#1076

THE MOBILE INFILTRATION TEST UNIT - Its Design and Capabilities: Preliminary Experimental Results.

A. K. Blomsterberg, M. P. Modera, D. T. Grimsrud

Energy Performance of Buildings Group
Energy and Environment Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

JANUARY 1981

ABSTRACT

The Mobile Infiltration Test Unit (MITU) is portable test structure designed and instrumented at Lawrence Berkeley Laboratory. It is a 12 m^2 (128 ft^2) construction-site office trailer modified to provide long-term field data for our air infiltration studies. This report describes the the trailer and its instrumentation, including some preliminary tests of the individual measurement systems. MITU has a completely automated data-acquisition system that records air infiltration rates, surface pressures and weather as half-hour averages. The shell of the trailer is well sealed, and the quantity, type and distribution of leakage area are controlled using removable leakage panels in 16 window openings. Using the trailer's fan pressurization system, the background leakage area of the shell was measured to be 12 cm^2 (1.9 in^2), while the two types of leakage panels have leakage areas of 13 cm^2 (2.0 in^2) and 17 cm^2 (2.6 in^2). The infiltration measurement system was tested by inducing a known flow rate with the fan pressurization system, and predicted the flow rates to within 10% in all cases.

This work was funded by the Assistant Secretary for Conservation and Renewable Resources, Office of Buildings and Community Systems, Buildings Division of the U.S. Department of Energy under contract No. W-7405-Eng-48.

INTRODUCTION

A survey of houses in California, the midwest, and New Jersey has shown that it is possible to develop a correlation between the leakage area (measured by fan pressurization) and the natural infiltration rate of a house. As part of the air infiltration research program at Lawrence Berkeley Laboratory (LBL), investigators have developed a model that provides air infiltration predictions based on leakage area and prevailing weather conditions. [1] The infiltration predictions provided by this model have been within 20% of the measured values.

In addition to leakage area and weather conditions -- the dominant factors determining infiltration -- the model also utilizes the class of terrain, local shielding, building height, and leakage area distribution. Wind speed, terrain class and local shielding determine the wind-induced infiltration, while the indoor-outdoor temperature difference and the building height are the determining factors for stack-induced infiltration. Both wind-induced and stack-induced infiltration are somewhat dependent on the leakage area distribution.

Until now, we have validated the predictions obtained with this model through short-term survey measurements in occupied houses. Because this procedure places an imposition on the occupants, we generally limit the length of our stay at any one site and, as a result, are unable to measure air infiltration during a significant sample of weather conditions. Consequently, we have constructed and instrumented a Mobile Infiltration Test Unit (MITU) with which we can simultaneously monitor air infiltration, surface pressures, weather, and terrain data, for extended periods of time.

The MITU facility is a portable test structure whose primary function will be to construct, from the data collected, a catalog of air infiltration rates and surface pressures for specific weather patterns and terrain influences. Related infiltration research tasks for which MITU was designed are:

(1) Determination of the functional dependence of surface pressures on local weather and shielding;

(2) Controlled experiments on the combination of wind and stack

effects for different leakage locations and types;
(3) Validation of existing model and testing of improvements to add forced infiltration (i.e., exhaust fans, open fireplaces) to natural (weather-induced) infiltration;
(4) Examination of the reliability of the pressurization technique for measuring the leakage areas needed for infiltration predictions;
(5) Exploration of the use of AC pressurization to determine the low-pressure leakage function (and therefore leakage area) of a structure;
(6) Determination of the dependence of the neutral pressure level on weather, shielding and leakage distribution.

The decision to develop a full scale mobile test unit was based on a number of technical and economic considerations. For example, although proper scaling in a wind tunnel can be used to relate surface pressures to wind speeds and directions, the correlation of surface pressures, stack effect, and air infiltration rate can be examined only in a full-scale facility. To determine a correlation between surface pressures and air infiltration rate in a wind tunnel, the leakage sites normally found in an actual structure have to be modeled, including Reynolds number similarity. In order to maintain the Reynolds number of the flow through the cracks, a liquid or a pressurized gas must be used in the tunnel. In addition, thermal scaling is required to explore the combination of wind-induced and stack-induced infiltration, and scaling of terrain class and local shielding is required to maintain compatibility with actual building sites. These considerations lead to high costs for wind tunnel testing which, when combined with concerns about the general acceptance of the technique, resulted in our decision to construct the MITU facility.

DESIGN FEATURES OF MITU

General Design Considerations

Due to the scope of its research applications, versatility was a major design criterion for the MITU. The test structure had to be designed to allow changes to be made in: (1) the local shielding of the structure, (2) its orientation with respect to wind, (3) the severity of its thermal and wind environments, and (4) its leakage types and locations. In a survey of occupied houses, these variables are fixed at each site (even the weather is essentially fixed because of the short duration -- 3-4 days -- of the tests).

To allow for environmental changes, including wind speed, orientation, and shielding, the structure had to be mobile. Manpower considerations dictated that no more than two persons be required for field operations (moving the trailer from site to site, performing required set-up procedures, and adjusting the orientation of the trailer with respect to the wind). Size and weight considerations were imposed by the need to house the required instrumentation and automated data collection system that must travel with the trailer.

To control leakage types and locations, the shell of the structure had to be as air-tight as possible, i.e., the uncontrolled leakage area of the shell had to be minimized. A group of adjustable leakage sites were constructed to represent the majority of the leakage area of the structure.

Trailer Specifications

The test structure chosen was a commercially available construction-site office trailer, modified at LBL for our application. (A view of the trailer exterior is shown in Figure 1.) The following sections describe the trailer specifications required to meet the performance goals described above.

<u>General Construction.</u> The trailer is a wood-frame structure, 4.9 meters (16 ft) long, 2.4 meters (8 ft) wide, and 2.4 (8 ft) meters high, supported by studs 0.41 meter (16 inches) on center. It has a galvanized roof and is mounted on a two-wheel steel frame trailer base. Including the height of the trailer base, the roof of the structure is 3.4 meters (11 ft) above grade. The shell consists of exterior plywood sheathing painted white; the interior is covered with wood paneling. The vehicle weighed 1500 kg (3300 lbs) as delivered, and was fitted with instrumentation weighing approximately 250 kg (550 lbs).

<u>Air Tightness.</u> To insure the air-tightness of the trailer, a continuous 0.2 mm (8 mil) polyethylene vapor barrier was installed behind the interior paneling and on the floor and ceiling. The seams are located on the studs and have an overlap of 0.2 meter (8 in), compressed between the studs and the paneling. All penetrations of the building shell go through the studs, and are sealed with silicone sealant (3145 RTV adhesive/sealant, Dow Corning). In addition, polyurethane foam (Polycel-I, Coplanar Co.) was injected around the door frame to reduce the possibility of leakage. The door itself is steel with a polystyrene core, and is sealed with magnetic weatherstripping (Pease Ever-Strait Door Systems).

<u>Windows and Leakage Panels.</u> A total of sixteen, 0.37 meter (14.5 inches) square, window openings are located in the walls and the floor. Each side of the trailer has six window openings, the back has two, and the front of the trailer and the floor each have one. Each opening is fitted with an air-tight mounting system for interchangeable calibrated leakage panels (see Figure 2). The mounting system consists of a frame and four quick-release clamps which press the leakage panels against the weather-stripping installed on a lip inside the opening. The panels are mounted parallel to the exterior shell and are recessed 2 cm (0.8 inch). The leakage panels consist of 1 cm (0.4 inch) thick plywood panels with leakage sites representative of those found in residential houses (i.e., round holes, long narrow slits). There are 16 panels of each style, and 16 solid panels to allow for various configurations of leakage area. For protection during transport, the window openings can be sealed on the outside with metal plates (see Figure 1).

Thermal Integrity. To explore stack-driven infiltration and to maintain a suitable indoor climate for the electronic equipment, the trailer must be capable of operating under large indoor-outdoor temperature differences. Providing these temperature differences without using prohibitively large heating and cooling systems requires that the trailer be well insulated. The floor, ceiling, and walls are therefore insulated with 9 cm (3.5 inches) of fiberglass insulation. The thermal integrity of the door is insured by its 4 cm (1.5 inch) thick expanded polystyrene core.

Heating and Cooling Systems. To meet the thermal requirements mentioned above, the trailer is equipped with thermostated heating and cooling systems. Heating is provided by four radiant heaters (Aztec Radiant Heating, model ASH surface mount) rated at 375 W each. They are 0.6 meter (2 feet) square and are mounted mid-height on the walls. Cooling is provided by a 3075 W (0.875 ton) air conditioner (Comfort Aire, model MTR111, by Heat Controller Inc). It is a split-component unit: the condenser is mounted inside the trailer, and the evaporator is mounted outside on the front wall of the trailer. Their only connection is via freon lines, which go through a stud in the wall. A split-component unit was chosen to eliminate the air leakage that normally occurs through a self-contained air conditioner.

Electric Power. When estimating the power requirements for the trailer, both peak demand and supply availability had to be considered. A 115/230V system was chosen for its availability throughout the United States, and an 80A/115V load panel was chosen to meet the expected 50A peak demand of the trailer. Power is brought into the trailer through a connector mounted under the front of the trailer, while the 80A panel is mounted on the front wall inside the trailer. At each test site the trailer will be parked near a power pole that has to be fitted with a watt-hour meter by the local utility company.

Skirt. To simulate the existence of a crawl space, a Naughahyde skirt is attached to the bottom of the trailer using hooks and Velcro strips. The skirt extends from the lower edge of the walls on to the ground, where weights are placed on top of it to avoid flapping in the wind. A Naughahyde skirt was selected because of its versatility, low weight and ease of handling.

INSTRUMENTATION OF MITU

The MITU facility contains a variety of instrumentation: a system for measuring leakage area; automated systems for monitoring air infiltration, differential pressures across the shell, and weather; and a microcomputer for controlling the automated systems, and recording, reducing, and plotting the data. The data-acquisition equipment rack is shown in Figure 3, and a brief description of each system is given below.

Leakage Area Measurement

The leakage area of the trailer shell is measured by fan pressurization. The centrifugal blower used to pressurize and depressurize the structure has a capacity of 1200 m^3/hr (700 cfm) at 125 Pa (0.5 inches of water) (Cincinnati Fan model LM6, Dayton speed controller with a 20 to 1 speed range). A sharp-edged orifice plate is used to determine the flow through the fan (and therefore the trailer). The fan flow is directed through a 15 cm (6 in) duct which can be fitted with orifice plates of various sizes. One end of the duct is set into a special window panel to provide a well-sealed opening for communication with outside air and to allow for easy installation. The measurement requires the use of two differential-pressure transducers, one for the pressure drop across the orifice and one for the indoor-outdoor pressure difference. The transducers used for the surface pressure measurement system are also used for this purpose.

Air Infiltration System

Infiltration rates are monitored continuously with a tracer gas technique. In this technique, tracer gas is injected continuously, and its concentration is continuously monitored. This type of injection system was chosen instead of a pulsed-injection decay system because it directly determines the effective volume of the structure.[2]

The MITU trailer uses the Continuous Infiltration Monitoring System (CIMS) developed at LBL. This completely automated system is implemented on the trailer's microcomputer which records the reduced data on floppy disk. The volumetric air infiltration rate is calculated using the Equation:

$$C = \frac{F}{Q} + \left(C_o - \frac{F}{Q}\right) e^{\frac{-Qt}{V}} \quad (1)$$

where

- Q is the volumetric air infiltration rate [m^3/hr],
- F is the tracer gas flow rate [m^3/hr],
- C is the tracer gas concentration [ppm],
- C_o is the tracer gas concentration at time zero [ppm],
- V is the effective volume of the structure [m^3], and
- t is the time elapsed since time zero [hr].

The CIMS system measures tracer gas concentration (C), tracer gas flow rate (F), and elapsed time (t), leaving three unknown parameters: the infiltration rate (Q), the tracer gas concentration at time zero (C_o), and the effective volume of the structure (V). The unknown parameters are determined using a SIMPLEX [3] likelihood maximization algorithm. The control algorithm then adjusts the tracer gas flow rate to maintain a target concentration.

The hardware used to implement this system consists of an infrared gas analyzer and two mass-flow controllers in conjunction with the microcomputer. The MITU system uses ethane as the tracer gas and a Wilks 101 ethane analyzer is used to monitor concentration in the parts per million (ppm) range. This detector continuously monitors the ethane concentration in the indoor air, and the computer samples this measurement every 30 seconds. Using two solenoid valves, the analyzer samples outdoor air once every half hour to measure the zero drift of the device. Because the analyzer is temperature-sensitive, it is fitted with a thermostated electrical resistance heater on the sample input line to insure that outdoor air and indoor air flow through the analyzer at the same temperature. The mass-flow controllers (Matheson, Model 8240) that meter the tracer-gas injection rates are controlled by analog signals from the computer.

From the computer's point of view, the control sequence is: (1) the tracer gas concentration and flow rate are read once every 30 seconds, (2) the SIMPLEX algorithm is called once every half hour to calculate the infiltration rate using the concentration and flow rate values collected during that period, (3) to maintain the target concentration, the ethane flow rate is then adjusted using the air infiltration rate calculated by the SIMPLEX routine, (4) the reduced data, including concentration, C_o, flow rate, F, and infiltration rate, Q, are recorded onto a floppy disk, (5) the analyzer solenoids are switched and the zero of the analyzer is determined by measuring the ethane concentration in outside air.

A gas alarm system (Gastech, Model 1220) automatically shuts off the supply of ethane when the concentration exceeds 20 percent of the lower explosive limit (the lower explosive limit is three percent ethane in air).

Surface Pressure Measurement Equipment

The MITU trailer is fitted with an automated surface pressure measurement system. There are 82 holes in the shell of the trailer (64 in the walls, 12 in the ceiling, and 6 in the floor), through which plastic (Polyflow) tubing, mounted flush with the exterior surface, passes to connect to solenoid valves (Skinner Electric Valves, Model V57DA1030) inside the trailer. Every hole is drilled through a stud and is sealed with silicone adhesive/sealant to eliminate the possibility of leakage. The indoor-outdoor pressure difference is measured at six heights, one for the floor, four for the walls, and one for the ceiling. Each height contains a maximum of 16 pressure taps. All of the taps are connected with horizontal pressure lines to differential-pressure transducers (Validyne, Model DP103, range 70 Pa) mounted at each height. The transducers use a physical filter (an insulated volume fitted with a flow-controlling orifice) as an indoor pressure reference. The physical filter has both pressure and temperature time constants of approximately five minutes, thereby damping out short-term fluctuations in indoor pressure. An additional pressure transducer is used to measure these short-term fluctuations by comparing the instantaneous indoor pressure to the pressure in the physical filter.

During sampling, each tap is kept open for ten seconds. The pressure signal, sampled 40 times per second, is electronically filtered using a one-second time constant in order to remove any ringing in the pressure signal due to solenoid operation. Between one and sixteen taps can be opened simultaneously at a given height. The zero of the pressure transducers is checked every 30 minutes by connecting the two sides of each transducer. All surface pressures are stored on a floppy disk in the form of 30-minute averages, along with their standard deviation during that period.

Weather Station

Two collapsible weather towers are permanently mounted on the rear corners of the trailer. One tower is in three, 3-meter (10 ft) sections which, when fully extended, rise 9.5 meters (31 ft) above ground level. Once extended, the tower is supported by two telescoping diagonals which are attached to the two adjacent corners of the trailer. The other tower consists of two 1.8-meter (6 ft) sections, which extend to 5 meters (16 ft) above the ground. The weather towers are retracted during transport and do not extend above the roof level. Having the towers mounted on the trailer allows simple on-site installation and a convenient storage place during transport.

The weather measurement equipment includes instrumentation for monitoring temperature, wind speed, and wind direction (Weathermeasure). The outdoor dry-bulb temperature is measured by blowing air past a radiation-shielded thermistor probe 7 meters (23 ft) above the ground. Wind-speed and wind-direction sensors are located on top of each weather tower. A cup anemometer registers the wind speed, while wind direction is determined by a wind vane connected to a potentiometer. The weather conditions are sampled every 10 sec and averaged over 30-minute periods. These averages, together with their standard deviations, are stored on a floppy disk.

Microcomputer Installation

A Z-80 microprocessor-based computer (Monolithic Systems) is used to control and monitor the systems described above and to reduce and record data on a floppy disk. The system includes an Arithmetic Processing Unit (APU), an ADC/DAC (analog/digital conversion) board, 56k bytes of read/write memory, 3k bytes of read only memory, and a dual floppy disk drive.[4,5]

The computer samples, reduces, and records data from the air infiltration, surface pressure, and weather systems. It can record up to nine days of reduced data on a single floppy disk. In addition, it controls the tracer gas flow rate for the infiltration system, opens and closes solenoids for the surface pressure measurement system, and outputs error messages to a line printer.

PRELIMINARY TESTING

Before the MITU trailer can be sent out into the field, all of the systems have to be checked and calibrated. The preliminary tests on the leakage-area measurement system and the air-infiltration system have been completed and are discussed below.

Leakage Area Measurements

Before testing the leakage-area adjustment system (windows and window panels), the air-tightness of the trailer shell (or background leakage area) had to be checked and improved. Leakage sites were first located by pressurizing the trailer and using smoke sticks to identify flow through the shell of the structure. After sealing any discernible leakage sites and fitting all window openings with solid panels, orifice/blower tests were performed. These tests measured the background leakage area of the trailer shell as 11.4 cm^2 (1.77 in^2). To determine how this value compares with the leakage areas of typical residential dwellings, it can be normalized to the size of the trailer. We divided the effective leakage area of the MITU trailer (11.4 cm^2) by its floor area (11.9 m^2, 128 ft^2) and found the "specific leakage area" to be 0.96 cm^2/m^2. Residential dwellings typically have specific leakage areas between three and ten [cm^2/m^2]. The background leakage-area tests also included a check on the air-tightness of the leakage-panel sealing systems. After installing and taping metal protection plates over the window openings, the background leakage area was again measured. This measurement yielded 10.5 cm^2 (1.63 in^2) which, when subtracted from the background leakage area noted above, yielded a leakage area for the leakage-panel sealing system of only 0.9 cm^2 (0.14 in^2), verifying that the window sealing system is effective.

The leakage areas of the window panels were measured both individually and with multiple panels installed. Initially, two different leakage geometries were tested: round 2.4 cm (0.94 inch) diameter orifices and slits 32.4 cm (12.8 inch) long by 0.24 cm (0.094 inch) wide. One set of window panels has four orifices per panel, while the other set has seven slits per panel. The panels with four orifices were found to have a leakage area of 12.9 cm^2 (2.00 in^2), compared to an actual area of 18.5 cm^2 (2.88 in^2). The panels with seven slits have a leakage area of 16.9 cm^2 (2.62 in^2) and an actual area of 36.3 cm^2. The measured discharge coefficients for the holes and the slits, 0.70 and 0.47 respectively, are reasonably consistent with the values measured by independent researchers for similar geometries.

Table 1: Multiple-panel leakage area tests.			
Panels		Leakage Area [cm^2]	
Type	Number	Predicted	Measured
Orifice	2	25.8	26.7
Orifice	3	38.7	37.6
Orifice	4	51.6	49.4
Orifice	5	64.5	67.5
Orifice	6	77.4	82.7
Orifice	7	90.3	97.0
Orifice	8	103.2	110.2
Slit	2	33.8	34.0
Slit	3	50.7	53.6

The results of the multiple panel tests are displayed in Table 1. The leakage-area predictions were obtained by adding the leakage areas of the individual panels. These predictions show good agreement with the leakage areas measured by the multiple panel tests, demonstrating that leakage areas are additive.

Our leakage model (Equation 2) is used to determine the leakage area at a reference pressure (Equation 3).

$$Q = A \sqrt{\frac{2}{\rho} \Delta P} \tag{2}$$

where

Q is the air-flow rate [m^3/s],

A is the effective leakage area [m^2],

ΔP is the pressure drop [Pa], and

ρ is the air density [kg/m^3].

$$A = Q_{\Delta P_r} \sqrt{\frac{\rho}{2\,\Delta P_r}} \tag{3}$$

where

ΔP_r is the reference pressure [4 Pa].

The reference pressure (4 Pa) represents typical pressure differences imposed across a building shell by winds and stack effect. Fan pressurization measures the air flow through the trailer shell at indoor-outdoor pressure differences between 5 and 50 Pa. The flow at 4 Pa can be determined by extrapolating fan pressurization data down to that pressure.

A graphical extrapolation technique for determining leakage area at 4 Pa is depicted in Figures 4 and 5. This technique fits the data to a power law function of the form:

$$Q = C\left[\Delta P\right]^n \tag{4}$$

where

C,n are empirical constants.

Plotting both the pressure and the flows on logarithmic scales yields a straight line with the power law exponent (n) as its slope. As can be seen in Equation 3 , leakage area is directly proportional to the flow rate (Q) at ΔP equal to 4 Pa. The leakage area can be read directly on the left side of the graph, the scale having been multiplied by the proportionality constant.

Air Infiltration Measurements

The MITU trailer's air infiltration system was also tested. The testing procedure involved overcoming natural infiltration by sealing the trailer and pressurizing it with the orifice/blower system, thereby providing a known infiltration rate. For this purpose, all windows were fitted with solid panels, excluding the two windows at the rear of the trailer that were fitted with the intake for the blower (lower window), and a seven-slit panel (upper window) to provide a vent for the exfiltrating air. The flow rate of incoming air was monitored with the orifice, while the trailer's infiltration system simultaneously measured the infiltration rate. As can be seen in Table 2, the two measurement techniques showed good agreement.

Table 2: Comparison of infiltration rates as measured by air infiltration system and orifice/blower system.

Infiltration System (± 5%)	Orifice/Blower (± 3%) System
(m^3/hr)	
45	50
146	153
250	250

SUMMARY

The Mobile Infiltration Test Unit (MITU) constructed and instrumented at LBL is now ready to serve as a test station for validating modeling techniques for air infiltration. Its first field trip will be to Reno, Nevada for cold climate infiltration tests.

REFERENCES

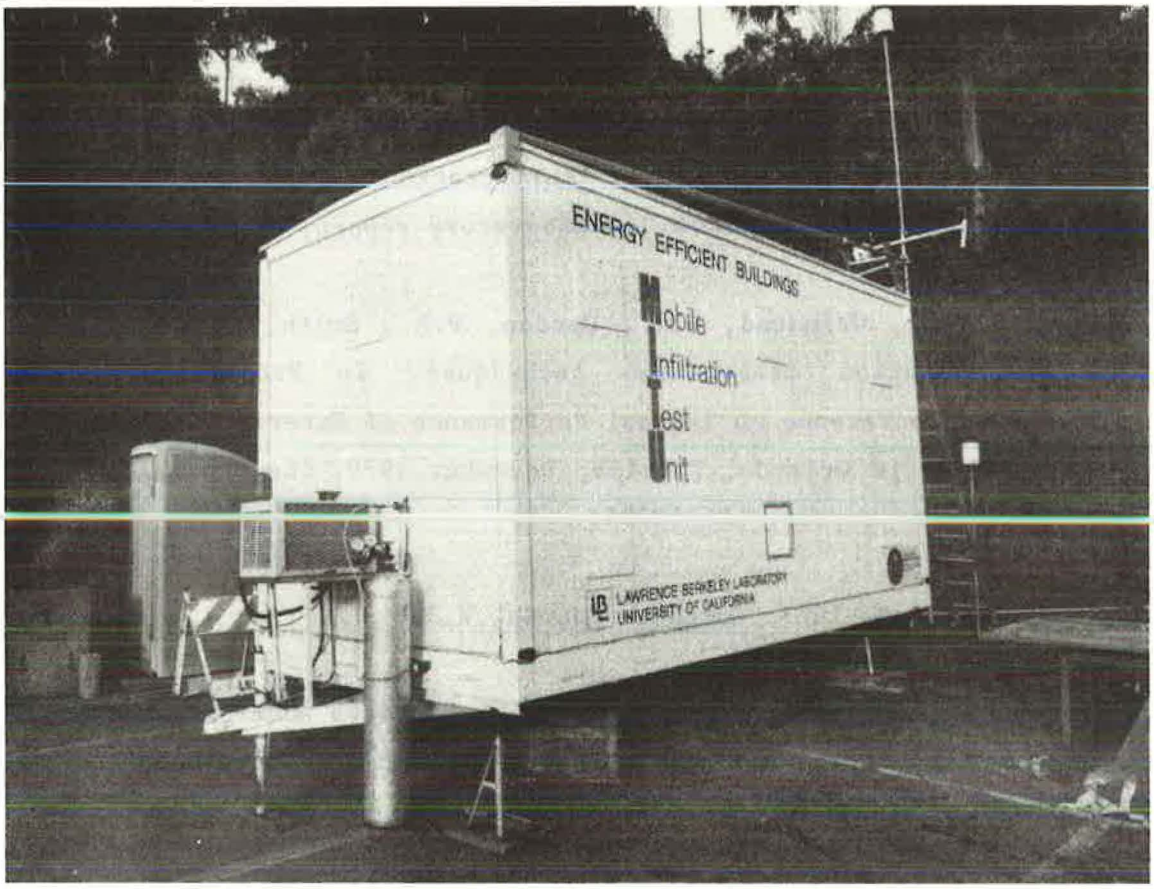
1. Sherman, M.H., Grimsrud, D.T.. 1981. The measurement of infiltration using fan pressurization and weather data. In the Proceedings of the First International Air Infiltration Centre Conference, London 1980. (Lawrence Berkeley Laboratory report, LBL-10852).

2. Sherman, M.H., Grimsrud, D.T., Condon, P.E., Smith, B.V.. 1980. Air infiltration measurement techniques. In Proceedings of ASHRAE-DOE Conference on Thermal Performance of Exterior Envelopes of Buildings in Orlando, Florida, December 1979. (Lawrence Berkeley Laboratory report, LBL-10705).

3. Nelder and Mead, 1967. Computer Journal,7,308.

4. Smith, B.V., Condon, P.E.. 1981. The LBL-EPB data acquisition system: its description and construction. Lawrence Berkeley Laboratory report, LBL-11739.

5. Condon, P.E., Smith, B.V., Strong, P.. 1981. TORX-80: A multi-task real-time executive for 8080 and Z-80 microprocessors. Lawrence Berkeley Laboratory report, LBL-9377.



CBB 800-13932

Figure 1 Exterior view of Mobile Infiltration Test Unit in Blackberry Canyon at Lawrence Berkeley Laboratory.

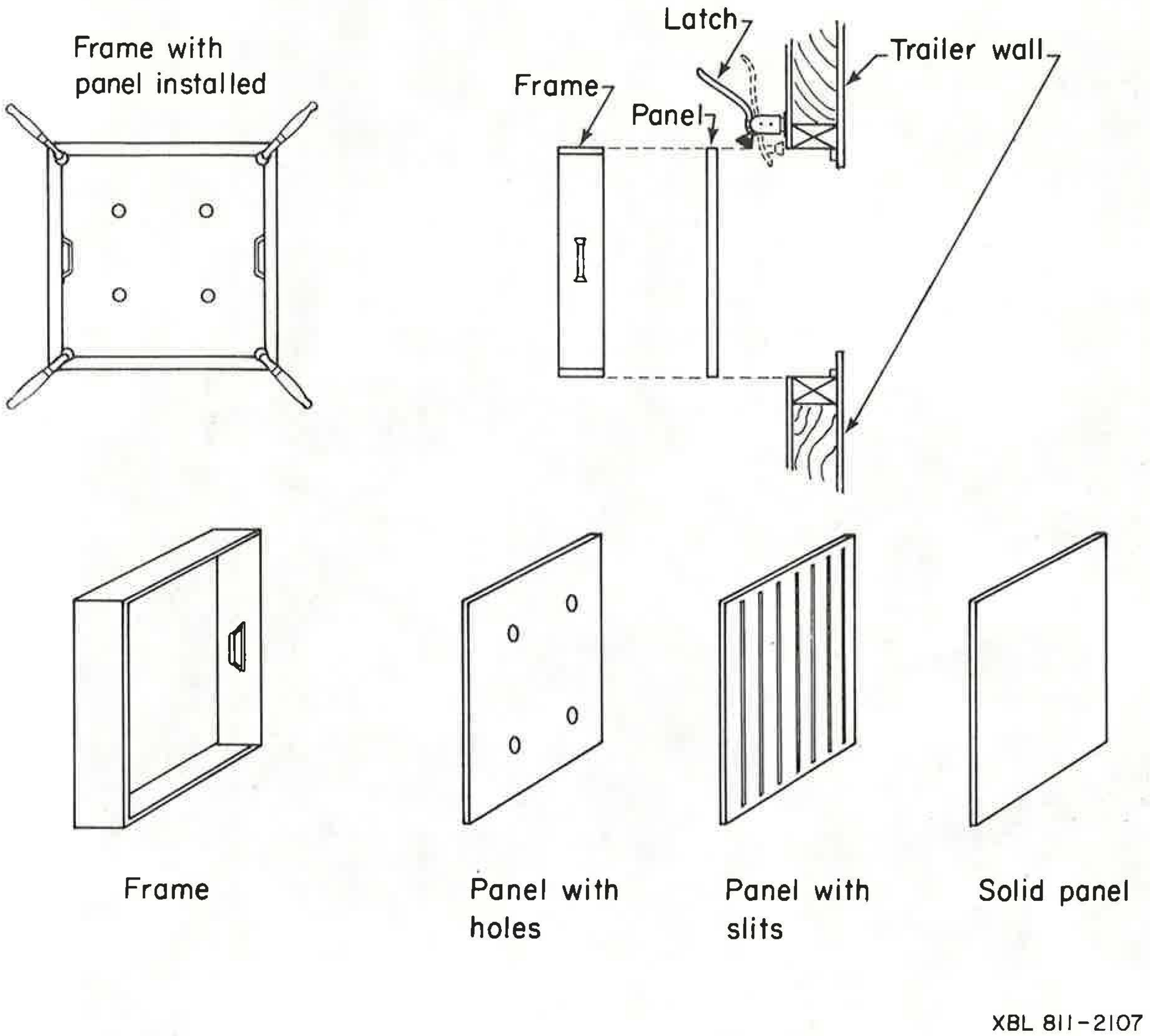
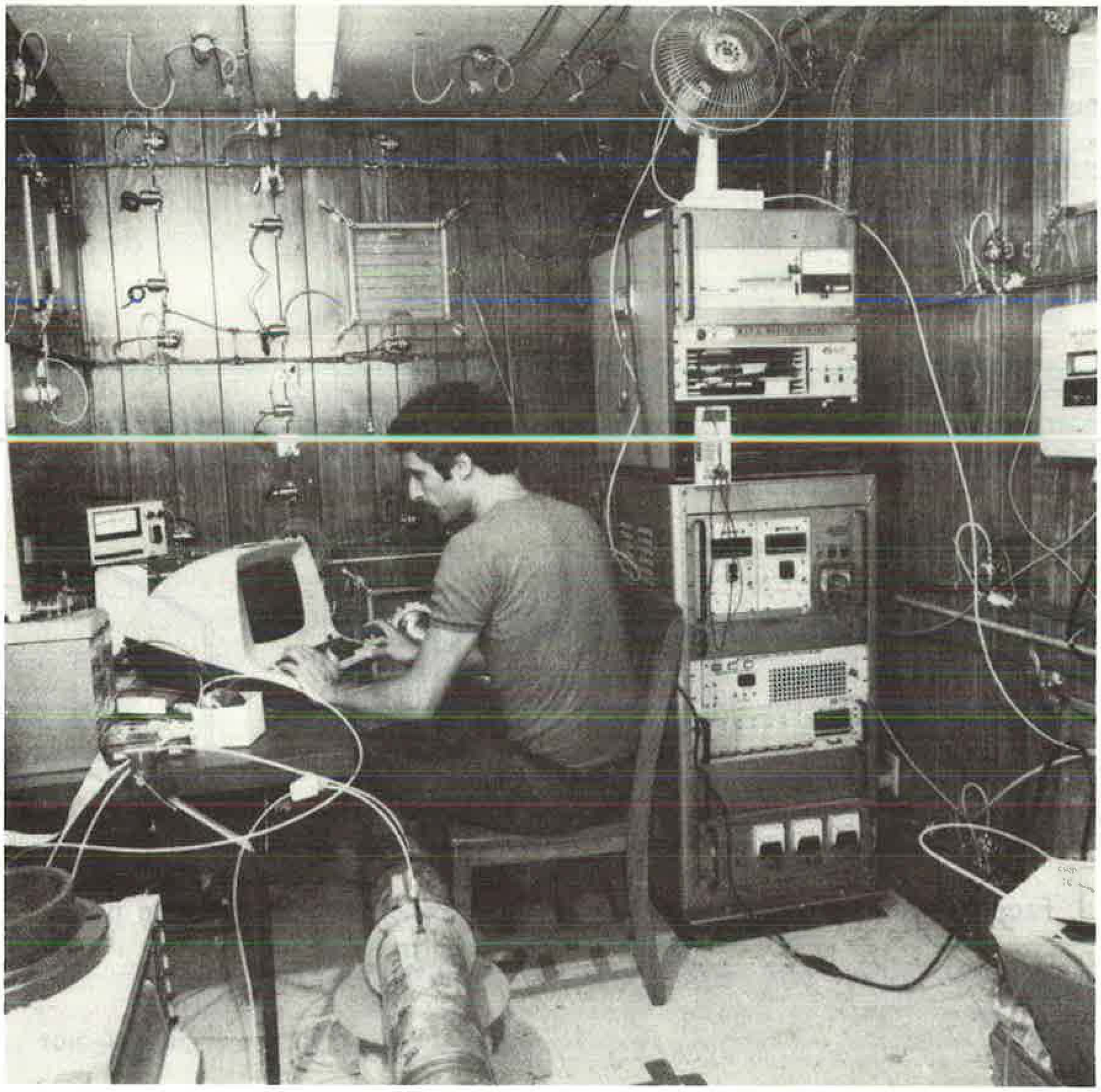


Figure 2 Leakage Area Adjustment System.



CBB 809-11263

Figure 3 Interior view of Mobile Infiltration Test Unit, showing data acquisition rack.

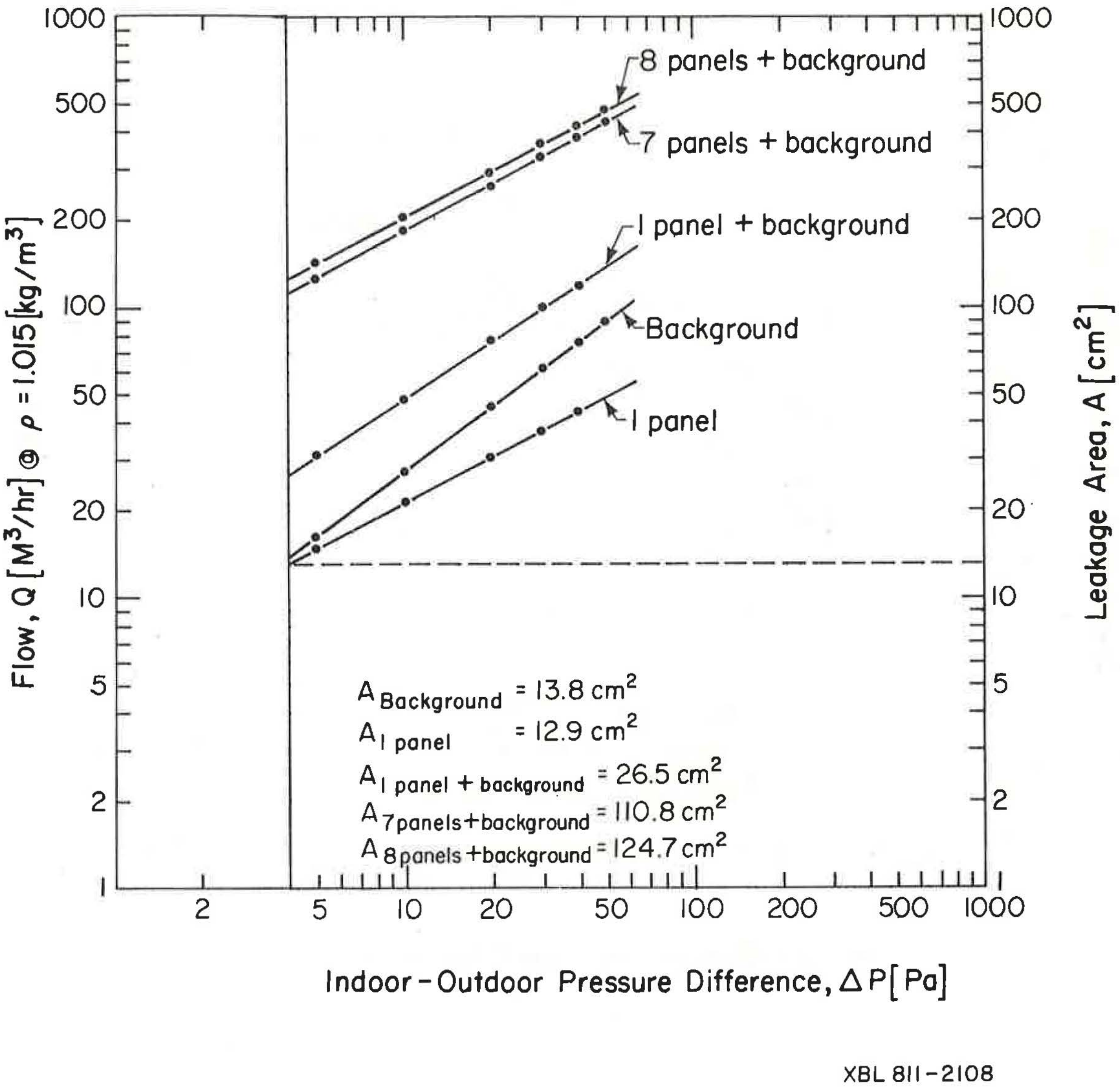


Figure 4 Plot of fan pressurization test results for four-hole panels. All scales are logrithmic, the leftside vertical scale representing the measured flowrates, the righthand veritical scale representing the leakage area calculated at 4 Pa.

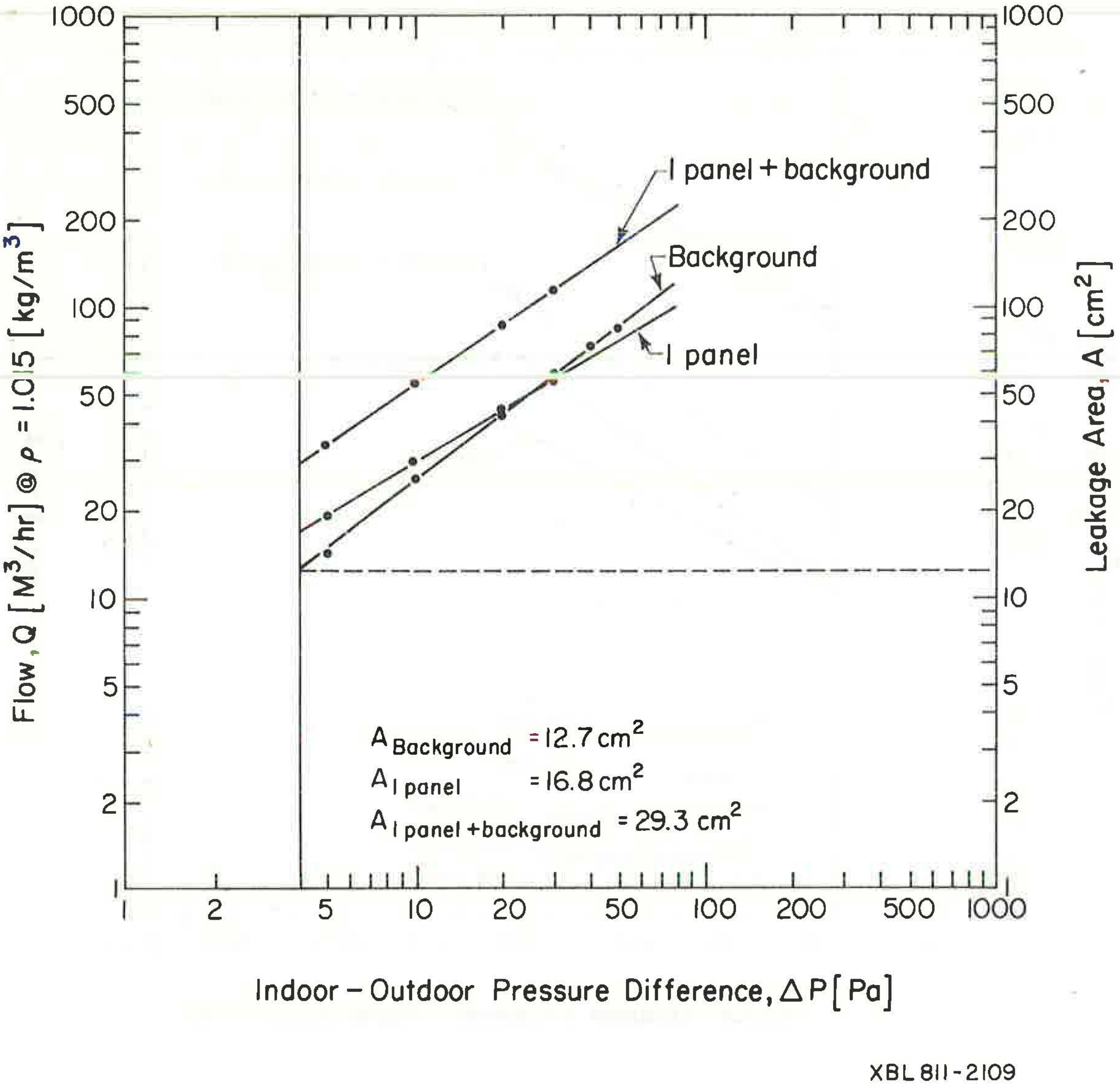


Figure 5 Plot of fan pressurization test results for seven-slit panels. All scales are logrithmic, the leftside vertical scale representing the measured flowrates, the righthand veritical scale representing the leakage area calculated at 4 Pa.