METHODOLOGY AND RESULTS OF BLOWER DOOR TESTING IN SMALL MULTI-FAMILY BUILDINGS

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ABSTRACT

The determination of natural infiltration rates in multi-family buildings has been subject to the same uncertainties found in single-family residences. While the use of blower door testing has enabled analysts to develop reasonable estimates of infiltration rates in single-family buildings, these methods cannot be directly applied to multi-family buildings.

1. Blower door testing methodology assumes that the building performs as a single zone with respect to air movement and air pressure distribution. This is clearly not the case in multi-family buildings.
2. During blower door pressurization/depressurization tests, a substantial portion of the observed air leakage is through common walls into neighboring units. This transfer of conditioned air does not effect the overall heat loss rate.
3. The exterior exposure in individual units which share floors, ceilings or walls with adjacent units is substantially less than in single-family residences. This results in significantly less surface to volume ratio, subsequently smaller relative wind effects resulting from more shielding, and lower infiltration rates.

A methodology was developed to adjust data from standard blower door tests to account for these problems and to arrive at an estimate for infiltration rates in multi-family buildings. This technique relies on pressurizing individual units and uses "smoke sticks" to assess the degree to which leakage is occurring in common walls between units. Through this process, a methodology was derived for reducing the effective leakage area, and thus, correcting the blower door results to arrive at a more accurate estimate and a bracketed range of possible values for the leakage area and air infiltration on a unit-by-unit basis in small multi-family buildings. The method was applied to several new two and three story multi-family buildings in the Pacific Northwest and compared with alternative methods of infiltration measurement.

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INTRODUCTION

Air leakage measurements in residences are extremely important to predict future heating requirements of a building and the impact of energy conservation measures on long-term performance. Furthermore, infiltration and ventilation control has become an area of great concern as information on indoor air quality becomes more available and present building techniques further reduce the amount of fresh air introduced by air leakage in the building envelope. In single-family residences, the use of a blower door fan depressurization test has proved very useful, especially in providing an index of the airtightness of a building exterior envelope. This has been made much more useful through the introduction of calculation techniques which take into account weather conditions during the heating season (i.e., wind speed, temperature, and air density) along with blower door depressurization data to generate an estimate of long-term infiltration rates. For single-family residences, some uncertainty remains regarding the interpretation of the results of these tests and their applicability to predict long-term air change rates in houses, but this uncertainty is minor compared to the problem of applying blower door techniques to multi-family (and multi-cellular) buildings.

A testing and calculation procedure was developed to estimate the amount of natural air infiltration in new multi-family buildings from data collected during unit-by-unit blower door depressurization tests. A single blower door and a "smoke stick" were employed to assess the leakage sites throughout the unit. This methodology relied on a calculation procedure derived from work performed at the Lawrence Berkeley Laboratory (LBL) (Grimsrud, et.al., 1982). To use this procedure, equations related to the allocation of leakage area were modified to allow adjustment for interzone leakage areas observed during the testing, which were included as part of the effective leakage area (E.L.A.) by the blower door evaluation. By carefully accounting for the location and size of leakage points in each unit, the blower door results were adjusted to account for leakage between apartment units. This made it possible to estimate an upper and lower bound of the natural infiltration rate of each unit and the entire building.

The model developed here is intended for application to small apartment buildings or "motel-style" buildings with individual exterior entrances for each unit. Typically, "platform" construction techniques were used in these buildings, with continuous glued floors and minimal plumbing and wiring chases to reduce interzone leakage. The central assumption is that each cell is largely independent with negligible "whole building" effects relating to stack- and wind-driven infiltration. Thus, each unit has a separate and unique neutral pressure zone.

The literature on blower door infiltration testing in multi-family buildings is limited, especially where interzone leakage is identified or modeled. Few results have been published (Modera, et.al., 1985, Diamond, et.al., 1986). Furthermore, the methodology proposed in this literature centers on a multi-zone evaluation using multiple blower doors simultaneously. This results in a series of input parameters to a simulation which is then developed to derive an infiltration rate simultaneously among the various apartment units. While such a method is potentially accurate (or at least internally consistent) it presents problems as a field tool for evaluating infiltration rates in multi-family buildings.

1. Multiple blower doors require more operators and coordination than typically available to a "blower door contractor".
2. The number of tests required for a relatively simple apartment building is quite large. In a three-story, 12-unit building with exterior entrances for each apartment which open off a central corridor, for example, up to 41 tests would be required using a two blower door technique, to get all combinations of adjacent units.
3. The number of doors required severely limits the application of these techniques for documenting construction tightness, Code compliance or air leakage diagnostics (the most common reasons for conducting blower door tests in residential buildings).

The remaining literature on blower door pressurization/depressurization focuses on the blower door as an indicator of building tightness but does not correct for interzone leakage. (See Harrje, et. al., 1983, Bohac, et. al., 1987) All of these efforts as well as numerous others use tracer gas techniques to assess the magnitude of the problem and apply multi-cellular evaluation to assess the overall impact. This is of course necessary if an accurate assessment is to be made. Like the multiple blower door methods the ability of private contractors or code officials to apply this type of evaluation in short term field tests is limited. There remains a need for a simplified method which can be used to assess air leakage in multi-family buildings for purposes of construction diagnostics or overall quality assurance.

The methodology described below is designed to develop an infiltration estimate which can be compared to other buildings and air leakage standards, and can be used to estimate overall heat loss rates as a part of simplified energy performance analysis (e.g., SUNDAY® or WATTSUN®). A second goal was to evaluate a method for use by building inspectors to evaluate compliance to a building standard which limits allowable air leakage in the building shell. The work was conducted in three jurisdictions that have adopted the Northwest Model Energy Code as a part of the Bonneville Power Administration's (BPA) Early Adopter Program.

The methodology developed here is designed to be applied to the style of apartment developments typical in new developments in the Pacific Northwest. The developments are characterized by complexes of buildings, two- to three-stories, with eight to sixteen units per building. In most cases, each unit has an exterior door opening onto an open corridor or stairwell. This methodology was also applied with some success to buildings with a limited, enclosed corridor which could easily be opened to the outside.

These buildings were new and, in most cases, unoccupied, and were constructed with the express intent of limiting incidental infiltration rates to .35 ACH. Air-to-air heat exchangers were present in most of the buildings and all construction employed either airtight drywall techniques or a plastic vapor barrier as infiltration control. Compliance inspections were made under the Super Good Cents and Early Adopter programs during installation of infiltration control measures. Infiltration rates were low and leakage between units represented a relatively small fraction of the total effective leakage area as measured by a blower door test.

In these buildings, the common wall leakage area typically represented approximately 25% of the total leakage area. Since most units tested have a windward and leeward side, the wind driven infiltration component has been assumed to apply only to the leakage areas on the exterior surfaces, with the impact of the common wall leakage confined to the stack driven infiltration rate.

METHODOLOGY

Blower door tests were performed in each unit of these multi-family buildings using identical procedures. During the testing, a "smoke stick" was used to locate and measure the length and observe the relative width of all cracks in the sills, windows, doors and around the shower or bathtub. All outlets were examined for leakage and recorded by their locations on interior, exterior or common walls. Ceiling fixtures and plumbing penetrations were examined for leakage and recorded. Leakage around the air-to-air heat exchanger (AAHX), blower door, fireplace, bathroom fans, and electric panels was measured once and assumed to be constant throughout the units in each building unless noticeably different upon inspection. Openings were accounted for either by estimating an equivalent length of crack or square inches of opening.

Separate tests were conducted with major openings, such as fireplaces or bathroom fans, sealed off to determine the proportion of the total leakage area which should be assigned to these components.

Leakage area and crack lengths were then allocated by percentage of total leakage to exterior walls, ceilings, floors and common walls:

1. Floor leaks were assumed to be leaks at the sill or around the bottom of doors.
2. Ceiling leaks include all leakage driven by stack effects; i.e., fireplace damper, chimney leaks, attic hatches, ceiling fixtures, bathroom fans, duct leaks from attic duct runs, and air leaking into interior walls and driven into the attic.
3. Exterior wall leaks are wind-driven and include window cracks, exterior wall outlets and any other leakage occurring on exterior walls.
4. "Common walls" were walls, ceilings, or floors separating units. Leakage into interior partition walls was assigned to the "common wall" accounting except on the top floor, where it was equally divided between "common wall" leakage and ceiling leakage. A specific common wall leakage site identified during the inspection may or may not result in air leakage to the outside (through chases, wiring channels, etc.) Since this cannot be determined, the common leakage area estimate is used to set the lower bound of the leakage area estimate (assuming the actual value is somewhat higher).

We assumed that wind effects on interior and common walls were negligible, given the unit-by-unit exposure and the small leakage area between units. Thus all the leakage identified in the common wall was assigned to either "floor" or "ceiling" and used in calculating the stack parameter only. The only observable path by which air could proceed directly outside from the common wall was through the joist space and then through the rim joists or follow the plumbing chases to the building's attic. Since most of the actual leakage was near the floor (outlets and sill plates), it did not seem reasonable to assign the entire area to the ceiling. To account for this, we assigned 80% of the interior and common wall leakage to ceiling leakage and 20% to floor leakage. Sensitivity analysis was performed to assess the impact of this assumption. In estimating the infiltration rate for the whole building or an individual unit, the variation due to this assumption was less than ±8% unless all of the leakage was assigned to either the floor or the ceiling. In the latter case, a 30% reduction in predicted air change rate was observed.

Calculations for maximum, minimum and estimated values were made by adjusting that percentage of the total infiltration rate allocated to common or interior walls as defined below:

1. The maximum infiltration rate assumes all of the common wall leakage area exits the building. This is the rate indicated by the initial blower door test before any adjustments are made.
2. The minimum infiltration would occur if all of the common wall leakage is transferred from one heated unit to another.
3. The estimated leakage is defined as the overall infiltration rate if 1/2 of the interior and common wall leakage area is neglected. This estimate was arbitrary; however, it seems to be consistent with the observations made on site.

CALCULATION PROCEDURE

The calculation procedure proposed by Grimsrud, et.al. (1982) relies on simplifying the relationship between flow and pressure as measured by the blower door:

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

where

Q = the flow through the fan

ΔP = the pressure difference across the building shell at that flow rate

C = emperical constant

n = emperical constant

Since air infiltration in a particular house is a function of both stack effect (due to temperature differences between inside and outside) and wind effect (due to differential pressure between windward and leeward sides of the building), two factors were necessary to describe the distribution of leakage. The fraction of total leakage at the floor and ceiling is labeled "R", and the difference between the ceiling and floor fractions is labeled "X".

The equations used to calculate the <u>minimum</u> possible leakage rate (neglecting all common wall leakage) is shown below:

$$R_{\min} = L_c + L_f$$

$$X_{\min} = L_c - L_f$$

where

L_c = Percentage of total leakage at ceiling

and

L_f = Percentage of total leakage at floor

For the maximum possible leakage (assuming all common wall leakage is exiting the building, and assigning 80% to ceiling and 20% to floor leakage), the following equations were used:

$$R_{\max} = L_c + L_f + L_{com}$$

$$X_{\max} = [L_c + (0.8 \cdot L_{com})] - [L_f + (0.2 \cdot L_{com})]$$

where

L_{com} = Percentage of total leakage in common walls

The equations used to calculate the "estimate" value assume 50% of the common wall leakage to be active:

$$R_{est} = L_c + L_f + \left[\frac{L_{com}}{2}\right]$$

$$X_{ext} = L_c + (0.3 \cdot L_{com}) - L_f$$

These factors are then used to calculate maximum, minimum and estimate values for the wind and stack parameters.

Because the LBL methodology was developed as a single-zone model, a single building height value is used for both wind and stack effects. However, under the methodology used for these multi-family buildings, each unit was considered separately. Current multi-family building practices utilize the "platform" construction method, where stories are built one at a time with a continuous glued floor between each level. Therefore, the ability for air to move from one floor to another is significantly reduced from the older "balloon" framing techniques. All but one of the apartment buildings examined in this report had exterior entrances and no interior stairways or corridors, and all had individual heating systems. This further reduces the possible creation of whole building stack effects from stairwells or heating chases. In addition, Code requires all penetrations be sealed and dictates large amounts of fire blocking. Therefore, we have assumed that the stack height of each unit (the floor to ceiling height) will determine the stack parameter. The wind effect is governed by the height of the walls above grade, so the height used in the calculations of wind effects for each unit is the height of the ceiling above grade. The stack and wind parameter specifications were therefore altered to use two different heights. The stack parameter F_s is:

$$F_s = \frac{1}{3}\left(1 + \frac{R}{2}\right)\left(1 - \frac{X^2}{(2-R)^2}\right)^{\frac{3}{2}}\left(\frac{gH_s}{T}\right)^{\frac{1}{2}}$$

where

$g =$ acceleration due to gravity (9.80665 m\sec2)

$H_s =$ height of stack (m)

$T =$ thermostat set point $(°K)$

and the wind parameter F_w is:

$$F_w = C_b(1-R)^{1/3} \times \left[\frac{Z_b\left(\frac{H_b}{10}\right)^{Y_b}}{Z_m\left(\frac{H_m}{10}\right)^{Y_m}}\right]$$

where

$C_b =$ shielding coefficient of the unit

$Z_b, Y_b =$ terrain parameters of unit

$Z_m, Y_m =$ terrain parameters of wind measurement site

$H_b =$ height of ceiling above grade (m)

H_m = height of wind measurement site above grade (m)

The terrain parameters were taken directly from the LBL Methodology (see Grimsrud, et. al., 1982) while the shielding coefficient was adapted to account for the self-shielding nature of multi-family buildings, with each unit assigned a shielding factor according to the number of sides that were exposed to the wind. In buildings with moderate local shielding, units with two exposed sides were assigned to shielding class V; for units with three exposed sides, a class of IV was used, and for units with four exposed sides, a class of III was used. This procedure was modified for buildings with light local shielding, lowering the shielding class for each unit one step.

Wind data was used from standard airport weather sites with wind speed indicators located 10 meters above grade, and we assumed airport terrain factors (Z_m) of 1.00 to simplify the general wind parameter equation to:

$$F_w = C_b(1-R)^{\frac{1}{3}}(Z_b)\left(\frac{H_b}{10}\right)^{Y_b}$$

Three values were determined for each of these parameters using the maximum, minimum and estimated values for R and X.

Weather data was then examined for each site and average wind speed and indoor-outdoor temperature differences were calculated for the eight primary heating season months (October through May). This data was used with each of the three wind and stack parameter values to arrive at the final estimates of leakage rates.

FINDINGS

This procedure has been applied to 10 multi-family buildings. The maximum, minimum, and estimated infiltration rates for each building are summarized in Table I. Nine of these were constructed under the Early Adopter Program in Cheney, Washington, Tacoma, Washington and Idaho Falls, Idaho. One is a new building in Kirkland, Washington built under the 1986 Washington State Energy Code.

Some independent assessment of this method and the assumptions of leakage area allocation was possible. The eight-unit apartment building in Idaho Falls was arranged in such a way that each unit opened into a small central entry area with a single door to the outside. We tested each of the unit types using the procedures outlined in this report. We then opened all the unit doors, placed the blower door in the entry door and tested the entire building at once. We assumed the additional leakage area and volume of the entry area to be negligible and so were able to directly compare the results of the single test to the weighted sum of the individual units. The unit-by-unit method yielded a maximum leakage rate of 0.30 ACH, a minimum of 0.16 ACH and a final estimate of 0.24 ACH. The entire building test yielded a value of 0.22 ACH.

Table I: Infiltration measurement results.

SITE	NO. OF UNITS	MAXIMUM LEAKAGE RATE (ACH)	MINIMUM LEAKAGE RATE (ACH)	ESTIMATED AVG. LEAKAGE AREA
Tacoma 1	6	0.32	0.28	0.30
Tacoma 2	8	0.25	0.22	0.23
Tacoma 4	12	0.22	0.17	0.19
Tacoma 5	10	0.24	0.17	0.21
Tacoma 6	10	0.20	0.14	0.17
Cheney 4	4	0.13	0.08	0.11
Cheney 5	4	0.10	0.05	0.08
Kirkland 1	12	0.23	0.15	0.19
Idaho Falls 1	8	0.30	0.16	0.24
Idaho Falls 1*	8			0.22 *

* Idaho Falls building was re-tested using a single blower door test for the entire building.

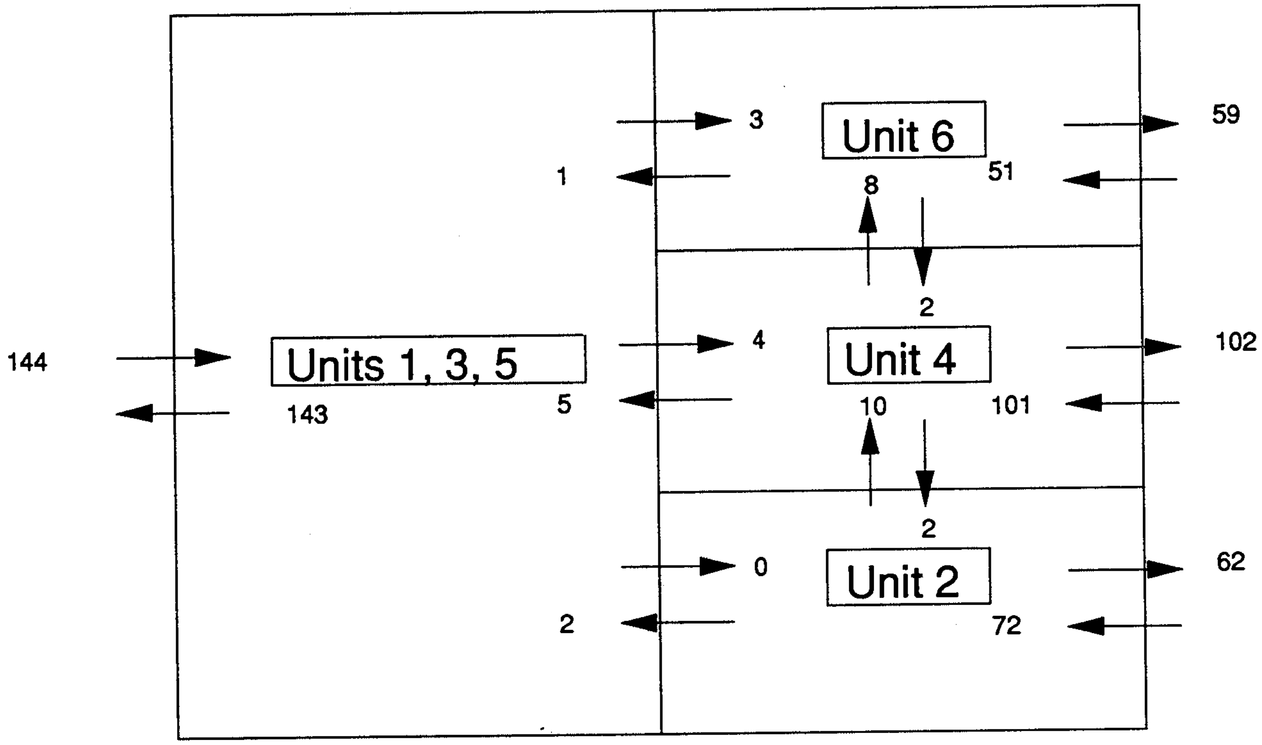
In the Tacoma 4 building, additional tests were also performed. Short term tracer gas decay tests were conducted in November of 1987 on six of the 12 units. A single gas was used and the units were tested sequentially, so no effort was made to adjust for interzone leakage. For each test the unit was injected with a tracer gas, mixing fans were used to maintain a uniform concentration throughout the unit, and the concentration decay was monitored for approximately one hour. Blower door predictions were corrected for the temperature and wind conditions present during the test. This comparison suggests that the boundaries on the leakage developed by this method are relatively consistent with the tracer gas results. (See Table II).

A four-zone PFT test was conducted on the same Tacoma building. Six identical adjacent units were tested with four distinct types of gas. These six units were divided into two columns, three units high. The units on one side were each given a unique gas source, the units on the other side were all given a fourth gas type. Figure 1 illustrates the total flows observed between the six identical adjacent units. All of the units had air-to-air heat exchangers. In some of the units, the AAHX's operated continuously so that flows to the outside were elevated by 70 to 100 cfm for the entire three week test period. Since these devices were "balanced", however, relatively little impact on interzone air transfer might be inferred.

Table II: Comparison of the results of short-term tracer gas tests with blower door tests in one multi-family building (Tacoma 4).

	AIR CHANGES PER HOUR (ACH) (CORRECTED)			TRACER GAS RESULTS
UNIT NO.	MAX	MIN	ESTIMATED	ACH
3	.27	.21	.24	.25
5	.32	.23	.28	.24
6	.43	.33	.38	.35
8	.16	.13	.14	.20
9	.19	.12	.16	.21
12	.35	.31	.33	.33
Volume Weighted Average	.28	.22	.25	.26

Figure 1: Average airflow in CFM for six multi-family units in Tacoma, Washington from 23 February 1988 through 15 March 1988.



The magnitude of the interzone air leakage, as shown, is 10% to 20% of the overall leakage in absolute terms, which is reasonable for this construction type. The stack effects could be inferred from the vertical flow between units 2 and 4, and between units 4 and 6. The total impact on all three units appears to be .04 ACH on the total volume of the units. When all three units are taken together, the impact of air movement laterally is approximately half that size. This outcome supports the assumption that wind-driven air flow laterally between units would be minimal. The stack effect dominates the interzone flow. The absolute volume of all air flows is larger than was predicted by the blower door methodology for both infiltration and interzone air flow. This is most likely due to the use of mechanical ventilation during the testing period, however, we do not have sufficient data to evaluate the PFT results in this context. While these results are instructive, they are inconclusive.

CONCLUSION

The procedure provides a useful bracket on the estimated seasonal infiltration in multi-family units and buildings. These estimates are subject to the same uncertainty that surrounds all blower door evaluations, especially the impacts of the average outdoor temperature and wind speeds. Nevertheless, accuracy of the procedure is within an allowable range, and provides a much simpler means of determining overall infiltration than other reported methods. The use of a single blower door and some software to facilitate the calculations allow this procedure to be used by both independent blower door contractors and building inspectors. As a result, it shows great promise in providing a methodology to facilitate Code compliance inspections.

The procedure does present some problems:

1. The smoke stick will assess the location of leaks, but the size of the leaks relative to other cracks and holes in the envelope is very difficult to determine.
2. While common walls, floors and ceilings may be leaking between units, there are also rim joists and other wiring and plumbing stacks which allow common wall leakage to migrate into the exterior shell to vent directly outside. As a result, it is difficult to accurately estimate the percentage of common wall leakage that is actually contributing to infiltration.
3. The procedure may not be appropriate for older buildings with large amounts of leakage into common walls or large buildings with interior stairwells and halls, since it depends on the assumption that air flow between units is small for purposes of computing overall infiltration rates.

This procedure can, however, bracket the estimated leakage area with a high value that is derived directly from the blower door test and ignoring common wall leakage, and the low value being the air infiltration rate derived from the blower door test with the common wall leakage removed from the formula. An intermediate estimate can be derived from the blower door auditor's most probable estimate of the ratios between common wall leakage between zones, and that which vents directly outside. The subjective estimate of the common wall leakage area appears to be adequate to estimate the maximum proportion of the leakage area in each unit for buildings of the configuration surveyed. Using the estimate in this case as a lower limit appears reasonable and consistent with the tracer gas test results. More work is needed to establish this method; however, it appears to offer a promising method to perform field evaluations on small multi-family buildings.

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