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BALANCED FAN DEPRESSURIZATION METHOD FOR MEASURING COMPONENT AND OVERALL AIR LEAKAGE IN SINGLE- AND MULTIFAMILY DWELLINGS

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ABSTRACT

The balanced fan depressurization technique has been applied to measure the air leakage characteristics of row houses and individual house stories. Controlled field tests on two detached, two-story houses with full basements were carried out to verify the consistency of the method. The technique was then used to measure the air leakage rates of three row house units and the stories of two other houses. The results are presented and discussed.

INTRODUCTION

The fan depressurization or "blower door" method was developed to measure the air leakage characteristics of a whole building (see CGSB 1986 and ASTM 1986). Fan depressurization cannot be applied directly to semi-detached houses, row houses, or apartments because these units are not independent of their adjacent units for air leakage from outside. For example, if a single unit is depressurized, outside air will be drawn into that unit as well as adjacent units. Therefore, outside air enters the depressurized unit directly through its exterior envelope and indirectly through the interior partitions that the unit shares with adjoining units. Furthermore, if individual building components are tested with the depressurization technique, outside air will be drawn in through the component itself and indirectly through the wall cavities connected to it. These applications of the simple fan depressurization method can give misleading results.

The balanced fan depressurization technique was developed to avoid problems with indirect air leakage (Shaw 1980). It employs balancing fans, in addition to the primary depressurization fan, that are used to eliminate the pressure differences between the tested component and adjacent components. As pressure differences are eliminated, so too is air leakage from adjacent components. Applications of the balanced fan depressurization technique to measure the air leakage characteristics of apartment units and of individual components of their exterior envelopes, e.g., windows, doors, and floor-wall joints, have been described elsewhere by Shaw (1980). The balanced technique was validated by comparing its results with those obtained using the Indirect Method (Shaw 1980). A similar technique has been used to measure the air leakage characteristics of individual row houses (Lagus and King 1984). The balanced fan depressurization technique has not been applied to measure the air leakage rates for individual stories of a house. This paper describes the application of the technique to measure the airtightness of the exterior walls of individual house stories and of single- and multilevel row houses.

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THE BALANCED FAN DEPRESSURIZATION TECHNIQUE

The balanced fan depressurization technique uses at least two fans, a main fan to depressurize the test component and another fan to balance the pressures between the test component and its adjacent surroundings. Although this paper describes the method's application to house stories and row house units, in this section, the term "component" can mean any part of a building envelope, ranging from the entire exterior of an apartment, row house, or house story, to individual doors, windows, and joints such as a wall-ceiling joint. Specific examples for house stories and row houses will be used for illustrative purposes. A schematic diagram of the simplest setup for a balanced fan depressurization test is shown in Figure 1.

The primary depressurization apparatus consists of a fan, a means for controlling the flow rate through the fan, and a means for measuring that flow rate (CGSB 1986; ASTM 1986). It is set up to depressurize the building component to be tested. The space between the component being tested and the fan's intake is called the main or primary test chamber. The outlet of the apparatus is usually ducted to the outside through a plywood panel, which is used to replace a door or a window, and tightly sealed in order that the test method not introduce extra leakage area. For the case of testing an entire house story or dwelling unit, the entire indoor space of the story or the dwelling unit comprises the main test chamber.

The tested component must be isolated as much as possible from its neighboring building components using existing and temporary partitions (if necessary) to establish the boundaries of the primary test chamber. Temporary partitions should be as rigid as possible to permit reasonably quick pressure adjustments. In the case of measuring the air leakage for individual stories in a house, the basement door is closed and sealed with tape to form a partition between the basement and first story. An open stairwell between a first and second story normally requires a temporary partition of plywood panels sealed with tape to isolate the second story from the first story. Adjacent row houses are naturally separated by their party wall.

The balancing fans, which also require flow rate controls but not flow rate measurement capabilities, are set up to depressurize building components adjacent to the tested component, thus establishing secondary test chambers. This will allow the pressure differences between the main and the secondary test chambers to be reduced to zero. Since airflow requires a driving pressure difference, these balancing fans are used to prevent any air leakage (other than that through the tested component directly from outside) into the test chamber.

If the balancing fans are equipped with the capability to measure flow rates, i.e., if depressurization apparatuses are used as balancing fans and are installed in a manner similar to the primary depressurization apparatus, the air leakage characteristics of more than one component can be measured simultaneously. Very large leaks in the exterior envelopes of the adjacent building components may make it difficult for the balancing fans to do their job, if the fan capacity is marginal for the task. Therefore, reasonable efforts should be made to seal leakage openings; the more tightly sealed the adjacent building components, the less flow capacity is required of the balancing fans.

Manometers are connected to measure pressure differences across the tested component(s) and between the main test chamber and each secondary chamber. To check accuracy and to confirm the pressure balance, manometers may also be used to measure the pressure differences between the secondary chambers and the outside. (At the balanced condition, the pressure differences between the secondary chambers and the outside should equal the pressure difference(s) between the primary chamber(s) and the outside.)

Finally, all doors and windows should be closed tightly. All intentional leakage openings not to be included in the envelope leakage measurement should be well sealed. Examples of such intentional openings are clothes dryer exhaust vents, bathroom and kitchen fan exhaust vents, and flues (CGSB 1986).

With the setup as described previously, the air leakage measurements can proceed as described below.

1. The primary depressurization fan is powered on and the flow rate through it is adjusted until the desired pressure difference across the tested component is obtained. The maximum pressure difference to be used in the test is usually the first pressure difference set; this confirms the abilities of the fans to generate all the pressure drops or balanced conditions.

2. The flow rate through each balancing fan is adjusted until the pressure difference between the main and the secondary test chambers is reduced to zero.

3. The flow rates through the depressurization fans, the pressure differences across the tested component(s), and the pressure differences between the tested component and its interior surroundings are measured and recorded.

4. Steps 1 through 3 are repeated for other pressure differences across the tested component(s) to obtain five or six flow rate/pressure drop data pairs for the tested component(s). Generally, the pressure differences are reduced from the maximum at the start to the minimum at the end of the test.

5. The resulting data can then be curve fitted either graphically, or analytically, and reported as

$$Q = C \cdot (\Delta P)^n \tag{1}$$

<u>where</u>

Q = the volumetric flow rate, in L/s
ΔP = the pressure difference driving the flow rate, Pa
n = the flow exponent, an empirical value in the range 0.5 to 1.0
C = the flow coefficient, an empirical dimensional value that includes the area of the leakage opening(s), $L/s \cdot Pa^n$.

The minimum measurable pressure drop depends upon instrument capabilities and wind conditions. The first limitation is a consequence of the calibration accuracy and resolution of the manometer. Any wind can disturb the differential pressure measurements between inside and outside in both a steady and a time-varying manner. When a whole dwelling unit is being tested, manifolding the outside pressure taps can minimize the steady effects of low to moderate wind speeds (< 15 km/h or 10 mph). However, little can be done to salvage leakage data measured during a period of excessive wind velocities or gustiness; tests should not be performed under such conditions.

It may not be possible to directly apply the balanced fan depressurization technique to measure the leakage characteristics of a specific building component of interest, such as an individual story of a house. This may be due to a lack of equipment, in which case the leakage characteristics of interest must be calculated from several measurements of combined leakage characteristics. For example, the leakage rates for each of three stories in a house (the basement and the first and second floors) can be measured using only one depressurization apparatus and one balancing fan. The depressurization apparatus is installed in the middle story and first used to measure the leakage rate for the entire house, Q_T. After installing the balancing fan in the lowest story and isolating it from the two upper stories, a set of of measurements is made to obtain the leakage through the two upper stories combined, Q_{1+2}. Finally, the balancing fan is moved to the top story which is then isolated from the two lower stories, after which a set of measurements is made to obtain the leakage through the two lower stories combined, Q_{b+1}. These three sets of measurements can then be used to calculate the leakage rates for the individual stories using the following equations (illustrated in Figure 2):

$$Q_b = Q_T - Q_{1+2} \tag{2}$$

$$Q_2 = Q_T - Q_{b+1} \tag{3}$$

$$Q_1 = Q_T - (Q_b + Q_2) \tag{4}$$

In addition to measuring leakage characteristics of components of the house envelope, this technique can also be used to measure the air leakage characteristics of the partitions between the various building components tested. This is done by selectively unbalancing certain pressures, one at a time, with respect to the "tested" component. The difference between the air leakage measured with pressures balanced across all interior partitions and that with the pressure balanced across all but the partition of interest yields the air leakage characteristics of that partition. This procedure is particularly appropriate for measuring the leakage through the party wall separating two row houses. In the case of a row house, the air leakage rate of the unit, Q_U, is first measured when pressures inside the unit are balanced with those in adjacent units. The measurements are repeated with the pressures balanced in all but the adjacent unit that shares the party wall of interest to obtain Q_{U+PW}. The leakage rate through the party wall, Q_{PW}, can then be determined from:

$$Q_{PW} = Q_{U+PW} - Q_U \tag{5}$$

CONTROLLED FIELD TESTS

Controlled field tests were carried out on two tightly built, electrically heated houses (H2 and H3) of the HUDAC/NRC Mk XI project (Quirouette 1978; Scheuneman 1982) to verify the consistency of the balanced fan depressurization technique. These houses are described in Table 1. Four tests, as shown in Figure 3, were performed on each house. For these tests, depressurization apparatuses were used in place of balancing fans to permit comparisons between the directly measured and calculated airflows. Thus, the order in which these tests were carried out does not correspond to the procedural order for normal field tests.

In the first test for each of these two-story houses (Figure 3a), one fan apparatus was installed in the basement of the house and another in the first story. The exits of the fan units were ducted to the outside through carefully sealed panels replacing a basement window and a door, respectively. The basement door was closed and carefully sealed to isolate the basement from the two upper stories of the house. All the registers and grills in the forced-air heating system were sealed with tape. The stairwell between the first and second stories was unobstructed, and all outside doors and windows were tightly closed. A balanced fan depressurization test was carried out using the two fans to balance the pressures between the basement and the upper stories. The flow rates through both fans were measured, as well as the three pressure differences: that between the upper story and the outside, between the basement and the outside, and between the basement and the upper stories.

For the second test in each house (Figure 3b), a third fan apparatus was installed in the second story and ducted to the outside through a well-sealed panel replacing a window. The second story was isolated from the first using plywood panels and tape to seal the stairwell. The setup from the first test was not disturbed. A depressurization test was carried out with the pressures on all three stories balanced using the three fan units. The flow rates through all three fan units were measured, as well as the five pressure differences: that between each story and the outside (3) and between each story and its adjacent story or stories (2).

For the third test (Figure 3c), the basement fan apparatus was removed, and its exit panel was replaced with a window that was closed tightly. The door between the basement and the first story was unsealed and left open. A depressurization test was performed using both fans to balance the pressures between the second story and the lower stories. The flow rates through the remaining two fan units were measured, as well as the three pressure differences: that between the second story and the outside, between the first story and the outside, and between the first and second stories.

For the fourth test (Figure 3d), the depressurization fan in the second story was removed, and its exit panel was replaced with a window that was closed tightly. The temporary partition separating the first and second stories was removed. A depressurization test of the whole house was carried out using the fan unit remaining on the first story. The flow rate through the fan and the pressure difference between the inside and the outside were measured.

The results of the first test on each house provide the leakage characteristics of the basement, $Q_{b,1}$, and of the first and second stories combined, $Q_{1+2,1}$. The second tests provide the leakage characteristics of each individual story, $Q_{b,2}$, $Q_{1,2}$, and $Q_{2,2}$, which are used as the basis for comparisons with other measured and calculated results. The third tests provide the leakage characteristics of the basement and first story combined, $Q_{b+1,3}$, and the second story, $Q_{2,3}$. The fourth tests provide the leakage characteristics of the whole house, $Q_{T,4}$.

Tests 1 and 2 provide comparisons of direct independent measurements of the air leakage of the basement, $Q_{b,1}$ and $Q_{b,2}$, of each house. Tests 2 and 3 provide similar comparisons for the second story, $Q_{2,2}$ and $Q_{2,3}$, of each house. All four tests provide the data required to compare the independently measured air leakage of the entire house, $Q_{T,4}$, with that calculated from the other measurements, $Q_{b,1} + Q_{1+2,1}$, $Q_{b,2} + Q_{1,2} + Q_{2,2}$, and $Q_{b+1,3} + Q_{2,3}$. Test 2 and independent combinations of the results of tests 1 and 3 provide comparison measurements of the first story's air leakage, that is, $Q_{1,2}$, $Q_{1+2,1} - Q_{2,3}$, and $Q_{b+1,3} - Q_{b,1}$.

These consistency verifications of the measurements of the air leakage for individual stories in the two HUDAC test houses are shown in Figures 4 and 5. The agreement between independent measurements of the same quantities are within 15% in all cases, and much better in most. Verifications of the method's consistency in measurements of the whole house air leakage for the two test houses are shown in Figures 6 and 7. The agreement, indicating consistency, is again within 15%. These consistency agreements are the same as the accuracy agreements measured in the validation tests of the method with the Indirect Method carried out on windows and wall-floor joints in apartments (Shaw 1980).

FIELD APPLICATIONS OF THE TECHNIQUE

Field applications of the balanced fan depressurization technique have been undertaken to measure component air leakage characteristics in several residential buildings. Tests were performed on a relatively leaky two-story research house (A1) to determine the method's applicability for a very leaky house. Measurements of the air leakage of individual stories in a third house (H4) of the HUDAC/NRC Mk XI project were made using only one depressurization apparatus and one balancing fan to illustrate the usefulness of the technique with minimum equipment. The method was also used to measure the air leakage of an end unit of a two-story row house (R1) and of the lower and upper end units of a four-story multilevel, multi-unit row house (R2 and R3) to determine both the method's applicability to such buildings and the airtightness of some party wall constructions typical in row houses. All these buildings are described briefly in Table 1.

Case 1: Two-Story Research House (A1)

Two fan depressurization apparatuses were installed in the house, one on the first floor and one on the second floor. For test purposes, the crawl space was treated as part of the first story. The individual air leakage characteristics of the two stories were measured directly using the balanced fan depressurization technique. After this, a routine fan depressurization test was carried out on the whole house after the obstruction of the stairwell connecting the two stories had been removed. Figure 8 shows the results of these tests; the sum of the two stories' individual air leakage rates compares very favorably (within 5%) with the air leakage rate of the whole house, which was measured directly.

Case 2: Two-Story House (H4)

The calibrated depressurization fan unit was installed in the first story of the house, as it would normally be for a routine whole house depressurization test. For the first test, the balancing fan was installed in the basement, the basement was sealed off from the rest of the house, and the air leakage rate through the first and second stories' exterior was measured with the basement pressure balanced with that of the upper floors. For the second test, the balancing fan was moved to the second story, the second story was sealed off from the rest of the house, and the air leakage rate through the exterior of the basement and first story combined was measured with the pressure in the second story balanced with that of the lower floors. For the third test, the balancing fan was removed and the total air leakage rate for the whole house was measured.

These tests provided direct measurements of Q_{1+2}, Q_{b+1}, and Q_T, which are plotted in Figure 9. Also plotted in Figure 9 are the air leakage characteristics for the three stories, Q_b, Q_1, and Q_2, calculated using the scheme described previously in Equations 2-4.

This house turned out to be the most airtight of the three HUDAC houses tested (Q_T = 2.58 ach at 50 Pa (0.2 in water), compared to 2.94 ach for H2 and 3.22 ach for H3). It also exhibited a vertical distribution of leakage area similar to the other two HUDAC houses with the basement being the leakiest story (up to 45% of the total air leakage) and the first story the most airtight (as little as 22% of the total air leakage).

Case 3: Two-Story Row House (R1)

The end unit (R1) of the two-story row house was tested with a depressurization apparatus installed in it and a balancing fan installed in the adjacent unit with which it shares a common interior wall. All the doors and windows of both the end unit and the adjacent unit were closed tightly, and a depressurization test of the end unit was carried out using the balancing fan to balance the pressures between the two units. Next, the door of the adjacent unit was opened and a second depressurization test was made on the end unit with no pressure balancing. Finally, the balancing fan was removed, its opening sealed, and the door of the adjacent unit closed tightly. A final depressurization test of the end unit was performed with no pressure balancing. The results of these three series of measurements are shown in Figure 10. They indicate that air leakage across the party wall, calculated using the scheme described previously in Equation 5, accounted for approximately 17% of the total air leakage rate (through the exterior walls and the party wall combined) as measured in tests 2 and 3. No measurable difference was observed between the results of tests 2 and 3, indicating that opening or closing of the adjacent unit's door had no effect on the measurement of the total air leakage rate in the end unit.

Case 4: Four-Story Multi-Unit Row House Units (R2 and R3)

For the measurements in the lower and upper end units (R2 and R3) of the four-story row house, a depressurization apparatus was installed in each end unit and a balancing fan was installed in the lower adjacent unit. Access was not available to install a balancing fan in the upper adjacent unit. This building has a variety of construction types for the exterior walls and the party walls and floors, and these tests provided an opportunity to measure their air leakage characteristics.

A series of five tests, summarized in Table 2, were carried out on these dwelling units. In the first test, the air leakage through the exterior of the lower end unit (Q_{V2}) was measured with the pressures in the lower adjacent unit and the upper end unit balanced with it. The second test measured the air leakage through the exterior walls and the party wall (Q_L) of the lower end unit with the pressure in only the upper end unit balanced with it. The third test measured the air leakage through the exterior walls, the party wall, and the party floor (Q_F) of the lower end unit, i.e., its total air leakage, with no balancing used. In the fourth test, the air leakage through the exterior walls (Q_{V3}) and the party wall (Q_U) of the upper end unit was measured with the pressures in the lower end unit and the lower adjacent unit balanced with it. The fifth test measured the total air leakage in the upper end unit, i.e., through its exterior and party walls and the party floor, with no balancing used. These tests provided direct measurements of Q_{V2}, $Q_{V2}+ Q_L$, $Q_{V2}+ Q_L+ Q_F$, $Q_{V3} + Q_U$, and $Q_{V3}+ Q_U+ Q_F$, respectively, which are plotted in Figure 11. Also shown in Figure 11 are the air leakage curves for Q_L and Q_F calculated from the direct measurements, and the curve for Q_{V3} calculated by assuming $Q_U = Q_L$ (due to the similar construction used in the two party walls).

The results plotted in Figure 11 indicate that the exterior envelope of the upper end unit has approximately twice as much leakage area as the lower unit's exterior envelope. The air leakage through the lower party wall accounts for approximately 18% of the lower end unit's total air leakage, while leakage through the party floor accounts for approximately 4% of that total leakage. If the assumption is valid that the air leakage through the upper party wall is the same as that through the lower party wall, then the upper party wall and the party floor contribute approximately 9% and 4%, respectively, of the total air leakage in the upper end unit.

These trends were expected due to the construction types of these various parts of the building. The majority of the lower end unit's exterior envelope is cast-in-place concrete, which should be very airtight. Two-thirds of the remaining exterior of the lower end unit is masonry construction and only the back facade, above grade, is wood frame construction. On the other hand, all the exterior of the upper end unit is wood frame construction. The floor separating the two end units is a cast concrete slab, which also should be very airtight. The masonry party wall, finished with drywall on both sides, is leakier than the cast concrete party floor, although it is more airtight than the wood frame exterior walls. Consequently, the air leakage of the lower end unit was expected to be less than that of the upper end unit for two reasons: (1) much of the lower unit's envelope is concrete and below grade, and hence very airtight, and (2) the lower unit has no exposed ceiling/roof. The wood frame exterior of the upper end unit provides a generally leakier envelope, and its exposed roof is probably its major leakage site. In the other houses measured in this study, the stories with exposed roofs were leakier than stories without exposed roofs. Exceptions were basements and crawl spaces.

DISCUSSION

The order in which the field tests were performed was deliberately chosen. By employing all the depressurization and balancing fans for the first test on each unit, the capability of the test setup to carry out the complete series of measurements was confirmed at the start of the procedure. If the simplest measurements were made at the start, a partial series of test results might be obtained before any inadequacies in the fan equipment could be discovered. Such an approach could result in a waste of expensive time in the field.

The air leakage rates at 10 Pa and 50 Pa (0.04 in water and 0.2 in water) for all the buildings and building components measured during this study are listed in Table 3. As mentioned earlier, the vertical distributions of leakage in the three HUDAC houses agree quite well with each other. This indicates that one of the objectives of the field test on house H4 was met, namely to demonstrate the use of the technique with minimum equipment. The major site for leakage in the HUDAC houses seems to be in the basement and is probably the sill joint. The distribution of leakage between the first and second stories suggests that the second most important leakage site in modern houses occurs in the upper envelope (and is often assumed to be along the eaves, through the exposed ceiling/roof). The distribution of leakage in house A1 suggests that the exposed ceiling/roof is its major leakage site. The relative leakage rates for row houses R2 and R3 suggest that the exposed ceiling/roof may be the major leakage site for that type of building as well.

This study has described the application of the balanced fan depressurization technique to measure the vertical distribution of leakage area in detached houses and row houses. It should be noted that the method is not restricted to measuring vertical leakage distributions. It can be applied equally well to measure the horizontal distribution of leakage in a building's envelope. In such applications, the various horizontal zones of interest in the house would be isolated from each other by partitions, and their pressures would be balanced with balancing fans. The procedure is a straightforward extension of those described here.

CONCLUSIONS

1. The balanced fan depressurization method may be used to measure air leakage rates through various sections of both detached houses and row houses.
2. In the HUDAC Mk XI houses, the basement contributed approximately 45%, the first story approximately 25%, and the second story approximately 30% of the total air leakage.
3. In the leaky test house, the basement contributed approximately 45% of the total air leakage.
4. The results suggest that an exposed ceiling/roof can be a major leakage site for houses and row houses. This conclusion is based on a limited number of measurements however, and, for its general application, a more extensive study is required.

5. The party walls between adjacent row houses can contribute approximately 17-18% of the unit's total air leakage.

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TABLE 1

Description of Residential Buildings Tested

	House H2, H3, H4	House A1	House R1	House R2	House R3
Type	Single, detached 2-story	Single, detached 2-story	Row house end unit 2-story	Row house lower end unit, 2-story	Row house upper end unit, 2-story
Floor Area, m^2	118	195	109	85.5	101.1
Ceiling Area, m^2	63.7	97.5	56	39	54.3
Volume, m^3 (including basement)	386	520	375	208	274
Outside envelope area, m^2	228	316	162	65.3	166.5
Outside wall area, m^2	164	218	106	65.3	112.2
Window area, m^2	15.5	17.0	7.7	6.4	9.2
Outside door area, m^2	4.2	5.6	8.1	5.9	3.9
Length of sash crack, for window, m	67.6	93.3	35.3	35.9 (incl. doors)	49.8 (incl. doors)
Exterior wall finish	Brick veneer and aluminum siding	Brick veneer, concrete block plaster, and wood siding	Brick veneer and vinyl siding	Wood siding, concrete, and plaster	Wood siding
Interior wall finish	Plasterboard	Plasterboard	Plasterboard	Plasterboard	Plasterboard
Vapor barrier	Complete polyethylene vapor barrier	Partial polyethylene vapor barrier	Complete polyethylene vapor barrier	Complete polyethylene vapor barrier	Complete polyethylene vapor barrier
Airtightness @ 50 Pa (ach)	2.6 – 3.2	7.5	7.0	3.5	5.0
Window	Triple-glazed, wood frame, casement	Double-glazed wood frame removable	Double-glazed wood casement	Double-glazed wood awning	Double-glazed wood awning

TABLE 2

Summary of Tests Performed on Row Houses R2 and R3

Test	Unit Tested	Measured Flow Rate	Balanced Units
1	Lower end unit	Q_{V2}	Lower adjacent unit Upper end unit
2	Lower end unit	$Q_{V2}+Q_L$	Upper end unit
3	Lower end unit	$Q_{V2}+Q_L+Q_F$	------
4	Upper end unit	$Q_{V3}+Q_U$	Lower end unit Lower adjacent unit
5	Upper end unit	$Q_{V3}+Q_U+Q_F$	------

Q_{V2} = leakage flow rate through exterior envelope of lower end unit

Q_{V3} = leakage flow rate through exterior envelope of upper end unit

Q_L = leakage flow rate from lower adjacent unit to lower end unit through lower party wall

Q_U = leakage flow rate from upper adjacent unit to upper end unit through upper party wall

Q_F = leakage flow rate between upper end unit and lower end unit through party floor.

TABLE 3

Component Air Leakage Rates at 10 and 50 Pa

		10 Pa		50 Pa		
House	Component Leakage Tested	Leakage Rate (L/s)	Air Change Rate[1] (ach)	Leakage Rate (L/s)	Air Change Rate (ach)	Fraction Total Leakage[2]
H2 (386m^3)	Q_T	109	0.282	315	2.94	
	Q_{b+1}	74	0.192	215	2.01	0.68
	Q_{1+2}	62	0.161	180	1.67	0.57
	Q_b	47	0.122	134	1.25	0.43
	Q_1	27	0.070	77	0.72	0.25
	Q_2	35	0.091	102	0.95	0.32
H3 (386m^3)	Q_T	113	0.293	345	3.22	
	Q_{b+1}	75	0.194	229	2.14	0.66
	Q_{1+2}	62	0.161	191	1.78	0.55
	Q_b	51	0.132	156	1.45	0.45
	Q_1	25	0.065	75	0.70	0.22
	Q_2	37	0.096	115	1.07	0.33
H4 (386m^3)	Q_T	90	0.233	277	2.58	
	Q_{b+1}	63	0.163	193	1.80	0.70
	Q_{1+2}	53	0.137	163	1.52	0.59
	Q_b	37	0.096	114	1.06	0.41
	Q_1	26	0.067	79	0.74	0.29
	Q_2	27	0.070	84	0.78	0.30
A1 (520m^3)	Q_T	305	0.587	1080	7.48	
	Q_{b+1}	131	0.252	467	3.23	0.43
	Q_2	177	0.340	625	4.33	0.58
R1 (375m^3)	Q_T	220	0.587	733	7.04	
	Q_{V1}	183	0.488	608	5.84	0.83
	Q_{PW}	37	0.099	125	1.20	0.17
R2 (208m^3)	Q_T	65	0.313	204	3.53	
	Q_{V2}	51	0.245	160	2.77	0.78
	Q_L	12	0.058	36	0.62	0.18
	Q_F	3	0.014	8	0.14	0.04
R3 (274m^3)	Q_T	119	0.434	382	5.02	
	Q_{V3}	104	0.380	332	4.36	0.87
	(Q_U)	11	0.040	36	0.47	0.09
	(Q_F)	5	0.018	15	0.20	0.04

10 Pa = 0.04 in.water, 1 L/s = 2.119 cfm, 1 m^3 = 35.3 ft^3

1. Normalized with respect to the total internal volume.

2. Normalized with respect to the total leakage rate Q_T.

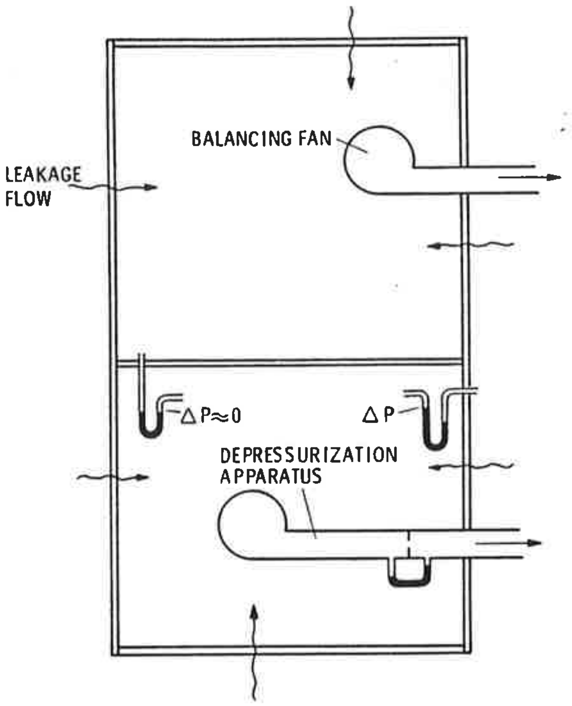

Figure 1. Schematic of the setup for a balanced fan depressurization test

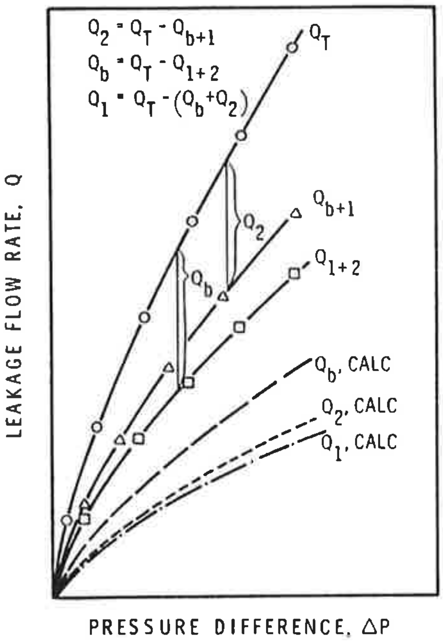

Figure 2. Illustration of calculation method and typical measurement results for indirect application of the balanced fan depressurization technique

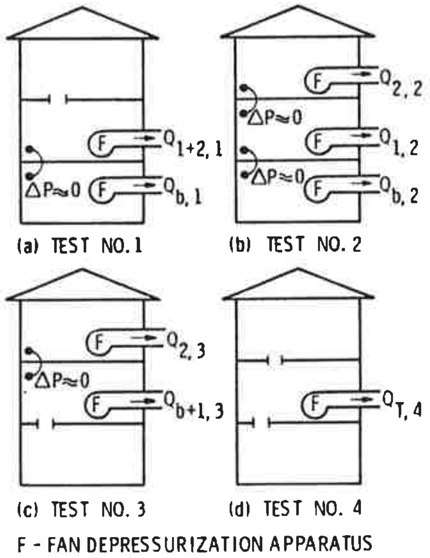

Figure 3. Schematic test setup for controlled field tests

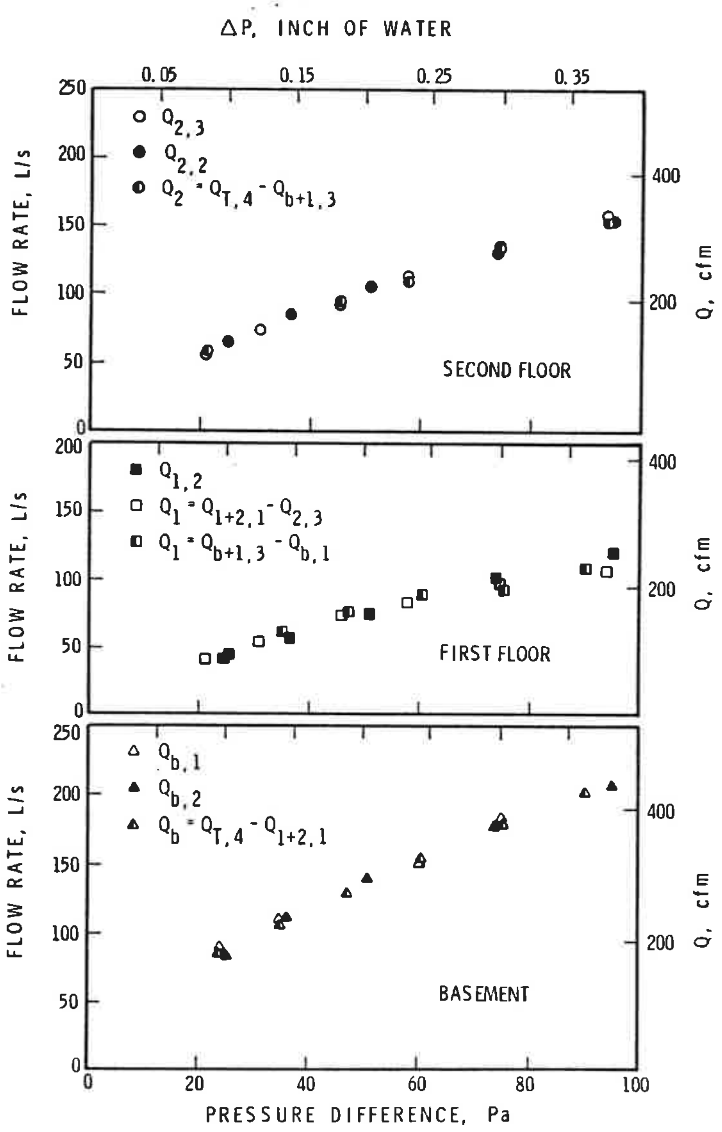

Figure 4. Air leakage characteristics for individual stories of test house H2

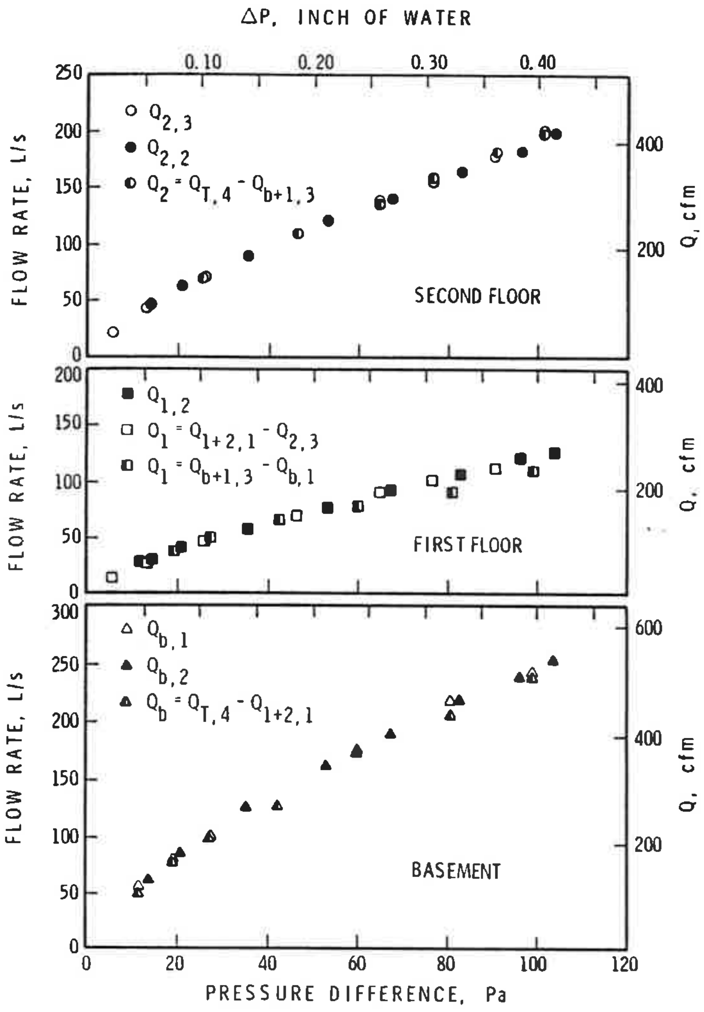

Figure 5. Air leakage characteristics for individual stories of test house H3

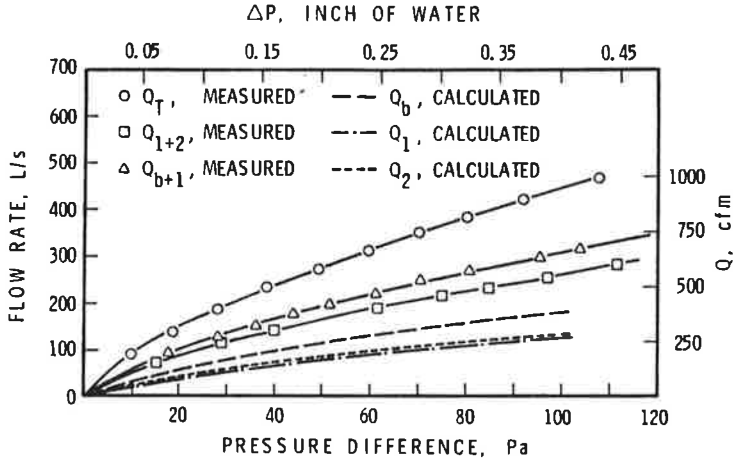

Figure 9. Air leakage measurements in test house H4

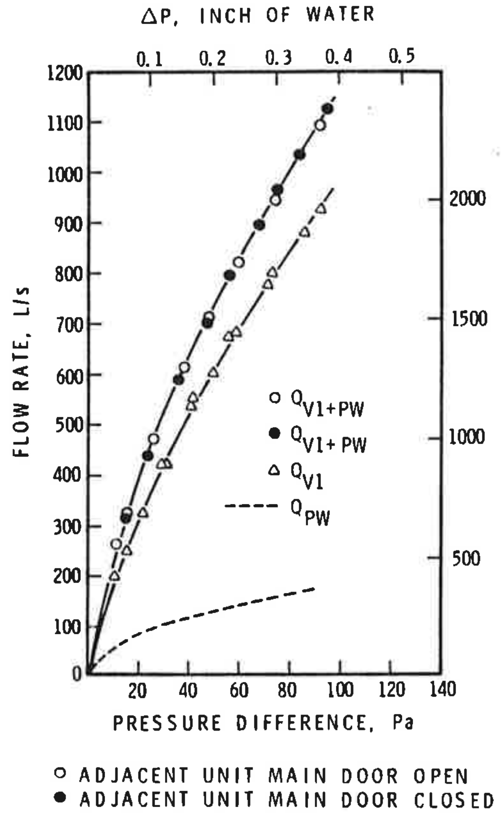

Figure 10. Air leakage measurements in the two-story row-house end unit R1

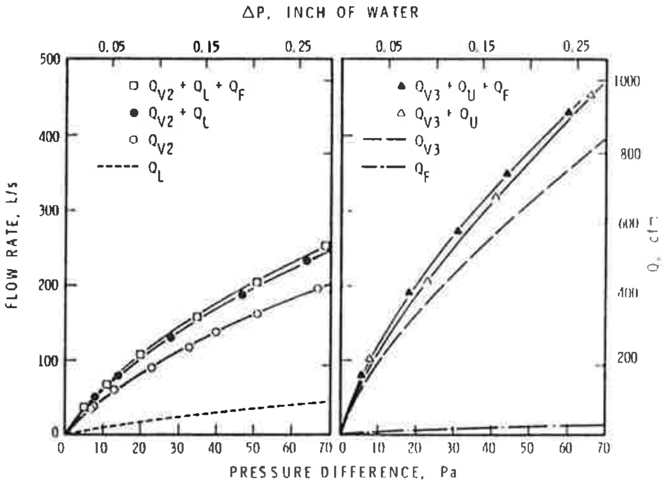

Figure 11. Air leakage measurements in the four-story row-house end units R2 and R3

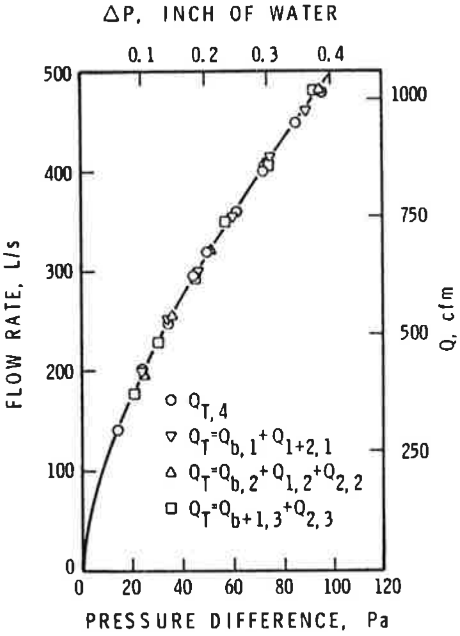

Figure 6. Total air leakage characteristics of test house H2

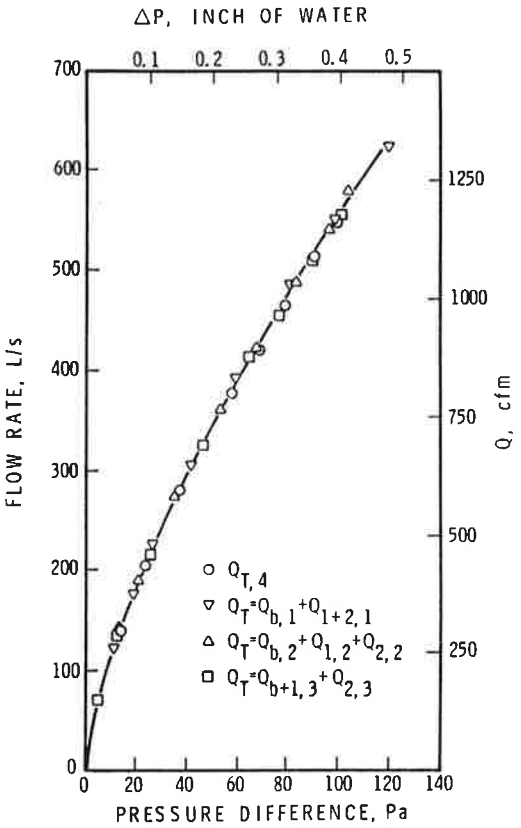

Figure 7. Total air leakage characteristics of test house H3

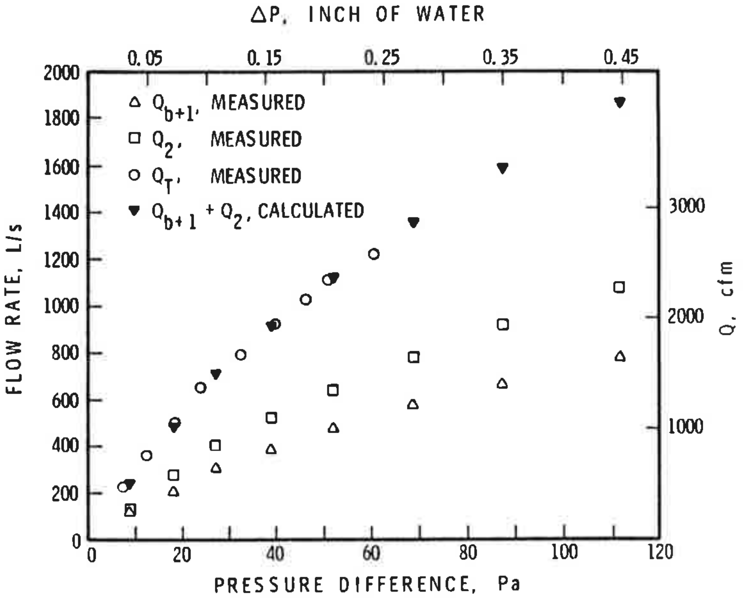

Figure 8. Air leakage measurements in the research house A1