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Authors
Modera, M.P.
Sherman, M.H.

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Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

APPLIED SCIENCE DIVISION

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M.P. Modera and M.H. Sherman

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AC PRESSURIZATION:
A Technique for Measuring Leakage Area in Residential Buildings

Mark P. Modera and Max H. Sherman

Applied Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

March 1986

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ABSTRACT

This report presents a new technique for measuring the leakage area of residential buildings. This technique, called AC pressurization, is designed to overcome most of the shortcomings of fan pressurization, the conventional technique for measuring leakage area. The fan pressurization technique (often performed using a *blower door*) has several known deficiencies: (1) the pressures it exerts on the building envelope are significantly higher than those experienced under natural conditions, thereby requiring extrapolation outside of the measurement range to calculate the leakage area; (2) it cannot make real-time leakage area measurements; and (3) the large volumes of air displaced by the fan can cause inconveniences such as large indoor temperature changes. AC pressurization, which induces sinusoidal pressure differences across the building envelope, can make real-time leakage measurements at low pressures without inducing large flows through the building envelope. The AC pressurization apparatus and analytical technique, as well as the laboratory measurements that determined the specifications for the field device are described herein. Field measurements of leakage area obtained with our prototype AC pressurization device are compared with those obtained by fan pressurization tests of six single family residences.

Keywords: Air Leakage, Air Infiltration, Ventilation, Pressurization

NOMENCLATURE

C	= Leakage (regression) coefficient [m^3/s Pa^n]
c	= (Effective) capacity of internal volume [m^3/Pa]
	(1 m^3 /Pa = 8796 ft^3 /in H_2O)
f_{bp}	= Break-point frequency [Hz]
L	= Leakage area [m^2] (1 m^2 = 10.76 ft^2)
n	= Leakage flow exponent [dimensionless]
P	= Internal pressure [Pa] (1 Pa = 0.004 in. H_2o)
ΔP	= Inside-outside pressure difference [Pa]
P_r	= Reference pressure [4 Pa]
$\dot{P}$	= Time rate of change of internal pressure [Pa/s]
P_{rms}	= The cycle-averaged root mean square pressure [Pa]
P_{rmn}	= The cycle-averaged exponent-weighted pressure [Pa]
ρ	= Air density [1.2 kg/m^3] (0.075 lb/ft^3)
Q	= Infiltration [m^3/s] (1 m^3/sec = 35.3 ft^3/sec)
V_d	= Displacement of the drive [m^3] (1 m^3 = 35.3 ft^3)
$\dot{V}_d$	= Time rate of change of drive displacement [m^3/s]
$< \cdots >$	= Indicates a cycle average of the enclosed quantity

INTRODUCTION

For the past several years, the airtightness of residential buildings has been explored for energy conservation purposes. Of the many air tightness surveys that have been made,[1-3] the largest single review to date - one that included over 700 independent measurements - was presented at a recent ASTM symposium on "Measured Air Leakage Performance of Buildings"."[4]

The standard way to measure the airtightness of a building is the fan pressurization technique. Two standards, one Canadian[5] and one American[6] (which is currently under revision), specify how this test is to be made. A fan pressurization test measures the relationship between steady-state pressure differences across a building envelope and the resulting flows through the envelope. The most common device used for making these tests, a *blower door*, consists of a variable-speed fan mounted in the building doorway, a device to measure the flow rate through the fan, and a differential pressure gauge for measuring the pressure drop across the building envelope. Although it is the air leakage at low (weather-induced) pressures (-5 Pa $< \Delta P <$ 5 Pa) that is needed to model infiltration,[7-9] the pressure differences induced by fan pressurization typically range between ± 10 to 50 Pa. The tests are made at higher pressures because weather-induced pressures interfere with measurements (and thus cause large measurement uncertainties) at low pressures. This lack of precision at low pressures is one of the major disadvantages of the fan pressurization technique.

This paper describes a new technique that can measure building air tightness directly at small pressure differences. This technique, called AC pressurization, differs from fan pressurization (DC pressurization) in that it creates a periodic pressure difference across the building envelope that can be distinguished from naturally occurring pressure fluctuations. The airtightness of a building affects the pressure change in that building due to a periodic volume change, including both the amplitude and phase of the pressure change. Assuming that there are no leaks at all in the building envelope and that the structure is rigid*, the change in pressure can be precisely determined from the structure's volume and the piston's displacement. Therefore, any deviation from this predicted pressure can be attributed to leakage through the envelope. The measured volume change and pressure response can be used to calculate the airflow through the envelope.

* Flexible structures can be treated as an additional capacity as long as they are far from any resonances. This subject is not within the scope of this report and will be discussed in a future publication.

The concept of using a periodic volume change to measure the airtightness of a building is not unique to this report. A previous report[10] describes the forerunner of the AC pressurization technique, a device consisting of a large piston and guide/sleeve assembly that was installed in place of the existing exterior door. A motor/flywheel crank mechanism moved the piston back and forth within the guide, pumping air in and out of the building. Independent work that attempted to use alternating pressures to measure air tightness was done at Syracuse University.[11] The Syracuse University efforts used electrical engineering circuit analysis to extract the airtightness. However, in both of the previous efforts, the initial work was not extended to the point of making a feasible, accurate field measurement tool.

GENERAL DESCRIPTION OF AC PRESSURIZATION EQUIPMENT

The AC pressurization apparatus includes components that perform four basic functions: (1) volume drive, (2) displacement monitoring, (3) pressure measurement, and (4) analysis/control. Several options for accomplishing each of these functions have been investigated. Depending on the application, several combinations of these options can be used to build a working device.

The purpose of the *drive component* is to provide a sinusoidal change in the internal volume of the building at a known or specified amplitude and frequency. Generally, the device should be able to operate over a range of frequencies between 0.01 - 10 Hz and displace approximately 1 - 200 liters. Several options for the drive component are:

1. A *sealed back-volume* drive component, in which a piston is driven by a variable-speed electric motor to compress air in a sealed volume. This option does not require piercing of the building envelope;
2. An *external bellows* drive component, in which a piston is installed in the building envelope (usually with a door or window insert) via a flexible, but airtight bellows. (Our present field prototype uses a scotch yoke mechanism to turn the circular motion of a variable-speed motor into true sinusoidal motion at the piston face.);
3. A *condensing fluids* drive component is similar to the sealed back volume option, the difference being that the back pressure is minimized by filling the back volume with a mixture of fluids that have boiling points near room temperature. This option is designed to combine the advantages of the previous options, not requiring piercing of the envelope and having low power requirements because of low back pressures.

The *displacement-monitoring* component provides the instantaneous value of the piston velocity, which is one of the two inputs used to compute airtightness. The type of displacement monitoring necessary depends both on the drive component and the means used to drive it. For example, if a stepper-motor is used in any of the drive components, a displacement monitor is redundant, as the velocity can be inferred directly from the motor drive. Some displacement monitoring options are:

1. A *back-volume pressure monitor*, which is only suitable for the sealed back-volume drive component. This option uses a pressure transducer to calculate the displacement from the back pressure, which is then differentiated to obtain the velocity;
2. A *velocity sensor*, which provides the piston velocity directly;
3. A *shaft encoder*, which uses a sensor (usually optical) to read the position of a rotating shaft. The velocity of the piston is computed from the derivative of instantaneous shaft position.

The *pressure measurement* component measures the instantaneous pressure response of the building to the volume changes. It is required only to measure pressure signals at the drive frequency and its harmonics; other frequencies can be filtered out or eliminated with no loss of accuracy. The following three options, each of which has a different accuracy and cost implication, have been found acceptable. Listed in order of decreasing cost and accuracy, they are:

1. A *low-frequency microphone*, a high-accuracy, AC-coupled condenser microphone;
2. An *inductively coupled pressure transducer*, a commercial-grade low-pressure differential pressure transducer connected to a physical filter;
3. A *solid-state pressure transducer*, a piezo-resistive element mounted on an IC chip and connected to a physical filter.

The *analysis/control* component uses the velocity and pressure signals to calculate and display the effective leakage area. If an automatic-operation device is desired, this component will control the volume drive to attain a specified pressure signal. Several options for this component are:

1. The *passive digital analysis* option, in which a general purpose microcomputer is used to analyze the data;
2. The *active digital analysis* option, which uses the same hardware as the passive option, but controls the speed of the motor to maintain a specified pressure signal;

3. *Analogue analysis*, which can be either active or passive; it replaces the microprocessor with analog math processing and direct display, thereby eliminating the need for ADCs, DACs and general-purpose software.

THEORETICAL DERIVATION

Both AC pressurization and DC pressurization are based on certain assumptions about the relationship between the air flow through the building envelope and the pressure difference across the envelope. This section presents the major assumptions and short mathematical derivations, first for the standard fan pressurization technique (i.e., DC pressurization) and then for the AC pressurization technique.

DC Pressurization

The term DC pressurization comes from electrical engineering terminology and implies that we use direct current to measure building airtightness (or flow resistance). DC pressurization uses direct measurements of air flow as a function of pressure difference to determine the flow characteristics of leaks in a building envelope:

$$Q = Q(\Delta P) \tag{1}$$

In addition to the work already sited (References 4, 6, 8) and our own work,[12] earlier research[13,14] had determined empirically that the simplest mathematical description of the relationship between the pressure difference and the airflow through leaks is a power law, of the form:

$$Q = C \ \Delta P^{n} \tag{2}$$

Because of the exponentiation in the previous expression, the sign of the pressure difference must be taken into account:

$$Q = C \left| \Delta P \right|^{n} sign(\Delta P) \tag{3}$$

With this expression, the measured data can be fit using standard linear regression methods[15] to find the parameters C and n. The regression could be performed on the entire data set to find a single C and n, although separate regressions are usually performed for positive and negative pressure differences because of possible asymmetric leakage.

It is often desirable to convert the leakage (regression parameter) information into an *effective leakage area*, L.[16-18] The effective leakage area is determined by assuming that the flow at a particular reference pressure is similar to perfect orifice flow (i.e., a flow exponent of 0.5):

$$Q(P_r) = L \sqrt{\frac{2P_r}{\rho}} \tag{4}$$

The regression parameters (C and n) and the effective leakage area (L) are related as follows:

$$L = C \sqrt{\frac{\rho}{2}}\, P_r^{\,(n-0.5)} \tag{5}$$

Combining this definition with our power law expression (Equation 2.2), the flow can be expressed as a function of the leakage area (L) and the flow exponent (n):

$$Q = L \sqrt{\frac{2P_r}{\rho}} \left| \frac{\Delta P}{P_r} \right|^n sign\,(\Delta P) \tag{6}$$

AC Pressurization

The pressure-flow relationships used for AC pressurization measurements are substantially more complex than those for DC pressurization. Because the drive component provides a periodic volume change, and thereby induces a periodic pressure response, the flow through the envelope must be determined from the continuity equation for a compressible medium:

$$Q + \dot{V}_d + c\,\dot{P} = 0 \tag{7}$$

Theoretically, this expression could be used to calculate the instantaneous infiltration (Q) directly from the measured volume and pressure changes. In practice, this is not possible because of the accuracies required for both the estimation of the capacity, c, and the measurement of the pressure (especially its time derivative). However, because all the terms are periodic (i.e., AC), we can use ***synchronous detection*** [19] (i.e., phase-sensitive detection) to analyze the data and increase the accuracy. Specifically, we lower our precision requirements by extracting the component that is in phase with the pressure signal:

$$< Q\ \Delta P > + < \dot{V}_d\ \Delta P > + c < \dot{P}\ \Delta P > = 0 \tag{8}$$

Because the pressure signal is periodic and the outside pressure is independent of our drive signal, we can make a quick simplification:

$$< \dot{P}\ \Delta P > = 0, \tag{9}$$

which leads to the following expression:

$$< Q\ \Delta P > = - < \dot{V}_d\ \Delta P > \tag{10}$$

If we insert our previous definition of air flow in terms of effective leakage area, we get the following:

$$L \sqrt{\frac{2P_r}{\rho}} < \left| \frac{\Delta P}{P_r} \right|^n sign(\Delta P)\ \Delta P > = - < \dot{V}_d\ \Delta P > \tag{11}$$

Simplifying and solving for the leakage area yields the following:

$$L = - \sqrt{\frac{\rho}{2P_r}} \frac{< \dot{V}_d \frac{\Delta P}{P_r} >}{< \left| \frac{\Delta P}{P_r} \right|^{n+1} >} \tag{12}$$

This is the basic equation of AC pressurization. It is used to determine the leakage area directly from the measured piston velocity and pressure response.

Break-point Frequency

The break-point frequency is a standard concept in electrical engineering analysis of AC circuits.[20] For an RC circuit, it is the frequency at which the asymptotes of the resistance-dominated regime (low-frequency) and the capacitance-dominated regime (high-frequency) intersect. When applied to AC volume changes in a building (see Reference 11), the break-point frequency is the frequency at which the pressure-response asymptotes of the leakage-dominated regime (low-frequency) and the compression-dominated regime (high-frequency) intersect. These asymptotes are determined by solving Equation 7 at its low-frequency and high-frequency limits. The break-point frequency can be visualized in a plot of the pressure response amplitude versus volume drive frequency. The typical response curve in Figure 1 shows the break-point frequency qualitatively. It is is effectively a separation between the two regions, and can be expressed as:

$$f_{bp} = \frac{L \sqrt{\frac{2P_r}{\rho}}}{c^n\ V_D^{1-n}\ P_r^n} \tag{13}$$

The break-point frequency for most single-family residences is between 1 and 2 Hz; but for large tight houses, it can be as low as 0.2 Hz, and for small leaky houses, it can be as high as 4 Hz. In the sections that follow, we will use the concept of break-point frequency to determine the optimal sizing and design of AC pressurization prototypes.

APPARATUS DESIGN

Laboratory experiments, in combination with careful analysis of the governing equations, established important design constraints for AC pressurization field measurement devices and resolved several important issues concerning the limitations of the AC pressurization technique.

Design Constraints

The size constraints on the volume drive stem directly from the expression used to determine the leakage area (Equation 12). Because the analysis does not determine the flow exponent of the leaks, an estimated value of the flow exponent has to be used in the denominator of Equation 12. The accuracy of the measured leakage area will thus depend on the accuracy of the flow exponent estimation. This estimation problem can be avoided if the denominator in Equation 12 is equal to unity. This can be accomplished by running the volume drive to make the (n+1) root mean pressure equal to the reference pressure. Specifically,

$$P_{rmn} = P_r \tag{14}$$

where:

$$P_{rmn} = \left(< \left| \Delta P \right|^{n+1} > \right)^{\frac{1}{n+1}} \tag{15}$$

This (n+1) root mean pressure can be related to the rms pressure (a more easily measured quantity), as the relationship between these two pressures has only a weak dependence on the flow exponent. From a large data set of measured flow exponents (see Reference 4), we have an empirically determined mean value for the flow exponent of 0.65 with a standard deviation of 0.09, which allows us to express the relationship as:

$$P_{rmn} = 0.97(\pm 0.01)\, P_{rms} \tag{16}$$

Thus, the measured rms pressure can be used to minimize the impact of the exponent on the analysis by adjusting the volume drive so that:

$$P_{rms} = 1.03\, P_r \tag{17}$$

If we assume that the exponent-weighted pressure is exactly equal to the reference pressure, the denominator of the basic AC pressurization equation becomes unity and we can express the leakage area as:

$$L = - \sqrt{\frac{\rho}{2P_r}}\; \frac{< \dot{V}_d \; \Delta P >}{P_r} \tag{18}$$

Thus, actively controlling the drive component to keep the pressure at a specified level can simplify the analysis.

Given that we have constrained the size of the pressure signal, this translates into a constraint on the displacement of the drive component. It can be shown from Equation 7 that the maximum sinusoidal pressure in a building is directly proportional to the displacement of the drive component and the capacity of the building. The total capacity of the building can be determined from the volume of the building and the capacity associated with the flexing of the envelope. Laboratory tests in two buildings provided an approximate relationship between the building capacity due to flexing and that represented by the volume. These tests, performed with an early prototype (see Figure 2), indicated that the flexing capacity is approximately one quarter the size of the volume capacity. Thus, by choosing a maximum size for the buildings to be tested, we can establish a lower limit for the drive-component displacement.

Design constraints on operating frequency are the result of several effects: 1) The size of the volume drive determines the frequency at which the rms pressure will be equal to the reference pressure, 2) Precision limitations on the pressure measurements dictate that the tests should be performed below the break-point frequency, as the signal-to-noise ratio drops off near the break-point frequency, and 3) Resonance effects tend to occur near the break-point frequency when there are large leaks in the building (see Reference 11). These effects indicate that the operating frequency should be as low as possible. On the other hand, limitations on the physical size of the device and the time required to make a test encourage the use of higher operating frequencies. The solution then, is to select a drive amplitude that allows the drive frequency to be in the range immediately below the break-point frequency.

Laboratory tests also established that resonant vibrations of the building envelope do not represent a significant problem. Resonant frequency calculations based on material properties of typical building shells, as well as building response measurements with a spectral analyzer, showed that the resonant frequencies are much higher than the frequency range established by the signal-to-noise ratio and large-leak resonance constraints.

Field Test Prototype

A field test prototype was built in accordance with the design constraints described above. The drive-component displacement, 50 liters, allows the device to operate in the 0.1-4.0 Hz frequency range (sufficiently below the breakpoint frequency of most houses) and allows the device to be small enough for easy installation in a doorway. The drive component, which uses a scotch yoke mechanism to drive a piston-bellows arrangement, is shown in Figure 3.

The first AC pressurization field prototype consists of a 60-cm round piston-bellows drive component, a low-frequency microphone, signal-conditioning filters, and a computer that computes the leakage area as well as intermediate experimental data. The piston-bellows assembly, as well as the DC motor and scotch yoke mechanism that drives it, is mounted in a doorway in much the same fashion as a standard blower door. The stroke of the scotch yoke mechanism can be varied between 4 cm and 18 cm, thus allowing the volume drive to be varied between 10 and 50 liters. The frequency of the device is controlled by adjusting the speed of the DC motor, and can be varied between 0.1 and 4 Hz. The speed of the piston is monitored with a wire-cable velocity transducer, and the pressure response is monitored with a low-frequency microphone that is sensitive to 0.01 Pa.

FIELD TESTS

We performed AC pressurization tests in six houses in the San Francisco Bay area. The houses, which differ in size, age, and air tightness, were chosen to represent a cross section of the houses whose airtightness is normally tested by DC pressurization. For each of the houses, DC pressurization was used to measure the leakage area and flow exponent, and the AC pressurization prototype (at maximum volume displacement) was used to measure leakage area and pressure response as a function of frequency. The effect of microphone placement was examined in all of the houses, and, in one house, leakage area measurements made with a low-cost piezo-resistive pressure transducer were compared with microphone-based measurements. Brief descriptions of the houses are presented in Table 1.

We see in Table 1 that the volumes of the houses vary by a factor of two, as do the leakage areas. The specific leakage areas, which range between 3 and 10 cm^2/m^2, are typical for the housing stock in California, with the exception of supertight construction, where the specific leakage is close to 1 cm^2/m^2.

A comparison of the leakage areas measured with AC pressurization and those measured with DC pressurization is presented in Table 2.

The comparisons in Table 2 show that measurements obtained by DC pressurization and AC pressurization agree reasonably well, but that AC values are consistently lower (averaging approximately 14%) than DC values. Because neither measurement technique is a primary (or secondary) standard, one cannot determine which technique is correct. The fan pressurization technique, for example, may be systematically high because of errors associated with extrapolating air flows to pressures below the measured range. We also hypothesized that AC pressurization might yield lower values than DC pressurization because of the effect of large leaks. To test this latter

TABLE 1

Descriptions of Test Houses

House	Type	Year Built	Volume [m^3]	Leakage Area* [cm^2]	Specific Leakage Area↓ [cm^2/m^2]
A	1 story	1920	360	1300	9.7
B	2 story	1915	320	1100	8.6
C	2 story	1909	300	940	6.7
D	2 story	1958	410	700	4.3
E	2 story	1912	530	1200	5.9
F	1 story	1979	450	580	3.4

* Based on DC pressurization measurements.
↓ Leakage area divided by floor area.

TABLE 2

Comparison of Leakage Areas from AC and DC Pressurization.

House	Leakage Area (DC Press) [cm^2]	Leakage Area (AC Press) [cm^2]	Difference [%]	Frequency at 4 Pa [Hz]	Break-Pnt Frequency [Hz]
A	1300	990	24	1.11	2.6
B	1100	930	15	1.03	2.4
C	940	910	3	1.04	3.4
D	700	600	14	0.69	1.4
E	1200	1000	17	1.21	1.9
F	580	520	10	0.62	1.0

All tests performed with fireplace damper closed.

hypothesis, two additional experiments were performed in several houses, one by opening the fireplace damper, and the second by opening a window. In the first experiment, in all cases the leakage area measured by AC pressurization did not change when the damper was opened. This finding indicated that AC pressurization was insensitive to this leakage area (approximately 200 cm^2). In the second test, we measured the leakage area of a window (62 cm wide) as it was opened further and further. The result of this test was that the leakage area increased with window opening up to a certain point (6 cm), after which the size of the opening no longer affected the measured leakage area. Both of these effects indicate that leaks over some critical size are treated by AC pressurization as though they were equal to that critical size.

One theory for why AC pressurization did not detect large leaks is that larger and longer leaks require the movement of relatively large masses of air, whose behavior is analogous to inductances in an electric circuit. These leaks, instead of being represented as simple resistances, are more closely approximated by resistances and inductances in series. This combination of circuit elements has a time constant associated with it, which limits the flow frequencies allowed to pass. The result is that certain leaks will not allow the proper amount of flow to pass at the measurement frequencies, thereby causing an underestimation of the leakage area.

An important outcome of our field tests is that they confirmed that, for most houses, our drive-component displacement of 50 litres can provide large enough pressures. It easily provided pressures larger than those required to make P_{rmn} equal to the reference pressure of 4 Pa. In addition, it was able to produce these pressures significantly below the breakpoint frequencies of the houses (i.e., in the region with a high signal-to-noise ratio). In Table 2 we see that the measurement frequency is approximately one half the breakpoint frequency. A sample pressure response spectrum (for house F) is shown in Figure 4. In this figure we see that the leakage area measurements are made on the leakage-dominated part of the response curve.

We also used the field tests to carefully examine the functioning of the pressure measurement component. The first test was to examine the sensitivity of the measured leakage area to the placement of the microphone. In all houses, we found that the location of the microphone did not affect the measured pressure signal, even on the second story of the two-story houses. The second test examined the use of an inexpensive piezo-resistive pressure transducer instead of the low-frequency microphone. These transducers were examined by using them in place of the low-frequency microphone to measure the leakage area in house F. It was found that the pressure transducer measured the same leakage area as the microphone, both under normal conditions and during the large-leak testing.

CONCLUSIONS

Since the introduction of the blower door, the AC pressurization technique represents the first major advance in the technology for measuring whole-house leakage. However, there are several tasks that DC pressurization performs better than AC pressurization. For example, because of the large volume of air displaced by DC pressurization, smoke sticks or infra-red cameras can be used to locate leaks. Although these leak-detection techniques can be used with AC pressurization, the results are less certain because of the lower flow rates. Additionally, DC pressurization permits measurement of large, long leaks such as undampered chimneys or flues. Thus, if a pressurization device is needed principally for these kinds of leaks, DC pressurization would be the better choice. On the other hand, a commercial version of the AC pressurization prototype described in this report would have several important advantages:

1. It operates at the pressures that actually drive infiltration, thus it is inherently more accurate than fan pressurization.

2. The measurement and analysis is done in real time. The leakage area is measured continuously and essentially instantaneously. For house-doctoring, for example, the device can be left running during retrofitting so that the effects of the retrofits can be quantified as they happen.

3. Because the device determines leakage area directly and automatically, little operator training is required and post-test calculations are not necessary.

4. Only small volumes of air are exchanged with the outside, which is especially important in severe climates. (Fan pressurization produces 3-20 air changes per hour, which can cause large indoor temperature changes, rain penetration, and/or flue reversal.)

5. The device potentially need not pierce the building envelope. This offers the advantage of both speed and convenience in setup and execution.

FUTURE WORK

This report has discussed the underlying principles behind AC pressurization as a technique for measuring leakage area in residential buildings and has described a prototype apparatus. That the concept is practical and has advantages over fan pressurization has also been demonstrated. The research needed to enhance its widescale use should focus on understanding the limitations on the size of the leaks that can be measured, the sensitivity of the results to the choice of frequency, and the quantitative effects of weather on the measurements. Similar work should be performed with DC pressurization, which has received little quantitative analysis of weather dependent effects. Finally, although the device used for the field measurements reported here is both portable and effective, further development is necessary before the device can be manufactured commercially.

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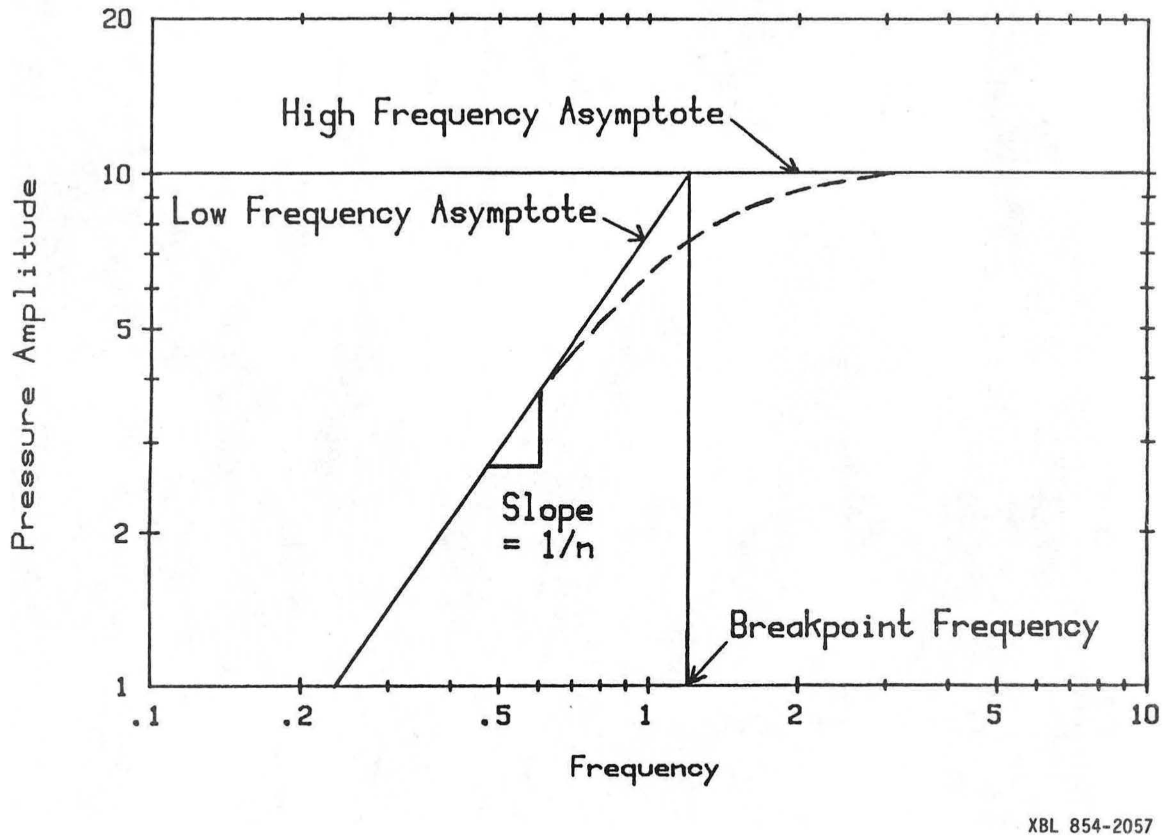

Figure 1. Typical pressure response versus frequency curve showing high-frequency and low-frequency asymptotes and break-point frequency.

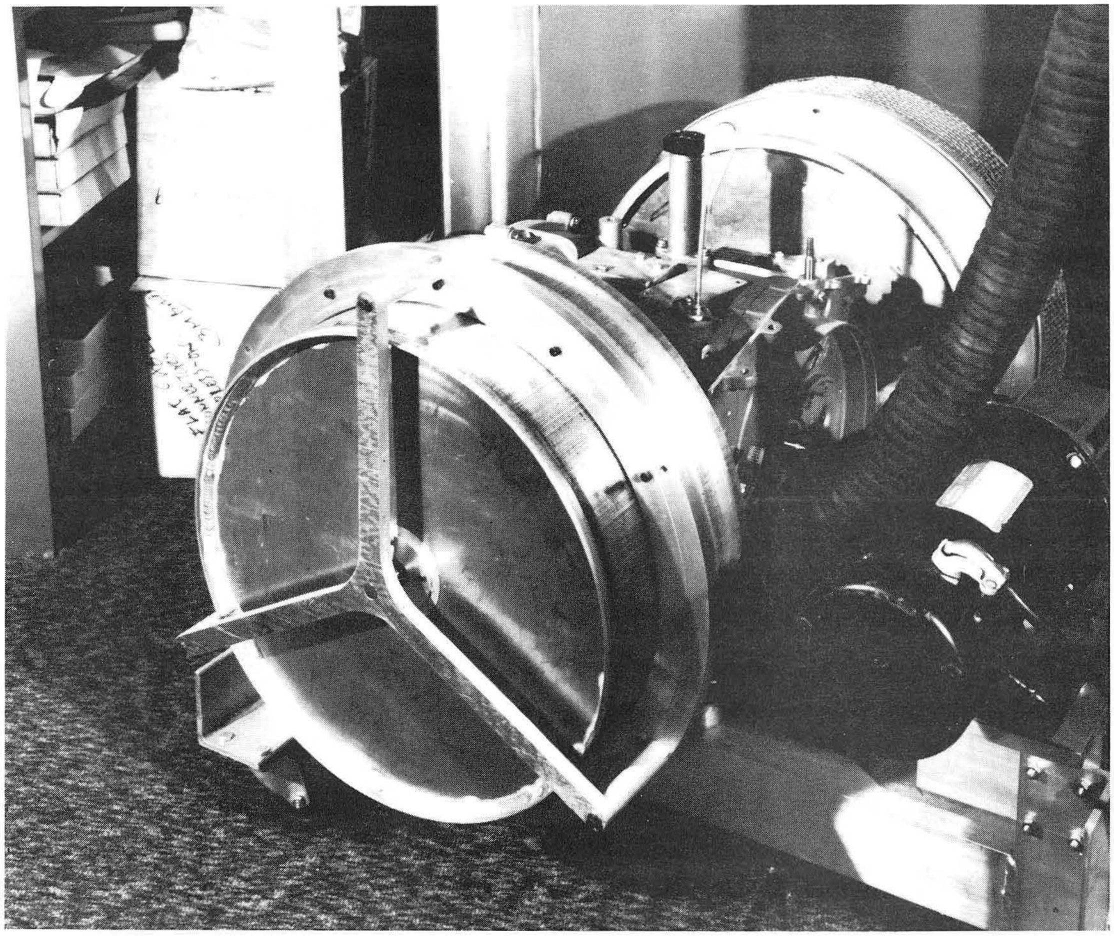

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Figure 2. Sealed back-volume AC pressurization prototype used for laboratory tests.

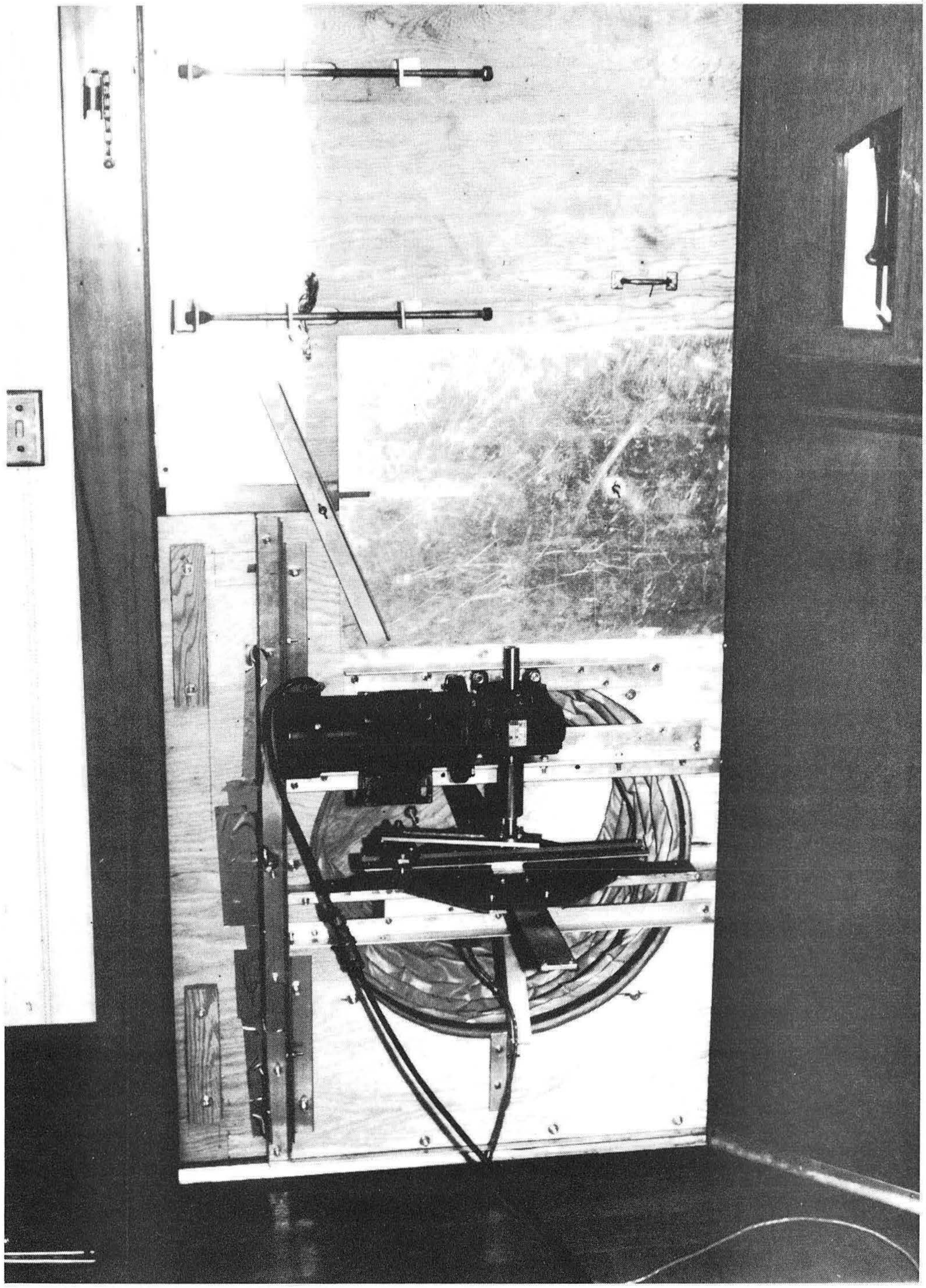

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Figure 3. Piston-bellows AC pressurization prototype used for field tests.

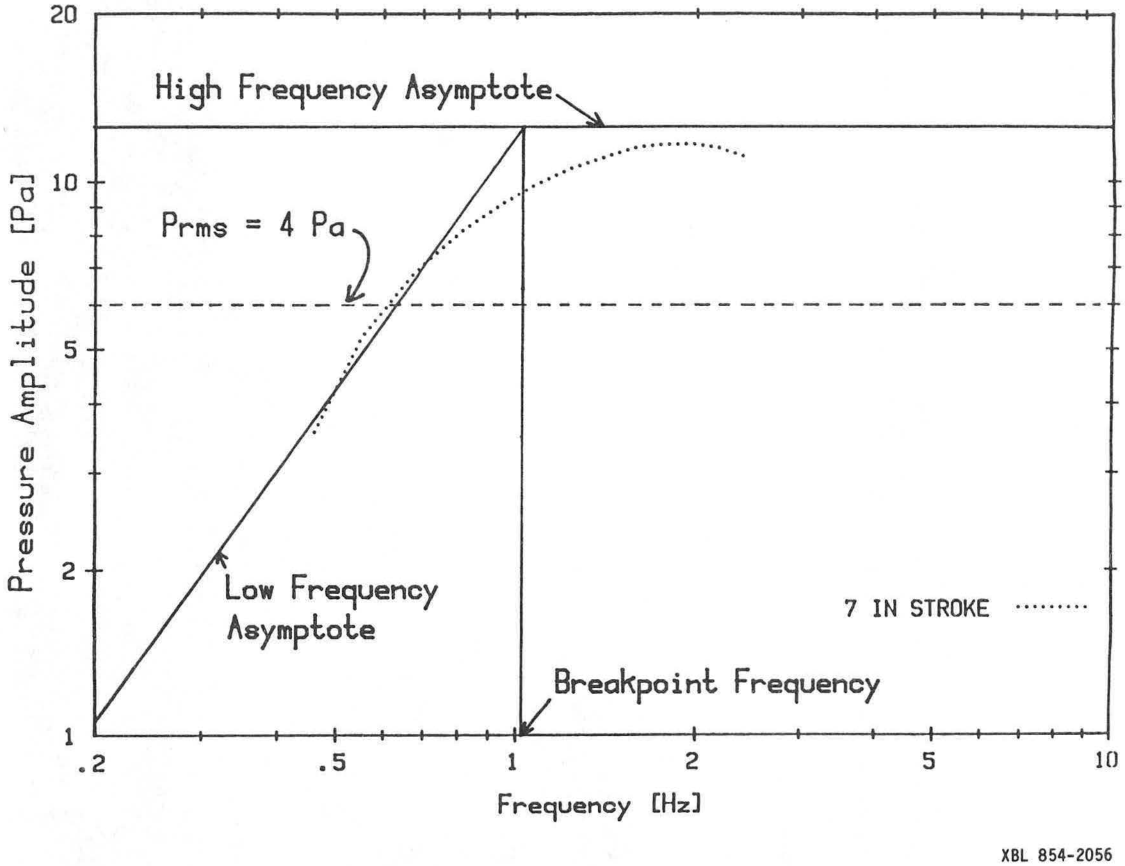

Figure 4. Sample pressure response versus frequency curve (house F).

LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720