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BS 68

An investigation of the infiltration characteristics of windows and doors in a tall building using pressurisation techniques

I C Ward and S Sharples

RERUM COGNOSCERE CAUSAS

Department of Building Science
Faculty of Architectural Studies
University of Sheffield

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AN INVESTIGATION OF THE INFILTRATION CHARACTERISTICS OF WINDOWS AND DOORS IN A TALL BUILDING USING PRESSURISATION TECHNIQUES.

I.C. WARD AND S. SHARPLES

University of Sheffield,
Department of Building Science,
SHEFFIELD.
S10 2TN

Tel. No. 0742 - 78555

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SUMMARY

This report sets out the design and construction of pressure test rigs for use in windows and doorways in the Arts Building at Sheffield University. Results of tests on windows and doors in this building are presented which indicate that the building has suffered a considerable amount of fabric deterioration.

NOMENCLATURE

Symbol		
C	Basic coefficient	non-dimensional
D	Internal diameter of upstream pipe	inches
E	Velocity of approach factor	non-dimensional
N	Value of $CZ\varepsilon Em$	non-dimensional
Q	Flow rate	L/S
R_e	Reynolds number	Non-dimensional
W	Mass flow	lb/hr
Z	Product of Z_e and Z_D	non-dimensional
Z_D	Pipe size connection factor	non-dimensional
Z_R	Reynolds number correction factor	non-dimensional
d	Diameter of orifice	inches
h	Pressure difference across device	in H_2O
m	Area ratio	non-dimensional
n	flow exponent	non-dimensional
Δp	Pressure difference across component being tested	Pascal
ε	Expansibility factor	non-dimensional
μ	Dynamic viscosity	poise
ρ	Density of fluid at working conditions	lb/ft^3

1. BACKGROUND

The Arts Tower at Sheffield University shown in Plate 1 is currently the subject of investigations into its energy performance.

During the heating season in windy conditions air change rates in the order of 15 per hour have been measured at the top of this building.

Using accepted calculation procedures for estimating infiltration rates it was found that such high values of air change rate could not be obtained. It therefore appeared that either the measurements were in error or that the infiltration coefficients of the windows were larger than those quoted in the literature. These errors stimulated the development of a component pressure testing rig to enable the actual values of infiltration coefficients to be established.

1.1 The Building

The building has 19 floors and is 78m high with a glazing ratio of 60%. Figure No. 1 shows a typical floor plan from which can be seen that there is a high degree of partitioning and plenty of scope for air infiltration due to the large number of windows.

The windows are of the vertically sliding type with an openable length of 5.1m. The window frames are mounted directly onto the concrete mullions and sealed by a mastic sealant on the inside.

The building is some 16 years old and a certain amount of deterioration of the building fabric has occurred.

2. THE COMPONENT PRESSURE TESTING RIG

In order to carry out the pressurisation tests it was necessary to design and construct a suitable test rig. The general criteria which had to be satisfied by the rig were:-

(i) the rig had to be capable of adjusting to variations in floor ceiling height as it was found that the floor ceiling height could vary by as much as 4cm per floor.

(ii) the measurement of air flows had to be as accurate as practically possible.

(iii) the rig had to have a low air leakage characteristic.

(iv) the rig had to be portable.

(v) the rig had to be able to allow both the positive and negative characteristics to be obtained.

The rig was designed in two distinct sections, the first dealt with obtaining a good seal around the component and the second dealt with the generation and measurement of the air flow. Plate 2 shows the rig in position for testing a window.

2.1 Sealing the Test Rig

The frame of the rig was constructed of 50mm square section timber and 20mm thick chipboard, glued, screwed and taped to ensure a good seal between the joints. Where the frame came in contact with the walls or ceiling commercially available weather stripping material was used as a gasket between the frame and the wall. Once the rig was positioned the edges were sealed with a plastic coated fabric tape around all edges.

2.2 Air Flow Measurement

Staged axial flow fans with speed controllers were used to pressurise the rig. The air flow rates using this set up ranged from 10 to 140 L/S with a pressure differential capability of 900 Pa. These characteristics were considered satisfactory for window and door pressurisation.

It was decided to use an orifice plate to measure the flow rates as generally these devices are very accurate. A suitable orifice plate was designed and constructed within the department, the detail calculations and calibration curve are given in Appendix I of this report.

The pressures were measured using strain gauge bridge transducers designed by the Building Research Station[1]. These were felt to be satisfactory as their responce was linear and drift negligible over the period of the tests. A typical calibration routine is given in Appendix II. The output from the pressure transducers was recorded either on a Fluke data logger or a multi channel flat bed recorder. During each test air temperatures were also recorded thus allowing density variations to be taken into consideration.

3. TESTING OF WINDOWS

The Arts Building has some 1,786 windows nominally identical. It would be a mammoth task to measure each window and it was therefore decided to categorise the windows in terms of the deterioration of the sealants. Selected windows in all four faces of the building were then tested. The results quoted in this report are intended to show the ranges into which the infiltration coefficients face rather than give precise coefficients for each window. Figures 2 and 3 show the experimental set up for carrying out a positive and negative pressure test on a window.

The rig leakage was established by taping up all the possible air flow paths and thus by removing the tape from various junctions the characteristics could be established.

3.1 Tests on Windows where the Sealant Appeared Defective

A sample curve for a window which had defective sealing between the frame and mullion is shown in Figure 4. The curves are characteristic of this group of windows and it can be clearly seen that when a pressure differential of 60 Pa across the window in the positive direction (i.e. the inside is positive with respect to the outside)it is possible to detect the leakage due to the operable part of the window. In the negative direction the differences are more apparent. This characteristic indicates that in the negative direction the weather stripping of the operable part of the window breaks down, which has serious consequences for infiltration on the wind-ward side of the building. It would also appear that cracks are opened up under negative pressure which are sealed under positive pressure. Furthermore in both cases the rig leakage was less than 10% of the component leakage.

3.2 Tests on Windows where the Sealant did not Appear Defective

Again a sample curve for a window where the sealant did not appear defective is shown in Figure 5. In these tests the difference in characteristics between frame leakage and total leakage was more apparent and consistant between positive and negative pressure indicating that no breakdown of weather-stripping or opening or closing of cracks was taking place.

3.3 The Overall Values of Window Coefficients

A series of windows in each category were tested and their characteristics plotted in Figure 6. It is clear from this figure that in both cases the leakage is far in excess of the suggested leakage from the CIBS Guide(2). The generally accepted form of flow characteristic takes the form of

$$Q = C\Delta p^{n}$$

values of n usually fall into the range 0.6-0.7 and C in the range 0.25-0.05 depending on the type of window.

Table I shows the measured values of infiltration coefficient and exponents.

Values of C	Values of n
0.911	0.693
3.790	0.445
2.591	0.528
1.022	0.693
1.189	0.630
1.714	0.581
1.494	0.578
5.182	0.639
4.468	0.582
6.097	0.533

TABLE 1 Values of Flow Constants

3.4 Weather-stripping of a Window

During the test programme a manufacturer of weather-stripping material weather-stripped a window as a demonstration of his product. A pressure test was subsequently carried out on this window and the flow characteristic is shown in Figure 7.

The resulting flow characteristic was

$$Q = 0.599 \; p^{0.63} \text{ in the positive direction}$$

and

$$Q = 0.317 \; p^{0.627} \text{ in the negative direction}$$

The difference in flow characteristics between positive and negative flow characteristic was not unexpected as the product was of the folded 'V' type of weather-strip. On the positive pressure test the 'V' would be closed thus allowing more air to pass. Even allowing for this movement the product did reduce the flow by some 65%.

4. PRESSURISATION OF DOORS

Part of the energy analysis of the Arts Building includes modelling the air flow paths through the building. In order to do this the characteristics of the doors must be known. It was therefore decided to test several doors including the fire doors. In these tests smoke was also used to visualise the air flow paths. Finally the effectiveness of a door weather-strip was tested on a door which had a particularly poor performance.

For the tests on the doors it proved impractical to use the full orifice plate test rig and therefore the vane anemometer set up was used. Plate 3 shows the rig in position for testing fire doors and Plate 4 shows the pressure transducers positioned in the fire lobby. It should be noted that in Plate 4 the centre pressure transducer has been modified to become a remote pressure differential sensor.

4.1 Tests on Fire Doors

The fire doors leading on to the escape stair wells form a fire lobby with double doors opening on to the stair well. It was decided to treat the double doors as a single unit and a series of tests carried out to establish the characteristics of each door type. The results of these tests are presented in Figure 8 and the flow equations are shown in Table 2.

Single Doors	Flow into Lobby	Flow from Lobby
	L/S m length of opening	L/S m length of opening
Types 1 and 2	$1.71 \; p^{0.577}$	$1.53 \; p^{0.572}$
Type 3	$1.95 \; p^{0.599}$	$2.67 \; p^{0.502}$

TABLE 2 Equations for Fire Doors

4.2 Tests on Office Doors

The office doors in this building have an openable window above the door, the tests were therefore carried out with this window sealed and unsealed. The results of these tests are presented in Figure 9 and the flow equations shown in Table 3.

The experimental results show that 56% of the air flow across the doorway was due to the gap between the door bottom and the floor 30% of the total flow was due to the openable window at the top of the door.

Office Doors	Flow in Direction of Opening L/S m length of opening	Flow in Direction of Closing L/S m length of opening
Flow across bottom of door	$20.03\ \Delta p^{0.417}$	$16.38\ \Delta p^{0.499}$
Flow across whole door	$3.25\ \Delta p^{0.483}$	$2.866 \Delta p^{0.527}$
Flow across window	$1.29\ \Delta p^{0.658}$	$1.66\ \Delta p^{0.639}$

TABLE 3 Flow Equations for Doors

Note: In deriving these equations the actual length of opening for each case was used which explains why the bottom of the door appears large.

Comparing the results between the office doors and fire doors it can be seen that on average the fire doors were in the order of 50% tighter than the office doors.

4.3 Weather-stripping the Bottom Edge of the Office Doors

As over 50% of the flow across the office doors was attributed to the bottom edge a test was carried out on the effectiveness of a door weather-strip device.

The weather-strip used was a commercially available flexible rubber type. The results of the pressure tests carried out in this weather-strip are shown in Figure 10. It is clear from this figure that the weather-strip reduced the flow by 51.9% when the rubber was pushed against the floor (Direction A in the figure) and by 44.7% when the flow was in the oposite direction (Direction B in the figure).

4.4 Flow Visualisation

Flow visualisation using smoke was used when testing the office doors, this was done purely as a method of noting where the air was escaping Plates 5 and 6 show two photographs taken during the tests. In Plate 5 the air can be seen flowing predominantly under the door with some escaping through the edges. Plate 6 shows the effectiveness of the weather-strip on the bottom of the door. The air leakage through the sides of the door can be clearly seen along with the flow through the window edges.

5. DISCUSSION

The objectives behind this report was to set out the general characteristics of the infiltration coefficients of both windows and doors in the Arts Building and to describe the pressure test rig built in the department.

The characteristics quoted are the result of a limited set of tests and it is now intended to embark on a comprehensive analysis into the degree of variability of infiltration coefficient. One objective behind such a study would be to establish the viability of proposed improvements to the building fabric

REFERENCES

1. Mayne, J.R. A Wind Pressure Transducer. BRE Current Paper CP 17/70, 1970. Building Research Establishment, Watford.

2. CIBS Guide to Current Practice Section A4 - Ventilation. London 1978.

APPENDIX I

The Design of the Orifice Plate

The orifice plate used in the pressure test rig was designed using British Standard 1042 : Part 1. This standard being initially produced in 1964 all the graphs relating to the design calculations were in Imperial Units and therefore it was easier to convert the flows and pressures required to these units for the purpose of the calculations.

The initial requirements for the orifice plate were

(a) Flow rate of 660 lb/hr. (0.083 Kg/s) of air at a pressure difference of 0.293" wg (73 Pa).

(b) The upstream diameter of the pipe was 6" (152.4mm)

A square-edged orifice plate was selected as being the most appropriate type for the flow conditions required.

The Calculations

Clause 15 of the standard was used to carry out the calculations.

Step 1

Using the following equation the non-dimensionless number N was obtained.

$$N = \frac{W}{359.2\ D^2 \sqrt{hp}} \qquad \text{A1}$$

$$= \frac{660}{359.2 \times 6^2 \sqrt{0.073 \times 0.293}}$$

$$= 0.3489$$

Next the value of mE was established

$$mE = 1.65N$$

$$mE = 1.65 \times 0.3489$$

$$= 0.5758$$

From Figure 63 the ratio of the orifice diameter to pipe diameter was found using the value of mE

$$\frac{d}{D} = 0.708 \quad \therefore \quad d = 4.25$$

$$E = 1.1532$$

From Table 1 the maximum error would not exceed ±3%.

Calculation of the Flow Equation for the Orifice Plate

As the orifice plate would be used in situations where the flow rate was not constant it was necessary to establish the flow equation. This equation takes the form

$$W = 359.2\ CZ\ E\varepsilon d^2 \sqrt{hp} \qquad \text{A2}$$

Each constant has to be evaluated to arrive at the solution. Initially the factor Z is set to unity and the flow equation calculated. This answer is used to calculate the Reynolds number which is then used to calculate Z .

Step 1 Basic Coefficient

Find m

$mE = 0.5758$

$E = 1.1532$

$\therefore m = 0.4993$

From figure 38

$C = 0.606$ for $m = 0.4993$

Step 2 Expansibility Factor

The ratio of pressure drop across the orifice plate to upstream gauge pressure was taken as unity, and the ratio of specific heats taken as 1.4.

From Figure 39

$\varepsilon = 0.99$

Step 3 Approximate Flow

Using equation A2

$$W = 359.2\ CZ\varepsilon E\ d^2 \sqrt{hp}$$

$$W = 359.2 \times 0.606 \times 1 \times 0.99 \times 1.1532 \times 4.25^2 \sqrt{0.293 \times 0.073}$$

$$= 656.48 \text{ lb/hr}$$

Step 4 Reynold's Number Calculation

The Reynold's Number is given by the following equation

$$R_e = \frac{W}{15.8\mu\ D \sqrt{m}} \qquad \text{A3}$$

using values already calculated.

$$R_e = \frac{656.48 \times 10^5}{15.8 \times 6 \times 18.5 \times \sqrt{0.4993}}$$

$$= 5.29 \times 10^4$$

Step 5 Reynold's Number and Pipe Size Correction Factors

(a) Reynold's Number
From Figure 47
Z_R for m = 0.4993 is 0.995

(b) Pipe Size
From Figure 47
Z_D for m = 0.4993 is 1.045

$$\therefore \; Z = Z_R \times Z_D = 0.995 \times 1.045$$

$$= 1.0398$$

Step 6 Flow Equation

Using Equation A2 and substituting for Z.

$$W = 359.2 \times 0.606 \times 1.0398 \times 0.99 \times 1.1532 \times 4.25^2 \sqrt{0.073 \times h}$$

$$= 1261.066 \sqrt{h}$$

As these units are Imperial it is necessary to convert to Metric.

The flow in metric units is therefore

$$W = 36.33 \sqrt{\Delta p} \qquad \text{A4}$$

where W is in Kg/hr and Δp in Pascals.

Step 7 Check on Calibration

A check on the calculation procedure was carried out by means of a pitot tube traverse of the duct. Figure A1 shows the results of this check plotted on the same graph as the calculated performance.

APPENDIX II

Calibration of the Pressure Transducers

The output of the transducers was linear with pressure with a nominal sensitivity of 0.6 V $V^{-1} N^{-1} m^2$. The individual transducers differed from each other in sensitivity owing to slight variations in the thickness of cantilevers.

The transducers were calibrated by loading them with dead-weights and noting the voltage output.

A typical calibration test is shown in Table A1 with the corresponding graph in figure A2.

Applied Weight	Conversion factor to Pressure 1248.6631	Voltage Reading mV			
Kg	Pa	1	2	3	Mean
0	0	1.03	1.02	1.03	1.02
0.001	1.25	1.05	1.04	1.05	1.04
0.005	6.24	1.12	1.11	1.12	1.11
0.025	31.24	1.50	1.49	1.50	1.49
0.050	62.43	1.94	1.94	1.94	1.94
0.075	93.65	2.41	2.40	2.41	2.40
0.100	124.87	2.90	2.90	2.91	2.90

Transducer No. 118A

$$\text{Gradiant} = \frac{\Delta p}{\Delta mV} = \frac{124.87 - 31.24}{2.9 - 1.49} = 66.88$$

$$\therefore 1mV \equiv 66.88 \text{ Pa}$$

TABLE A1

Calibration Run for Pressure Transducer

APPENDIX III

Calibration of Vane Anemometer

As the pressure test rig was some 6m in length it proved difficult to fit into certain rooms to carry out tests. It was therefore decided to use a vane anemometer to measure the flow rate in situations where the full rig could not be accommodated. A vane anemometer was therefore fitted to a length of duct (10D equivalent diameter) and calibrated against the orifice plate.

The resulting calibration graph is shown in Figure A2.

APPENDIX IV

The Equations Used to Derive the Flow Constants

All the results obtained from the tests were fed into a standard statistical package run on a HP 85 desk top computer. The equations used in this package are as follows.

(a) Power Curve Fit

The form of the equation is

$$y = a\,x^{b}$$

$$b = \frac{\sum(\ell n\, x_i)(\ell n\, y_i) - \dfrac{(\sum \ell n\, x_i)(\sum \ell\, y_i)}{n}}{\sum(\ell n\, x_i)^2 - \dfrac{(\sum \ell n\, x_i)^2}{n}}$$

$$a = \exp\left[\frac{\sum \ell n\, y_i}{n} - b\,\frac{\sum \ell n\, x_i}{n}\right]$$

$$r^2 = \frac{\left[\sum(\ell n\, x_i)\,(\ell n\, y_i) - \dfrac{(\sum \ell\, x_i)\,(\sum \ell n\, y_i)}{n}\right]^2}{\left[\sum(\ell n\, x_i)^2 - \dfrac{(\sum \ell n\, x_i)^2}{n}\right] \times \left[\sum(\ell n\, y_i)^2 - \dfrac{(\sum \ell n\, y_i)^2}{n}\right]}$$

(b) Linear Fit

The form of the equation is

$$y = a + bx$$

$$b = \frac{\sum x_i\, y_i - \dfrac{\sum x_i \sum y_i}{n}}{\sum x_i^{\,2} - \dfrac{(\sum x_i)^2}{n}}$$

$$a = \left[\frac{\sum y_i}{n} - b\,\frac{\sum x_i}{n}\right]$$

$$r^2 = \frac{\left[\sum x_i y_i - \dfrac{\sum x_i \sum y_i}{n}\right]^2}{\left[\sum x_i^{\,2} - \dfrac{(\sum x_i)^2}{n}\right]\left[\sum y_i^{\,2} - \dfrac{(\sum y_i)^2}{n}\right]}$$

Plate 1: The Arts Tower

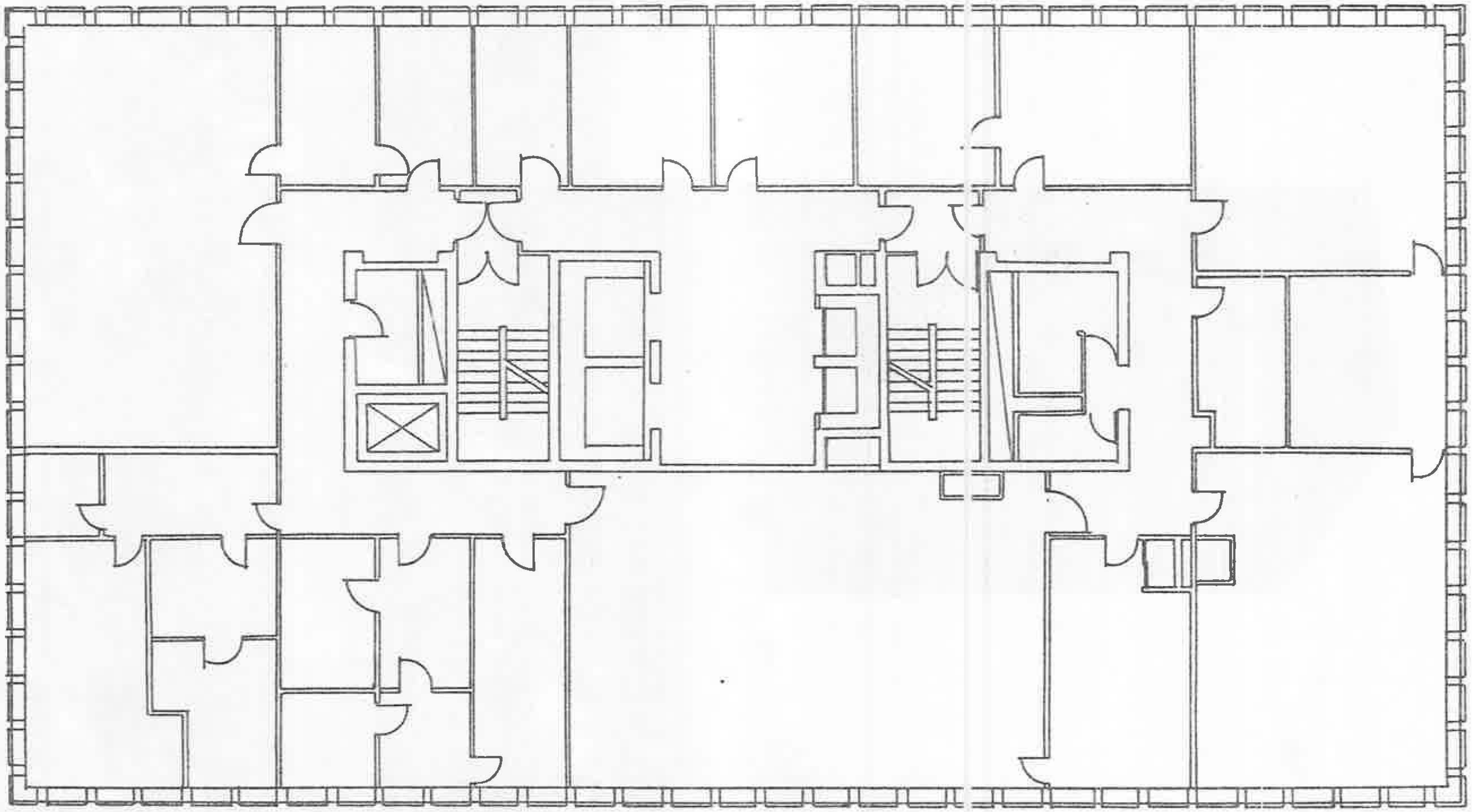


FIGURE 1 TYPICAL FLOOR PLAN OF THE ARTS BUILDING

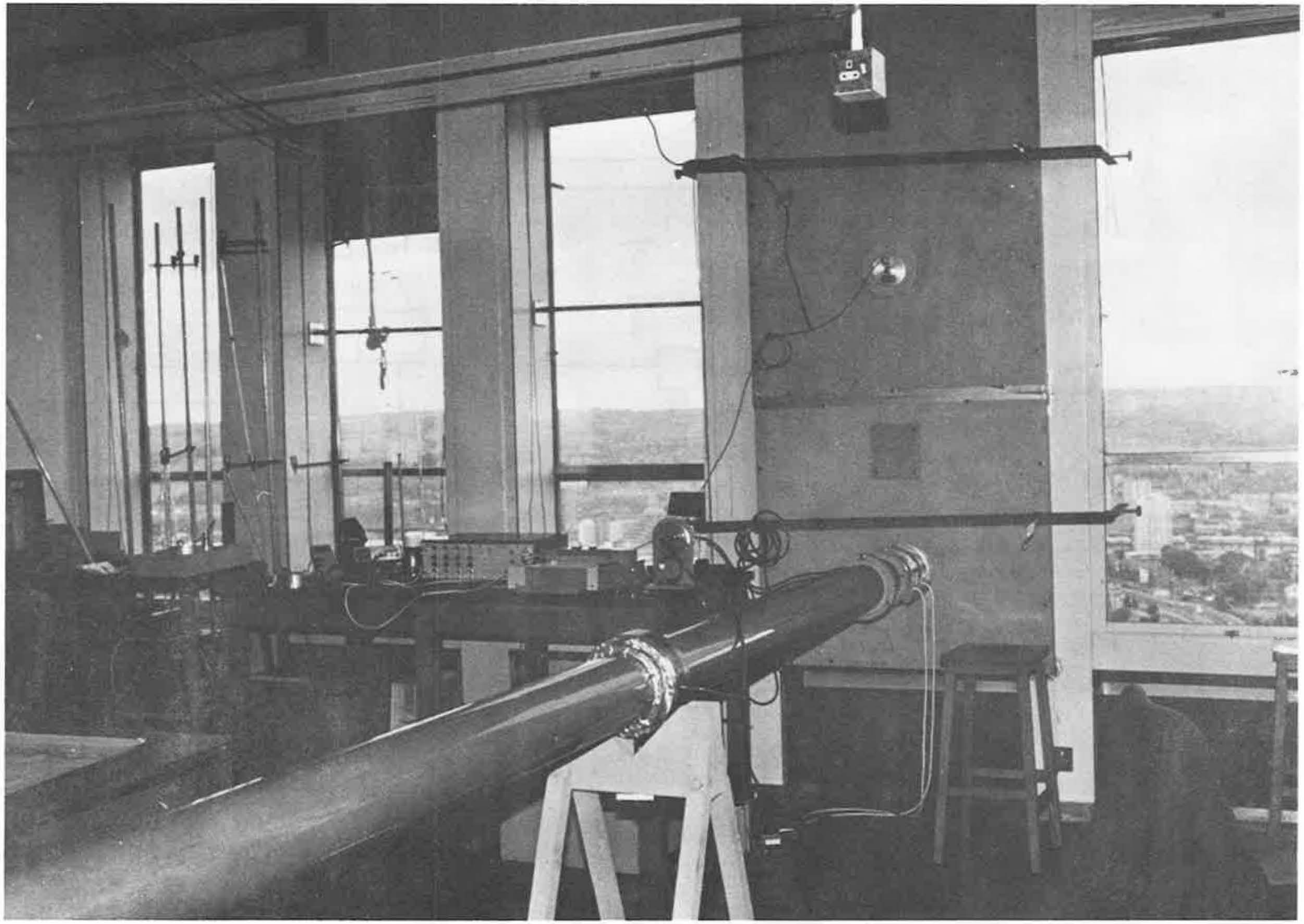


PLATE 2

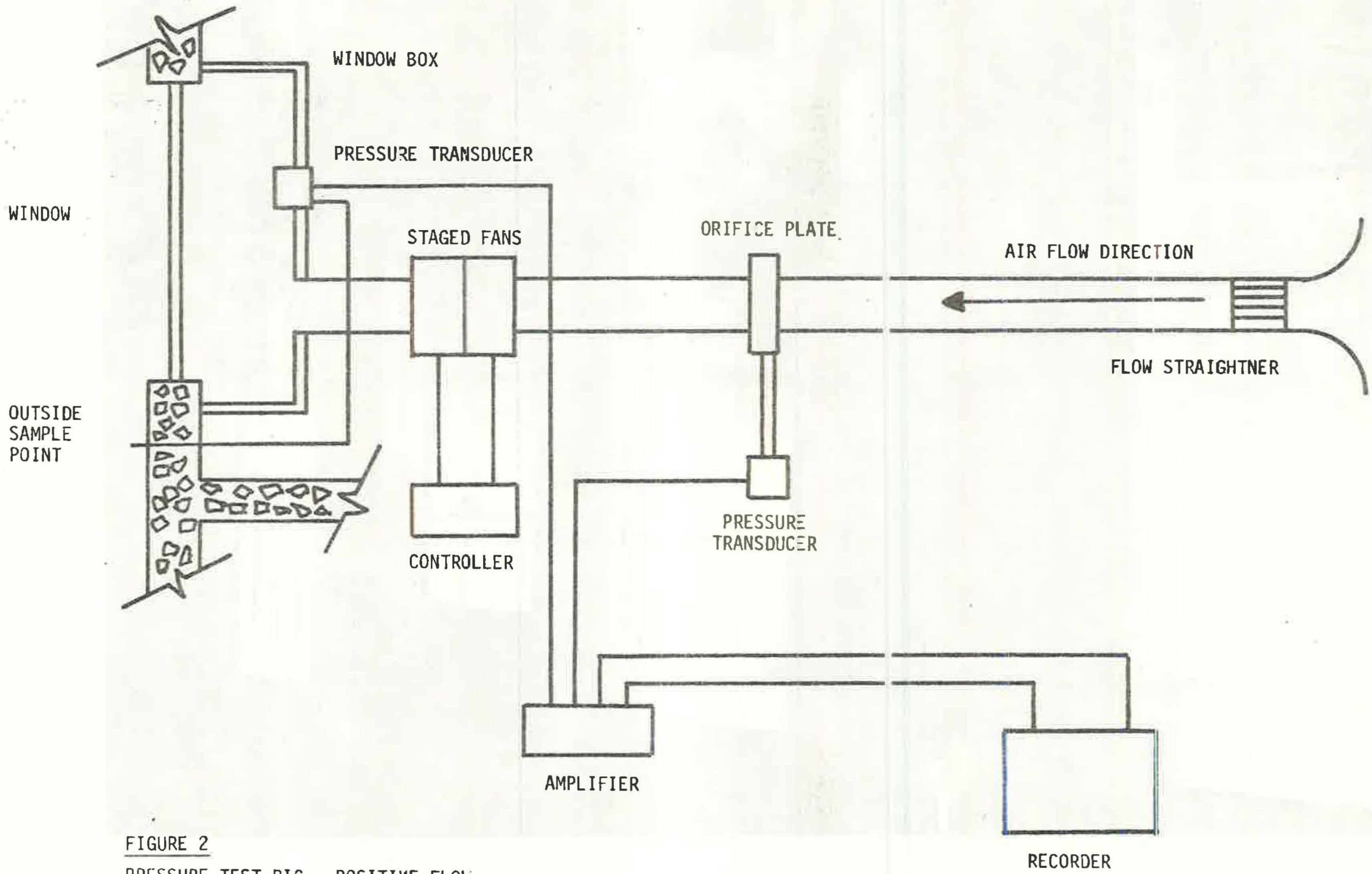


FIGURE 2

PRESSURE TEST RIG   POSITIVE FLOW

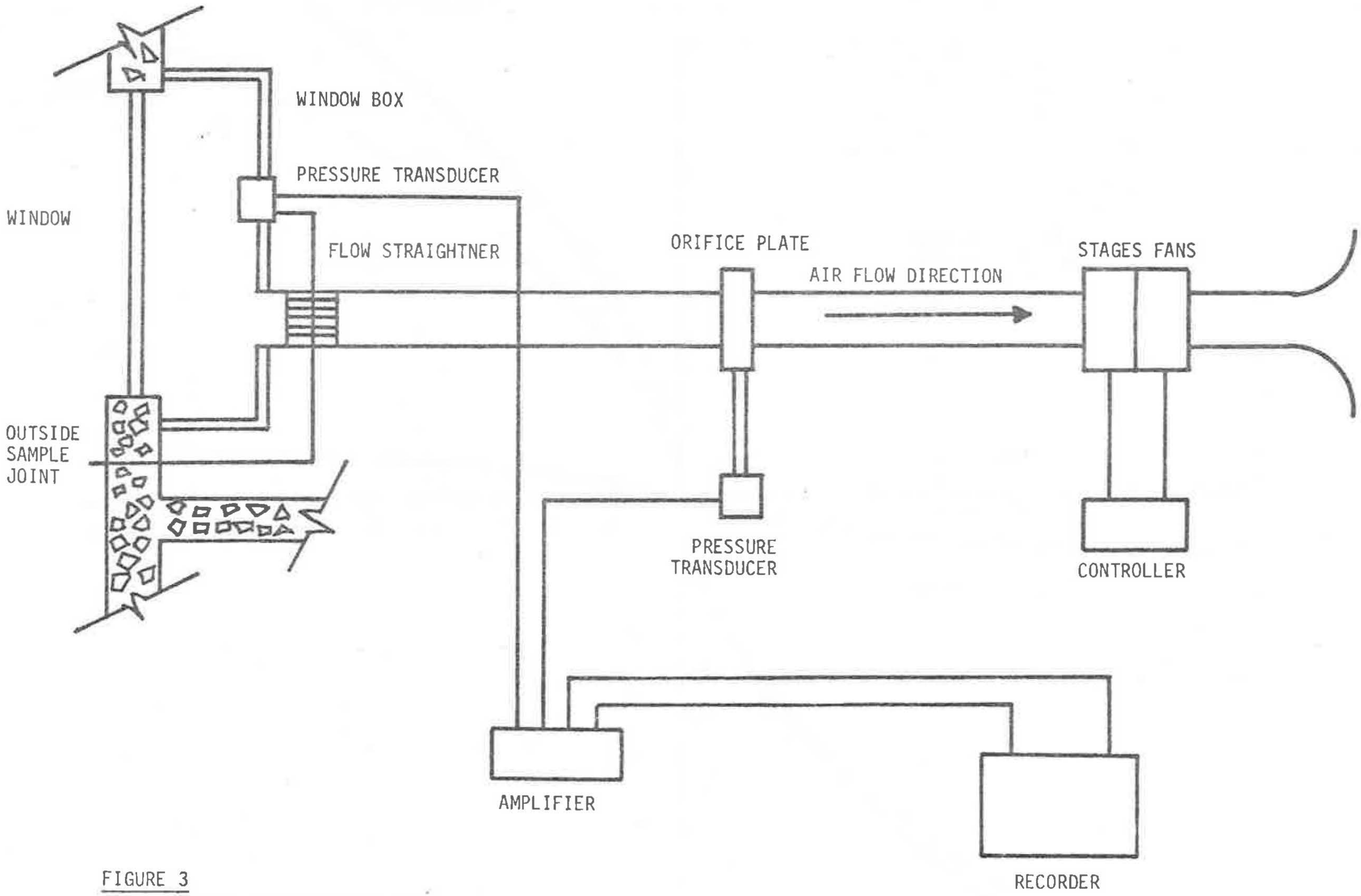


FIGURE 3
PRESSURE TEST RIG NEGATIVE FLOW

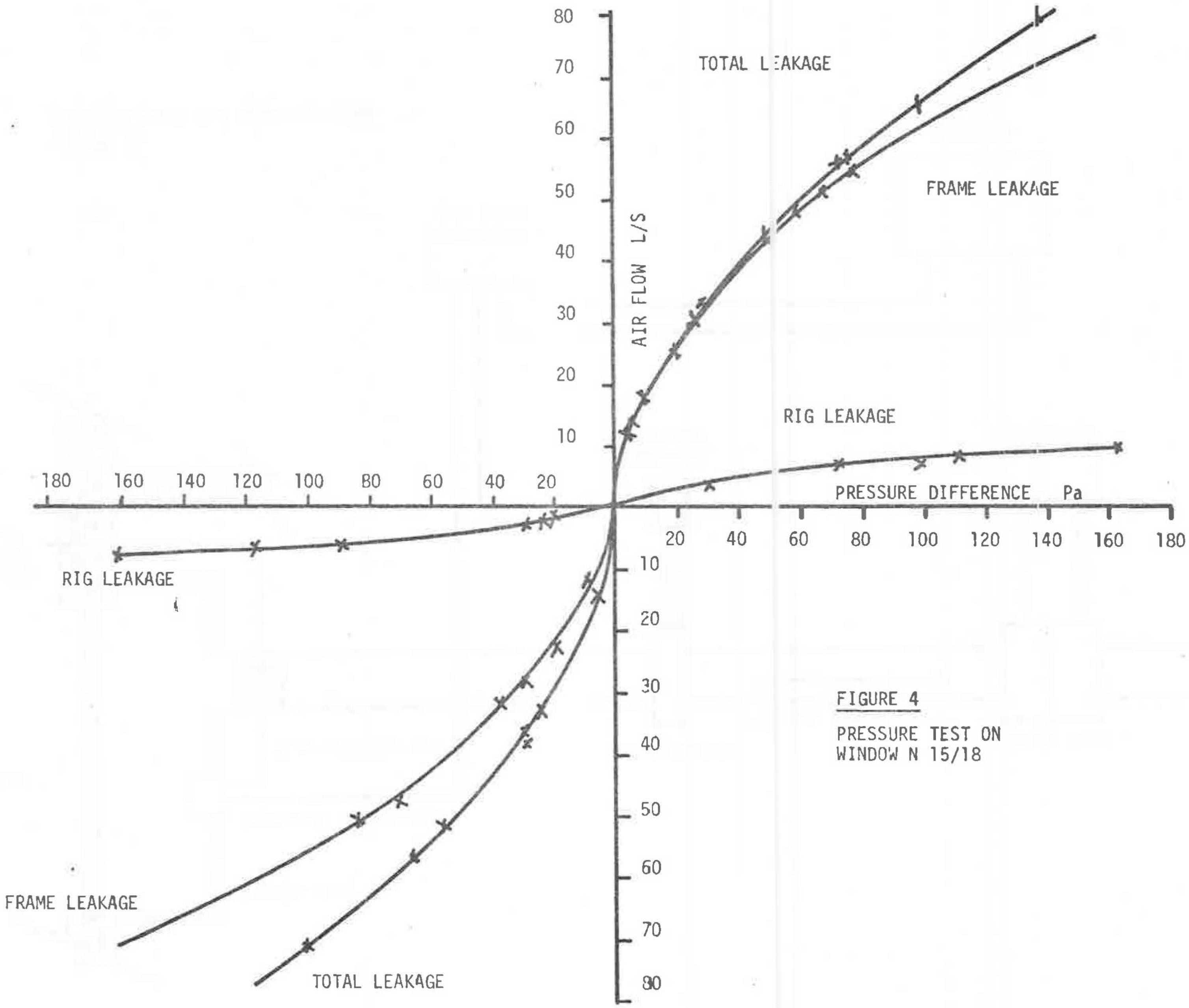
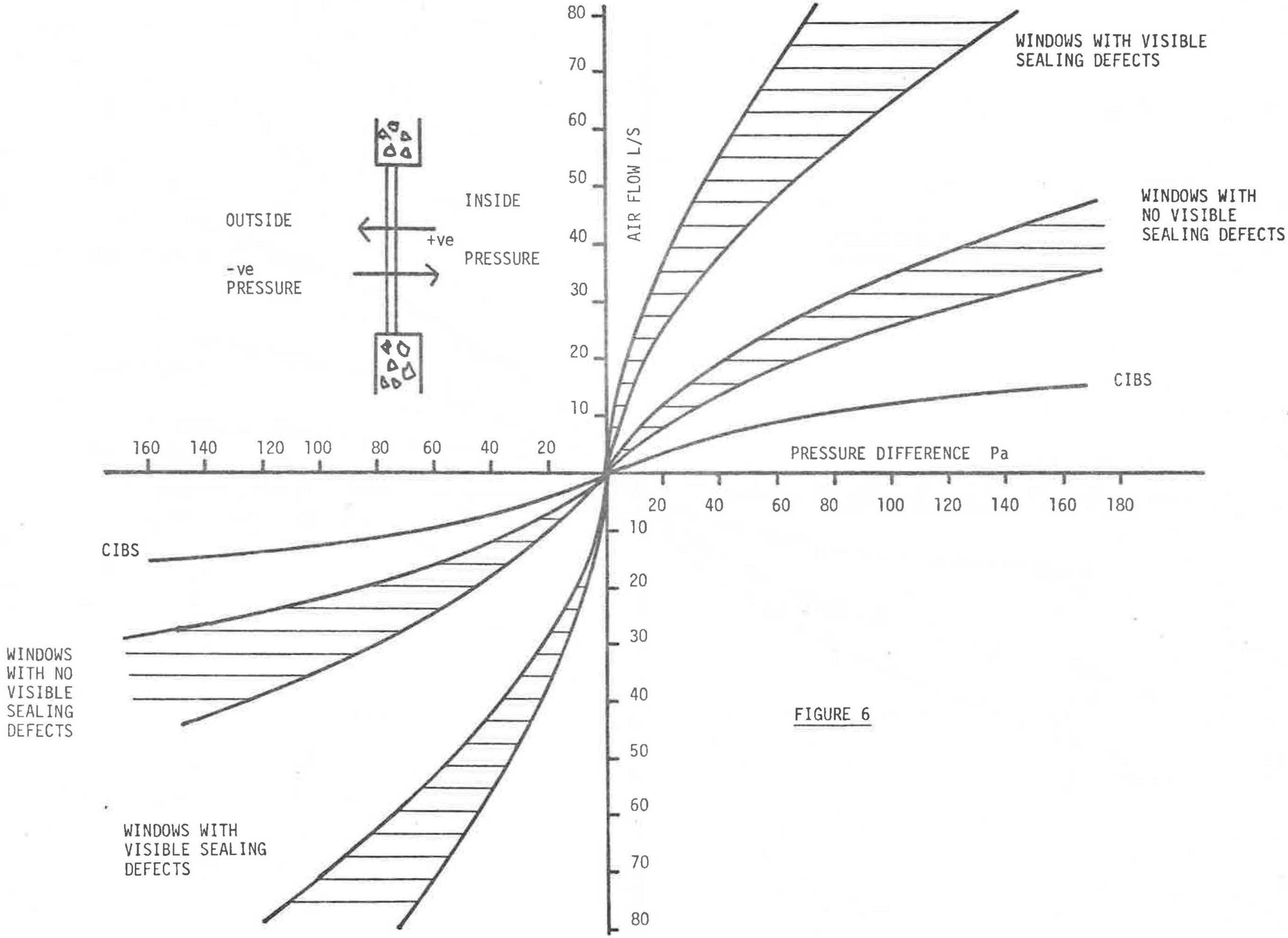


FIGURE 4

PRESSURE TEST ON WINDOW N 15/18



WINDOWS WITH VISIBLE SEALING DEFECTS
WINDOWS WITH NO VISIBLE SEALING DEFECTS
CIBS
AIR FLOW L/S
PRESSURE DIFFERENCE Pa
INSIDE
OUTSIDE
+ve
PRESSURE
-ve
PRESSURE
80
70
60
50
40
30
20
10
160
140
120
100
80
60
40
20
20
40
60
80
100
120
140
160
180
10
20
30
40
50
60
70
80
CIBS
WINDOWS WITH NO VISIBLE SEALING DEFECTS
WINDOWS WITH VISIBLE SEALING DEFECTS

FIGURE 6

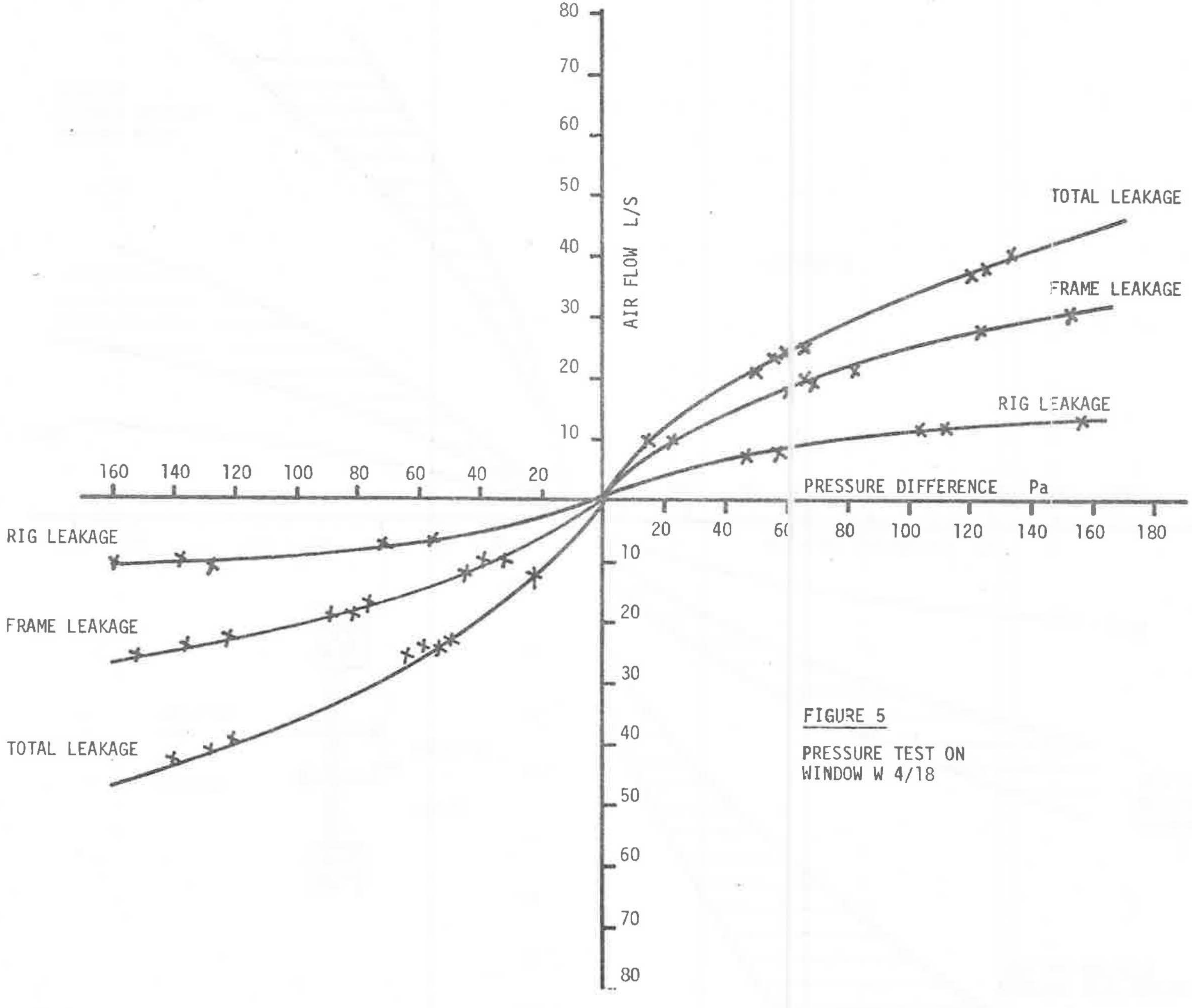


FIGURE 5

PRESSURE TEST ON
WINDOW W 4/18

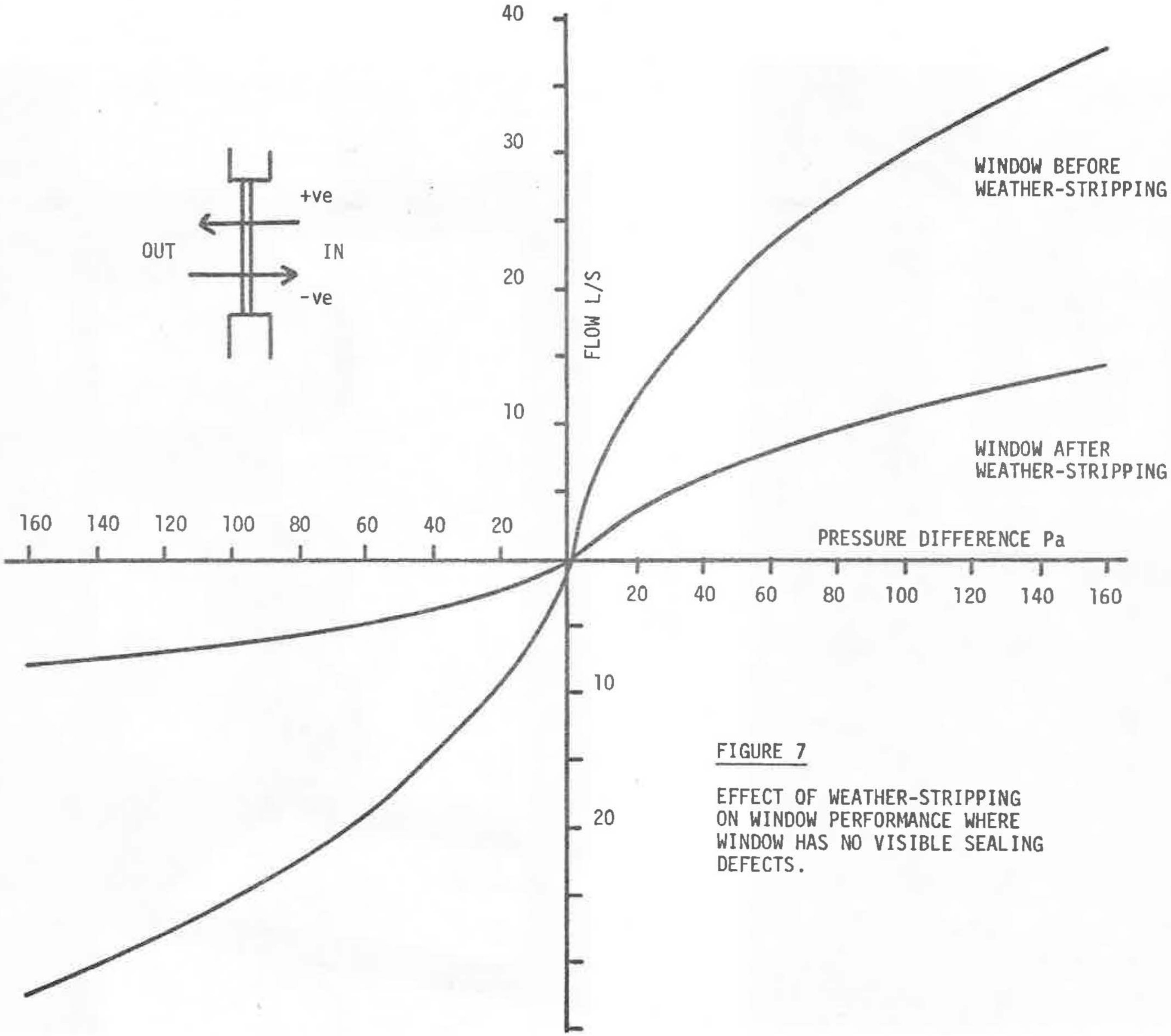


FIGURE 7

EFFECT OF WEATHER-STRIPPING ON WINDOW PERFORMANCE WHERE WINDOW HAS NO VISIBLE SEALING DEFECTS.

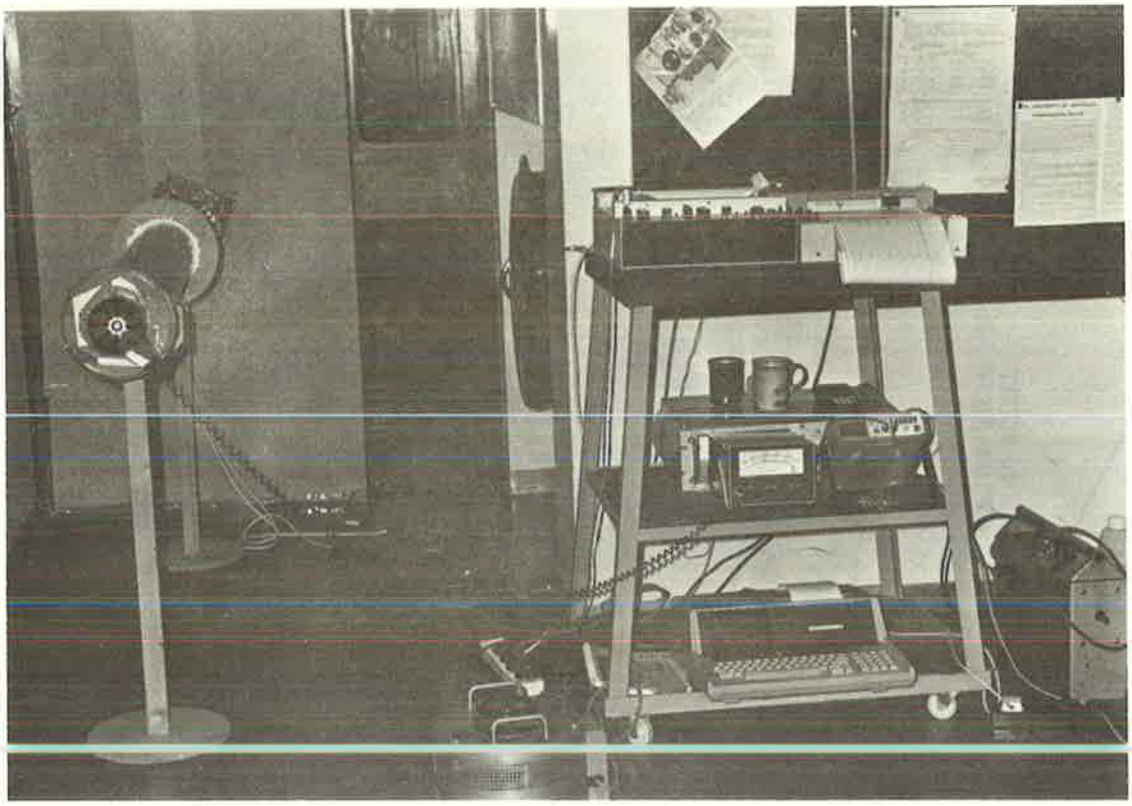


PLATE 3

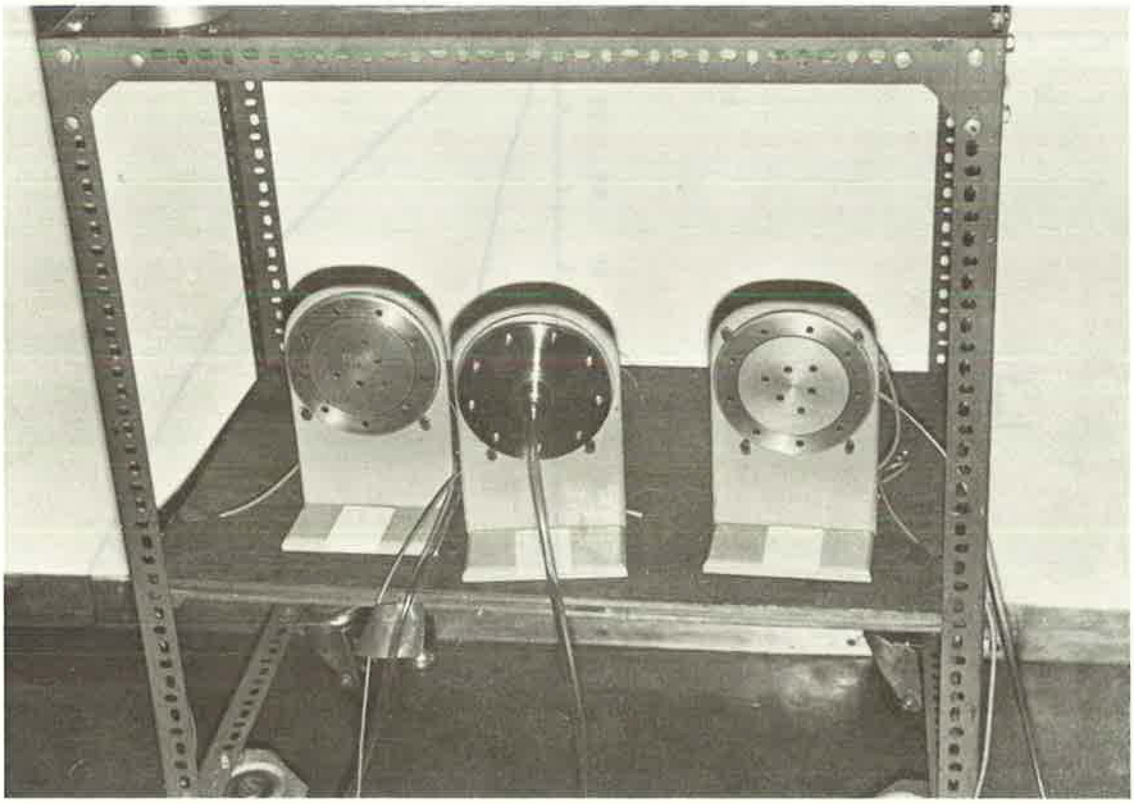


PLATE 4

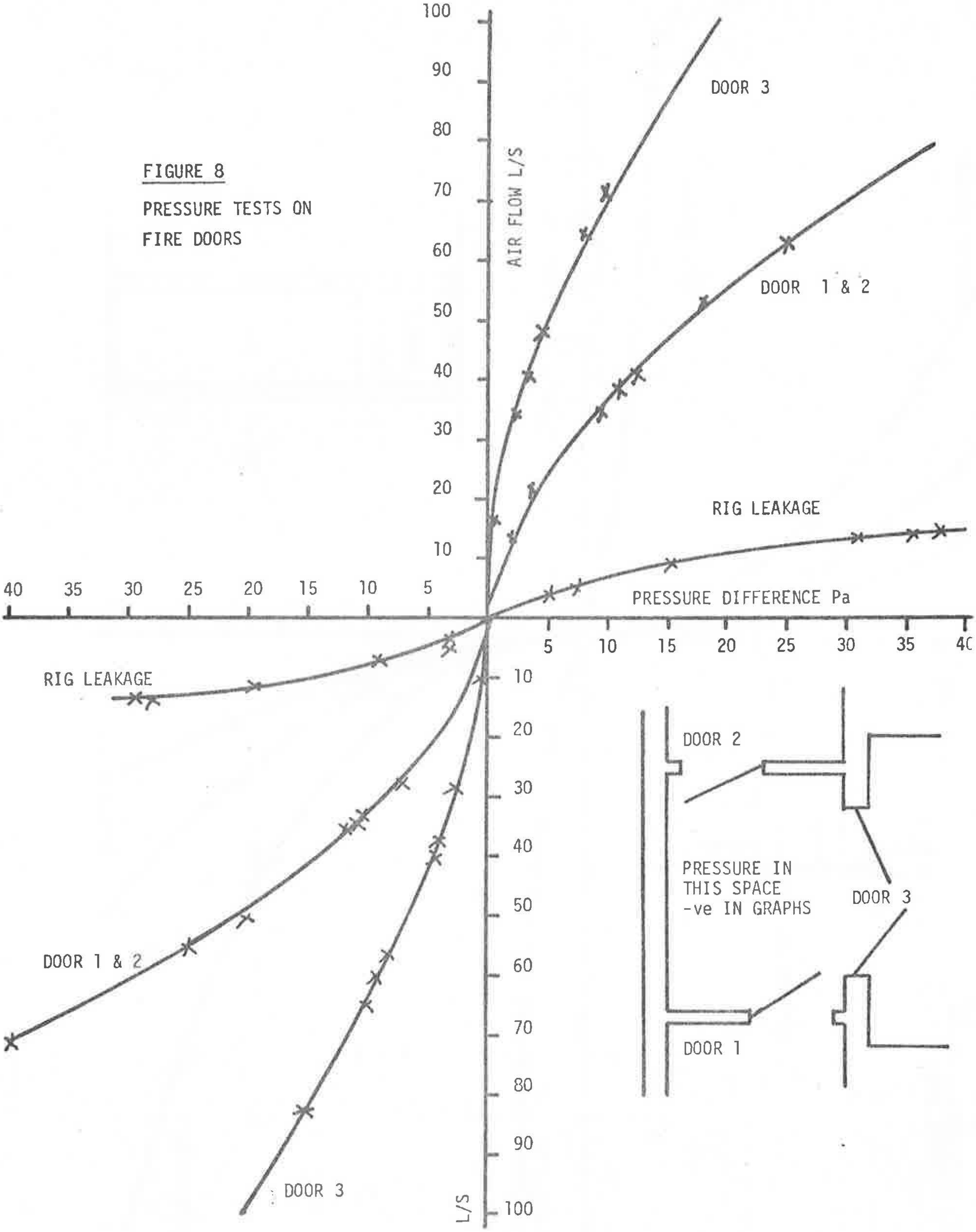
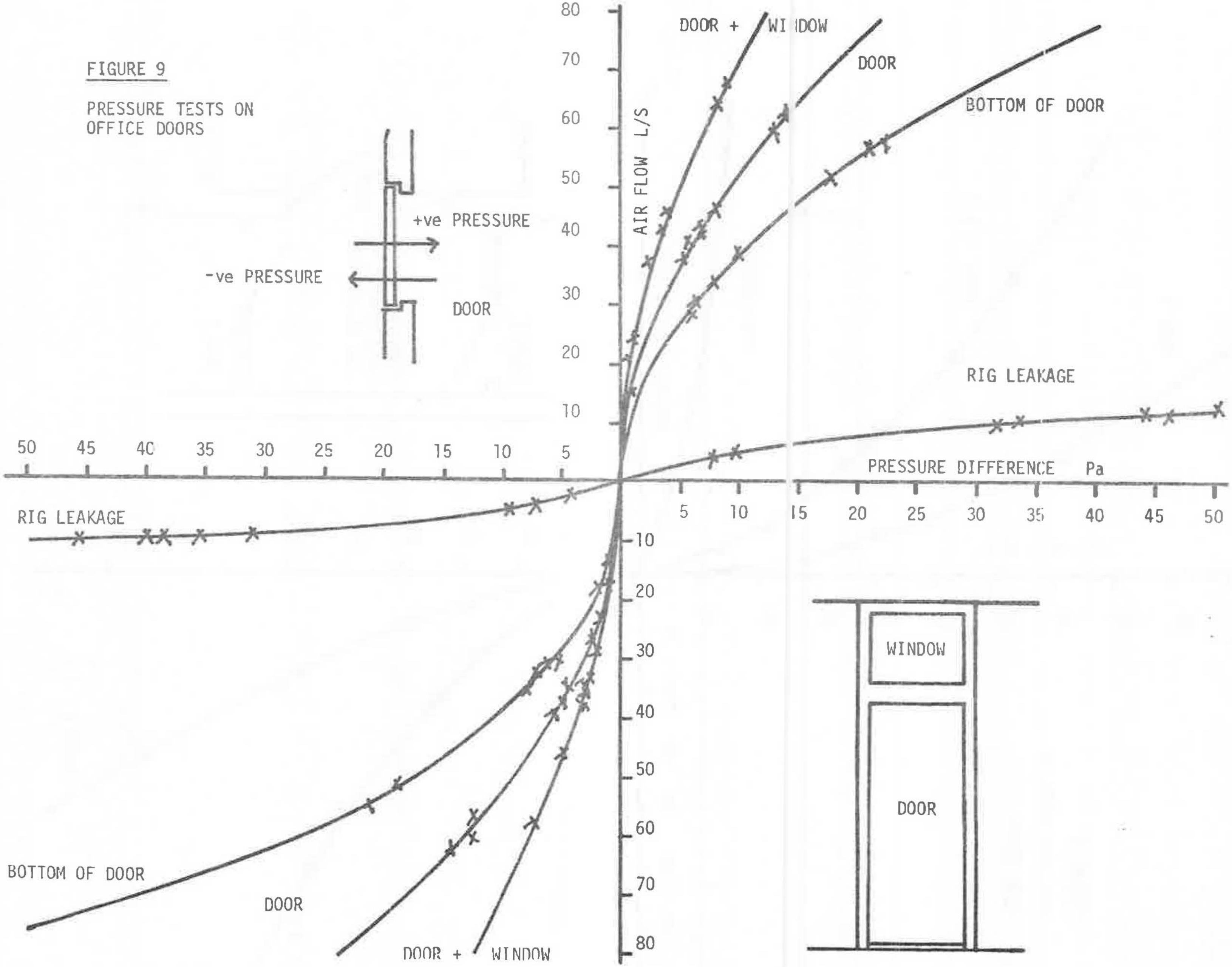


FIGURE 8
PRESSURE TESTS ON
FIRE DOORS
AIR FLOW L/S
DOOR 3
DOOR 1 & 2
RIG LEAKAGE
PRESSURE DIFFERENCE Pa
RIG LEAKAGE
DOOR 1 & 2
DOOR 3
L/S
DOOR 2
PRESSURE IN
THIS SPACE
-ve IN GRAPHS
DOOR 3
DOOR 1

FIGURE 9

PRESSURE TESTS ON OFFICE DOORS



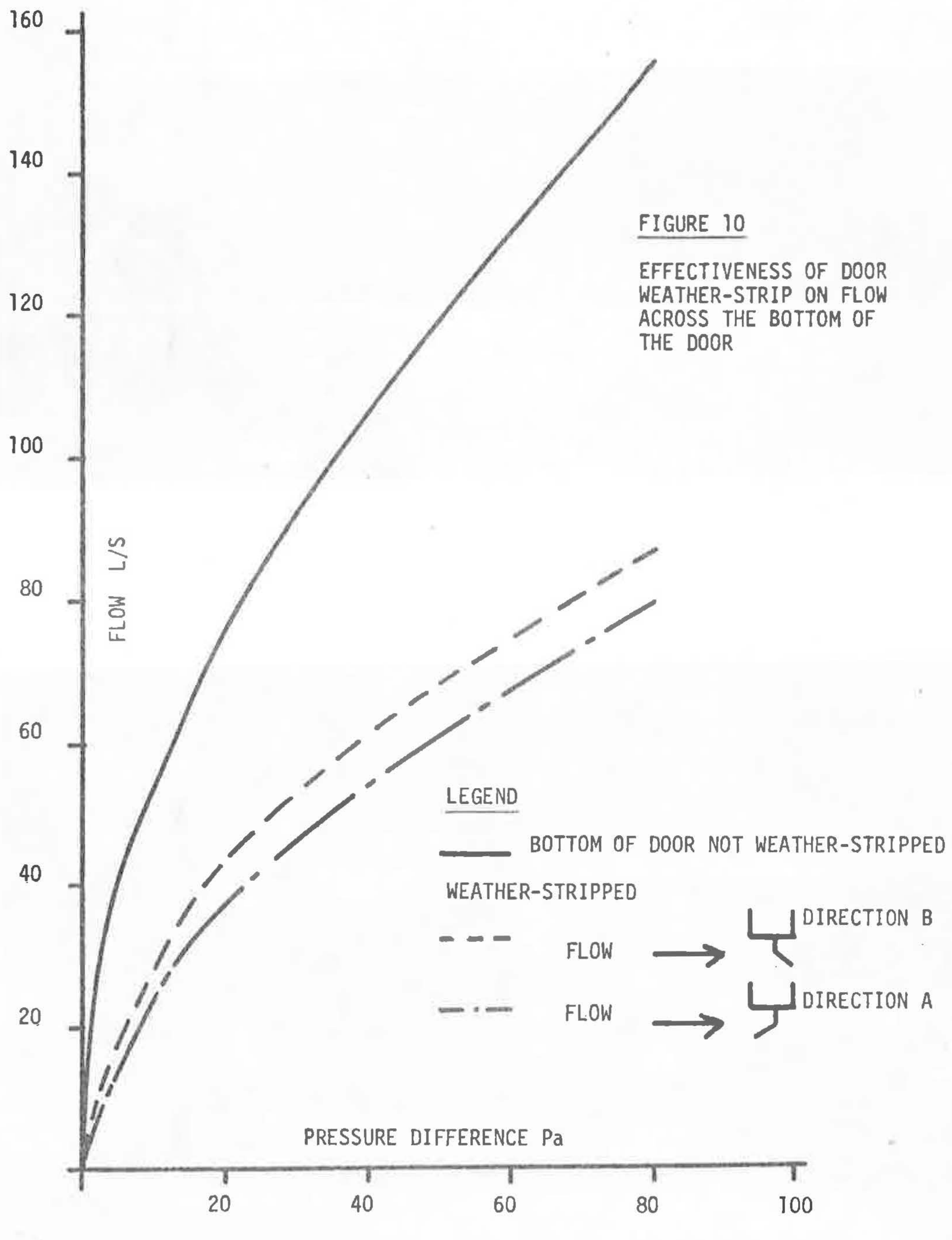


FIGURE 10

EFFECTIVENESS OF DOOR WEATHER-STRIP ON FLOW ACROSS THE BOTTOM OF THE DOOR

PLATE 5

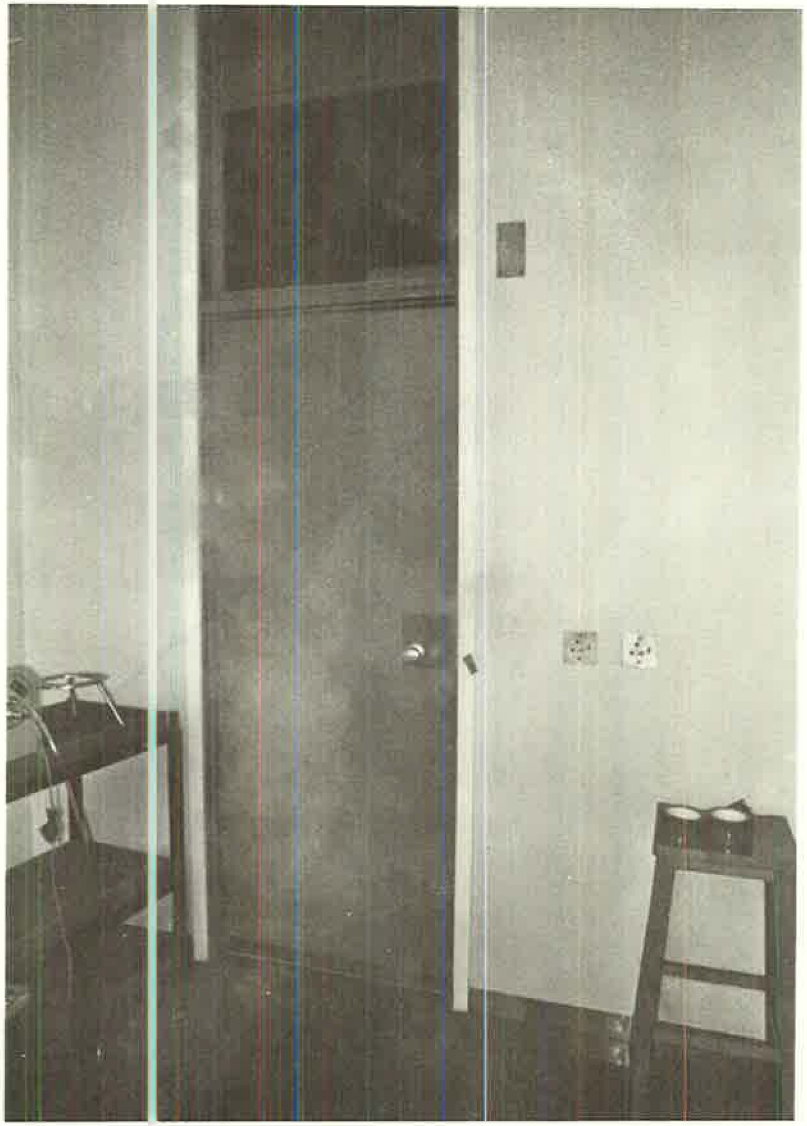


PLATE 6

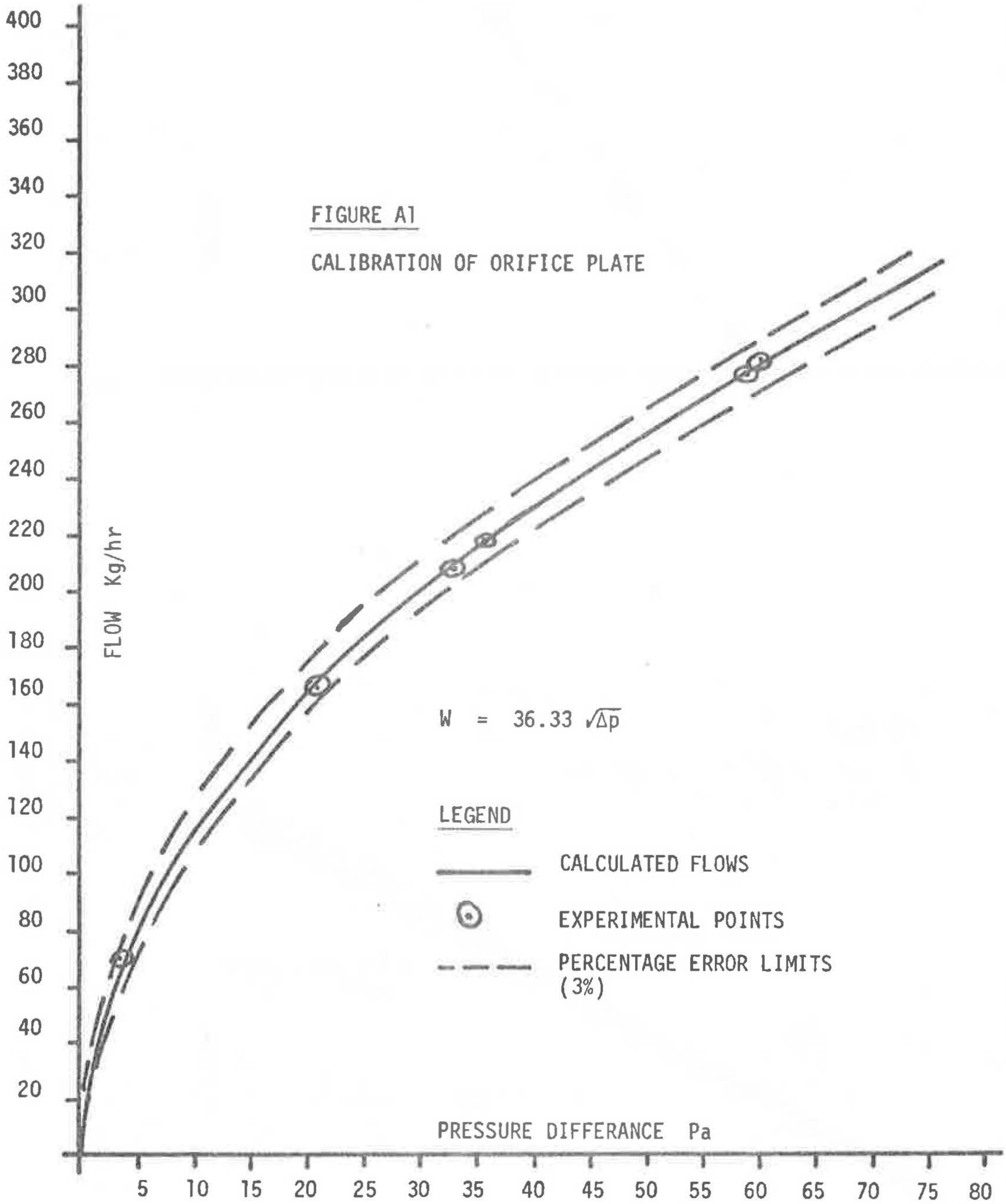


FIGURE A1
CALIBRATION OF ORIFICE PLATE
FLOW Kg/hr
400
380
360
340
320
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
W = 36.33 $\sqrt{\Delta p}$
LEGEND
CALCULATED FLOWS
EXPERIMENTAL POINTS
PERCENTAGE ERROR LIMITS (3%)
PRESSURE DIFFERANCE Pa
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80

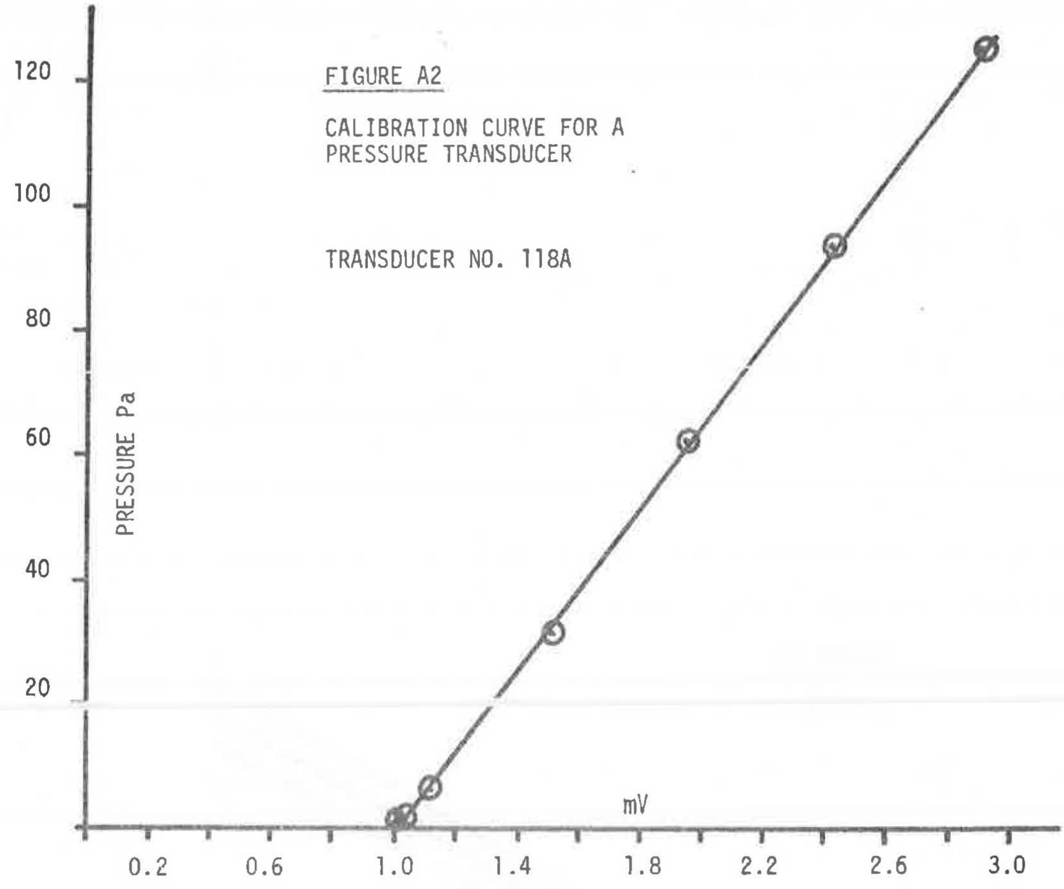


FIGURE A2
CALIBRATION CURVE FOR A PRESSURE TRANSDUCER
TRANSDUCER NO. 118A
PRESSURE Pa
120
100
80
60
40
20
mV
0.2
0.6
1.0
1.4
1.8
2.2
2.6
3.0

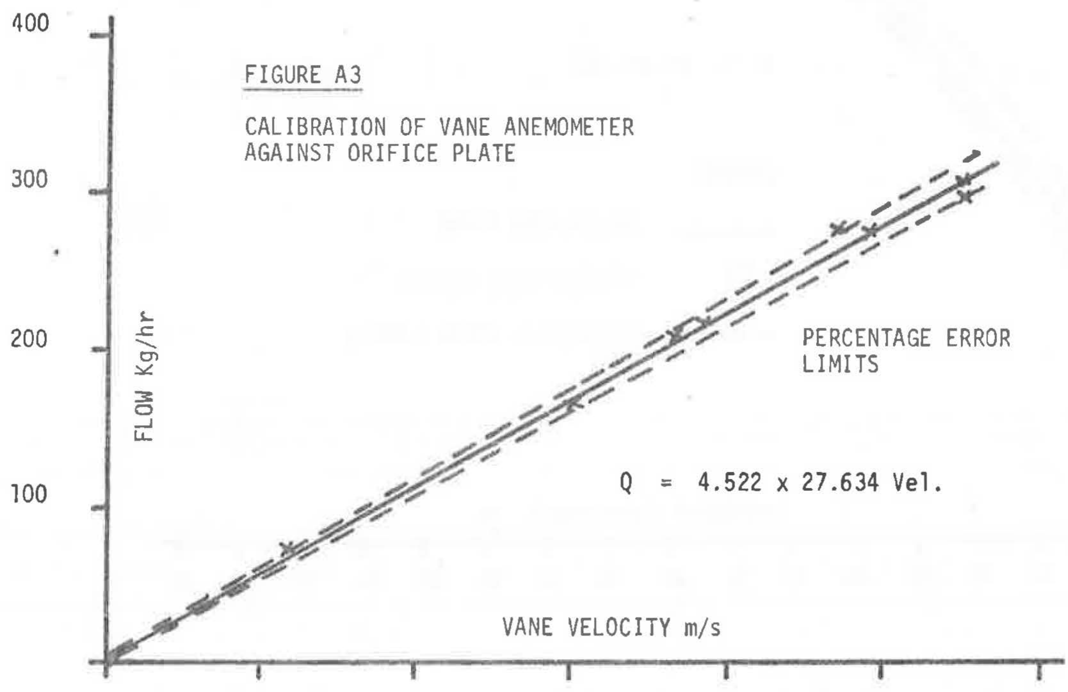


FIGURE A3
CALIBRATION OF VANE ANEMOMETER AGAINST ORIFICE PLATE
FLOW Kg/hr
400
300
200
100
PERCENTAGE ERROR LIMITS
Q = 4.522 x 27.634 Vel.
VANE VELOCITY m/s
2
4
6
8
10
12