

# The Low Pressure Leakage Function of a Building

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ASRAE MEMBERS

## ABSTRACT

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.

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 weather induced noise, 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, yet this is the pressure range that often drives natural infiltration. 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.

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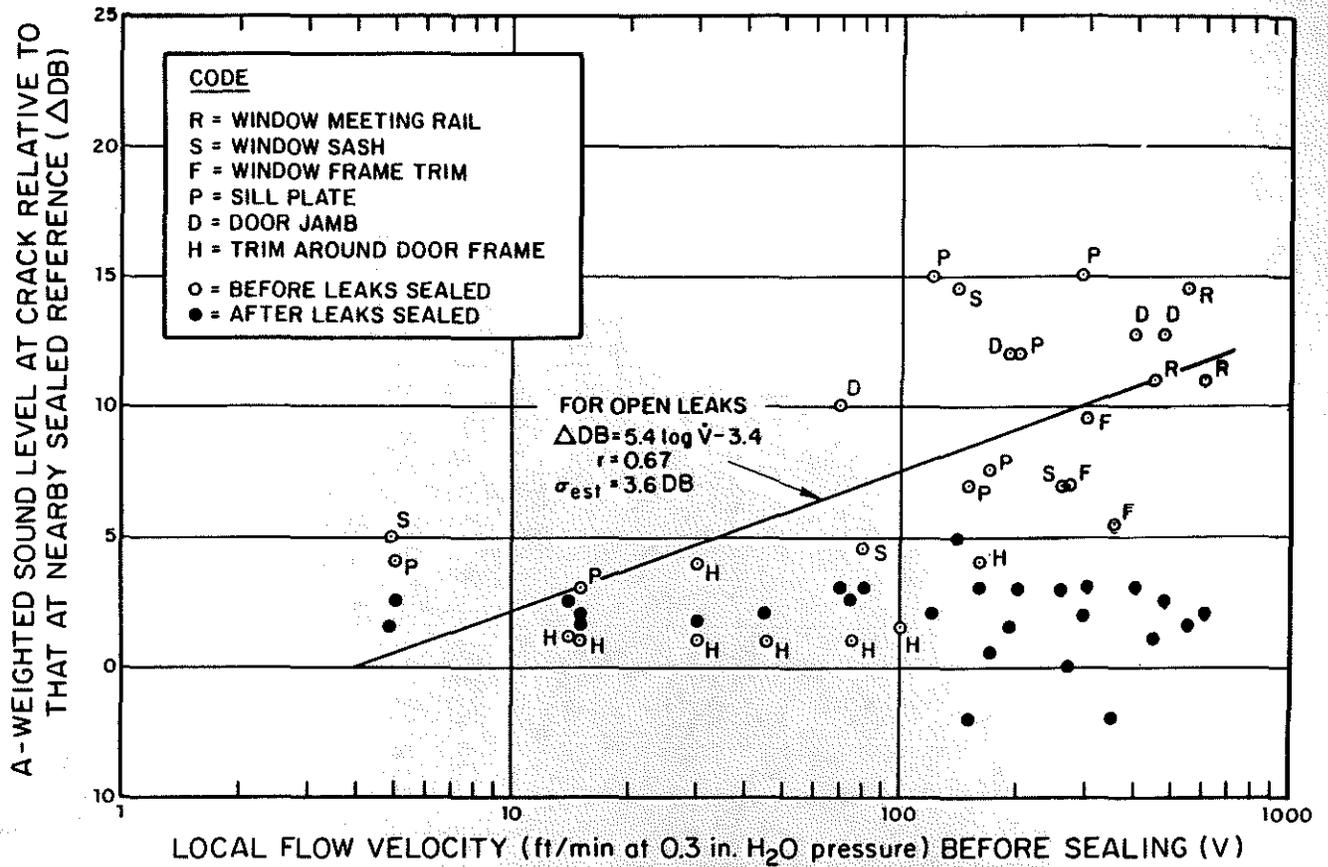


FIGURE 6. INCREASE IN SOUND LEVEL NEAR CRACK VS LOCAL AIR FLOW FROM CRACK AT 0.3 IN. PRESSURE DIFFERENTIAL.

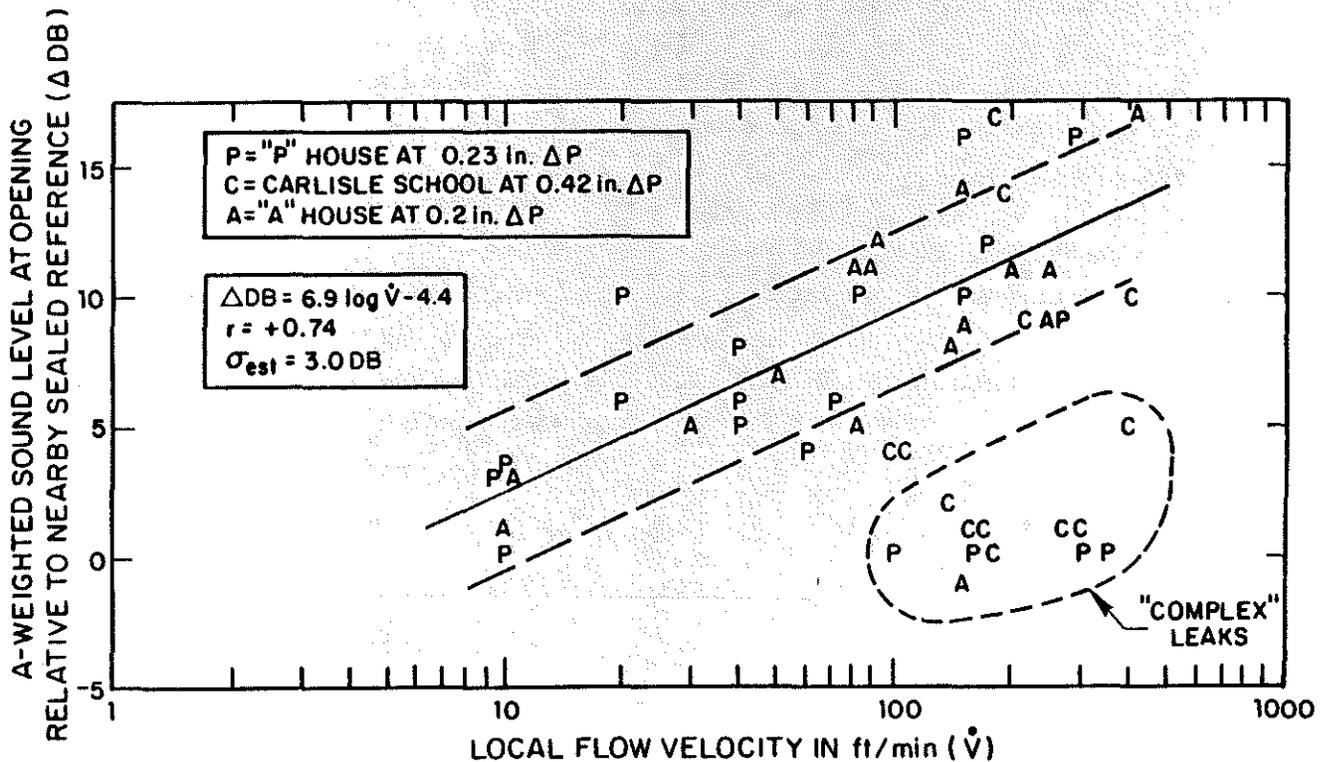


FIGURE 7. INCREASE IN SOUND LEVEL NEAR CRACK VS LOCAL AIR FLOW FROM SAME CRACK.

## INTRODUCTION

Infiltration (air leaking through openings in the shell of a building due to natural pressure fluctuations) is a conceptually simple process. The hydrodynamic details of the flows for real buildings, however, are complex and make calculation or modeling infiltration a difficult problem.

Infiltration models while used primarily for calculating energy-loads, either by simple steady state procedures or by dynamic computer programs, also contribute to our basic physical understanding of infiltration which, in turn, aids in developing both 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 and independent of outside weather conditions. To calculate energy loads, in that case, only required knowing the steady infiltration value for a structure and the total number of degree-days. The next level of modeling used field measurements of infiltration values and weather to draw an empirical relationship between infiltration, wind speed and indoor-outdoor temperature differences. Although this multiple linear regression technique allows us to predict the 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, to assure statistical significance, data have to be collected over a wide variation of weather parameters.

Physical models are characterized by applications of physical principles, rather than by semi-empirical correlations, as are the models indicated above; physical models view infiltration as the result of pressure differences across openings in the building shell, and, accordingly, require measurements of (a) the leakage of the shell and (b) surface pressures (or weather parameters combined with a model to predict the surface pressures) in order to compute the air flows through the openings yielding the infiltration.

Leakage measurements are, traditionally, 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). These measurements of the pressure-flow characteristics of the structure are most reliable when the pressure applied is large compared to the weather-induced differential pressure already present. Measurement ranges typically used extend to at least 50 Pa; ambient surface pressures are usually less than 10 Pa, therefore, it is leakage at low-pressures ( $-5 \text{ Pa} < \Delta P < 5 \text{ Pa}$ ) that is needed to model infiltration.

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:

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

and

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

where

$Q(\Delta P)$  is the leakage [ $m^3/hr$ ] (as a function of the pressure drop)

$\Delta P$  is the applied pressure [Pa]

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

Any attempt to use these forms, however, will fail because these regression constants (A, B, C, n) 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 ( $Q^2 \sim \Delta P$ ).<sup>1</sup> The transition between low and high-pressures depends critically on the crack geometry; because in a real structure 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.

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 low-pressure measurements, a technique is needed to measure the important low-pressure leakage. We call our technique AC pressurization because it uses an alternating pressure signal as opposed to the standard DC pressurization, which uses a constant pressure drop across the envelope. Card et al<sup>2</sup> used a similar concept which they called the infrasonic technique.

Because the pressure signal used in the AC technique is dominated by one well-known frequency, (unlike the pressures caused by wind which have a broad frequency range) the amount of interference caused by the weather at the frequency is negligible. Thus, the complete leakage curve can be accurately measured using AC pressurization.

#### GENERAL TECHNIQUE

To measure leakage at very low pressures by means of AC pressurization, we change the volume of the structure and measure the resultant pressure response. By measuring only at that pressure response which is at the same frequency as the volume drive (i.e. synchronous detection) we avoid the noise associated with DC measurements, which gives us much greater signal to noise resolution and allows us to work at applied pressures that are smaller than the random weather induced pressures.

The volume is changed by installing a large piston and guide assembly in place of an existing exterior door (See Fig 1). The piston is moved in the guide by a motor/flywheel assembly that allows adjustable displacement and frequency control. 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. Our leakage measurements were made at frequencies between 6 and 60 rpm.

If the structure is rigid we can use the measured volume drive and pressure response 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

calculate exactly how much air leaks out for a given drive and thus to calculate the air flow for a given (constant) external pressure.

In general, building structures are not rigid, and when the pressure inside the structure changes, the envelope flexes to counteract the change in pressure. By assuming that the flexing is proportional to the differential pressure across the shell, we can correct for this effect.

The movement of the piston increases the air flow through the envelope. If the piston movement is regular the change in infiltration can be measured by means of standard tracer gas methods and can serve as an independent check on the leakage measurement.

### THEORY

In DC pressurization, the calculation of the leakage is straightforward. Because the applied pressure is constant and small compared to ambient pressure, we can treat the air inside the structure as incompressible. If we assume that the pressure applied to the structure is greater than any weather induced pressure, the leakage can be obtained by applying the continuity equation:

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

where

- $\Delta P$  is the pressure [Pa] across the envelope,
- $Q(\Delta P)$  is the airflow [ $m^3/hr$ ] through the envelope at pressure  $\Delta P$  and
- $F_{fan}(\Delta P)$  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 it 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 equation:

$$Q(\Delta P) = -\frac{dV}{dt} + \left[ \lambda + \frac{V_0}{\gamma P_a} \right] \frac{d(\Delta P)}{dt} \quad (3)$$

where

- $Q$  and  $\Delta P$  are air flow and pressure as above,
- $dV/dt$  is the time change in volume of the structure [ $m^3/hr$ ],
- $\lambda$  is the flexing constant of the envelope [ $m^3/Pa$ ],
- $V_0$  is the volume of the structure [ $m^3$ ],
- $\gamma$  is the ratio of specific heats of air (1.4),
- $P_a$  is the atmospheric pressure ( $1.013 \times 10^5$  Pa) and
- $d(\Delta P)/dt$  is the time change in internal pressure [ $Pa/hr$ ]

The term in brackets in Eq. 3 is the effective capacity of the structure. It contains two parts: the first part is due to 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.) Given the change in volume and associated change in pressure, the continuity equation can be used to calculate the air flow through the structure; however, the quantity of interest is the steady-state flow associated with a steady-state pressure. In order to translate an oscillating flow into a steady state one, 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.

$$Q(\Delta P) = L_o \Delta P \quad (4)$$

where

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

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.<sup>3</sup>

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

$$Q(\Delta P) = L(\Delta P) \Delta P \quad (5)$$

where

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

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. In some situations, however, 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.

$$Q(\Delta P) = [L(\Delta P) (1 + \alpha \Delta P)] \Delta P \quad (6)$$

where

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

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

The effect of this asymmetry term is to cause a DC offset in the internal pressure. If the structure is leakier on depressurization than pressurization, the average internal pressure will be higher than the average external pressure.

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 air flow 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

To conduct our test we used a research house that has been extensively studied.<sup>4</sup> The house was tested in two configurations: loose and tight. In the loose configuration, the structure in its normal operating condition: all vents open, all dampers and windows shut. In the tight configuration, all vents were sealed and the heating system (registers, return duct and furnace closet) was also sealed. In no configuration was any weather-induced noise noted above the other random errors.

Figs. 2 and 3 are plots of the data points for the AC pressurization data in both configurations. Also drawn, is the average leakage curve calculated from a weighted average of the data points. 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 indicates the points from the AC pressurization run as well as the points from the DC pressurization run, and 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 range is duplicated on Figs. 4 and 5.

All AC tests were done with a variety of different piston displacements and frequencies. There appeared to be a systematic difference between sets of data at different displacements, but this difference was within the error bars and did not effect the interpretation of the data.

As reflected by the non-zero value of the asymmetry constant, there is some difference between the leakage curves for pressurization and depressurization. An explanation for this asymmetry might be that the windows in the test structure are the sliding aluminum type, which, upon pressurization are pushed against their seals making them less leaky; upon depressurization, are pulled away from their seals, increasing the leakage.

## Infiltration

During AC pressurization many interesting qualitative effects were observed. As detected using smoke sticks and other visual indicators, pulsating air flow in and out of cracks was frequently observed around windows and fixtures. Leakage was evident in interior partitions around light switches and outlets, indicating good communication between the interior partitions and the attic or crawl space and hence to the outside. This set of data was taken at only one frequency ( 1 Hz. ) but at several different piston displacements.

Infiltration was measured at many different times with the test space in different leakage configurations. When the house was in a normal or tight configuration, infiltration rates due

to AC pressurization were only about 20% of the expected values. The experimental error of the tracer gas measurement was, at most, 10%; the absence of an infiltration increase is statistically significant. 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 because storage of the tracer gas, during pressurization, is pushed out of the test space and into wall cavities, the attic, and the crawl space, where it is not able to mix with the outside air before it is sucked back into living space on the depressurization stroke. Evidence for this assumption comes from observations with smoke stick; i.e. smoke can be observed to pulsate in and out of light fixtures, electrical outlets and cracks, both in the interior partitions and outside walls. Because a good part of natural infiltration is driven by pulsating wind pressures, it would be interesting to speculate on the extent to which the geometry of such connected spaces influences infiltration in the living space.

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

The infiltration measurements made concurrently with the AC pressurization measurements were always far less than the predicted values for air flow through the envelope. The prediction, however, assumes that all of the air forced out of the envelope by the piston mixes with the outside air and disperses before air is pulled back in. Whereas, in actual testing, 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. Because of these circumstances, the amount of infiltration measured by tracer gas was only a small part of the air flow through the envelope as measured by AC pressurization. The lack of mixing is pronounced in our case, indicating that a significant amount of air leaks 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 frequency of at most 1 Hz).

## DISCUSSION

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. If the leakage function approaches zero at least as fast as the inverse of the pressure, the increase in the leakage function would correspond 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 (See 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<sup>5-7</sup> 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. Our data, however, cannot distinguish between a curve that approaches zero as an inverse power of the pressure or as an inverse square root of the pressure; we, therefore, feel reluctant to conclude that the discontinuity at zero pressure is a real effect.

Our data clearly contradicts that hypothesis that the leakage function approaches a constant at low pressures. This fact suggests that laminar flow is not a significant consideration at any pressure which is typical of weather driven infiltration, suggesting that infiltration is dominated by cracks that exhibit turbulent flow characteristics (e.g. orifice flow). Since the house was tested in two tightness configurations and no appreciable difference was noted, we feel confident that leakage is dominated by turbulent flow for typical construction. While the leakage may be predominately turbulent, it is not completely so; our data does completely fit the  $\Delta P^{1/2}$  form that would be expected from fully developed turbulent flow, indicating that while laminar flow may not be dominant at any reasonable pressure, it is not negligible either.

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. Since no sharp transition was observed in the data, models using a flow exponent (Eq. 1.2) may fare better. Neither of these models scale correctly with Reynolds number, nor are they dimensionally consistent; therefore, they cannot be considered as general models but rather as empirical models which can only be justified if they describe the data within their range.

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, and have used the data from both the leaky configuration and the tight configuration. The model, as presented in the introduction is,

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

where

- Q( $\Delta P$ ) is the air flow [ $m^3/hr$ ],
- C is the scale constant [ $m^3/hr-Pa^n$ ] and
- n is the flow exponent.

The semi-empirical co-efficients are tabulated below:

TABLE 1. Values of leakage constants in power curve fit.(E7)

TYPE	CONFIGURATION	PRESSURE INTER- VAL [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

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 the AC 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.

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 consistent 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<sup>3</sup>). 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 the AC pressurization technique a mechanical assembly (See Fig. 1.) is used to modulate the volume of the test space (See Appendix B). In this appendix we shall derive the relations governing the interaction between a changing volume, the leakage through the envelope, and the change in internal pressure, which are necessary to interpret the data collected by the AC technique.

#### AIR FLOW

We begin the derivation by assuming the gas within the structure to be ideal, that is,

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

where

- P is the absolute pressure [Pa],
- V is the structure volume [m<sup>3</sup>],
- n is the number of moles of gas,
- R is the ideal gas constant (8.32 joules/mole-°K) and
- T is the absolute temperature [°K].

Conservation of energy for an ideal gas yields,

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

where

- C<sub>v</sub> is the heat capacity of air at constant volume [joules/mole-°K].

Using Eq. A1 to eliminate dT,

$$RT \, dn = P \, dV + \frac{1}{\gamma} V \, dP \tag{A3}$$

where

$\gamma$  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. We can use these definitions to eliminate the number of moles of gas from the expression for the air flow.

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

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

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

where

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

To conform to common usage in the field, we have used the convention that the air flow,  $Q$ , is positive when it flows out of the structure to correspond; 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 by their steady state values.

$$Q + \frac{dV}{dt} + \frac{V_0}{\gamma P_a} \frac{dP}{dt} = 0 \quad (A5)$$

where

$V_0$  is the normal structure volume [ $m^3$ ] and

$P_a$  is the normal internal pressure (1 atm.)

### AIR LEAKAGE

The continuity equation, Eq. A5, can be used to find the air flow through the envelope caused by given pressure and volume changes; however, the 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 one-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, which assumes that the flow through the envelope is proportional to the applied pressure:

$$Q = L_0 \Delta P \quad (A6)$$

$L_o$  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.

$$Q + \frac{dV}{dt} + k_o \frac{dQ}{dt} = 0 \quad (A7.1)$$

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

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

where

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

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.

$$V = V_d \sin(\omega t) \quad (A8)$$

where

$V_d$  is the displacement volume [ $m^3$ ] (half of peak to peak)  
 $\omega$  is the fundamental frequency of the drive [ $hr^{-1}$ ].

Solving the differential equation, Eq. A7, leads to a solution of the form,

$$Q = Q_o \sin(\omega t + \theta_o) \quad (A9.1)$$

or,

$$\Delta P = \Delta P_{AC} \sin(\omega t + \theta_o) \quad (A9.2)$$

where

$\Delta P_{AC}$  is the amplitude of the (AC pressure) response [Pa],  
 $Q_o = L_o \Delta P_{AC}$  is the amplitude of the (air flow) response [ $m^3/hr$ ]  
 $\theta_o$  is the phase shift between the response and the drive.

Solving the differential equation also leads to expressions for  $Q_o$  and  $\theta_o$  in terms of the drive, time constant, and fundamental frequency:

$$\tan \theta_o = \frac{1}{\omega k_o} \quad (A10.1)$$

$$Q_o = -\omega V_d \sin \theta_o \quad (A10.2)$$

$$= \frac{\omega V_d}{\sqrt{1 + \omega^2 k_o^2}} \quad (A10.3)$$

$$\Delta P_{AC} = \frac{\omega V_d / L_o}{\sqrt{1 + \omega^2 k_o^2}} \quad (A10.4)$$

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

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.

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

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

$Q_o$  is the size of the air flow through the structure in response to a sinusoidal drive. Assuming 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 that flows out during a half cycle and divide that by the cycle time to find the induced infiltration.

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

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

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

where

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

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

### Non-Linear Leakage

Our linear leakage model does not account for any non-linearities (i.e. if the leakage is not strictly proportional to the applied pressure our model, as it stands, fails). Therefore, we must relax the assumption of linearity and allow for the possibility of non-linearities in the model. (This is motivated by the fact that turbulent flow will be proportional to the square root of the applied pressure.)

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 that depends on pressure.

$$Q(\Delta P) = L(\Delta P) \Delta P \quad (A13)$$

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.

$$Q(\Delta P) = L(\Delta P) (1 + \alpha \Delta P) \Delta P \quad (\text{A14})$$

where

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

The presence of this asymmetric term has the interesting feature of changing the average internal DC pressure when there is a sinusoidal volume change in the structure. This DC offset arises because the leakage is larger on pressurization 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, EA5, over one cycle yields,

$$- \langle Q(\Delta P) \rangle = \left\langle \frac{dV}{dt} \right\rangle + \frac{V_0}{\gamma P_a} \left\langle \frac{dP}{dt} \right\rangle \quad (\text{A15.1})$$

$$= 0 \quad (\text{A15.2})$$

$$= \langle L(\Delta P) \Delta P (1 + \alpha \Delta P) \rangle \quad (\text{A15.3})$$

The brackets,  $\langle \dots \rangle$  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.

$$\langle L(\Delta P) \rangle \approx L \left[ \sqrt{\langle \Delta P^2 \rangle} \right] \quad (\text{A16})$$

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,

$$\Delta P_{DC} = \sqrt{\langle \Delta P^2 \rangle} \quad (\text{A17})$$

where

$\Delta P_{DC}$  is the equivalent applied pressure. [Pa]  
 $\langle \Delta P^2 \rangle$  is the mean square pressure [Pa<sup>2</sup>].

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

$$L(\Delta P_{DC}) (\langle \Delta P \rangle + \alpha \langle \Delta P^2 \rangle) = 0 \quad (A18)$$

Since the leakage function is never zero it can be divided out and the equation can be solved for  $\alpha$ :

$$\alpha = - \frac{\langle \Delta P \rangle}{\langle \Delta P^2 \rangle} \quad (A19)$$

where

$\langle \Delta P \rangle$  is the average DC pressure offset [Pa.]

This last expression allows the calculation of the asymmetry constant,  $\alpha$ , from the DC pressure offset,  $\langle \Delta P \rangle$ , and the mean square pressure,  $\langle \Delta P^2 \rangle$ . 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 in terms of harmonics of the fundamental frequency,  $w$ .

$$\Delta P = \langle \Delta P \rangle + \Delta P_{AC} \sin(wt + \theta) + \Delta P_2 \sin(2wt + \phi_2) \dots \quad (A20)$$

where

$\langle \Delta P \rangle$  is the average pressure difference [Pa],  
 $\Delta P_{AC}$  is the component at the fundamental frequency [Pa],  
 $\theta$  is the phase shift between the drive and response and  
 $\Delta P_n$  is the component at the nth harmonic.  
 $\phi_n$  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.

$$\langle \Delta P^2 \rangle = \langle \Delta P \rangle^2 + 1/2 \Delta P_{AC}^2 + \Sigma(\text{higher harmonics})^2 \quad (A21.1)$$

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

$$\langle \Delta P^2 \rangle \approx 1/2 \Delta P_{AC}^2 (1 + 1/2 \alpha^2 \Delta P_{AC}^2) \quad (A21.2)$$

where we have used the definition of  $\alpha$  recursively.

Therefore,

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

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 cannot solve the equation exactly, nor could we do so if we 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 using a fourier analysis at that frequency. The analysis is the equivalent of multiplying our continuity equation by  $\sin(\omega t)$  and  $\cos(\omega t)$  alternately and then averaging over one cycle.

$$- \langle Q(\Delta P) \sin \omega t \rangle = \langle \frac{dV}{dt} \sin \omega t \rangle + \frac{V_o}{Y P_a} \langle \frac{d(\Delta P)}{dt} \sin \omega t \rangle \quad (A23.1)$$

$$= \omega V_d \langle \cos \omega t \sin \omega t \rangle + \frac{V_o}{Y P_a} \omega \Delta P_{AC} \langle \cos(\omega t + \theta) \sin \omega t \rangle \quad (A23.2)$$

$$= - \omega \frac{V_o}{Y P_a} \Delta P_{AC} \frac{\sin \theta}{2} \quad (A23.3)$$

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

$$- \langle Q(\Delta P) \sin \omega t \rangle = L(\Delta P_{DC}) (\langle \Delta P \sin \omega t \rangle + \alpha \langle \Delta P \sin \omega t \rangle) \quad (A24.1)$$

$$= L(\Delta P_{DC}) \Delta P_{AC} (\langle \sin \omega t \sin(\omega t + \theta) \rangle + 2 \alpha \langle \Delta P \rangle \langle \sin \omega t \sin(\omega t + \theta) \rangle) \quad (A24.2)$$

$$= L(\Delta P_{DC}) \Delta P_{AC} (1/2 + \alpha \langle \Delta P \rangle) \cos \theta \quad (A24.3)$$

Using Eq. A19,

$$- \langle Q(\Delta P) \sin \omega t \rangle = 1/2 L(\Delta P_{DC}) \Delta P_{AC} \cos \theta (1 - 2 \alpha^2 \langle \Delta P^2 \rangle) \quad (A24.4)$$

We can combine the two expressions for  $Q$  to get,

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

$$\tan \theta = - \frac{L(\Delta P_{DC}) Y P_a}{\omega V_o} (1 - 2 \alpha^2 \langle \Delta P^2 \rangle) \quad (A25.2)$$

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

$$L(\Delta P_{DC}) = - \frac{\omega}{1 - 2 \alpha^2 \langle \Delta P^2 \rangle} \left[ \frac{V_o}{Y P_a} \right] \tan \theta \quad (A26)$$

In a manner similar to the one above, the averaging can be done with  $\cos(\omega t)$  instead of  $\sin(\omega t)$ .

$$\langle Q(\Delta P)\cos\omega t \rangle = \langle \frac{dV}{dt}\cos\omega t \rangle + \frac{V_o}{Y_{P_a}} \langle \frac{d(\Delta P)}{dt}\cos\omega t \rangle \quad (A27.1)$$

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

$$\langle Q(\Delta P)\cos\omega t \rangle = L(\Delta P_{DC}) (\langle \Delta P\cos\omega t \rangle + \alpha \langle \Delta P\cos\omega t \rangle) \quad (A27.3)$$

$$= L(\Delta P_{DC}) \frac{1}{2} \Delta P_{AC}\sin\theta (1 - 2\alpha^2 \langle \Delta P^2 \rangle) \quad (A27.4)$$

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

$$\cos\theta = -\frac{\Delta P_{AC} V_o}{Y_{P_a} V_d} \quad (A28)$$

This is the same expression for the phase angle as the one from the linear case, however, the measured pressure response for a given frequency and displacement ( $\Delta P_{AC}$ ) will have a different value than it would have had in the linear case; therefore, the value of the phase angle will also be different. We can now eliminate the phase angle from Eq. A27 to yield an expression for the leakage.

$$L(\Delta P_{DC}) = \frac{\omega}{(1 - \alpha^2 \Delta P_{AC}^2)} \sqrt{\left[\frac{V_d}{\Delta P_{AC}}\right]^2 - \left[\frac{V_o}{Y_{P_a}}\right]^2} \quad (A29.1)$$

$$L(\Delta P_{DC}) = \frac{\omega V_d \Delta P_{AC}}{(1 - \alpha^2 \Delta P_{AC}^2)} \sin\theta \quad (A29.2)$$

With the exception of the asymmetry term Eq. A29 looks very similar to Eq. A10; however, the interpretation of the two equations is slightly different. EA10 is an estimate of leakage constant, which should be the same at any applied pressure. EA29 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 from a sinusoidal drive.

### 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 by an amount that is significant compared to the displacement volume ( $\approx .2 \text{ m}^3$ ). Because such flexing will decrease the pressure response making the leakage appear to be larger than it actually is, it is necessary to be able to account for its effects.

The resonant frequency of most structures is approximately 15 Hz.<sup>8</sup> 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.

"Linear flexing" is the term applied to the stretching or expanding of the envelope under an applied pressure and generally takes place in walls and windows. The change in volume of the structure is treated as being proportional to the applied pressure. Therefore, we define the flexing constant as the constant of proportionality between the applied pressure and volume change:

$$\delta V = \lambda \Delta P \quad (A30)$$

where

$\delta V$  is the volume [ $m^3$ ] change due to the flexing and

$\lambda$  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.

$$V' = V + \delta V \quad (A31.1)$$

$$= V_d \sin \omega t + \lambda \Delta P \quad (A31.2)$$

where

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

If we now substitute this in the continuity equation,

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

which can be rewritten as,

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

The effect of the flexing has been to increase the capacity term, ( $V_o/\gamma P_a$ ) by adding the constant flexing term,  $\lambda$ . Since we are working far below the frequency at which the capacity term is important, we will ignore the capacity term for the purpose of calculating the correction term. We define the apparent leakage as leakage that would occur if the capacity term were ineligible (i.e. the apparent leakage is the ratio of the drive term to the pressure response),

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

where

$L_a$  is the apparent leakage [ $m^3/hr-Pa$ ]

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  $-90^\circ$ . The actual leakage takes into account the effect of the flexing and the compressibility of air.

$$L(\Delta P_{DC}) = w \sqrt{\left[ \frac{v_d}{\Delta P_{AC}} \right]^2 - \left[ \lambda + \frac{v_o}{Y P_a} \right]^2} \quad (A34.1)$$

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

Squaring this expression and solving for the apparent leakage puts this equation into a form that demonstrates its dependence on the capacity:

$$L_a^2 = L^2 + w^2 \left[ \lambda + \frac{v_o}{Y P_a} \right]^2 \quad (A35)$$

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 to be constant; however, if we are using the non-linear equations, we expect the leakage to be slowly decreasing with 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. 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  $\lambda$ . 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. A5). 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,

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

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  $-90^\circ$  at low frequencies to  $-180^\circ$  at high frequencies. In the derivations elsewhere in this appendix we have derived the exact expression for the phase angle. Therefore by measuring infiltration concurrently with the AC pressurization an independently determined. This phase angle calculation is based on the assumptions of perfect mixing and dispersal of the air that flows in and out through the envelope, however, these assumptions are quite likely to be violated in a real experiment.

## SUMMARY

There are several assumptions that have gone into this derivation. 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 from 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 measure independently. 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.

$\alpha$  The asymmetry constant.  $\alpha$  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.

$\lambda$  The linear flexing parameter.  $\lambda$  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.

The full (non-linear) expression for the leakage function as a function of the frequency, displacement and measured pressure response contains the two experimentally determined parameters, the asymmetry constant ( $\alpha$ ) and the flexing parameter ( $\lambda$ ):

$$L(\Delta P_{DC}) = \frac{w}{(1 - \alpha^2 \Delta P_{AC}^2)} \sqrt{\left[ \frac{v_d}{\Delta P_{AC}} \right]^2 - \left[ \lambda + \frac{v_o}{y p_a} \right]^2} \quad (A37.1)$$

$$\Delta P_{DC} = \Delta P_{AC} \sqrt{\frac{1}{2} (1 + \frac{1}{2} \alpha^2 \Delta P_{AC}^2)} \quad (A37.2)$$

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

## APPENDIX B

### Procedure and Analysis

This appendix described the methods and techniques used in making the AC pressurization measurements. The experiments described below all took place in our research house in Walnut Creek, California, which has a volume of  $230\text{m}^3$  and a floor area of  $100\text{m}^2$ . 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 ( $\approx 1\text{m}^2$ ) 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  $0.3\text{m}^3$ . The flywheel is driven through a gearbox by a variable speed  $3/4$  hp motor, having a frequency range from 2 to 250 rpm.

Pressure Detection: The pressure response of the envelope is measured with a differential pressure sensor whose range is  $\pm 70$  Pa. 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 due to wind 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. noise from wind or unevenness of piston travel are ignored). 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 adjust 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 held 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 are placed 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

Two sets of test runs were used to measure the leakage. 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 and, since the ductwork does not go through the conditioned space, all of the registers as well as the closet containing the furnace were sealed with tape. 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, and 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.<sup>9</sup> Both pressurization and depressurization were measured. Then we did three different AC pressurization runs were then conducted 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  $\alpha$  and  $\lambda$  were calculated separately. To measure the asymmetry parameter,  $\alpha$ , 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 carried out at several representative pressures and the results averaged.

The flexing parameter,  $\lambda$ , becomes dominant at higher frequencies. Because its value is needed to correct the apparent leakage for envelope flexing at low frequencies. Accordingly, we measured the response at frequencies higher than that of any of the runs and fit the data to Eq. A35 to find  $\lambda$ . Data was taken at frequencies from 0.1 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.<sup>10</sup> 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.

## Data Acquisition and Analysis

Only two quantities 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  $V_0$ ,  $P_a$  and  $\gamma$  are known.

The pressure is recorded both on a strip chart recorder and by a microprocessor. The frequency is monitored by the microprocessor which incorporates 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  $1/2$  Pa 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.

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 ( $w > 10$ ) the apparent leakage is dominated by the flexing and the plot becomes linear. From this linear section the value of the flexing parameter,  $\lambda$ , 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	
$\alpha$	.0152±.001	.004±.003	Pa <sup>-1</sup>
$\lambda$	.0032±.001	.0032±.001	m <sup>3</sup> /Pa

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.

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.

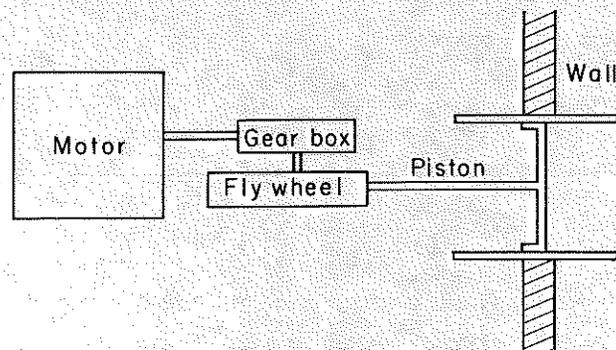
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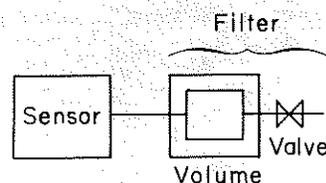
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*Fig. 1a Schematic of the piston motor and flywheel assembly. The piston is driven by a shaft connected to an 18-in. diameter flywheel which is driven through a gear box by a variable speed motor.*



*Fig. 1b Schematic of the pressure sensor and physical filter. The reference end of the differential pressure sensor is connected to a thermally insulated volume that has a high resistance leak in it. This volume and leak combination is an effective low-pass filter with a time constant of roughly 5 min. Thus, the reference end of the pressure sensor is at the average interior pressure.*

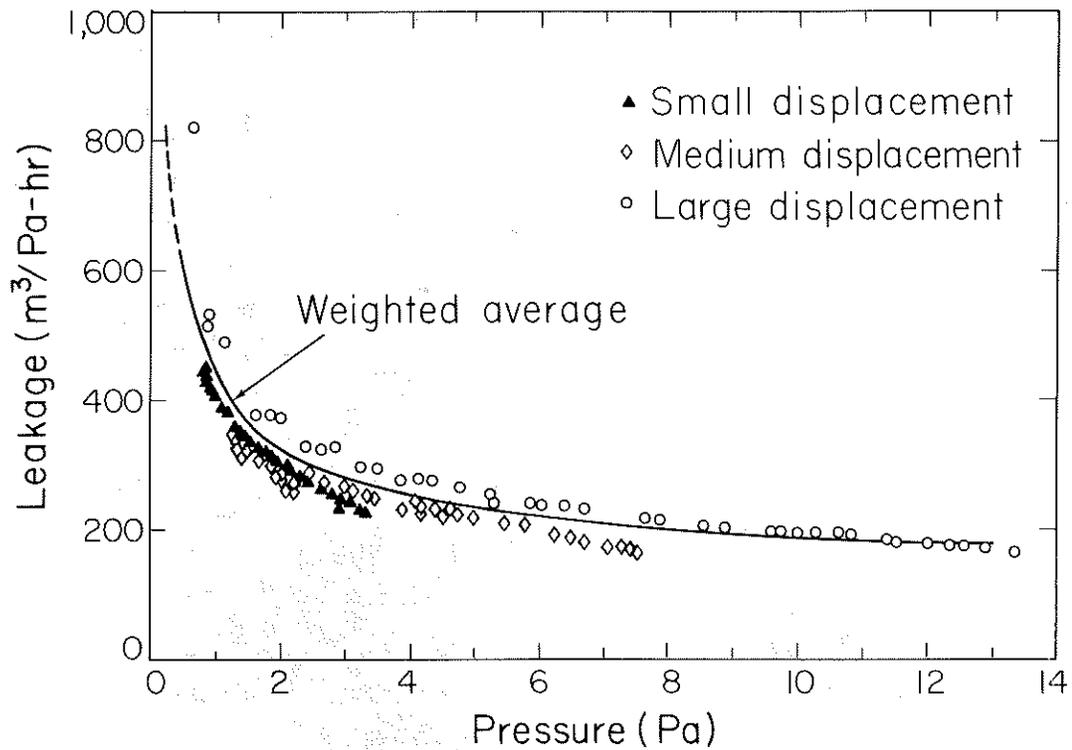


Fig. 2 The leakage function of the structure in the loose configuration is plotted against the applied pressure. Each point represents a minute average reading at a particular frequency and displacement. Points of the same displacement have the same symbol. The curve is the weighted average of all the data points.

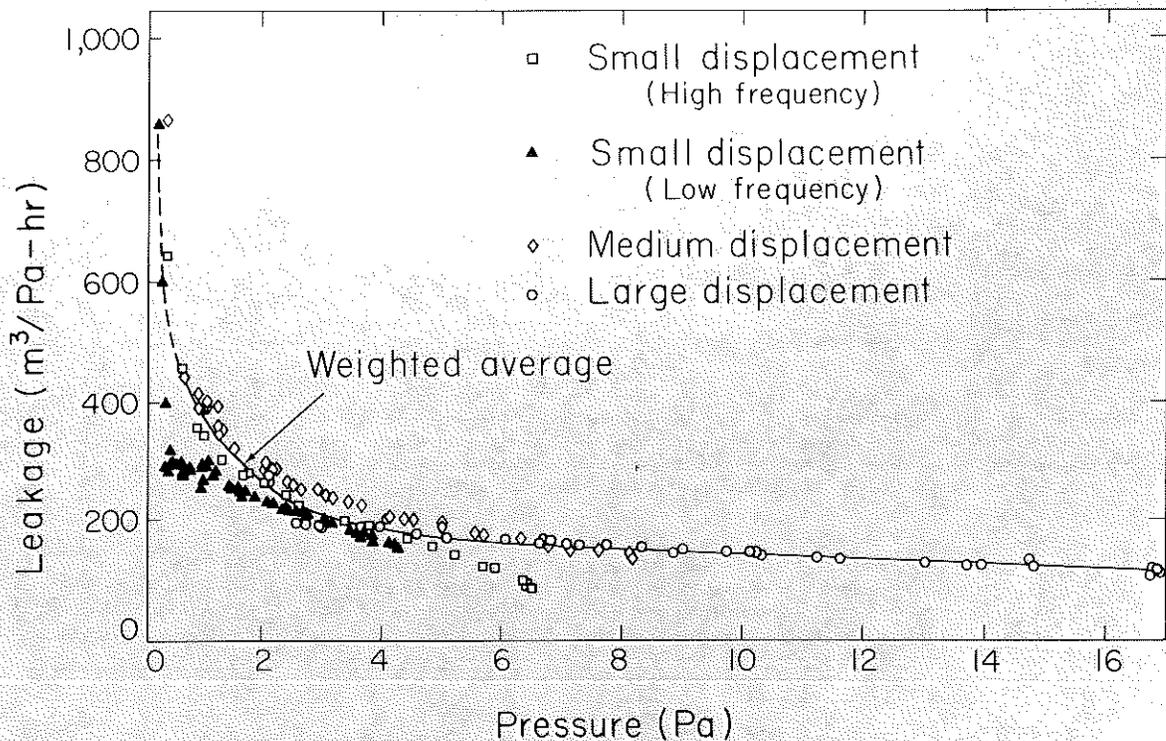


Fig. 3 The leakage function of the structure in the tight configuration is plotted against the applied pressure. Each point represents a minute average reading at a particular frequency and displacement. Points of the same displacement have the same symbol. The curve is the weighted average of all the data points.

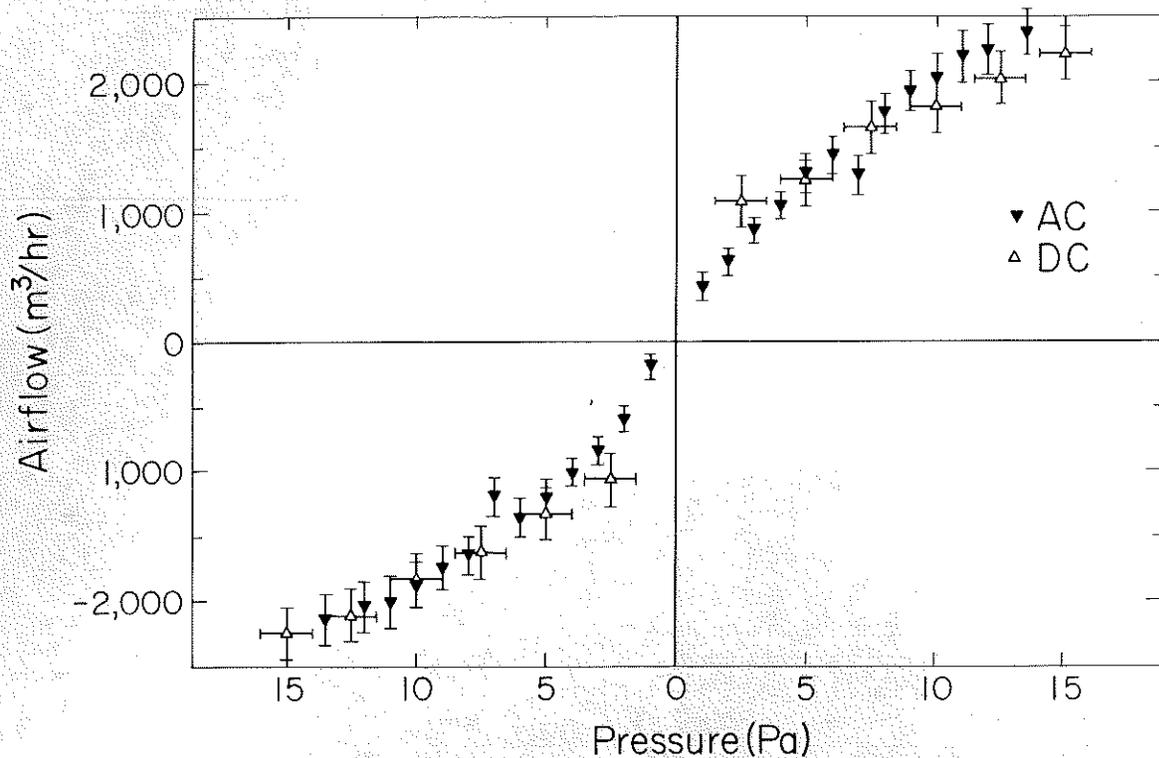


Fig. 4 The air flow through the envelope is graphed vs the applied pressure for the structure in the loose configuration. Both the AC pressurization graph, as derived from the low-pressure leakage function, and the DC pressurization are shown. The error bars are calculated from the measurement errors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

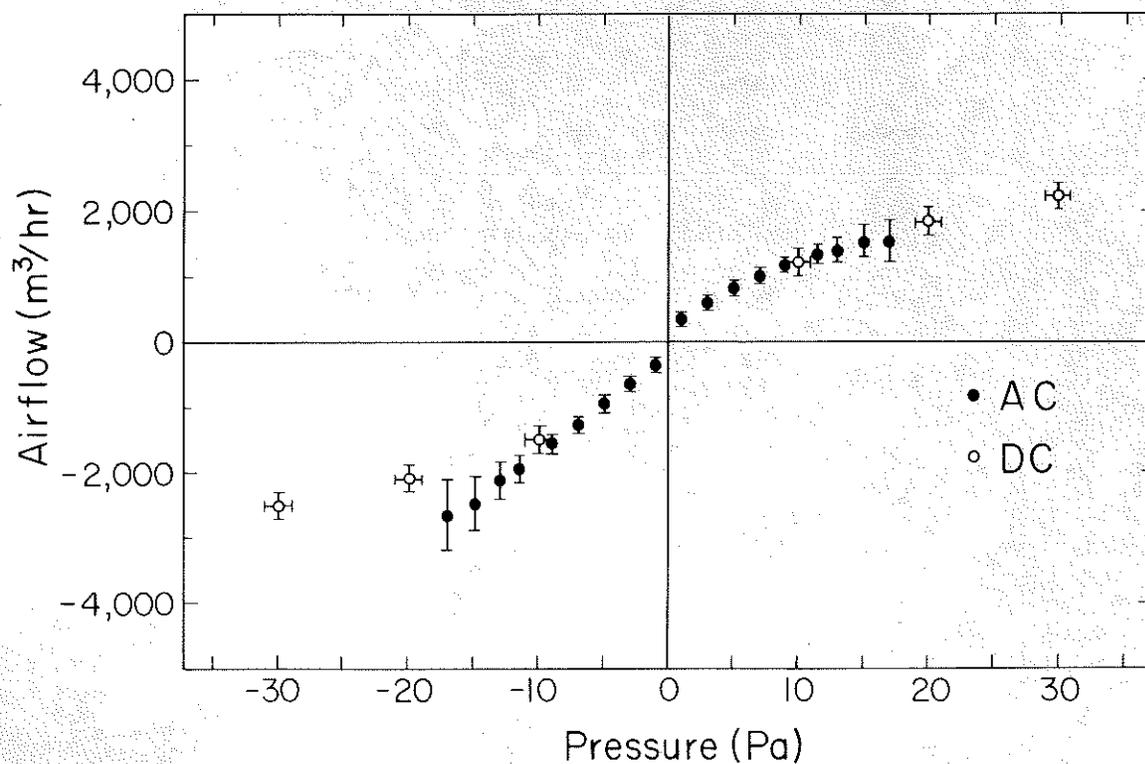


Fig. 5 The air flow through the envelope is graphed vs the applied pressure for the structure in the tight configuration. Both the AC pressurization graph, as derived from the low-pressure leakage function, and the DC pressurization are shown. The error bars are calculated from the measurement errors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

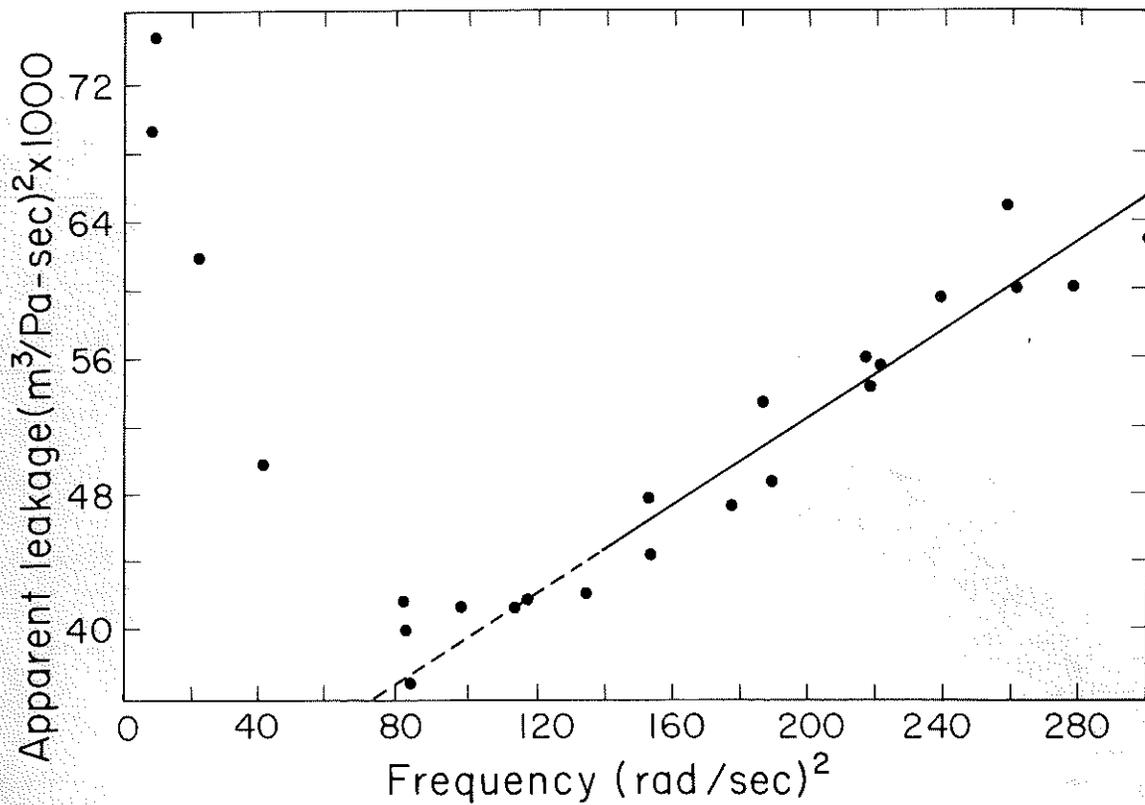


Fig. 6 The apparent leakage squared is plotted against the frequency squared for the smallest displacement. The total capacity can be inferred from the high-frequency slope.

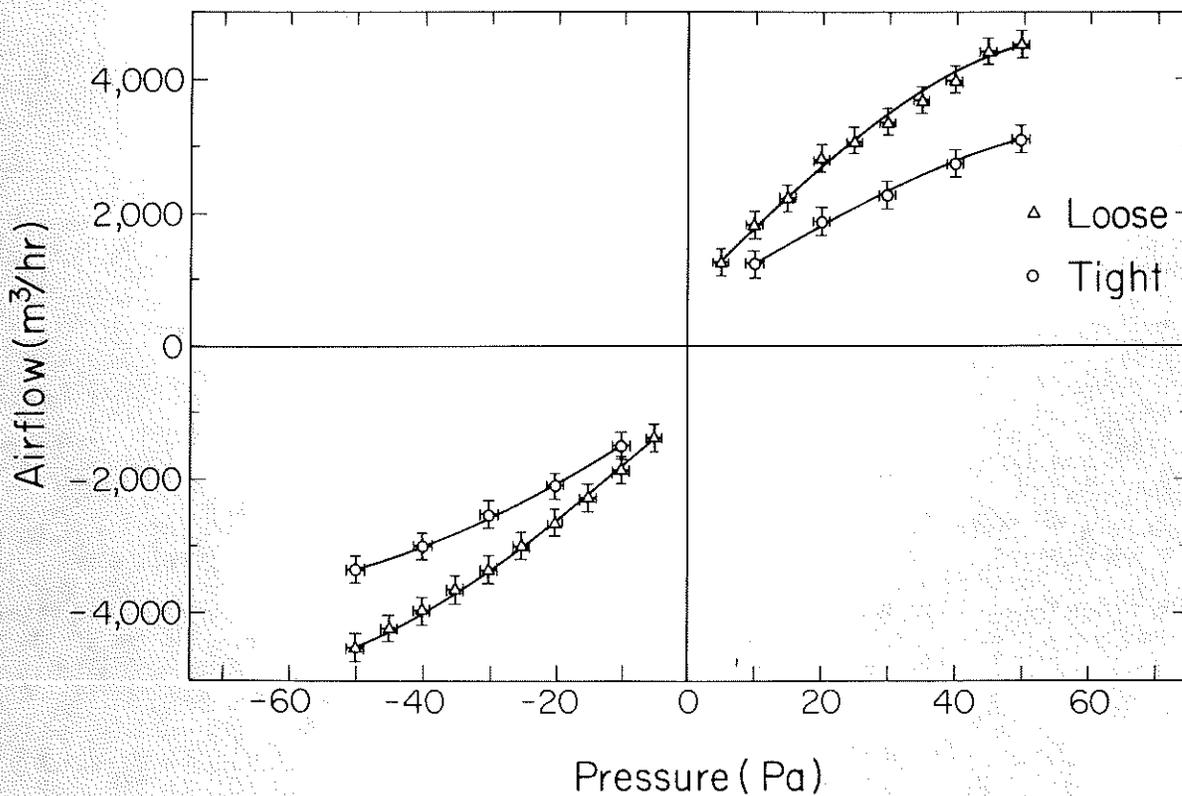


Fig. 7 The DC leakage curves for both the loose and tight configurations. The error bars are derived from the measurement error and equipment calibration errors.