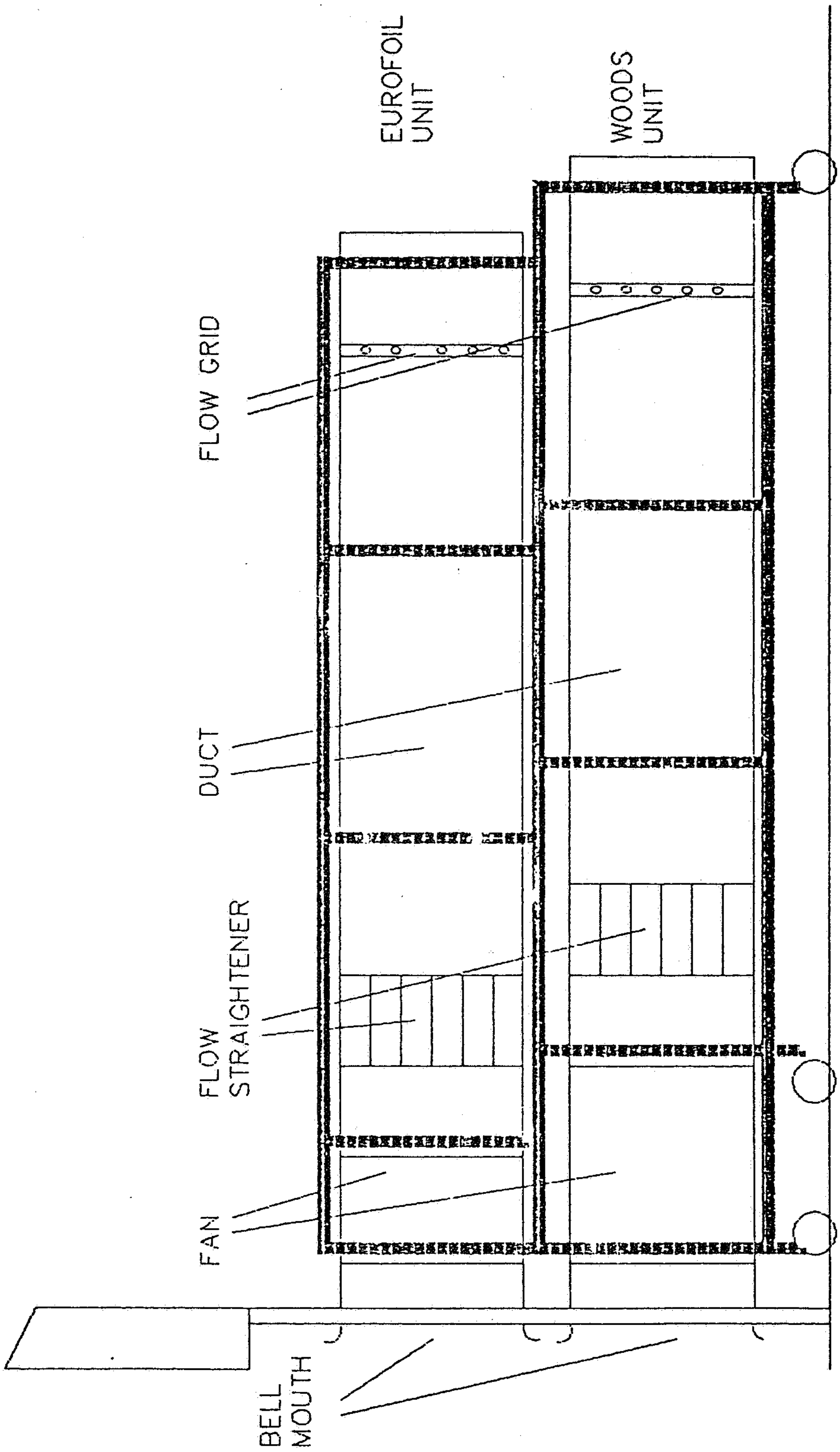

Figure 2: Fan Pressurisation Rig

Figure 3: Tracer Decays
Tests D01, D02 and D03

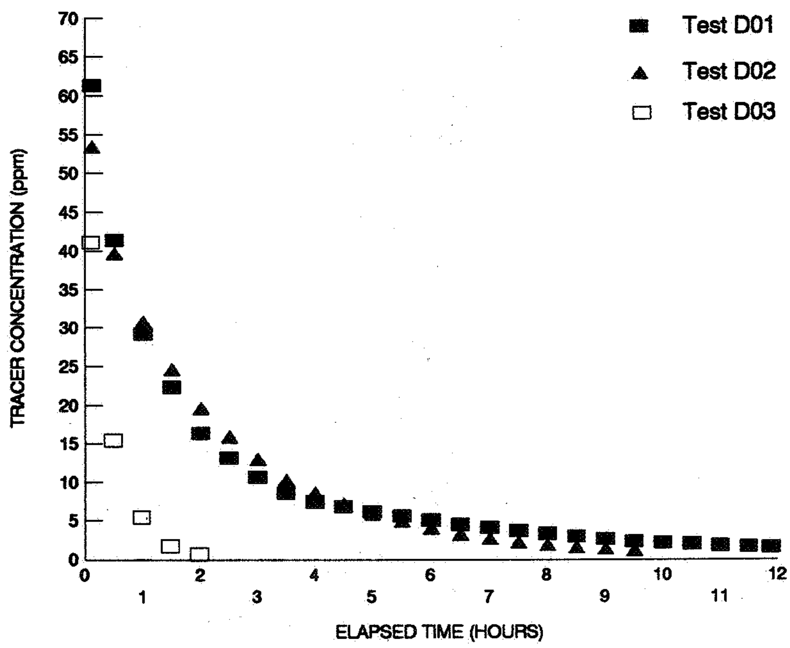

Figure 4: Logarithmic Tracer Concentrations
Tests D01, D02 and D03

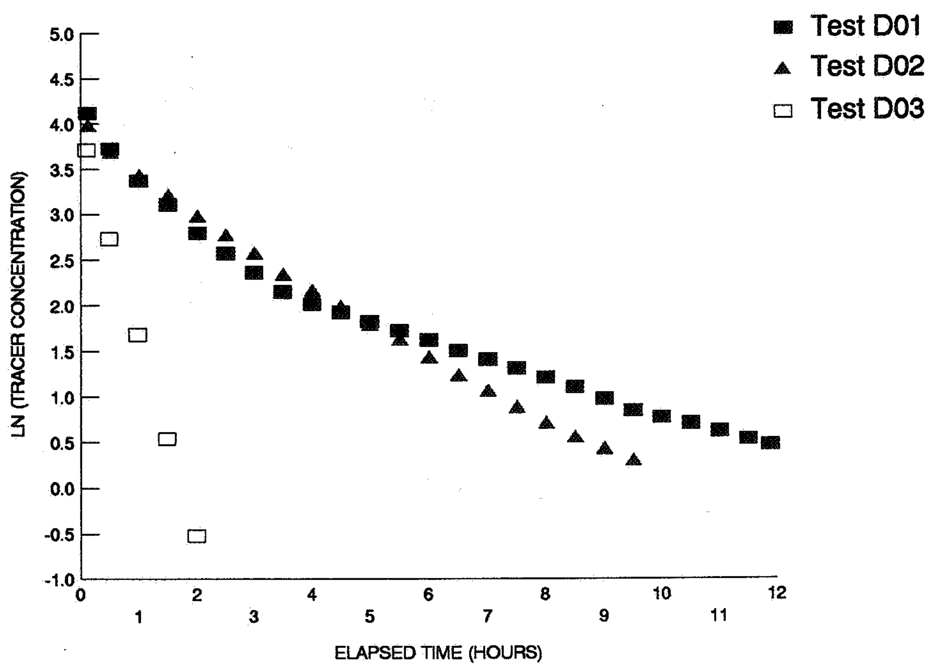

Figure 5: Air Infiltration Rate Versus Windspeed (All Wind Directions) For Factory As-Built and Door+Vents Sealed Cases

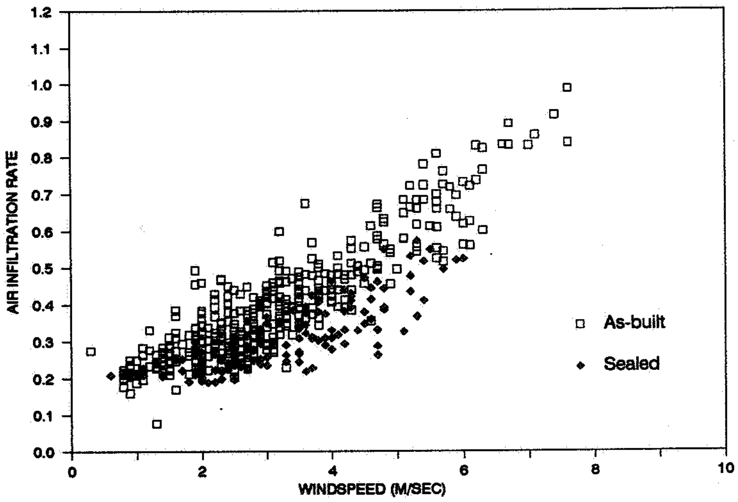

Figure 6: Air Infiltration Rate Versus Windspeed (South Only) For For Factory As-Built And Door + Vents Sealed Cases

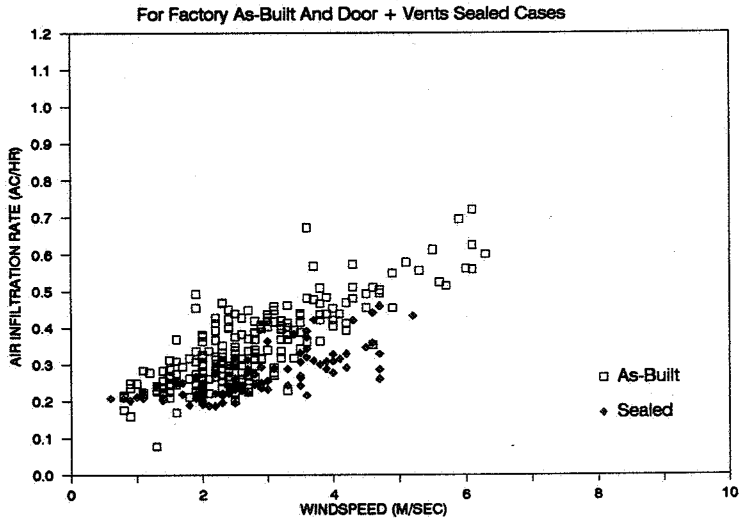

Figure 7: Air Infiltration Rate Versus Windspeed (South West) For Factory As-Built And Door+Vents Sealed Cases

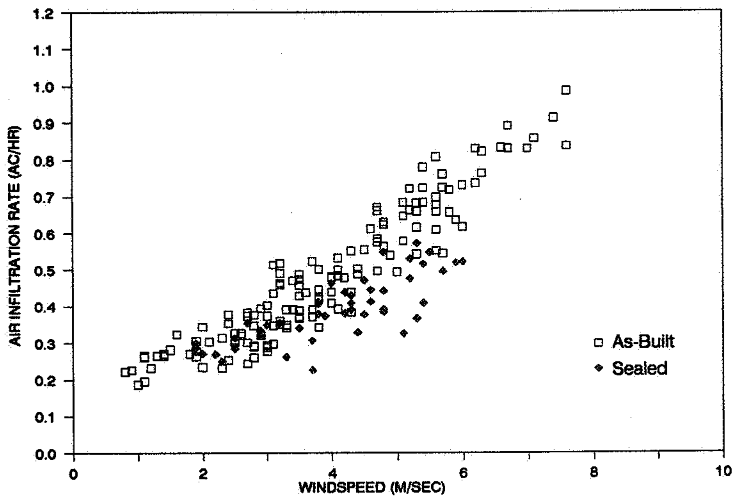

Figure 8: Regression Fits For Air Infiltration Rate Versus Windspeed
All Wind Directions

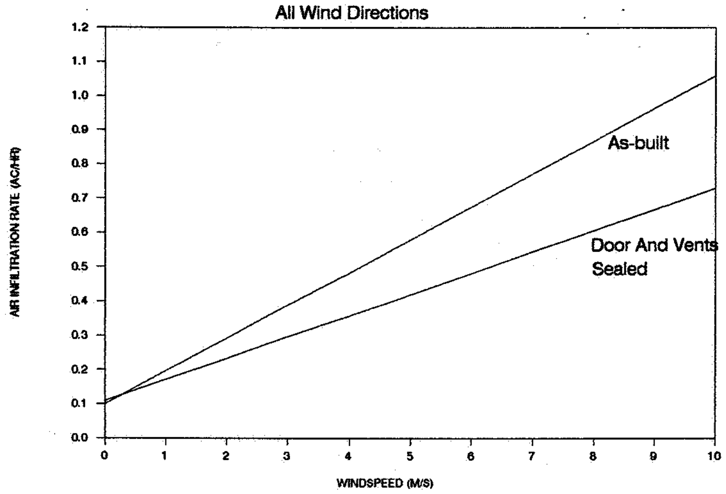

Figure 9: Regression Fits For Air Infiltration Rate Versus Windspeed
Wind Direction: South

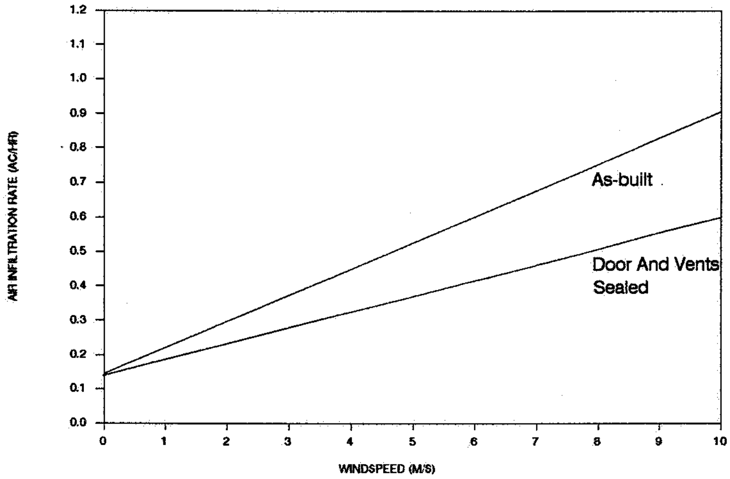

Figure 10: Regression Fits For Air Infiltration rate Versus Windspeed
Wind Direction: South West

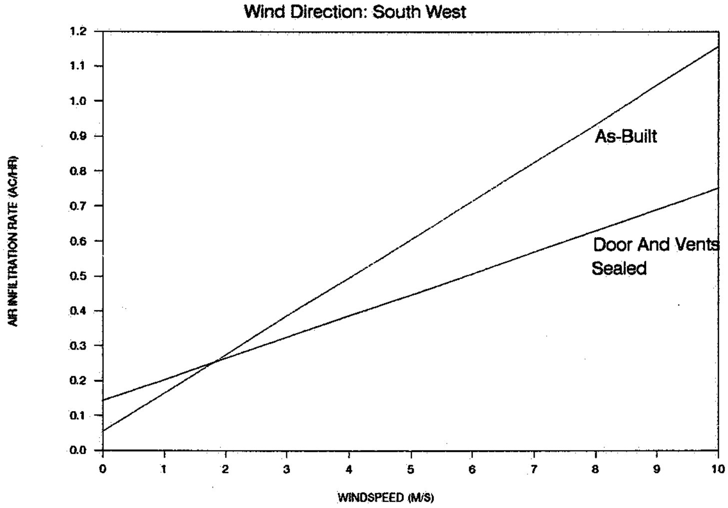

Figure 11: Air Infiltration Rate/Stack Versus Windspeed/Stack (All Directions)
For Factory As-Built and Door+Vents Sealed Cases

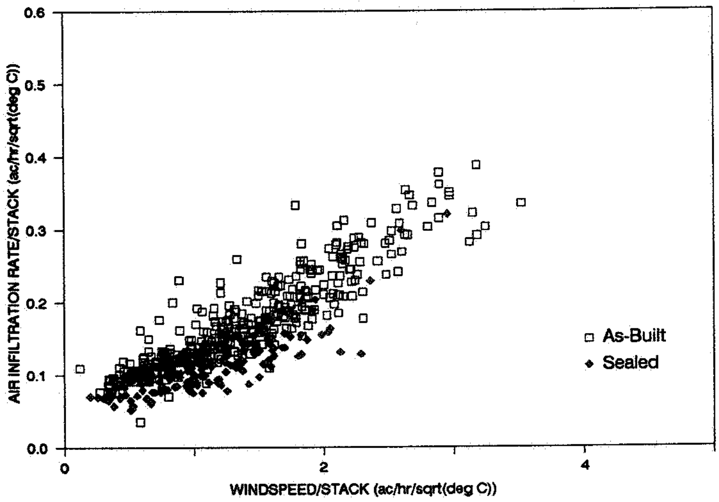

Figure 12: Air Infiltration Rate/Stack Versus Windspeed/Stack (South Only)
For Factory As-Built And Door And Vents Sealed Cases

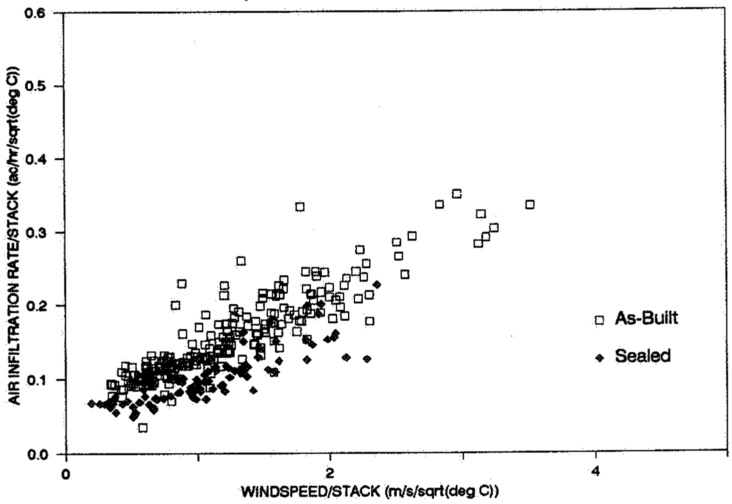

Figure 13: Air Infiltration Rate/Stack Versus Windspeed/Stack (South West)
For Factory As-Built And Door And Vents Sealed Cases

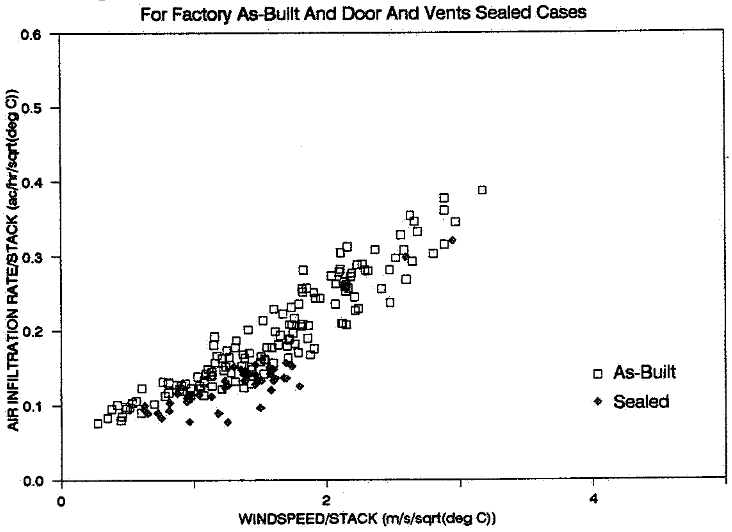

Figure 14: Regression Fit For Air Infiltration Rate As A Function Of Windspeed And Stack. All Wind Directions, Stack = 1

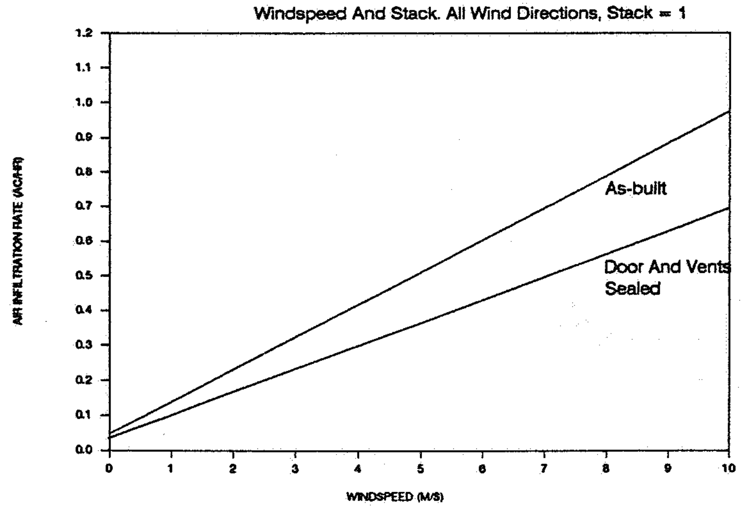

Figure 15: Regression Fit For Air Infiltration Rate As A Function Of Windspeed And Stack. All Wind Directions, Stack = 3

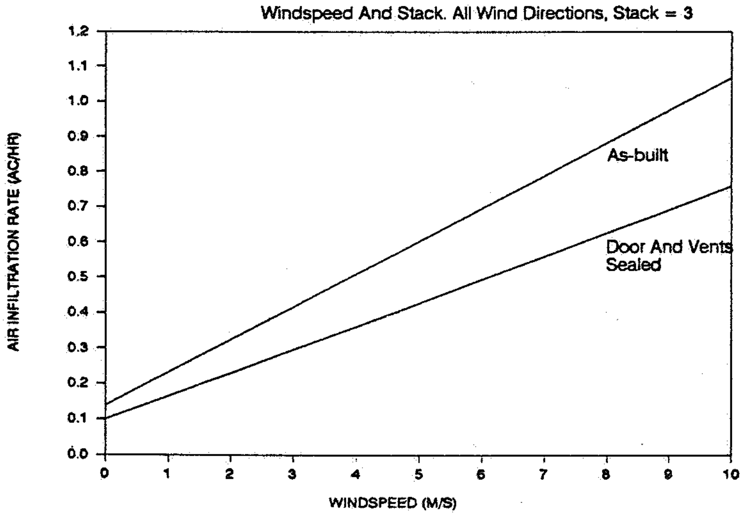

Figure 16: Air Leakage Tests P01, P02 and P03.