The Low Pressure Leakage Function of a Building

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with weather parameters. A particularly promising strategy is to predict the
air flow through the building envelope from surface pressures, which in turn
are predicted from measured weather parameters. Due to interference of the
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at pressures less than 5-10 Pa, but this is the pressure range that often
drives natural infiltration. Thus, it is of interest to make direct measure-
ments of air leakage vs. pressure in this low pressure region. This paper
reports measurements of the leakage function measured at low pressures using
an alternating (AC) pressure source with variable frequency and displacement.
Synchronous detection of the indoor pressure signal created by the source
eliminates the noise due to fluctuations caused by the wind. Comparisons are
presented between these results and extrapolations of direct fan leakage meas-
urements.

Keywords: Pressurization, infiltration, low pressure leakage, ventilation

Infiltration models are primarily useful in performing energy load calculations whether using simple steady-state procedures or dynamic computer programs. However, model development also contributes to the basic physical understanding of infiltration which, in turn, aids in developing instrumentation for measurement and procedures to reduce infiltration in buildings.

Historically, infiltration models have developed slowly. The simplest, and perhaps oldest calculation model assumes that infiltration is constant in time, independent of outside weather conditions. An energy load calculation, then, only requires information about the steady infiltration value for a structure and the total number of degree-days in order to calculate the load.

The next level of modeling uses field measurements of infiltration values and weather to find an empirical relationship between infiltration, wind speed and indoor-outdoor temperature differences. This multiple linear regression technique produces a result which can predict infiltration for a structure when the outside weather is known; it is not a good predictor, however, of infiltration for structures other than the one which was tested originally. Furthermore, data have to be collected over a wide variation of weather parameters to assure statistical significance.

Physical models of infiltration are based upon a different set of assumptions and measurements than those used above. Infiltration is the result of pressure differences across openings in the building shell which produce air flow through these openings. Measurements of (a) the leakage of the shell and (b) surface pressures (or weather parameters combined with a model to predict the surface pressures) are combined to compute the air flows through the openings yielding the infiltration.

Leakage measurements have been made by applying a steady pressure to the building shell using a variable speed fan and measuring the flow through the fan (which is assumed equal to the flow through the leaks in the shell) to determine the pressure-flow characteristics of the structure. These measurements are most reliable when made at pressures which are large compared to the weather induced differential pressure already present. Measurement ranges typically used extend to at least 50 Pascals; ambient surface pressures are usually less than 10 Pascals, for it is leakage at low pressures (-5 Pa $< \Delta P <$ 5 Pa) that is needed to model infiltration.

The AC technique allows accurate measurements of the low pressure leakage function because it is insensitive to noise induced by weather. The pressure signal used in AC pressurization is dominated by one well-known frequency, while the pressures caused by wind have a broad range. Accordingly, the amount of interference caused by the weather at the frequency of interest will be small. Thus, the complete leakage curve can be measured using AC pressurization.

OVERVIEW

To accomplish AC pressurization measurements we change the volume of the structure and measure the pressure response due to this change. By looking only at the pressure response which is at the same frequency as the volume drive (i.e. synchronous detection) we eliminate the noise associated with DC measurements. This allows us to measure the leakage at very low pressures.

The volume is changed using a large piston and guide assembly that is installed in place of an existing exterior door (cf. Fig 1). The piston is moved in the guide by a motor/flywheel assembly that allows adjustable displacement and frequency control. Our leakage measurements were made at frequencies between 6 and 60 rpm. The piston rides on sliding teflon seals to prevent leakage and reduce drag. The pressure is monitored using a differential pressure sensor with .1 Pa resolution and a full scale reading of 70 Pa.

If the structure is rigid we can use the measured volume drive and pressure response volume to calculate the airflow through the envelope during AC pressurization. If there were no leakage at all then the change in pressure would be precisely determined, given the volume of the structure and the displacement of the piston. Therefore, any deviation from this predicted pressure can be attributed to leakage through the envelope. The continuity equation allows us to calculate exactly how much air leaks out for a given drive. This can be used to calculate the steady-state air flow for a given external pressure.

It is tempting to fit a curve to the high pressure leakage function in order to extrapolate to the low pressure region of interest. Many forms of the equation have been used, but two of the most typical ones are:

$$Q(\Delta P) = A \Delta P + B \Delta P^{1/2} \qquad (1.1)$$

and

$$Q(\Delta P) = C \Delta P^n \qquad (1.2)$$

where:

Q   is the leakage $[m^3/hr]$

ΔP is the applied pressure [Pascals]

A, B, C, n   are semi-empirical parameters.

However, any attempt to use these forms will fail because these regression constants themselves are functions of pressure. If the leaks in the building shell were all simple cracks we would see a flow characteristic dominated by linear leakage at low pressures $(Q \sim \Delta P)$ and quadratic leakage at high pressures $(Q^2 \sim \Delta P)$.[1] The transition between low and high pressures depends critically on the crack geometry; since we are considering a collection of cracks of many dimensions as well as orifices whose edges can be both sharp and broad, the transition between low and high pressure flow will be indistinct and blurred in any real structure.

Because of the difficulty of measuring the low pressure portion of the leakage function and the inherent uncertainty associated with extrapolating from high pressure to the low pressure measurements, a technique is needed to measure the important low pressure leakage. AC pressurization is a technique which uses an oscillating piston mounted in the shell of the building to alternately pressurize and depressurize the interior volume. The technique is an extension of the work of Card et al.[2]

The structure in general will not be rigid. Therefore, when the pressure inside the structure changes, the envelope will flex to counteract the volume change. By assuming that the flexing is proportional to the differential pressure across the shell we can correct for this effect.

The air flow through the envelope caused by the movement of the piston results in an increase in the infiltration. If the piston movement is regular the change in infiltration can be measured using a standard tracer gas method. This measurement has the potential of being an independent check on the leakage measurement.

THEORY

In DC pressurization the calculation of the leakage is straightforward. Since the pressure is steady-state there is no time variation in pressure of the air inside the structure. If we assume that the pressure applied to the structure is greater than any weather induced pressure, the continuity equation gives the leakage.

$$Q(\Delta P) = F_{fan}(\Delta P) \tag{2}$$

where:

ΔP is the pressure [Pa] across the envelope,

Q   is the airflow [m^3/hr] through the envelope at pressure ΔP and

F_{fan} is the air flow [m^3/hr] through the fan

The flow through the fan is that flow which is necessary to keep the pressure drop across at a given value; it is therefore a function of the leakiness of the structure.

In AC pressurization the calculation of the leakage is not as simple. The continuity equation must take into account the effect of the compression of the air as well as the change in the volume of the structure with our drive. Taking these two effects into account we obtain a different continuity equa-

tion.

$$Q(\Delta P) = -\frac{dV}{dt} - \left[\lambda + \frac{V_o}{\gamma P_a}\right]\frac{d(\Delta P)}{dt} \qquad (3)$$

where:

Q and ΔP are air flow and pressure as above,

dV/dt is the time change in volume of the structure $[m^3/hr]$,

λ is the flexing constant of the envelope $[m^3/Pa]$,

V_o is the volume of the structure $[m^3]$,

γ is the ratio of specific heats of air (1.4),

P_a is the atmospheric pressure (1.013×10^5 Pa) and

$d(\Delta P)/dt$ is the time change in internal pressure $[Pa/hr]$

The term in brackets (eq. 3) is the effective capacity of the structure. It contains two parts: the first part accounts for the flexing of the envelope when a pressure is applied to it; the second part is due to the compressibility of air and depends only on the volume of the structure and fundamental constants. For a full derivation of the continuity equation see Appendix A.

The above equation can be used to calculate the air flow through the structure, given the change in volume and associated change in pressure. However, the quantity of interest is the steady-state flow associated with a steady-state pressure. In order to do this, we must introduce a model of leakage to relate the flow to the pressure difference across the envelope.

The simplest model is that of linear leakage. Linear leakage implies that the air flow through the structure is proportional to the pressure across it.

$$Q(\Delta P) = L_o \, \Delta P \qquad (4)$$

where:

L_o is the leakage constant $[m^3/hr\text{-}Pa]$.

Low Pressure Measurements of Air Leakage in Buildings:
Measurements and Applications

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ABSTRACT

Many models have been devised to correlate air infiltration in buildings with weather parameters. A particularly promising strategy is to predict the air flow through the building envelope from surface pressures, which in turn are predicted from measured weather parameters. Due to interference of the weather, it is difficult to measure the pressure-flow relationship in a manner that is valid for the low surface pressures which have been observed to drive infiltration. Conventional techniques rely on steady-state (DC) fan pressurization or depressurization of the structure. DC-measurements are unreliable at pressures less than 5-10 Pa, but this is the pressure range that often drives natural infiltration. Thus, it is of interest to make direct measurements of air leakage vs. pressure in this low pressure region. This paper reports measurements of the leakage function measured at low pressures using an alternating (AC) pressure source with variable frequency and displacement. Synchronous detection of the indoor pressure signal created by the source eliminates the noise due to fluctuations caused by the wind. Comparisons are presented between these results and extrapolations of direct fan leakage measurements.

INTRODUCTION

Infiltration, air leaking through openings in the shell of a building, is a conceptually simple process. The hydrodynamic details of the flows for real buildings, however, are complex and make the problem of calculating or modeling infiltration difficult.

While this is the simplest model possible, it is not physical. It may be true that when the flow is dominated by viscous laminar flow the air flow will be proportional to the applied pressure, but when orifice flow or turbulent flow is important the flow will not be linear. DC measurements indicate that at higher pressures the air flow becomes proportional to the square root of the applied pressure.[3]

To account for this effect we must relax the assumptions that the leakage be linear. We do this by allowing the leakage constant to become dependent on the applied pressure making it a leakage function ($L(\triangle P)$). The flow equation then becomes,

$$Q(\triangle P) = L(\triangle P) \, \triangle P \qquad (5)$$

where:

$L(\triangle P)$ is the leakage function $[m^3/hr\text{-}Pa]$.

Even though the form of the leakage function is not known, there are physical restrictions on its behavior. The function must be slowly varying and monotonically decreasing as the pressure increases. Ideally, the leakage function should be independent of the sign of the applied pressure. But, in some situations the airflow may be larger on pressurization than on depressurization (or vice versa). To account for this and still maintain the symmetry of the leakage function we introduce an asymmetry constant.

$$Q(\triangle P) = \left[L(\triangle P) \, (1 + \alpha \triangle P) \right] \triangle P \qquad (6)$$

where:

α is the asymmetry constant $[Pa^{-1}]$ and

$L(\triangle P)$ is an even function of the applied pressure $[m^3/hr\text{-}Pa]$.

Using eq. 6 as our defining relation for the leakage function we can find the leakage function using our AC pressurization source. Then, we can use the measured leakage function to calculate the airflow for a given steady-state

pressure across the envelope. The complete derivation of these equations is given in Appendix A and the experimental procedure, technique and data analysis are contained in Appendix B.

RESULTS

Figs 2 and 3 are graphs of the leakage function vs applied pressure for the house in the loose and tight configurations. Several test rusn were performed with a variety of combinations of piston displacement and frequency. All of the points from all of the runs are combined to give a weighted average leakage function. Note that there is a small amount of systematic difference between points at the same pressure but of different displacements. This asymmetry in probably due to the type of windows in the test structure. The windows a sliding aluminum windows. On pressurization the windows are pushed against their seals making them less leaky; on depressurization the windows are pulled away from their seals, increasing the leakage.

Figs. 4 and 5 are graphs of the predicted air flow vs applied pressure for the house in the loose and tight configurations. Each graph has the points from the AC pressurization run as well as the points from the DC pressurization run. Each point has the error bars associated with each measurement.

Fig. 7 is a plot of both the loose and tight configurations for the full range of DC leakage points. The low pressure points are duplicated on figs. 4 and 5.

Infiltration

During AC pressurization many interesting qualitative effects were observed. Pulsating air flow in and out of cracks was quite evident around windows and fixtures. This was detected using smoke sticks and other visual indications of the flow. Leakage was evident in interior partitions around light switches and outlets, indicating that there is good communication between the interior partitions and the attic or crawl space and hence to the outside.

The infiltration was measured at many different times with the test space in different leakage configurations. The results with the house in a normal or tight configuration, yield infiltration rates due to the AC pressurization only about 20% of the expected values. When all of the windows were open a crack the infiltration increased. While the total increase due to the AC pressurization was a large fraction of the expected increase it still did not increase as much as predicted.

We believe that this diminution of infiltration rise is due to storage of the tracer gas in connected spaces. That is, tracer gas is being pushed out of the test space and into such spaces as wall cavities, the attic, and the crawl space. From these spaces the tracer is not able to mix with the outside air before it is sucked back into living space on the depressurization stroke.

We have evidence of this mechanism from observations with smoke sticks. Smoke can be observed to pulsate in and out of light fixtures, electrical outlets and cracks, both in the interior partitions and outside walls. A good part of natural infiltration is driven by pulsating wind pressures; it would be interesting to speculate on the influence of geometry of such connected spaces on the infiltration in the living space.

Since the volume of the exterior wall cavities alone is greater than the displacement of the piston, if a large fraction of the leakage is via wall cavities, we will not see an increase in the infiltration. However, as a larger proportion of the leakage is through direct connection to the outside (e.g. open windows), we expect to see a larger increase in the infiltration.

The infiltration measurements made concurrently with the AC pressurization measurements do not agree with the predicted air flow through the envelope. The measured infiltration was always far less than the predicted value. The prediction assumes that all of the air that is forced out of the envelope by the piston mixes with the outside air and disperses before air is pulled back in. However, we have observed that air that is forced out lingers in the neighborhood of the exit leak, and is pulled back into the structure with little mixing. Under these circumstances, the amount of infiltration measured by tracer gas is only a small part of sum of all the air flows through the envelope, measured by AC pressurization. That the lack of mixing is so pronounced in our case is an indication that a significant amount of the leakage

is into the attic, crawl space, or wall cavities. This lack of mixing in the connected spaces is equivalent to a cut-off frequency in the leakage characteristic of the structure. That is, there is some frequency above which the weather induced pressures do not cause any infiltration. Our experiments indicate that this frequency may be very low (a period of less than one second).

DISCUSSION

In the range of overlap the AC and DC techniques show good agreement in their prediction of the leakage of the structure. Since they represent independent determinations of the same quantity, we feel that the agreement corroborates both techniques.

Each technique has its own strengths; together they provide an excellent characterization of the leakage of a house. DC pressurization is simpler, faster and uses inexpensive equipment. AC pressurization is more accurate in the range of pressures typically associated with infiltration. Since this technique does not measure flow directly, it is not subject to the problems of measuring low velocity flows. Because of the synchronous detection inherent in the system, the AC technique is capable of measuring the leakage at far lower pressures than the DC techniques.

The most intriguing result of this experiment was unexpected. We expected that the leakage function at low pressures would, assuming laminar flow, approach a constant and hence the air flow would be linear in the applied pressure. However, the leakage function seems to increase without bound at low pressures. The increase in the leakage function corresponds to a discontinuity in the leakage function as it crosses zero. In our DC measurements we often measure a curve that extrapolates to a non-zero air flow at zero pressure (cf. fig 7); we usually attribute this offset to poor data at low pressures but the AC results indicate that the effect may be real. This discontinuity implies that if there are even extremely low pressure fluctuations there will be some infiltration. Many researchers[4-6] have speculated about the existence of non-zero infiltration as the wind speed and temperature difference go to zero. This low pressure increase in the leakage would

correspond to exactly that, suggesting that the effect is physical and not simply an artifact of statistical curve-fitting or other semi-empirical models.

The fact that the low pressure leakage does not approach a constant implies that the low pressure leakage is dominated by orifice flow rather than by viscous flow. It would appear that at very low pressures the flow is dominated by orifices and hence the air flow would go as the square root of the pressure and the leakage function would approach infinity at zero pressure. At very high pressures the flow is dominated by turbulence and the air flow would again go as the square root of the pressure. But at intermediate pressures there would be some viscous (laminar) flow which is linear in the applied pressure. These three effects combine to make the leakage a complicated function of pressure.

Attempts using superposition of linear and square root type flow (eq 1.1) will not be very successful if the above analysis is correct. The constants involved with the model are themselves functions of pressure and will change as rapidly as the leakage changes. Models using a flow exponent (eq 1.2) may fair better. In order to test the validity of flow exponent type leakage models, we have fit both the AC and DC pressurization data to a power curve. We have split the data into low and high pressure sections for both AC and DC have used the data from both the leaky configuration and the tight configuration. The model, as presented in the introduction is,

$$Q(\Delta P) = C \, (\Delta P)^n \qquad (7)$$

where:

Q   is the air flow $[m^3/hr]$,

C   is the scale constant $[m^3/hr\text{-}Pa^n]$ and

n   is the flow exponent.

The semi-empirical co-efficients are tabulated below:

TABLE 1.				
Values of leakage constants in power curve fit.				
_TYPE	CONFIGURATION	PRESSURE INTERVAL [Pa.]	C	n
DC	Loose	0-20	667	0.45
		25-50	458	0.59
		0-50	603	0.51
DC	Tight	0-30	426	0.51
		30-50	327	0.59
		0-50	404	0.53
AC	Loose	0-6.5	432	0.62
		7-13.5	298	0.80
		0-13.5	423	0.65
AC	Tight	0-8.5	347	0.60
		9-17	314	0.68
		0-17	337	0.64

While the data in this table is not conclusive there are some general trends evident. For any given type and configuration, the flow exponent is larger at larger pressures, indicating that the very low pressure flow is dominated by orifice flow and not by viscous flow. The AC pressurization gives consistently higher flow exponents than does the DC pressurization; however, this may be due to the large uncertainties in the DC pressurization at low pressures.

CONCLUSION

A new technique for measuring low pressure leakage of a building is presented, based on AC pressurization. In this technique the volume of the building is modulated with a given frequency using a cylinder and piston assembly sealed into a door or window. By contrast the conventional DC pressurization technique measures the flow necessary to keep a given steady state pressure difference across the envelope. By measuring the interior pressure response synchronously to the volume oscillation AC pressurization can eliminate the pressure fluctuations caused by the weather, that make DC measurements difficult in the low pressure range.

The leakage characteristic of the our experimental house was measured in both a tight and a loose configuration with both the AC and DC pressurization techniques. The correlation is good in the pressure regime of overlap.

Several interesting phenomena were observed with AC pressurization. The equivalent flow resistance of the structure at low pressures appears to approach zero. Such behavior is consistence with often quoted empirical observation that air infiltration is non-zero even at weather conditions of no wind and equal indoor and outdoor temperatures. Furthermore, if confirmed on other houses, such a decrease of flow resistance at low pressures is consistent with infiltration models that use a flow exponent between 0 and 1.

Independent tracer gas measurements during AC pressurization indicate much lower infiltration than expected from the flow through the envelope. There is some evidence indicating that this may be the consequence of poor mixing of indoor and outdoor air in connecting spaces such as attic, crawlspace and wall cavities. This effect was noted at all frequencies used (maximum of 3 Hz.) and all displacements (maximum of .3 m^3). Such mechanisms have interesting potential for the reduction of natural infiltration induced by turbulence.

Low pressure leakage measurements using the AC pressurization technique can provide valuable information about the leakage characteristic of a structure that is available from no other source.

APPENDIX A

Theoretical Derivation

In this appendix we derive the equations used in AC pressurization. In order to measure the low pressure leakage, a piston and cylinder arrangement is added to the structure so that its volume is adjustable (see Fig. 1). With this set-up the volume can be increased or decreased from its initial value and the pressure response can be measured. If there were no leakage the pressure response due to a change in the volume could be easily calculated; however, if there is air leakage then the pressure induced by the changing volume will be smaller. The difference between the measured pressure response and the expected pressure response is attributed to leakage through the envelope.

AIR FLOW

We begin the derivation by assuming the gas within the structure to be ideal:

$$PV = nRT \tag{A1}$$

where:

P   is the absolute pressure [Pascals],

V   is the structure volume [m^3],

n   is the number of moles of gas,

R   is the ideal gas constant (8.32 joules/mole-$^\circ$K) and

T   is the absolute temperature [$^\circ$K].

Conservation of energy for an ideal gas yields,

$$RT\, dn = P\, dV + C_v dT \tag{A2}$$

here:

C_v is the heat capacity of air at constant volume [joules/mole-$^\circ$K].

Using eq. A1 to eliminate dT,

$$RT\ dn = PdV + \frac{1}{\gamma}\ VdP \qquad (A3)$$

where:

γ is the ratio of the heat capacities of air (1.4).

The leakage of air through the envelope is related to the time derivative of the number of moles of gas in the structure.

$$Q = -\frac{V}{n}\frac{dn}{dt} \qquad (A4.1)$$

$$= -\frac{RT}{P}\frac{dn}{dt} \qquad (A4.2)$$

$$= -\frac{dV}{dt} - \frac{1}{\gamma}\frac{V}{P}\frac{dP}{dt} \qquad (A4.3)$$

where:

Q is the air leakage out of the envelope [m^3/hr].

We have used the convention that the air flow, Q, is positive when it flows out of the structure to correspond to common usage in the field. However, the term dn/dt is positive when air flows into the structure, hence the minus signs in eq A4.

If the induced change in the volume of the structure is small then the change in internal pressure will be small compared to atmospheric pressure. In this case the volume and pressure in the above expression may be replaced

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by their steady state values.

$$Q + \frac{dV}{dt} + \frac{V_o}{\gamma P_a} \frac{dP}{dt} = 0 \qquad \text{(A5)}$$

where:

V_o is the normal structure volume[m^3] and

P_a is the normal internal pressure (1 atm.)

AIR LEAKAGE

Equation A5 allows us to calculate the air flow into or out of the structure induced by the pressure changes caused by the volume changes. However, he quantity of interest is not the flow itself but the leakage function. The leakage function relates the flow through the structure envelope to the instantaneous pressure across it. DC measurements suggest that at high pressures the leakage may be described by a power law expression, where the exponent of the pressure is between half and one. At low pressures we expect the leakage to be linear in the pressure drop across the shell because the flow must be laminar.

Linear Leakage Model

The simplest of all leakage models is the linear leakage model. We assume that the flow through the envelope is proportional to the applied pressure.

$$Q = L_o \, \Delta P \qquad \text{(A6)}$$

L_o is the leakage constant and it is the parameter of interest. Under the linear leakage assumption the continuity equation can be solved exactly. We can use eq A6 above to eliminate the pressure from eq A5.

$$Q + \frac{dV}{dt} + k_o \frac{dQ}{dt} = 0$$

(Note that $\frac{dP}{dt} = \frac{d(\triangle P)}{dt}$.) Equivalently,

$$\triangle P + \frac{1}{L_o} \frac{dV}{dt} + k_o \frac{d(\triangle P)}{dt} = 0 \qquad (A7.2)$$

where:

$$k_o = \frac{1}{L_o} \left[\frac{V_o}{\gamma P_a}\right] \qquad (A7.3)$$

The time constant, k_o, is a direct measure of the leakage function of the house. Equation A7 is a first-order linear differential equation with constant coefficients. It can be solved for a sinusoidal driving function.

$$V = V_d \sin(wt) \qquad (A8)$$

where:

V_d is the displacement volume $[m^3]$ (half of peak to peak)

w is the fundamental frequency of the drive $[hr^{-1}]$.

This leads to a solution of the form,

$$Q = Q_o \sin(wt+\theta_o) \qquad (A9.1)$$

or,

$$\triangle P = \triangle P_{AC} \sin(wt + \theta_o) \qquad (A9.2)$$

where:

$\triangle P_{AC}$ is the amplitude of the (AC pressure) response $[Pa]$,

Q_o is the amplitude of the (air flow) response $[m^3/hr]$

   $= L_o \triangle P_{AC}$ and

θ_o is the phase shift between the response and the drive.

Solving the differential equation leads to expressions for Q_o and θ_o in terms of the drive, time constant, and fundamental frequency.

$$\tan\theta_o = \frac{1}{wk_o} \qquad (A10.1)$$

$$Q_o = - wV_d \sin\theta_o \qquad (A10.2)$$

$$= \frac{wV_d}{\sqrt{1 + w^2 k_o^2}} \qquad (A10.3)$$

$$\Delta P_{AC} = \frac{wV_d/L_o}{\sqrt{1 + w^2 k_o^2}} \qquad (A10.4)$$

$$\cos\theta_o = - \frac{\Delta P_{AC} \, V_o}{\gamma P_a \, V_d} \qquad (A10.5)$$

From eq A10.5 we can calculate the phase angle from the measured pressure and the displacement. From eq A10.1 we can calculate the time constant from the phase angle. Using the definition of the time constant (eq A7.3) we can find the leakage constant.

$$L_o = - \frac{wV_d}{\Delta P_{AC}} \sin\theta_o \qquad (A11.1)$$

$$= w \sqrt{\left(\frac{V_d}{\Delta P_{AC}}\right)^2 - \left(\frac{V_o}{\gamma P_a}\right)^2} \qquad (A11.2)$$

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Q_o is the size of the air flow through the structure in response to a sinusoidal drive. Under the assumption of perfect mixing all of the air flow will contribute to an increase in infiltration. Since the air flowing in will be equal to the air flowing out we need only find the total amount of air the flows out during a half cycle and divide that by the cycle time to find the induced infiltration.

$$Q^I = \frac{\int_0^{\pi} Q_o \sin\beta \, d\beta}{\int_0^{2\pi} d\beta} \qquad (A12.1)$$

$$Q^I = \frac{Q_o}{\pi} \qquad (A12.2)$$

$$Q^I = - \frac{wV_d}{\pi} \sin\theta_o \qquad (A12.3)$$

where:

Q^I is the infiltration induced by the drive [m^3/hr] and

$$\beta = wt + \theta_o \qquad (A12.4)$$

Non-Linear Leakage

We have solved the case of low pressure leakage under the assumption that the leakage is linear in the applied pressure. This assumption may not be acceptable in certain situations and it is definitely not acceptable for high pressures. DC measurements indicate that at sufficiently high pressures the air flow through the structure is proportional to the square root of the pressure. It has also been noted that in many DC measurements the value measured under depressurization is not the same as that measured by pressurization.

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Our linear leakage model does not account for any of these observations. Therefore, we must relax the assumption of linearity and allow for the possibility on non-linearities in the model. The presence of non-linear terms in a differential equation always causes harmonic generation. That is, if a sinusoidal drive of frequency, w, is used there will be a pressure response at frequency w as well as at all of the higher multiples of w, (i.e. 2w, 3w, ...), as well as a possible constant term. For experimental reasons direct measurement of these higher harmonics is quite difficult. Therefore, we will derive a leakage function without requiring the measurement of the higher harmonics.

To allow for the non-linearities we generalize the concept of the leakage constant to that of a leakage function which depends on pressure.

$$Q(\triangle P) = L(\triangle P) \triangle P \qquad \text{(A13)}$$

Physically the leakage function must be slowly varying and monotonically decreasing. Furthermore we expect that at very high pressures it must decrease as the square root of the pressure.

In general the air flow due to a positive pressure on the structure will be nearly equal in magnitude to the air flow due to the same negative pressure on the structure. It is mathematically convenient to treat the leakage function as an even function of the pressure; But since there may well be a small asymmetry between the air flows, we must add a small asymmetric term to the symmetric leakage function.

$$Q(\triangle P) = L(\triangle P) (1 + \alpha \triangle P) \triangle P \qquad \text{(A14)}$$

where:

$L(\triangle P)$ is an even function $[m^3/hr\text{-}Pa]$ of pressure and
α is the asymmetry parameter $[Pa^{-1}]$.

The presence of this asymmetric term has the interesting feature that it changes the average internal DC pressure when there is a sinusoidal volume change in the structure. This DC offset arises because on pressurization (for example) the leakage is larger than on depressurization; thus to assure that the air flow in is equal to the air flow out, the average internal pressure must drop a little.

To obtain this DC offset for our equations we must use the fact that under AC pressurization the average flow through the envelope is zero. Averaging the continuity equation, Eq A5, over one cycle,

$$- <Q(\triangle P)> = <\frac{dV}{dt}> + \frac{V_o}{\gamma P_a} <\frac{dP}{dt}> \tag{A15.1}$$

$$= 0 \tag{A15.2}$$

$$= <L(\triangle P)\triangle P \ (1 + \alpha \triangle P)> \tag{A15.3}$$

The brackets, <...> around a quantity indicate that that quantity is to be averaged over a cycle.

Since we have assumed that the leakage function is slowly varying, we can replace it by its average value during the oscillation. The error introduced by doing this will be small as long as the leakage function does not change radically in the working range of pressure. Since the leakage function is slowly varying and the pressure is oscillatory we assume the average leakage function is approximated by the leakage function at the root mean square pressure.

$$< L(\triangle P) > \simeq L\left[\sqrt{<\triangle P^2>}\right] \tag{A16}$$

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Since we have assumed that the leakage function for the AC tests can be approximated by its value at the root mean pressure, there is an equivalent steady state pressure at which the leakage will have the same value, namely the root mean square pressure. Therefore, we define the equivalent DC pressure as,

$$\Delta P_{DC} = \sqrt{< \Delta P^2 >} \qquad \text{(A17)}$$

where:

ΔP_{DC} is the equivalent applied pressure.[Pa]

$< \Delta P^2 >$ is the mean square pressure $[Pa^2]$.

Substituting for the leakage function in eq A15.3, we can obtain a relation for the asymmetry.

$$L(\Delta P_{DC}) \ (< \Delta P > + \alpha < \Delta P^2 >) = 0 \qquad \text{(A18)}$$

Since the leakage function is never zero it can be divided out and the equation can be solved for α.

$$\alpha = - \frac{< \Delta P >}{< \Delta P^2 >} \qquad \text{(A19)}$$

where:

$< \Delta P >$ is the average DC pressure offset [Pa.]

This last expression, allows the calculation of the asymmetry constant, α, from the DC pressure offset, $< \Delta P >$, and the mean square pressure, $< \Delta P^2 >$. Conversely, once the asymmetry constant has been measured it allows the calculation of the DC offset from a measurement of the mean square pressure.

We can find the root mean pressure in terms of the component of the pressure at the fundamental frequency. In general, the pressure can be expanded

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in terms of harmonics of the fundamental frequency, w.

$$\Delta P = < \Delta P > + \Delta P_{AC} \sin(wt + \theta) + \Delta P_2 \sin(2wt + \phi_2) \cdots \quad (A20)$$

where:

$< \Delta P >$ is the average pressure difference [Pa],

ΔP_{AC} is the component at the fundamental frequency [Pa],

θ is the phase shift between the drive and response and

ΔP_n is the component at the nth harmonic.

ϕ_n is the phase angle of the nth harmonic

To calculate the average mean square pressure we must square the above expression and then average over one cycle. When we do the averaging all of the cross terms will drop out leaving only the squared terms of each fourier component.

$$< \Delta P^2 > = < \Delta P >^2 + \frac{1}{2} \Delta P_{AC}^2 + \Sigma (\text{higher harmonics})^2 \quad (A21.1)$$

If we assume that higher harmonics are negligible compared to the other two terms, we can approximate the mean square pressure.

$$< \Delta P^2 > \simeq \frac{1}{2} \Delta P_{AC}^2 (1 + \frac{1}{2} \alpha^2 \Delta P_{AC}^2) \quad (A21.2)$$

where we have used the definition of α recursively.

Therefore,

$$\Delta P_{DC} = \Delta P_{AC} \sqrt{\frac{1}{2} (1 + \frac{1}{2} \alpha^2 \Delta P_{AC}^2)} \quad (A22)$$

Once the asymmetry and equivalent DC pressure have been found we must derive a relation between the leakage function and the experimental parameters. In the linear case we derived a formula for the leakage by solving the linear differential equation for a sinusoidal driving function. In the non-linear case we can not solve the equation exactly, nor could we do so if we

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had an explicit form for the leakage function. We can, however, derive a similar expression for the leakage function by fourier analyzing the continuity equation at the frequency of the drive.

Since we know that the largest part of the pressure response will be at the fundamental frequency of the drive we can extract more information by fourier analyzing it at that frequency. That is the equivalent of multiplying our continuity equation by $\sin(wt)$ and $\cos(wt)$ alternately and then averaging over one cycle.

$$- < Q(\triangle P)\sin wt > \; = \; < \frac{dV}{dt}\sin wt > + \frac{V_o}{\gamma P_a} < \frac{d(\triangle P)}{dt}\sin wt > \qquad (A23.1)$$

$$= wV_d < \cos wt \; \sin wt > + \frac{V_o}{\gamma P_a}w\,\triangle P_{AC} < \cos(wt + \theta)\sin wt > \qquad (A23.2)$$

$$= - w\frac{V_o}{\gamma P_a}\triangle P_{AC}\,\frac{\sin\theta}{2} \qquad (A23.3)$$

The definition of Q can be used to expand the left hand side of the equation, using the same approximation for the leakage function.

$$- < Q(\triangle P)\sin wt > = L(\triangle P_{DC}) \; (< \triangle P\sin wt > + \alpha < \triangle P\sin wt >) \qquad (A24.1)$$

$$= L(\triangle P_{DC}) \; \triangle P_{AC} (<\sin wt \; \sin(wt + \theta)> + 2\,\alpha < \triangle P > <\sin wt \; \sin(wt + \theta)>) \qquad (A24.2)$$

$$= L(\triangle P_{DC}) \; \triangle P_{AC} \; (\tfrac{1}{2} + \alpha < \triangle P >)\cos\theta \qquad (A24.3)$$

using Eq A19,

$$- < Q(\Delta P) \sin wt > = \tfrac{1}{2} L(\Delta P_{DC}) \Delta P_{AC} \cos\theta \; (1 - 2 \alpha^2 < \Delta P^2 >) \quad (A24.4)$$

We can combine the two expressions for Q to get,

$$\tan\theta = - \frac{1}{k_o w} \frac{L(\Delta P_{DC})}{L_o} (1 - 2 \alpha^2 < \Delta P^2 >) \quad (A25.1)$$

$$\tan\theta = - \frac{L(\Delta P_{DC}) \gamma P_a}{w V_o} (1 - 2 \alpha^2 < \Delta P^2 >) \quad (A25.2)$$

This gives us an expression for the leakage in terms of the phase angle.

$$L(\Delta P_{DC}) = - \frac{w}{1 - 2 \alpha^2 < \Delta P^2 >} \left(\frac{V_o}{\gamma P_a} \right) \tan\theta \quad (A26)$$

In a manner similar to the one above the averaging can be done with cos(wt) instead of sin(wt).

$$< Q(\Delta P) \cos wt > = < \frac{dV}{dt} \cos wt > + \frac{V_o}{\gamma P_a} < \frac{d(\Delta P)}{dt} \cos wt > \quad (A27.1)$$

$$= \tfrac{1}{2} w V_d + \frac{V_o}{\gamma P_a} \tfrac{1}{2} w \Delta P_{AC} \cos\theta \quad (A27.2)$$

$$< Q(\Delta P) \cos wt > = L(\Delta P_{DC}) (< \Delta P \cos wt > + \alpha < \Delta P \cos wt > \quad (A27.3)$$

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$$= L(\Delta P_{DC}) \; {}^{1}\!/_{2} \; \Delta P_{AC} \sin\theta \; (1 - 2 \; \alpha^2 < \Delta P^2 >) \qquad (A27.4)$$

The last two equations can be combined with the definition of k_o to yield another expression for the phase angle.

$$\cos\theta = - \frac{\Delta P_{AC} \; V_o}{\gamma P_a \; V_d} \qquad (A28)$$

This is the exact same expression that was found in the linear case; however, since the value of the pressure will be different the value of the phase angle will be different for the same displacement and pressure than that in the linear case. Eliminating the phase angle from these two expression, we can solve for the leakage function.

$$L(\Delta P_{DC}) = \frac{w}{(1 - \alpha^2 \; \Delta P_{AC}{}^2)} \sqrt{\left(\frac{V_d}{\Delta P_{AC}}\right)^2 - \left(\frac{V_o}{\gamma P_a}\right)^2} \qquad (A29.1)$$

$$L(\Delta P_{DC}) = \frac{\dfrac{w V_d}{\Delta P_{AC}}}{(1 - \alpha^2 \; \Delta P_{AC}{}^2)} \sin\theta \qquad (A29.2)$$

With the exception of the asymmetry term eq A29 looks very similar to eq. A10; however, the interpretation of the two equations in slightly different. Eq A10 is an estimate of leakage constant, which should be the same at any applied pressure. Eq A29 is an estimate of the average leakage function at a particular applied pressure. The applied pressure is a known function of the pressure response at the fundamental frequency due to a sinusoidal drive.

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FLEXING

When an AC pressure is applied to the shell of the structure, there may be a small amount of flexing. The amount of flexing need not be very large in order to effect a significant change in the pressure response, it need only change the volume of the structure an amount significant compared to the displacement volume ($\approx$ .2 m^3). This flexing will decrease the pressure response and thus make the leakage appear to be larger than it actually is; it is therefore necessary to be able to estimate the effect of the flexing and account for its effects should they be important.

Linear flexing is the type associated with the stretching or expanding of the envelope upon an applied pressure. This sort of flexing takes place in walls and windows; the change in volume of the structure is expected to be proportional to the applied pressure.

The resonant frequency of most structures is approximately 15 Hz.[7] Since the frequency range we are working in is much lower than this (typically .1-1 Hz), we can assume that the additional volume created by the flexing will be in phase with the applied pressure.

$$\delta V = \lambda \, \Delta P \tag{A30}$$

where:

δV is the volume[m^3] change due to the flexing and

λ is the flexing constant [m^3/Pa]

The volume that belongs in the continuity equation is the sum of this volume and the drive volume.

$$V' = V + \delta V \tag{A31.1}$$

$$= V_d \sin wt + \lambda \Delta P \tag{A31.2}$$

where:

  V' is the effective (volume) drive $[m^3]$.

If we now substitute this into the continuity equation,

$$Q + \frac{dV}{dt} + \lambda \frac{dP}{dt} + \frac{V_o}{\gamma P_a} \frac{dP}{dt} = 0 \qquad (A32.1)$$

which can be rewritten as,

$$- Q(\Delta P) = \frac{dV}{dt} + \left(\lambda + \frac{V_o}{\gamma P_a}\right) \frac{d(\Delta P)}{dt} \qquad (A32.2)$$

The effect of the flexing has been to increase the capacity term, $(V_o/\gamma P_a)$ by adding the constant flexing term, λ. Since we are working far below the frequency at which the capacity term is important, for the purpose of calculating the correction term we will ignore the capacity term.

$$L_a = \frac{wV_d}{\Delta P_{AC}} \qquad (A33)$$

where:

  L_a is the apparent leakage $[m^3/hr\text{-}Pa]$

The apparent leakage is the leakage calculated assuming that capacity of the structure is negligible; this is equivalent to assuming that the phase angle is always -90°. The actual leakage takes into account the effect of the flexing and the compressibility of air.

$$L = w \sqrt{\left(\frac{V_d}{\Delta P_{AC}}\right)^2 - \left(\lambda + \frac{V_o}{\gamma P_a}\right)^2} \qquad (A34.1)$$

$$= \sqrt{1 - \left[\frac{w}{L_a} (\lambda + \frac{V_o}{\gamma P_a}) \right]^2} \qquad (A34.2)$$

Squaring this expression and solving for the apparent leakage puts this equation into a form the demonstrates it dependance on the capacity.

$$L_a^2 = L^2 + w^2 \left(\lambda + \frac{V_o}{\gamma P_a} \right)^2 \qquad (A35)$$

As expected this last equation shows that the apparent leakage is larger than the actual leakage. Furthermore, it shows that the disparity grows rapidly with increasing frequency.

If we are using the linear equations we expect the leakage with be constant; However, if we are using the non-linear equations we expect the leakage to be slowly decreasing will increasing pressure. In either case, a well established trend is present; in the presence of flexing there will be an increase in the apparent leakage from the trend. If we look for an upturn in a set of data for a particular displacement we should be able to use eq A35 to extract an upper bound on the value of λ. Once found, the flexing parameter can be used to correct all of the data points appropriately.

Infiltration

Movement of the piston causes an oscillating pressure difference between inside and out; this, in turn, causes air to flow alternately into and out of the test space. To calculate this air flow we again use the continuity equation (eq T1). When the pressure is positive the air flow will be out of the space; when negative the air flow will be into the space. To calculate the infiltration we assume that all of the air that flows out of the space is immediately dispersed into the environment. Thus the average infiltration will be the total volume of air moved out of the test space during the positive half cycle divided by the period of oscillation. Making the indicated

calculations we obtain,

$$Q^I = \frac{V_d}{T} \sin\theta \qquad (A36)$$

where:

Q^I is the average infiltration $[m^3/hr]$ and

T   is the period of oscillation $[hr]$.

The only dependence the induced infiltration has on the leakage is through the phase angle which varies from $-90°$ at low frequencies to $-180°$ at high frequencies. The exact expression for the phase angle in terms of leakage parameters can be found in Appendix A:

$$\cos\theta = -\frac{\Delta P_{AC}}{V_d} \times \frac{V_o}{\gamma P_a} \qquad (A37)$$

Therefore by measuring infiltration concurrently with the AC pressurization an independent determination of the phase angle can be made. However, this is based on the assumptions of perfect mixing and dispersal of the air that flows in and out through the envelope, which are questionable.

SUMMARY

There are several assumptions that have gone into this calculation. We have assumed that the actual values of the air temperature, room volume, and internal temperature could be replaced by their average values in the final equations. This assumption is valid as long as the deviations from the average are small compared to the average values. Since the induced volume displacement is on the order of .1% of the structure volume, the assumption of small deviations is justified.

We have assumed that the temperature of the gas entering the structure is the same as that of the gas leaving the structure; clearly the temperature of the outside air may well be different that of the inside air. However, two effects decrease the impact of this assumption: Heat exchange between the air and the structure mitigates the differences; and the net heat transferred is small compared to the total energy.

We have also assumed that the air flow through the structure is either linear in the applied pressure or that it is non-linear with the non-linearities slowly varying with pressure. If the leakage is non-linear then the average leakage function can be mapped out by making measurements throughout the pressure range of interest.

There are several parameters of the model that we can independently measure. Each one of these parameters has a physically meaningful interpretation. Therefore, the magnitude of these parameters can be checked to make sure that they are realistic.

α The asymmetry constant. α is a measure of how symmetric the leakage is with respect to the sign of the applied pressure. It is a measure of the unidirectionality of the leakage.

λ The linear flexing parameter. λ is in effect a compression term akin to the capacity of the structure. It is a measure of how much the structure flexes in response to the pressure drop across it. Both walls and windows are expected to stretch or bend when there is a pressure drop across them.

When all of these parameters are taken into account an expression for the actual leakage as a function of the measured variables and these parameters can be found:

$$L(\Delta P_{DC}) = \frac{w}{(1 - \alpha^2 \Delta P_{AC}^2)} \sqrt{\left[\frac{V_d}{\Delta P_{AC}}\right]^2 - \left[\lambda + \frac{V_o}{\gamma P_a}\right]^2} \qquad (A38.1)$$

$$\Delta P_{DC} = \Delta P_{AC} \sqrt{\tfrac{1}{2}(1 + \tfrac{1}{2}\alpha^2 \Delta P_{AC}^2)} \qquad \text{(A38.2)}$$

In this appendix we have solved the problem of low-pressure leakage measurements under a sinusoidal driving function of the internal volume. The exact solution to the linear leakage problem was found; and an approximate solution to the non-linear leakage equation was found.

APPENDIX B

Procedure and Analysis

The experiments described below all took place in our research house in Walnut Creek, California. It has a volume of $230m^3$ and a floor area of $100m^2$. The house is a single story ranch type house of wood frame construction. There is a fireplace and a forced air heating system with exterior ductwork in the attic and crawl space.

Equipment

Pressure Source: The source of the pressure signal is a large cross section ($\approx 1m^2$) rectangular piston which moves in and out of the shell through a suitably sized guide. (cf Fig 1a) The guide is installed in an exterior door of the test structure. As the piston moves outward through the guide the volume of the house is increased; as it moves inward the volume is decreased. The guide is made of plywood and has teflon seals all around it to minimize both friction and air leakage through the guide.

The piston is connected via a connecting rod to a light flywheel. The diameter of the flywheel is about 0.5m; there are nine different holes in the flywheel to allow for different displacements of the piston during a drive stroke. The maximum displacement peak to peak is about $0.3 \ m^3$.

The flywheel is driven through a gearbox by a variable speed 3/4 hp motor. With the current arrangement of motor, gearbox, piston and guide the frequency of oscillation ranges from 2 to 250 rpm.

Pressure Detection: The pressure response of the envelope is measured with a differential pressure sensor whose range is $\pm$ 70 Pascals. The reference end of the pressure transducer must be at a constant pressure in order to measure the pressure response of the system; but if it were connected to the outside a large amount of noise would be introduced into the data due to the wind.

Rather than use the outside as our reference pressure, we used the time-averaged interior pressure. To do this time averaging we built a physical low pass filter that responds to slow pressure drifts but does not respond to high frequency fluctuations (i.e. both weather and the pressure response due to the piston). The filter consists of a volume and a resistance: the volume is a large brass cylinder of about 3 liters and the resistance is a micrometering valve. (cf Fig 1b)

Since the resistance is variable we can adust the time constant of the filter to any desirable level. The time constant was chosen to be about 5 minutes so that wind fluctuations and our pressure signal would be filtered out, but the normal changes in atmospheric pressure would not. The volume is insulated with about 2cm of polystyrene insulation to minimize pressures induced by temperature fluctuations. This provides a reliably steady pressure with which to reference our measurements.

Infiltration: The infiltration was monitored using a continuous flow system. Tracer gas (nitrous oxide) was injected into the test space at a rate .eld constant by a mass flow controller. There are injection ports in several places in the test space and mixing of the tracer gas was assured by the operation of a mixing fan at each injection site.

The concentration of nitrous oxide was measured with a twin beam infrared analyzer. Samples were continuously drawn from several sites around the test space and mixed in a manifold before analysis. The data was put on a strip chart recorder for subsequent analysis.

Procedure

There were two sets of test runs that were used to measure the leakage; each with the house in a different condition. The first set of runs was done with the test house in a relatively tight configuration. The fireplace and kitchen vents were sealed with plastic to prevent leakage. Since the ductwork does not go through the conditioned space, all of the registers as well as the ·loset containing the furnace were sealed with tape to prevent leakage.

All of the points that fell within a half pascal range were averaged together to get a composite leakage function. The averaging was done using the standard deviation of each point to weight the average. This composite leakage function and the asymmetry parameter were combined with the pressure to give the air flow vs applied pressure curves in Figs 4-7.

Results

The measurement of the asymmetry parameter was done as indicated above for both the tight and loose configuration. To measure the flexing parameter (see Appendix A) the apparent leakage squared was plotted against the square of the frequency as per eq A35. This plot is shown in fig 6. Looking at fig 6 we can see that for high frequencies the apparent leakage is dominated by the flexing and the plot becomes linear. From this linear section the value of the flexing parameter, λ, can be found.

The asymmetry and linear flexing parameters were measured in order to subtract out their effects. Their values for our test house discussed above are tabulated below.

PARAMETER	VALUE		UNITS
	TIGHT	LOOSE	
α	.0152$\pm$.001	.004+.003	Pascals^{-1}
λ	.0032$\pm$.001	.0032$\pm$.001	m^3/Pascal

These constants were used with the measured pressures to produce a plot of the corrected leakage function vs pressure. Fig 2 is the leakage function of the house in the loose configuration and fig. 3 is leakage function of the house in the tight configuration. Each plotted point represents a one minute average at a certain frequency and displacement. The solid line represents a smooth weighted average of all of the points on the graph.

October 2, 1979

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Data Acquisition and Analysis

There are only two quantities that are measured during the course of the leakage experiment: the time dependent pressure and the frequency. The stroke of the piston is an experimental parameter that may be adjusted; the quantities V_o, P_a and γ are known.

The pressure is recorded both on a strip chart recorder and by a microprocessor. The frequency is monitored by the microprocessor by use of an infrared diode system that records each revolution of the flywheel. Digital filtering of the incoming data is used to remove noise and reduce aliasing.

Data at very high frequencies can be used to determine the flexing constant and data at high pressures can be used to determine the asymmetry constant. Once these two parameters are known the average leakage can be calculated for every measured data point.

During the infiltration experiments the data was collected on a separate chart recorder for later analysis. The leakage was calculated using eq. A38 for each of the one minute data points. Then all of the data points in a 1/2 Pascal range were averaged together using their standard deviations to weight the averages.

Error Analysis

An estimate of the error was made for each point on the air flow vs applied pressure curves. For DC measurements the error comes principally from two sources: the uncertainties involved in the calibration of the flow through the fan, and the uncertainty in the measurement of the pressure drop across the structure.

The error analysis for the AC measurements is a little more involved. Using the formula for the leakage function we can estimate the error in the leakage from the measurement error in the variables. At low pressures the error in the leakage is dominated by the uncertainty in the displacement and the measured pressure. At high frequencies the error is dominated by the uncertainty in the flexing parameter.

The second set of runs was done with the house in a loose configuration, more typical of normal operation. The fireplace was unsealed but the damper left closed. The kitchen vents and registers were untaped and left in their normal operating state.

For each set of runs the DC pressurization was measured using a fan pressurization technique.[8] Both pressurization and depressurization were measured. Then we did three different AC pressurization runs within each set, each run having a different displacement volume for the drive. In every run the frequency was varied from a minimum of about 3 rpm to a maximum of about 1 rps. Data was collected continuously by the microprocessor and processed every minute during a (40 minute) run.

The parameters α and λ were calculated separately. To measure the asymmetry parameter, α, the drive was left on for several minutes at the same frequency, allowing the physical filter on the pressure sensor to come to full equilibrium with the average pressure inside the structure. Once equilibrium was established, the volume drive was shut off and the DC pressure offset was noted. This procedure was done at several representative pressures and the results averaged.

The flexing parameter, λ, becomes dominant at higher frequencies. We need its, value at low frequencies to correct the apparent leakage for envelope flexing. Accordingly, we measured the response at frequencies higher than that of any of the runs and fit the data to eq A35 to find λ. Data was taken at frequencies from .1 Hz to 3 Hz using the smallest of the displacements.

Several other runs were performed for the purpose of measuring the infiltration due to the AC pressurization. There were three parts to each run and the infiltration was monitored continuously during each part using a continuous flow technique.[9] First the infiltration was monitored with the AC pressurization equipment off, to establish a baseline; then the AC pressurization was turned on and the increase in infiltration noted; finally the AC pressurization was shut off to re-establish the baseline infiltration.

Figs. 4 and 5 show the air flow through the envelope vs applied pressure curves for the loose and tight configurations respectively. The open points are calculated air flows from the average leakage curves and the solid points are the DC measurements made with fan pressurization.

The leakage function in both the tight and loose configuration increases as the pressure approaches zero (cf figs 2 & 3). If the leakage function approached a constant at zero pressure then air infiltration associated with very low pressure fluctuations around the envelope would vanish with the diminishing pressure. If, however, the leakage is increasing near zero, as our tests indicate, then there will be appreciable infiltration even when the surface pressures are quite low.

LIST OF FIGURES

1. Sketch of experimental set-up and apparatus (a) is a schematic of the piston motor and flywheel assembly. Fig (b) is a schematic of the pressure sensor and physical filter.

2. The leakage function of the structure in the loose configuration in plotted vs the applied pressure. Each point represents a minute average reading at a particular frequency and displacement. Points of the same displacement have the same symbol.

3. The leakage function of the structure in the tight configuration in plotted vs the applied pressure. Each point represents a minute average reading at a particular frequency and displacement. Points of the same displacement have the same symbol.

4. The air flow through the envelope is graphed vs the applied pressure for the structure in the loose configuration. Both the AC pressurization graph as derived from the low pressure leakage function, and the DC pressurization are shown. The error bars are calculated from the measurement errors and displayed for each point.

5. The air flow through the envelope is graphed vs the applied pressure for the structure in the loose configuration. Both the AC pressurization graph as derived from the low pressure leakage function, and the DC pressurization are shown. The error bars are calculated from the measurement errors and displayed for each point.

6. The apparent leakage squared is plotted against the frequency squared for the smallest displacement. From the high-frequency slope the total capacity can be inferred.

7 The DC leakage curves for both the loose and tight configurations. The error bars are derived from the measurement error and equipment calibration errors.
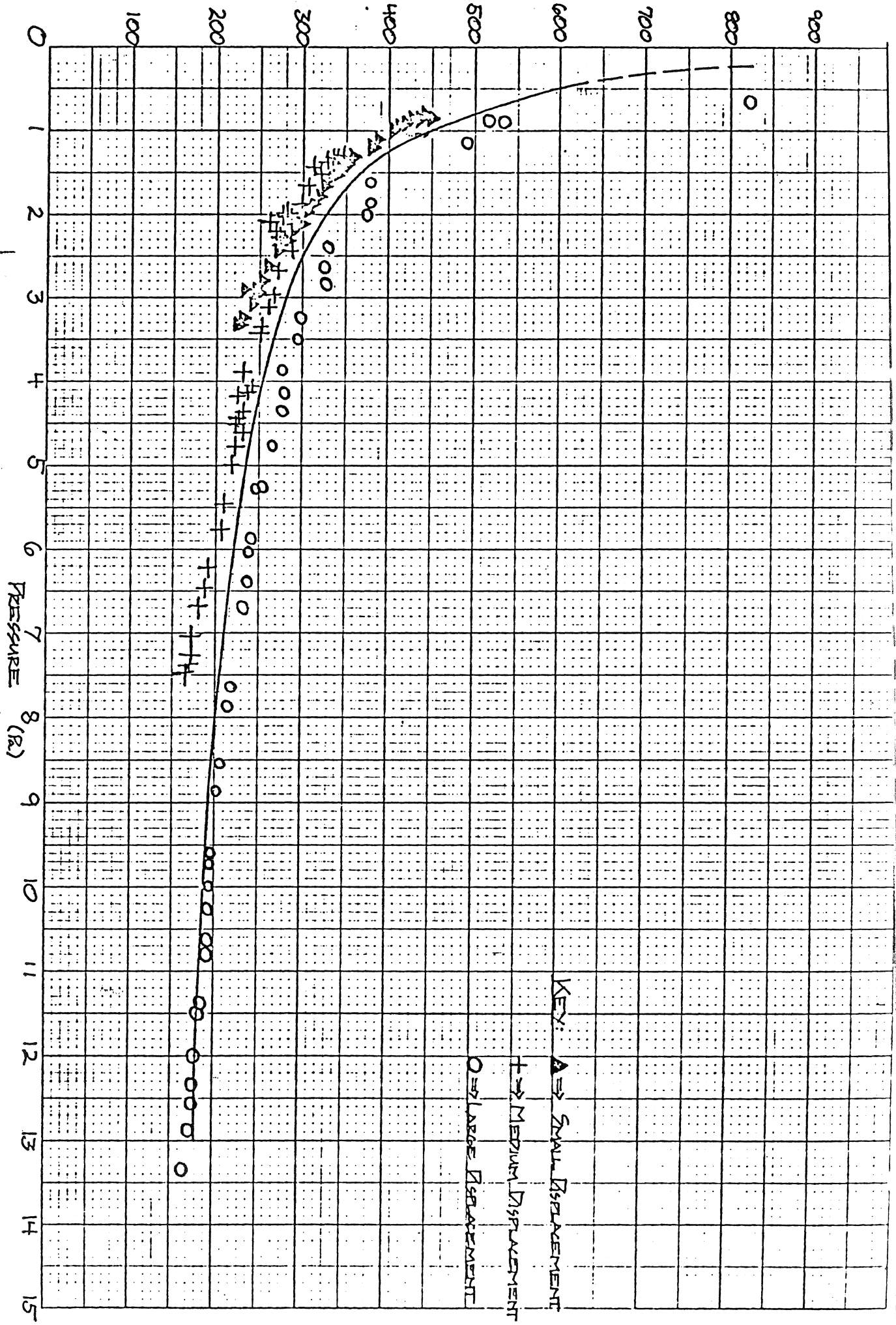
MOTOR

GEAR BOX

FLY WHEEL

PISTON

WALL

1A

FILTER

SENSOR

VOLUME

VALVE

1B

FIG. 1

FIG. 2
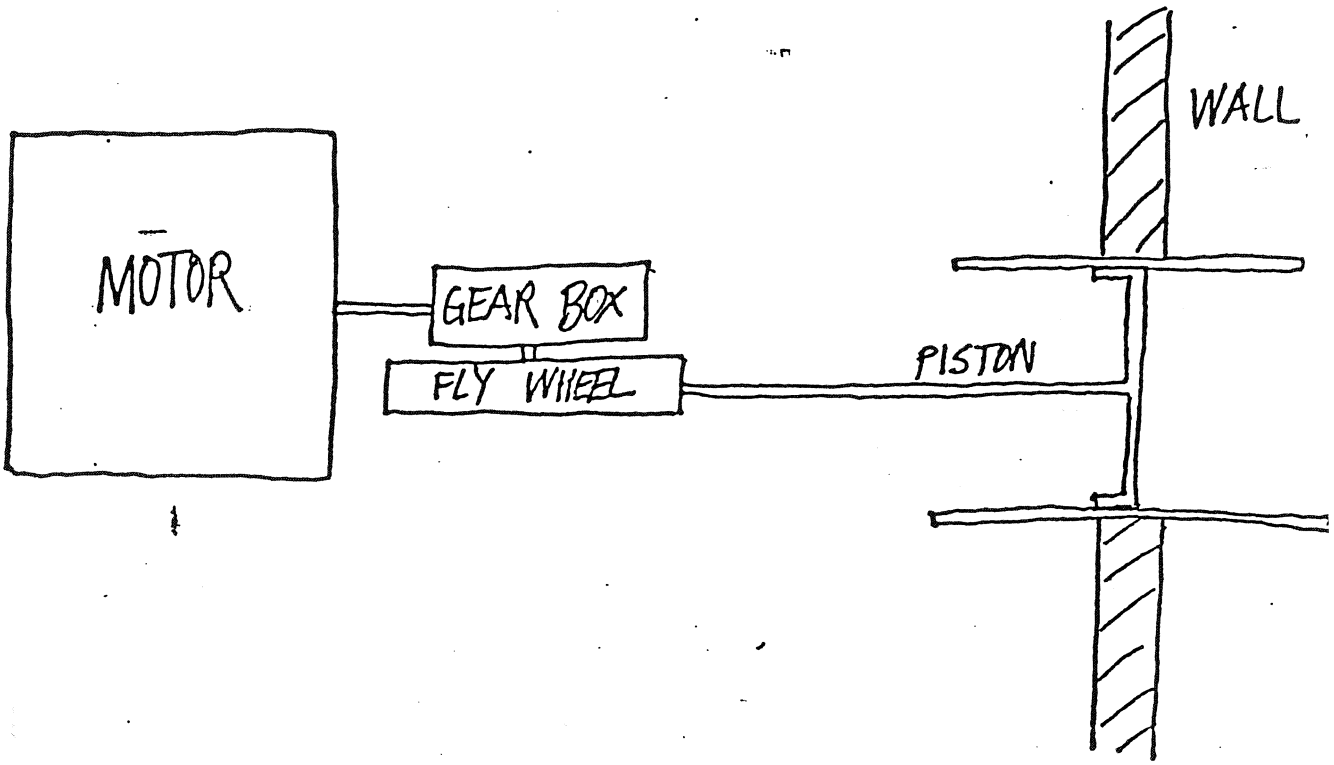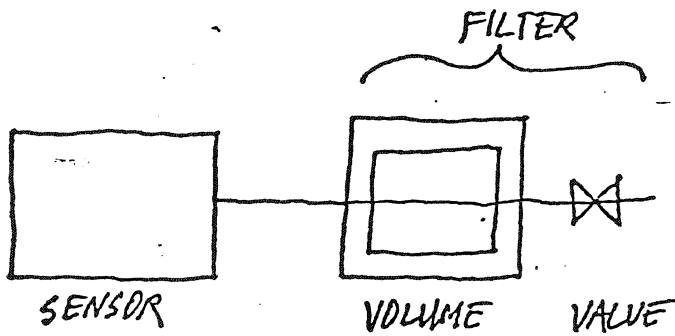
KEY: △ ⇒ SMALL DISPLACEMENT
      + ⇒ MEDIUM DISPLACEMENT
      ○ ⇒ LARGE DISPLACEMENT

LEAKAGE   (m³/Pa-sec)

PRESSURE (Pa)

FIG. 2

KEY:
□ => SMALL DISPLACEMENT (HIGH FREQUENCY)
△ => SMALL DISPLACEMENT (LOW FREQUENCY)
+ => MEDIUM DISPLACEMENT
○ => LARGE DISPLACEMENT
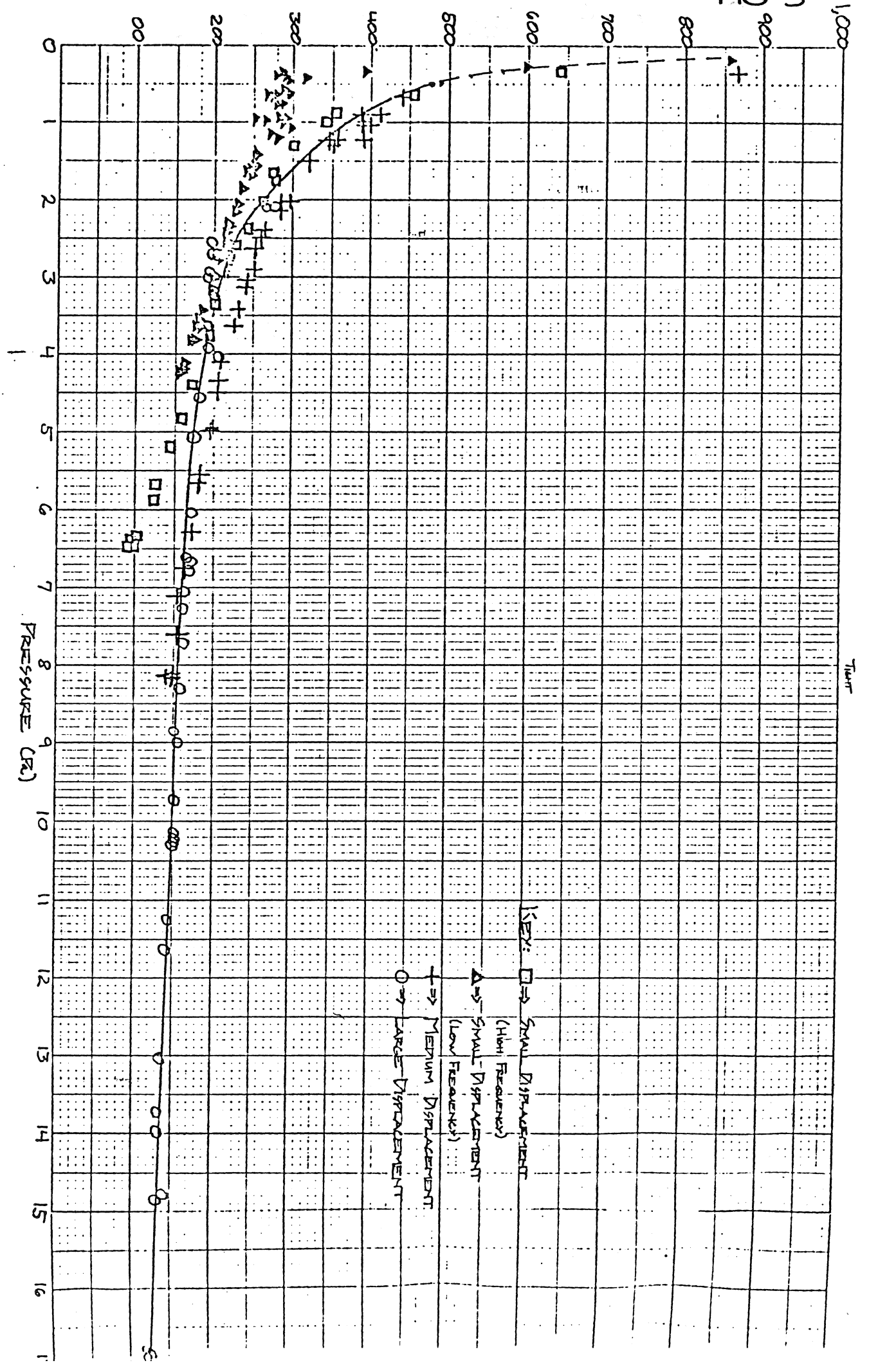
PRESSURE (P₁)

AIRFLOW (m³/hr)

-2,500 -2,000 -1,500 -1,000 -500 0 500 1,000 1,500 2,000 2,500

15

10

5
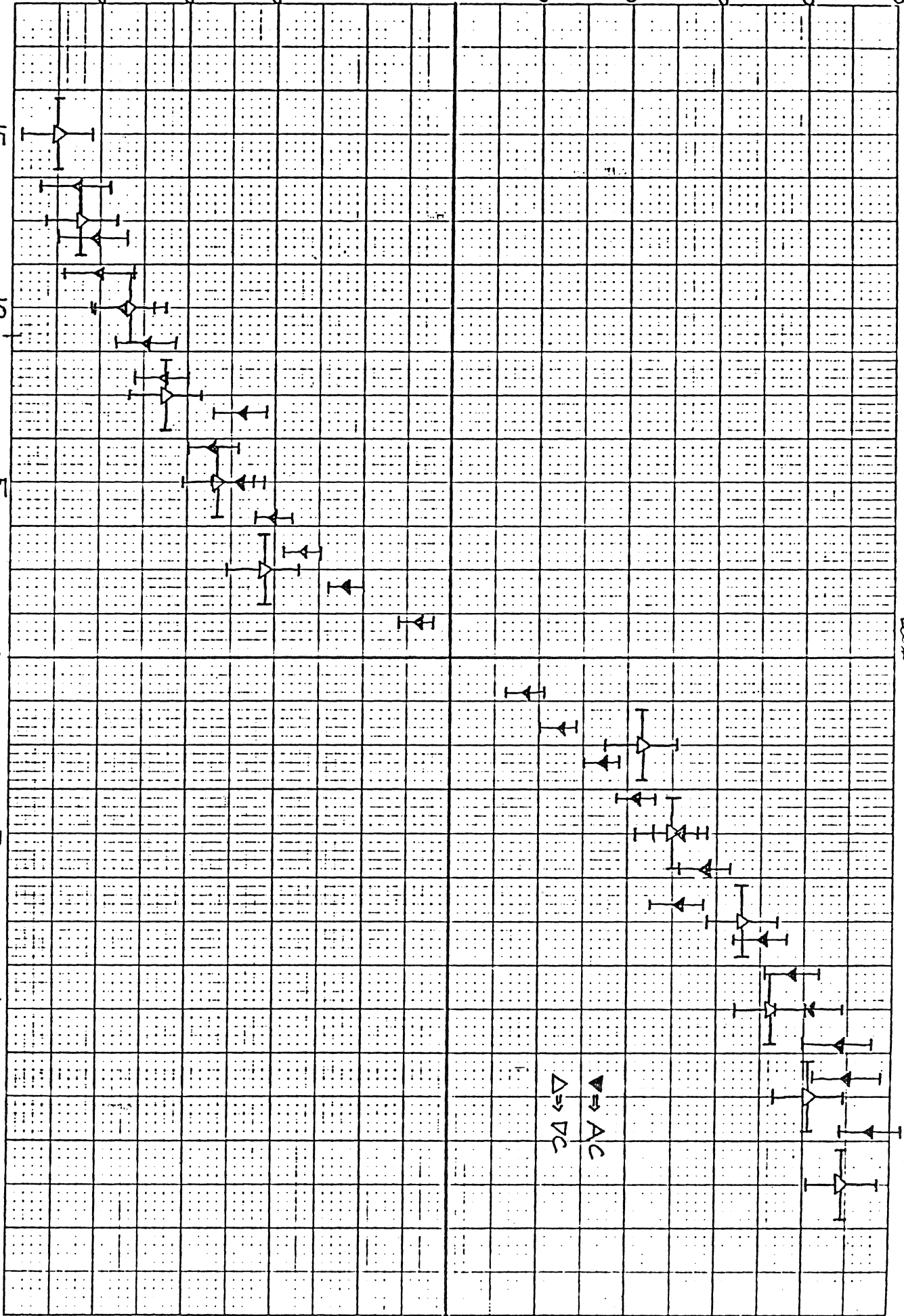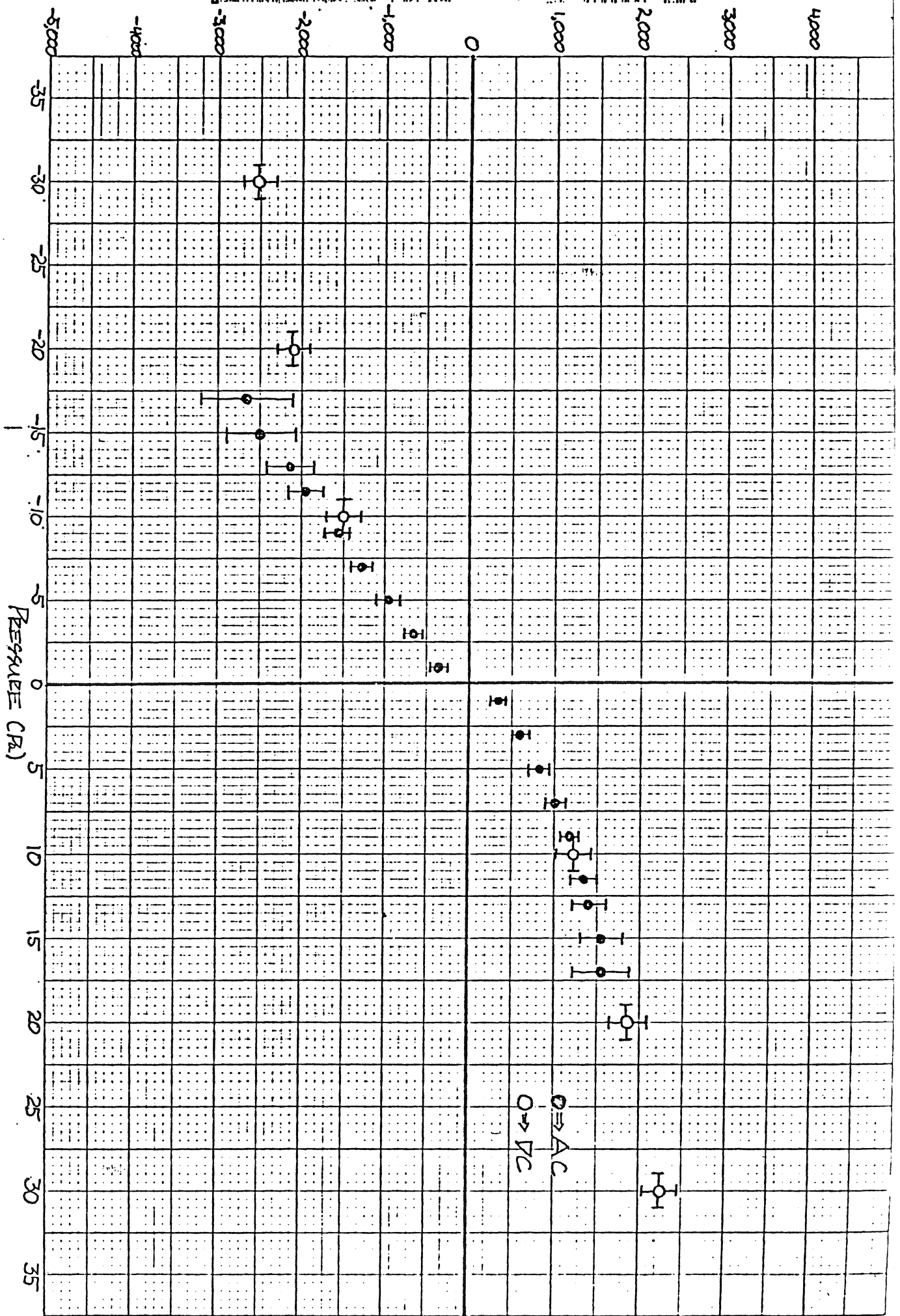
PRESSURE (Pa)

5

10

15

△ = DC
▲ = AC

FIG 5

FIG 6

APPARENT LEAKAGE $(m^3/R\text{-}sec)^2 \times 1000$

FREQUENCY (MHz)
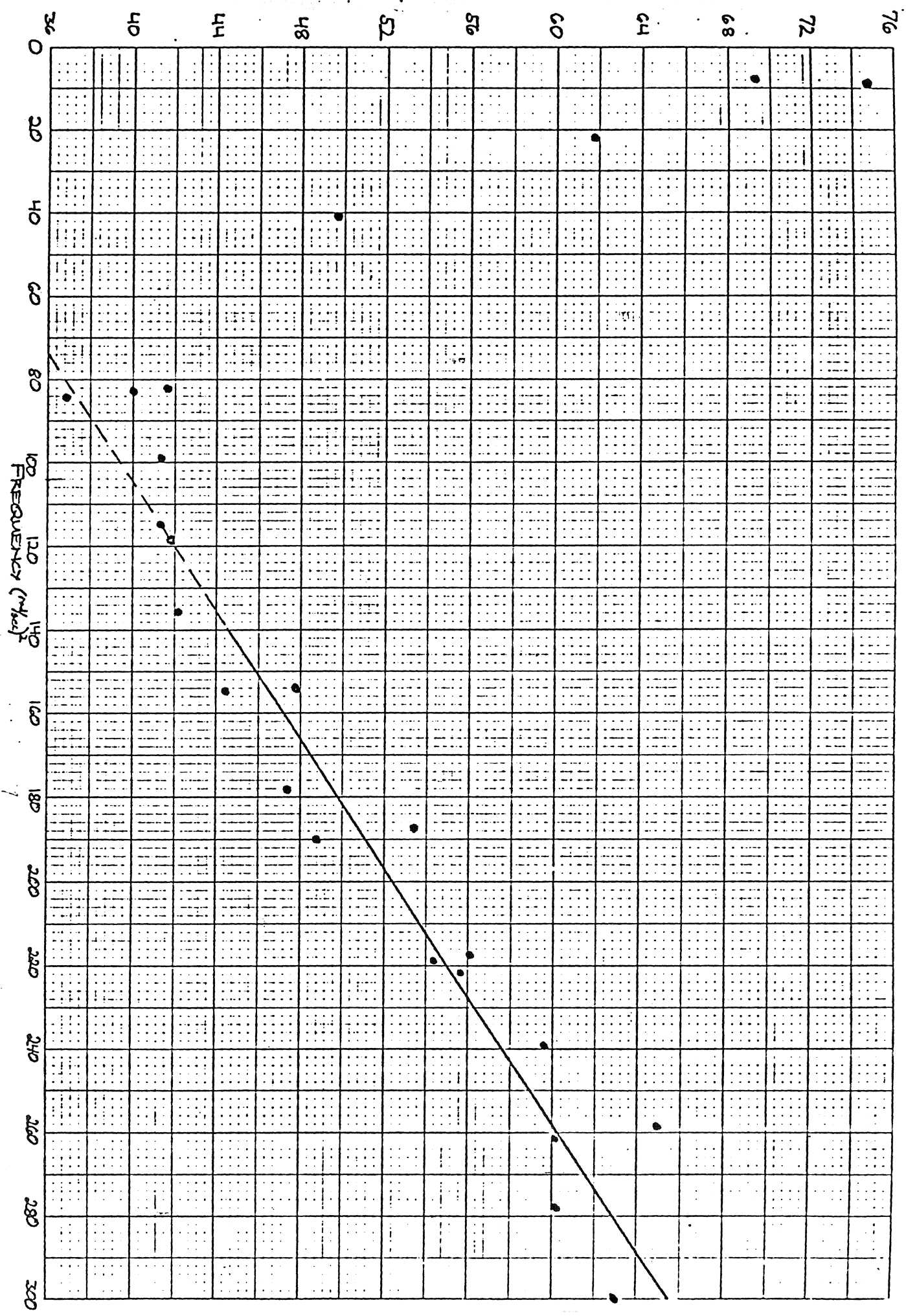
FIG 7
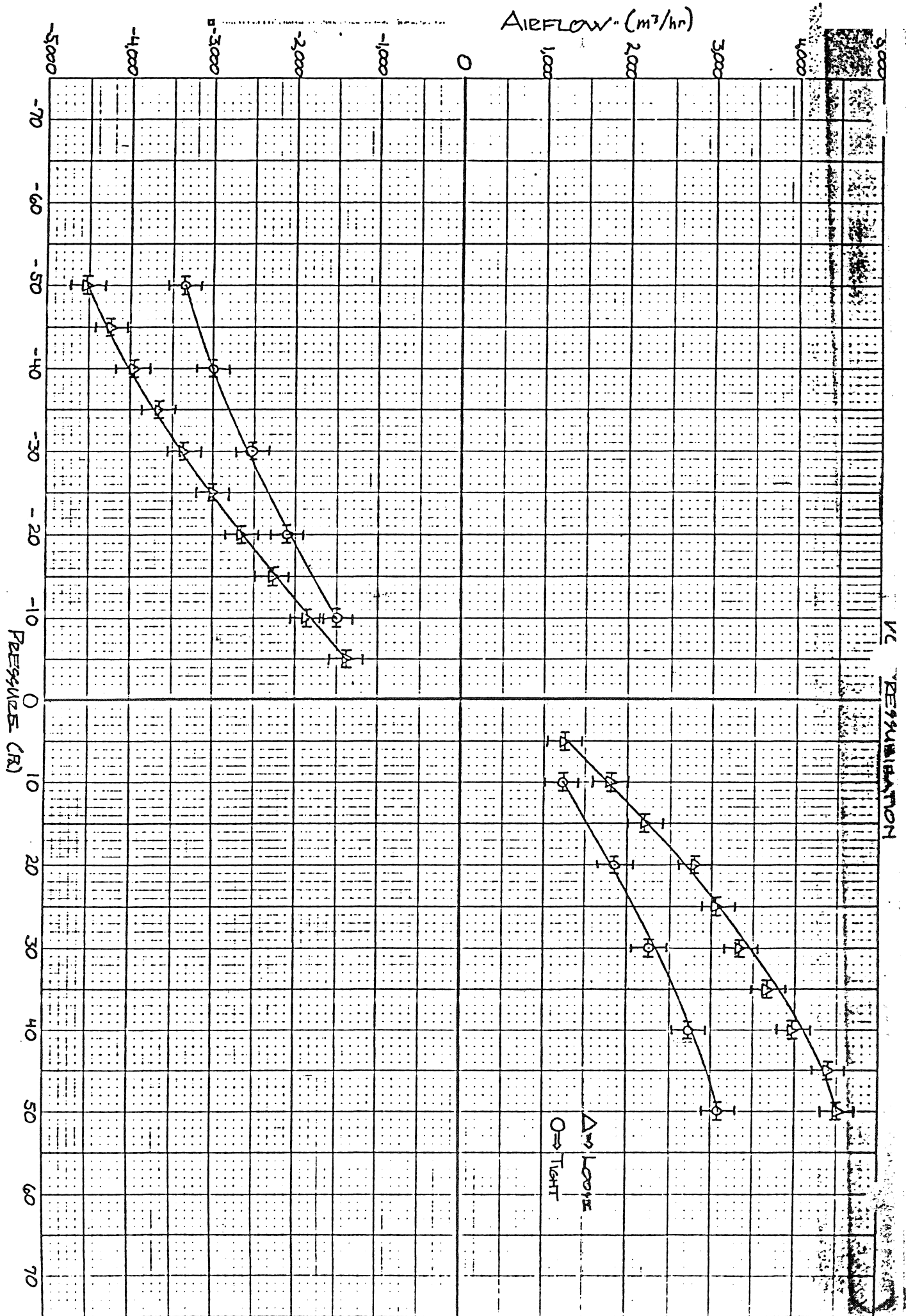
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