SIMPLIFIED MULTIZONE BLOWER DOOR TECHNIQUES FOR MULTIFAMILY BUILDINGS

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A NYSERDA Report in Brief

Report: **Simplified Multizone Blower Door Techniques for Multifamily Buildings Report No. 95-16**

Project Manager: **Norine H. Karins**

Contractor: **Steven Winter Associates**

Background: This report describes the results of a study that examined the applicability of two- blower-door and single-blower-door multizone pressurization techniques for estimating the air-leakage characteristics of New York State multifamily buildings. The research investigated the magnitude of external leakage areas, and used computer simulations to estimate the effect on air infiltration rates of decreasing external and internal leakage areas. The research also examined whether two blower doors can be used to determine the equivalent leakage area (ELA) of the exterior envelope, and the ELA of partitions. Two multizone versions of the single-door pressurization method also were investigated.

Objectives: The project's objectives were to refine and validate a test method that uses two blower doors to estimate air-leakage characteristics of low-rise, multifamily buildings and to determine the leakage of a multizone building's entire envelope. Tests were performed on two three-story, six-apartment buildings in Brooklyn.

R&D Results: Using air-tightness expertise of Lawrence Berkeley Laboratory (LBL), this project refined and applied the two-door fan pressurization technique to determine the external and interzonal leakage in two low-rise apartment buildings. The protocols involved the use of the ASTM E 779-88 blower-door measurement technique, as well as the techniques discussed in the similar Canadian standard (CGSB 149).

The results of the research indicate that measurements with two blower doors can be used successfully to quantify the external and interzonal air leakage in multifamily buildings. One version of the multizone single-blower-door method was found to be useful in quantifying the external air leakage from each apartment, and in estimating the amount of the interzonal air leakage when the interior partitions are not tight relative to the exterior envelope. Research results also indicated that the total interzonal leakage area was of comparable magnitude to the external leakage area. Consequently, interzonal leakage cannot be ignored when performing blower door tests.

Measurements using two blower doors yielded much more useful information than the single-zone, single-door technique (ASTM E 779-88) currently used by energy auditors. The two-door method allows the user to estimate air infiltration/exfiltration rates, which cannot be calculated based on ASTM E 779-88 data. The two-door method is faster than the multiple-blower-door method, but still requires substantial time. The two-door method is primarily useful for research (i.e. characterizing the building stock) and special situations. The two-door method can be used to assess whether weatherization of interior partitions should be recommended to reduce air infiltration rates and whether communication with the boiler room creates widespread problems. Specifically, the two-door method can be used on a large sample of buildings to characterize the air leakage and contaminant flow in the buildings.

Copies Available: A limited number of copies of the full report are available from the New York State Energy Research and Development Authority, 2 Empire State Plaza, Suite 1901, Albany, New York 12223-1253; (518) 465-6251, ext. 241.

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SIMPLIFIED MULTIZONE BLOWER DOOR TECHNIQUES FOR MULTIFAMILY BUILDINGS

Final Report

Prepared for

THE NEW YORK STATE
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ABSTRACT

This research focused on the applicability of (a) two-blower-door and (b) single-blower-door multi-zone pressurization techniques for estimating the air leakage characteristics of New York State multi-family apartment buildings.

The research also investigated the magnitude of external leakage area in multi-family buildings and used computer simulations to estimate the effect of decreasing external and internal leakage areas on air infiltration rates.

The single-blower-door pressurization technique described in ASTM E 779-88 is currently used in single-zone dwellings, such as slab-on-grade single family homes, to estimate the equivalent leakage area (ELA) of the building envelope (roofs, walls, floors). This single-zone, single-blower-door pressurization technique yields incomplete information when applied to multi-zone dwellings, such as apartment buildings. Specifically, the ELA includes both exterior surfaces and partitions between apartments. However, the ELA of interior partitions must be defined separately from that of the exterior envelope. Currently, the two ELAs can be determined with a complex, expensive and time-consuming technique that uses multiple blower doors. The technique is impractical.

This research investigates whether two blower doors can be used to determine the ELA of the exterior envelope and the ELA of partitions. Two multi-zone versions of the single-blower-door pressurization method are also examined.

Tests were performed on two 3-story buildings containing six apartments each, located in Brooklyn, New York. The results of the research indicate that measurements with two blower doors can be successfully used to quantify the external *and* interzonal air leakage in multi-family apartment buildings. One version of the multi-zone single-blower-door method was found to be useful in quantifying the external air leakage from each apartment, and in estimating the amount of the interzonal air leakage when the interior partitions are *not* tight relative to the exterior envelope.

The two-door method is faster, less complex and less expensive than the multiple-blower-door method, but still requires substantial time to apply. Because of its cost, the two-door method appears to be useful mostly to determine the characteristics of the building stock, and as a baseline against which to finalize the development of the multi-zone single-door method. The multi-zone single-door method is faster to apply than the two-door method. When fully developed, the multi-zone single-door method will be suited for use by energy auditors and weatherization crews.

Finally, this research indicated that window replacement can yield significant reductions in air leakage rates.

Keywords: air leakage, air tightness, blower door, leakage area, multi-family, pressurization, weatherization

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The Steven Winter Associates, Inc. team included Adrian Tuluca, R.A., Dennis O'Keefe, Jawad Zaidi, P.E., Ph.D., and Devashish Lahiri. The Lawrence Berkeley Laboratory team included Mark Modera, Ph.D., Darryl Dickerhoff, David Jump, Ph.D., and Max Sherman, Ph.D.

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Background

The single-blower-door pressurization technique described in ASTM E 779-88 is successfully used in single-zone dwellings, such as slab-on-grade single family homes, to estimate the equivalent leakage area (ELA) of the building envelope (roofs, walls, floors). The ELA is then employed to calculate the air leakage during the year and the effect of this air leakage on ventilation and energy consumption.

The same single-zone single-blower-door pressurization technique yields incomplete information when applied to multi-zone dwellings, such as apartment buildings. If one apartment is pressurized, the ELA obtained represents the sum of the ELAs of (a) the exterior envelope; (b) walls, ceilings and floors between this apartment and adjoining apartments; and (c) interstitial spaces, such as chases, that may be coupled to the outside, to other interior spaces, or to both.

However, it is important to distinguish between the ELA of the envelope and the ELA of partitions and interstitial spaces. Both figures are required to calculate the air leakage of the building and the effect of this air leakage on ventilation and energy use. Further, the ELA of interior partitions can be used to predict the air movement within the building and, therefore, the propagation of odors, smoke and radon.

The multiple-blower-door pressurization method has been found to yield all the data needed to estimate the ELAs. To this end, each apartment adjoining the one tested is also pressurized with a blower door. High cost and difficulty of coordination makes this method impractical.

This research investigated whether two blower doors could be used to determine the ELA of the envelope and the ELA of partitions. Two multi-zone versions of the single-door pressurization method were also examined.

Objective

This research focused on examining the applicability of (a) two-blower-door pressurization techniques and (b) single-blower-door multi-zone pressurization techniques for estimating the air leakage characteristics of New York State multi-family apartment buildings.

The research also investigated the magnitude of external leakage area in multi-family buildings and used computer simulations to estimate the effect of decreasing external and internal leakage areas on air infiltration rates.

Research

To achieve these goals, 10 tasks were undertaken:

1. Develop a preliminary protocol.
2. Identify and select two low-rise multi-family buildings.
3. Conduct pre-weatherization field measurements.
4. Perform pre-weatherization data analysis.
5. Conduct post-weatherization field measurements.
6. Perform post-weatherization data analysis.
7. Evaluate the air leakage reduction attributable to weatherization measures.
8. Evaluate the ventilation rates in each building before and after weatherization.
9. Produce a final report.
10. Participate in ASTM Standard proceedings.

Two apartment buildings located in Brooklyn, New York, were tested: 1348 Willoughby Avenue and 347 Grove Street. The buildings are over 50 years old and house low income tenants. Each building is part of a row of similar buildings, to which it is joined on both sides by fire separation walls. Each building has three stories with a central hallway and two apartments per floor, for a total of six apartments. The Willoughby building has tight masonry walls between apartments. The Grove building has loose walls between apartments (plaster-on-wood studs).

The windows in both buildings were in poor condition. Air leakage rates in apartments were calculated, based on tests, to be 1.1 air changes per hour (ach) for the Willoughby building and 1.5 air changes per hour for the Grove building during the heating season.

Weatherization of the Grove Street building consisted of replacing windows, caulking window jambs and weatherstripping exterior doors and apartment entry doors. One apartment entry door was also replaced. Weatherization of the Willoughby building encountered major delays because the windows ordered were unavailable. After waiting several months, the project schedule required that the building be retested with weatherization performed on only one apartment. The purpose of retesting was to improve the understanding of the multi-zone single-blower-door and double-blower-door methods.

Results

The research showed that the total interzonal leakage area is of comparable magnitude with the external leakage area. The latter varied in the apartments tested between 40% to 70% of the total leakage area. Consequently, interzonal leakage cannot be ignored when performing blower door tests.

The results of the research indicate that measurements with two blower doors, as described in detail in Appendixes A and D, yield much more useful information than the single-zone, single-door technique

(ASTM E 779-88) currently employed by energy auditors and weatherization teams. The two-door method can be used to quantify both the external *and* interzonal leakage in multi-family apartment buildings, regardless of whether the interior partitions are tight or loose relative to the exterior envelope. The two-door method allows the user to estimate air infiltration/exfiltration rates, which cannot be calculated based on ASTM E 779-88 data and are often very difficult to estimate with tracer gas because of mixing problems. Finally, results obtained from the two-door method can be used to predict the movement of smoke and contaminants. For the two buildings investigated in Brooklyn, the accuracy of the two-door method in predicting the average external ELA is estimated to be 20-25%.

The second version of the multi-zone single-blower-door method, as described in detail in Appendix B, is useful in quantifying the external air leakage from each apartment and in estimating the amount of the interzonal air leakage when the interior partitions are *not* tight relative to the exterior envelope. With just one door, quantification of interzonal air leakage is practically impossible to obtain when the interior partitions are tight relative to the exterior envelope; however, from a practical standpoint, the interzonal air leakage is not important when partitions are tight.

Overall, the accuracy of the multi-zone single-door procedure is lower than, but comparable with that of the double-door procedure. The multi-zone single-door procedure still requires development work to determine the best protocol and analysis method, and to define the range of applicability. However, this method is fast and relatively simple, and has yielded reasonable accuracy($\pm$ 25 to 30%) for the determination of the average external ELA of the two buildings tested.

Based on the information provided by the two-door technique or by the multi-zone single-door technique, the investigators can determine whether the interior partitions play an important role in air leakage (i.e., whether the leakage area is a sizable fraction of the envelope area). This determination is numerical for the two-door procedure; for the single-door procedure the determination can be numerical, but if the partitions are tight only a qualitative answer is obtained (i.e., partitions are so tight that no measurement can be made). The auditors can then decide whether tightening the partitions is desirable. Potentially dangerous situations, such as major air communication between apartments and boiler room, could also be detected.

The two-door method is faster than the multiple-blower-door method, but still requires substantial time to apply. Because of its cost, this method appears to be useful mostly for research and as a baseline against which to develop and ultimately check the multi-zone single-door method.

The multi-zone single-door method is faster to apply than the two-door method. When fully developed, the single-door method will be suitable for use by energy auditors and for weatherization teams. Such use will likely involve spot-checking of selected apartments, rather than full testing of all apartments in the building.

Recommendations

The two-door method yields good and comprehensive results within a shorter time than the multiple-door method; however, the test period is still too long to make the two-door method practical for energy auditing or weatherization work. The primary value of the two-door procedure resides in research (e.g., characterizing the building stock) and in special situations. The latter could include finding solutions when a problem related to air movement is present in a multi-family building (e.g., soot in apartments, fuel smell, visual evidence of poor fire-stopping).

Currently, very little is known on the air leakage characteristics of multi-family buildings in general, and of those located in New York State in particular. The current practice of measuring the total leakage of each apartment before and after weatherization gives no indication of inter-apartment air leakage. Consequently, air infiltration rates cannot be calculated and pollutant migration (e.g., from the boiler room) cannot be predicted. There is a need to understand these issues.

In view of the current state of pressurization methods, routine auditing with two doors cannot be undertaken. However, the general characteristics of the building stock can be determined. One can assess, for instance, whether weatherization of interior partitions should be recommended, in general, to reduce air infiltration rates, and whether communication with the boiler room creates widespread problems.

To respond to such questions, the double-blower-door method could be used on a larger sample of apartment buildings to characterize the air leakage and contaminant flow in these buildings. The multi-zone single-door method could be also employed on one or two buildings to fine-tune its application. This method holds promise for such applications but still requires some development work.

When perfected, the multi-zone single-door procedure could be spot-applied to a sample of apartments in a building, to indicate the airtightness of the exterior envelope relative to interior partitions. This, in turn, can help the weatherization crews decide if internal air tightening is a priority.

The multi-zone single door technique can also be used to detect reasons for soot, odors, CO_2 and CO migration within buildings.

Section 1
INTRODUCTION

The role of ventilation in multi-family housing is to provide fresh air and to dilute internally-generated pollutants. Ventilation uses energy, either directly for moving the air, or indirectly for heating and cooling the outside air.

Ventilation air is introduced in an apartment mechanically (fans), by opening windows and doors, through air leakage across the building envelope (roofs, walls, floors, windows), and across interior walls and interior floors. The split between air leakage across the exterior envelope versus air leakage to other conditioned spaces is critical for determining the dilution of pollutants as well as the energy requirements. This report investigates the use of a *multi-zone* single-blower-door pressurization technique and of a two-blower-door pressurization technique for determining the air leakage across the exterior and interior surfaces of apartments.

The single-blower-door pressurization technique described in the ASTM Standard E 779-88[1] has been successfully used to estimate the equivalent leakage area (ELA) of single-zone dwellings, such as slab-on-grade single family houses. However, the same single-blower-door technique yields incomplete information when applied to multi-zone dwellings, such as multi-family housing. The ELA obtained by pressurizing one apartment includes: (a) the exterior surfaces of that apartment; (b) walls, ceilings and floors between that apartment and adjoining apartments; and (c) interstitial spaces, such as chases that communicate to the outside, to other interior spaces, or to both.

Energy auditors and weatherization teams typically record this one ELA figure before and after weatherization, thus deriving the air tightening that can be attributed to the weatherization measures. Based on experience, it may be possible to use the reduction in the total ELA to guess at the magnitude of reduction in air leakage rates and on energy use. However, this estimate is bound to be erroneous in most instances, for the following reasons:

- The air leakage rates in an apartment building depend on the interaction between the ELA of the exterior surfaces *and* the ELA of interior surfaces. Thus, the same total ELA can yield very different air leakage rates as the ratio of (exterior ELA)/(interior ELA) changes.

- The air leakage rates in an apartment building depend on the distribution of interior surface ELAs. For instance, if two multi-story buildings have the same ELAs for interior partitions, the one with looser floors and ceilings will experience higher air leakage rates because of the stack effect.

- Air also leaks across interior surfaces from basements or from boiler rooms located on the first floor. The effect of these ELAs on air leakage and energy use is distinct from the effect of ELAs of exterior surfaces, or from the effect of ELAs of surfaces separating conditioned spaces.

Another limitation of the single ELA for the entire apartment is that it gives no information useful for predicting the movement of air within the building. Loose interior partitions facilitate the propagation of odors, smoke (in case of fire) and radon, if existent. If apartments are coupled to the basement or boiler room via shafts and pipe penetrations, there is the likelihood of increased CO, CO_2, NO, NO_2 and soot in apartments. Dust and mildew can also be circulated. For these reasons it may be advisable that, in some buildings, the interior partitions be tightened and the interstitial spaces sealed. However, it is difficult to know whether such measures need be taken if a single ELA is obtained.

To better predict the air leakage of apartments and to better understand the likelihood of pollutant propagation, the ELA of the exterior surfaces in the building must be obtained. This ELA must be distinct from the ELAs of partitions between apartments, and distinct from the ELA between apartments and critical unconditioned areas, such as basements and boiler/furnace rooms.

This detailed information can be obtained by using a multiple-blower-door technique. In this method, one blower door is located in the apartment being tested and in all but one of the adjacent apartments, as well as in the basement or boiler/furnace room.

The same pressure is maintained in the apartment tested and in all other spaces that have blower doors. As a result the ELA includes only the exterior surfaces of that apartment plus the partitions to the unpressurized apartment. The blower doors are then moved in sequence, so that another adjacent apartment is now left unpressurized and all remaining are pressurized. The test is repeated for as many times as there are spaces communicating with the apartment being tested. The results yield all detailed ELA information needed.

The multiple-blower-door method is complex. Four to eight blower doors could be needed. The blower doors must be all synchronized, either by an automatic system or by several people. The differences in pressures among the apartments must be measured and analyzed. Additionally, access must be simultaneously secured to many apartments, making the method impractical for occupied buildings.

In summary, the single-zone, single-blower-door technique described in the ASTM Standard E 779-88 gives incomplete data when applied to multi-family buildings, while the multiple-blower-door technique is impractical. There is a need to devise different techniques that can yield ELA information more quickly and at lower cost than the multiple-blower-door method.

This research examined the feasibility of two such techniques. The first technique uses one blower door and expands on the protocol described in the ASTM Standard E 779-88. For this multi-zone single-blower-door method, two versions were studied. The second technique studied uses two blower doors.

Section 2

APPROACH AND PROTOCOL DEVELOPMENT

Based on the air tightness expertise of Lawrence Berkeley Laboratory (LBL), this project refined and applied the two-door fan pressurization technique to determine the external and interzonal leakage in two low-rise apartment buildings. Two multi-zone single-blower-door pressurization techniques were also investigated. The protocols involve the use of the ASTM E 779-88 blower door measurement technique [1], and the use of techniques discussed in the similar Canadian standard (CGSB 149)[3].

As described in Appendix A, the two-door technique uses as its basis the ASTM E 779-88 protocol to determine the total air leakage of the primary zone, and then uses the second blower door as a compensating device to determine the air leakage between the primary zone and each adjacent zone. The protocol described in ASTM E 779-88 was developed from earlier LBL work [4,5,6]. Appendix D describes the detailed preparation and measurements performed on site.

The multi-zone single-door technique described in Appendix B does not use a compensating device. Rather, it measures the pressures in adjacent zones caused by combined interzonal and exterior leakage. The measurements are performed in two configurations: (1) with all apartment doors closed and (2) with all apartment doors open. During the tests with doors open, the hallway is brought to outside air pressure by opening the entry doors at both ends. The apartments are therefore brought to a pressure close to the one outside. (When the hallway cannot be open to outdoors in at least two opposite points, the apartment doors need to remain closed and the windows are opened and closed instead. Cold weather and the presence of occupants and pets makes this test strategy difficult to apply in occupied apartments.) Field procedures are not listed for the multi-zone single-door technique since development work is still required.

Tracer gas techniques were considered for use in the protocol development, but after careful analysis were discarded. Tracer gas techniques are accurate when determining real time air flows[7] and have been used in conjunction with other types of air tightness testing[8], but are too expensive and require too much expertise to be practical for weatherization crews. We did, however, use a limited amount of tracer gas testing as part of the development of the other protocols as described in following sections (see Appendix C).

The field tests were performed as described in Appendix D.

As with any measurement technique, blower door pressurization techniques are susceptible to errors[9]. For single-zone measurements, even with the best instrumentation and measurement protocols, fan pressurization measurements cannot be made in wind speeds higher than 11 mph (5 m/s). ASTM Standard E 779[1]-88 does not allow air leakage to be calculated if the wind speed is over 5 mph (2m/s).

LBL has completed extensive simulations[5] of the effect of wind on multi-zone systems. The results show that the uncertainties can be larger and are more dependent on good experimental procedure than in the single-zone case. Undoubtedly, any standard test method would be at least as restrictive on measurement uncertainties[10] as the current E 779.

No *a priori* estimates have been made for the multi-zone single-door test methods. Although preliminary protocols for this method had been drafted prior to the start of testing, the method itself developed during the course of the project. Therefore, the issue of uncertainties and wind effects is discussed in Section 6.

Section 3

DESCRIPTION OF BUILDINGS

Two apartment buildings were selected to be the subjects of the tests (see Figures 3-1a, 3-2a and 3-1b, 3-2b). These buildings were chosen to be typical of the New York State multi-family, low-income housing stock and typically in need of weatherization. Both buildings are part of a longer, attached row of apartments, from which they are separated through fire walls. The buildings have three stories and a full basement. Two apartments are located at each story, for a total of six per building. Each building has a central stairway, which opens to the front through two sets of doors on the first floor, and has either a door or a large access hatch to the roof. There are two doors from the stairway to each apartment, but only one is used as an entrance door, while the other is blocked by furniture. These doors have large undercuts and contribute a significant fraction of the air leakage.

1348 Willoughby Avenue

Figure 3-1a shows an elevation of the front of the building. Figure 3-2a shows a typical floor plan. The hallway has a door to the roof. Appendix E contains a more detailed description of this building.

347 Grove Street

Figure 3-1b and 3-2b are front elevation and floor plan of this apartment building. It did not have lightwells and the top of the stairway ended in a roof hatch rather than a door. Appendix E contains a more detailed description of this building.

Figure 3-1a: 1348 Willoughby Avenue Building, Brooklyn, New York City

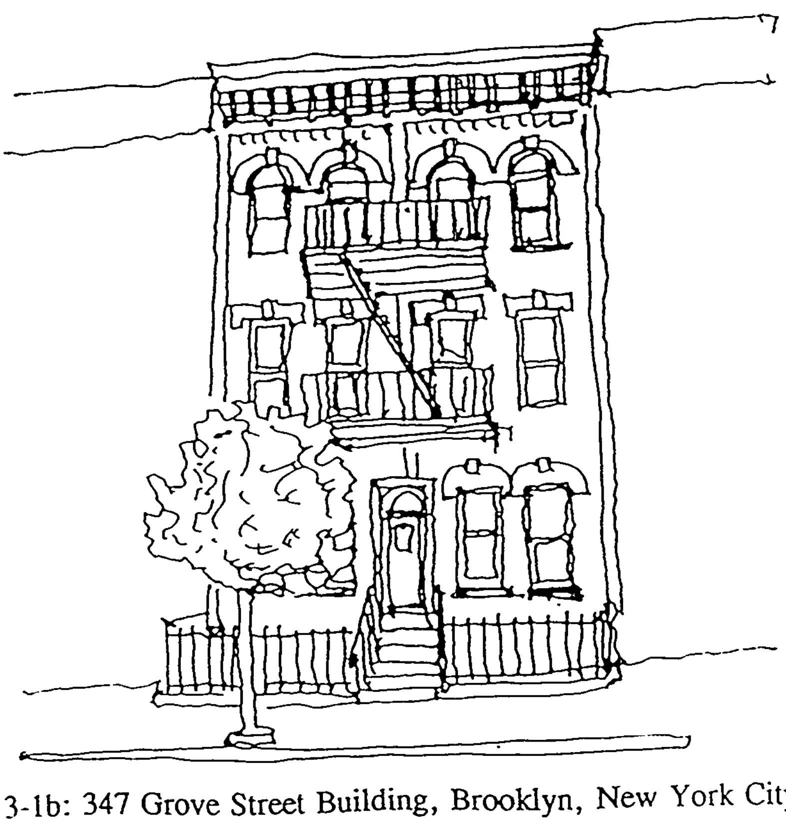

Figure 3-1b: 347 Grove Street Building, Brooklyn, New York City

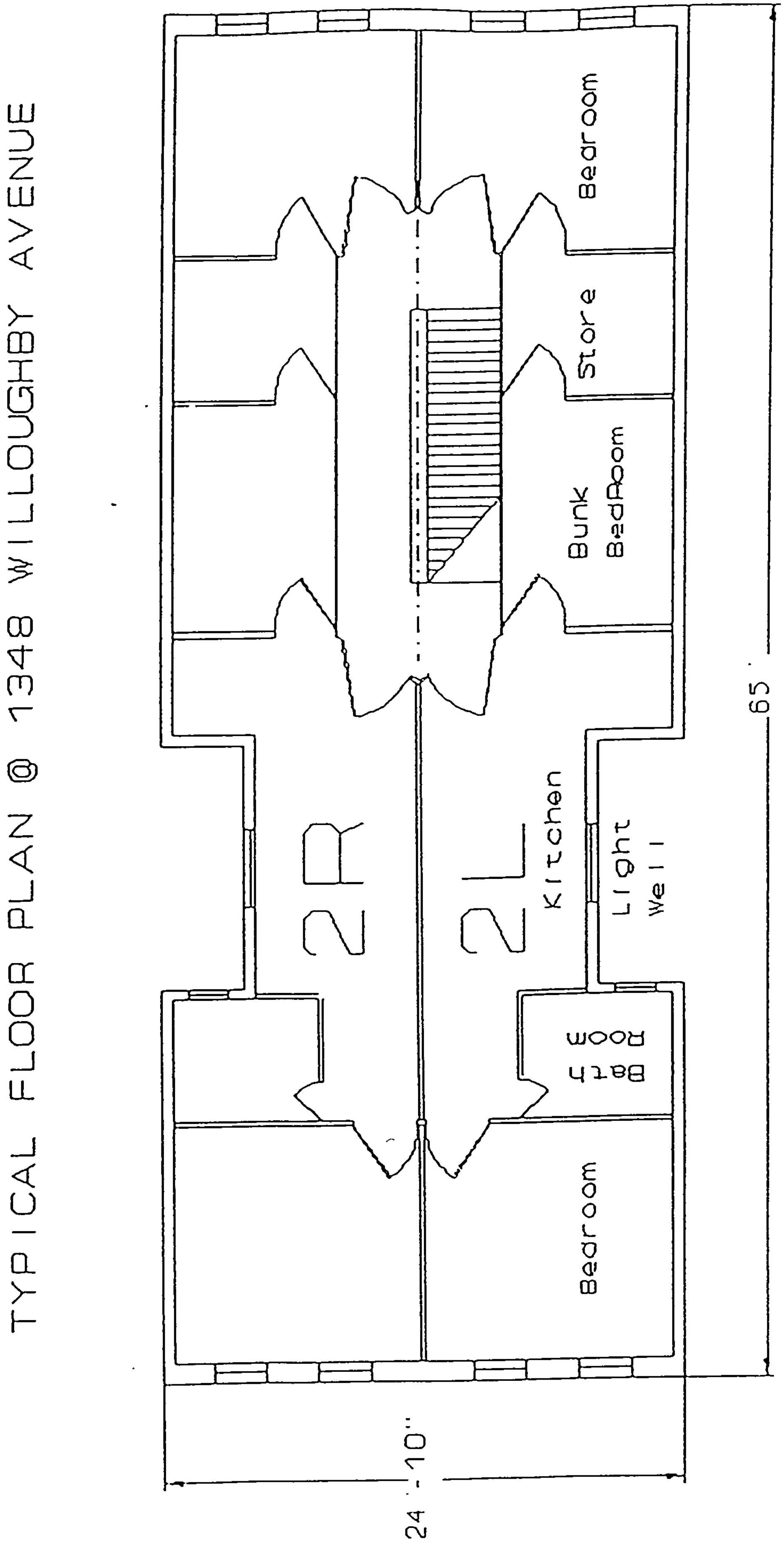

Figure 3-2a: Typical Floor Plan at 1348 Willoughby Ave., Brooklyn, New York City

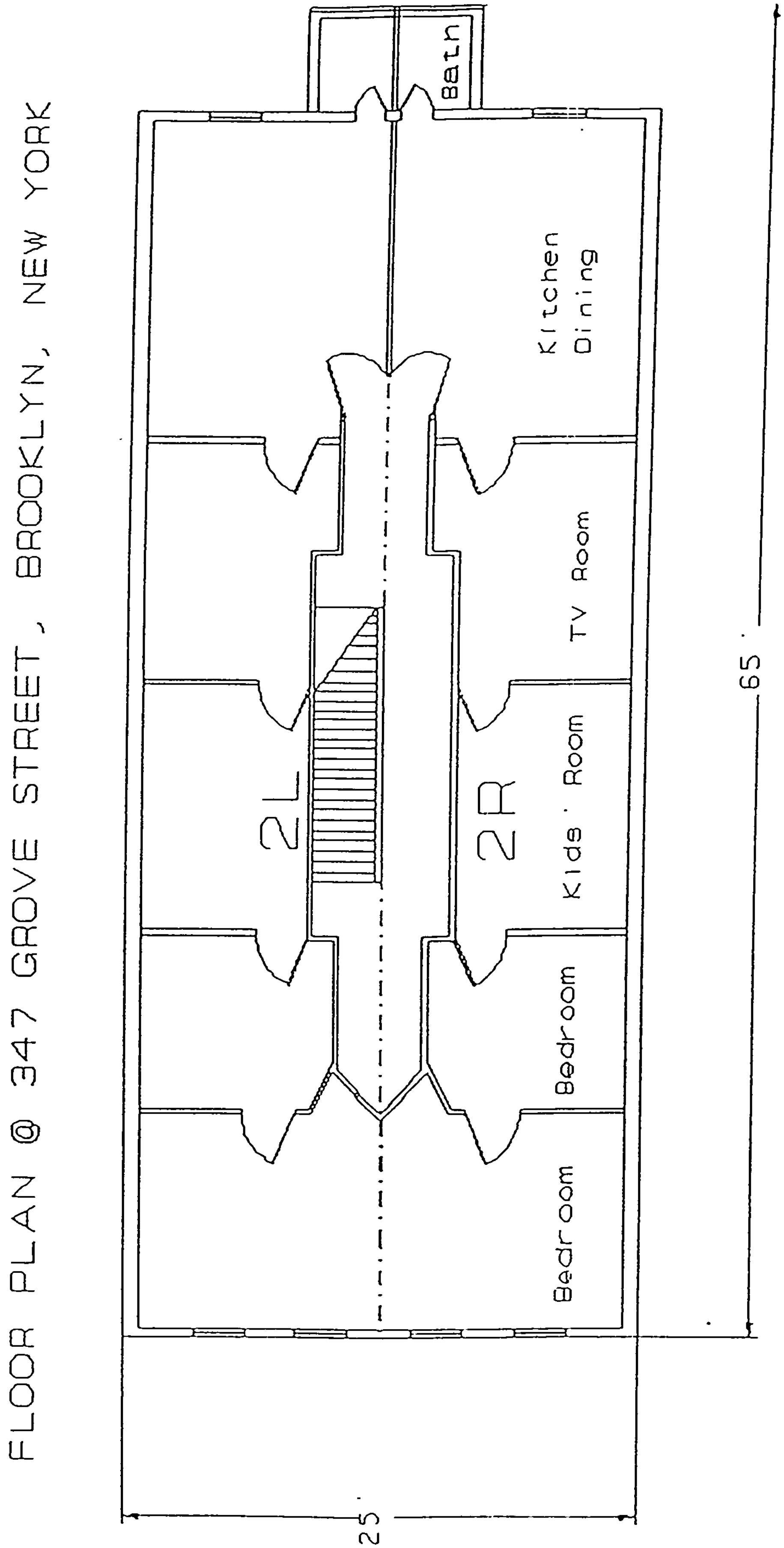

Figure 3-2b: Typical Floor Plan at 347 Grove Street, Brooklyn, New York City

Section 4
PRE-WEATHERIZATION TESTS

Section 4 and Section 5 list the test data. A discussion of these data follows in Section 6.

Each building was tested using the two-blower-door technique (see Appendix A) and the first version of the multi-zone single-blower-door technique (see Appendix B) prior to weatherization. A few units were tested using the tracer-assisted technique (see Appendix C). The emphasis for this initial series of tests was to determine the feasibility of the multi-zone single-door procedure. For this reason, most tests were performed with one door.

Previous multi-zone leakage measurements have shown that interstitial zones may have relatively large air leakage associated with them. The leakage of these zones cannot be determined directly (one is unable to mount a blower door to them) and may play a role in the air leakage and air movement in multi-zone buildings. To estimate the magnitude of these interstitial leakage areas, the first version of the multi-zone single-door technique was employed during the pre-weatherization tests.

In general, the analysis of the data collected using the first version of the multi-zone single-door technique failed. (The second version was applied to post-weatherization tests and was successful.) In the Willoughby building, the failure of the first version of multi-zone single-door technique was primarily due to the small leakage area between units (masonry walls between apartments). An error analysis suggested that neighboring zones must have a pressure in the range of 10% of the main zone pressure for the signal to be large enough to be useful. This situation is unlikely to exist for apartments where the interior walls, ceilings and floors are tight relative to the exterior surfaces. In the Grove building, the interzonal leakage was higher, but interstitial leakage that could not be measured also affected the results.

In the case of interstitial zones, the first version of the multi-zone single-door analysis failed each time, indicating that the leakage was too small to be detected using this technique, and/or that the suspected interstitial zone had a stronger connection to outside rather than between two zones within the building. Tables 4-1 and 4-2 list all leakage paths where measurement was attempted. An AF in a column indicates that the analysis failed for one of the reasons listed above.

These results show that the first version of the multi-zone single-door method is not practical. This version was replaced in the second set of tests with the one described at the end of Appendix B.

In all tests, the blower door was mounted in the front door of each apartment. This unavoidable position removes an important leakage site to the apartment. From physical measurements, the leakage of the front door was estimated as 21.7 in² (140 cm²). This value has been added to the total of each unit. The total leakage to the stairwell from each apartment is estimated as 25.6 in² (165 cm²). Where these doors were retrofitted, it was assumed that half of the total leakage from one apartment to the stairwell was sealed.

The "best estimate" of the leakage area in these tables is generally an average of all measurements made for the leakage site, exclusive of the single-blower-door. Tracer gas and two-blower-door measurements are averaged; single-blower-door results are not included unless they were the only ones available.

For example, in Table 4-2 (the pre-retrofit leakage of Grove) the "best estimate" of the leakage area between 1R and 2R is the average between the two-door method measurement of 21.5 in² and the tracer gas measurement of 19.8 in². When only one measurement type was available (e.g., single-blower-door), that measurement was used as the "best estimate". Single-blower-door measurements between two zones were averaged as exemplified below: Table 5-2 has the "best estimate" of the leakage between apartments 1L and 1R as 7.6 in². This number is the average of the 1L-1R leakage measured with 1L as the main zone (8.4 in²) and the 1L-1R leakage measured with 1R as the main zone (6.8 in²).

The "best estimate" for the leakage to the stairwell includes the leakage of the door as explained above. The "best estimate" was used in the computer simulations to predict airflow rates.

The "external leakage area" is obtained by subtracting the sum of interzonal leakage areas of one apartment from the total leakage area of that apartment. The "external leakage area as a fraction of total apartment leakage" is obtained by dividing the external leakage area to the total leakage area.

In interpreting the tables in this section, as well as those in subsequent sections, please note that the goal is to show the data in a way that allows the reader to follow the calculations. To this end, all leakage areas are reported with one digit after the decimal point. If the purpose of the table were to report the data as the result of this research, the uncertainties associated with the measurements and methods would impose a format which rounds at least to the nearest 5. By doing so, most of the information on interzonal leakage areas would be lost and the derivation of mean, standard error of the mean and uncertainty of the mean (see later sections) could not be illustrated numerically. This problem is resolved by listing the data in detail, with one digit after the decimal point, until the Summary of section 6.

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This set of tests is also referenced in the report as "set of tests #1" rather than "pre-weatherization" tests. This is because, for reasons noted in section 5, professional weatherization was not performed in time for the second set of tests and as a result most data on Willoughby was collected on unweatherized apartments. The exception is the data for apartment 1L which had been thoroughly weatherized by its tenant even before the "set of tests #1."

The main purpose of this first set of tests was to verify the applicability of version one of the multi-zone single-blower-door method. Extensive instrumentation, testing and re-testing showed that, in general, this version does not work. The results pointed toward the second version, employed in the "set of tests #2." This second version yields reasonable results and is much simpler.

The total effective leakage of the building shell to outside was calculated to be 460 in^2 (2970 cm^2). A measurement of the leakage of the stairwell was attempted, but because the building occupants kept opening doors no useful data were obtained. Even if a value was obtained, it would not have included the most significant leakage path: the door leakage area. As a result, the values listed in Table 4-1 are derived from measurements of the door undercuts using a graduated tape.

The first version of the multi-zone single-door method could only be used on one interzonal flow, because of the small leakage fraction of the interzonal flows as compared to the total flows from the apartments. Note that the two-door method cannot be directly applied to interstitial spaces.

Single-door pressurization detected no air leakage between the 1348 Willoughby building and the buildings attached to it.

TABLE 4-1: Effective Air Leakage Areas [in²] for 1348 Willoughby: Set of Tests #1

Zone Name	Total Apt. Leakage Area Measured with Single-Door, Single-Zone Method	Neighbor Zone Name	Interzonal Leakage Measurements			*** Best Estimate of Interzonal Leakage Area	**** External Leakage Area	External Leakage as Fraction of Total Apt. Leakage
			Single-Door, Multi-Zone Method #1	Two-Door Multi-Zone	Tracer-Gas Assisted			
2L	134.9	1L	* AF			4.3	100.5	0.74
		2R	AF		3.4	3.4		
		3L	13.6		1.1	1.1		
		Stairwell	** N/A	N/A	N/A	25.6		
		Interstitial to stairwell	AF	N/A	N/A	0		
		Interstitial to dumbwaiter	AF	N/A	N/A	0		
		Interstitial to above	AF	N/A	N/A	0		
		Interstitial to below	AF	N/A	N/A	0		
3R	170.5	2L	AF			0	133.4	0.78
		2R	AF	5.0		5.0		
		3L	AF	6.5		6.5		
		Stairwell	N/A	N/A	N/A	25.6		
		Interstitial to below	AF	N/A	N/A	0		
		Interstitial to above	AF	N/A	N/A	0		
		Interstitial to stairwell	AF	N/A	N/A	0		
		To building next door	0	N/A		0		

* The AF indicates that measurements were made, but that the analysis failed to determine the leakage area of this site. An empty cell indicates that no measurement was made.

** N/A indicates that a specific type of measurement cannot be applied to the site. For instance, since the blower door is positioned in the apartment entry door, one cannot use the blower door to measure the leakage area of the entry door. This leakage area is estimated by measuring the door undercut with a graduated ruler or with a measuring tape. Similarly, the two-door method cannot be used to measure leakage areas to interstitial spaces, since one cannot mount a blower door on an interstitial space. Finally, the tracer gas technique cannot be applied to interstitial spaces since one cannot sample tracer gas from interstitial spaces.

*** The "Best Estimate" of the interzonal leakage area in this table is obtained either from tracer-gas measurements or from two-door measurements. If properly applied, these measurements are more accurate than the multi-zone single-door measurement. Please refer to page 4-2, second, third and fourth paragraphs, for further discussion.

**** The external leakage area is calculated by subtracting the sum of interzonal leakage areas from the total leakage area of the apartment. The latter is measured with the single-door, single-zone method.

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None of the apartments in the Grove Street building were weatherized before this first set of tests (also called "pre-weatherization tests"). The main purpose of the pre-weatherization tests was to verify the feasibility of the first version of the multi-zone single-door procedure. Consequently, the instrumentation and checking was focused on this type of measurement.

TABLE 4-2: Effective Leakage Areas [in^2] for 347 Grove: Pre-Weatherization Tests

Zone Name	Total Apt. Leakage Area Measured with Single-Door, Single-Zone Method	Neighbor Zone Name	Interzonal Leakage Measurements			*** Best Estimate of Interzonal Leakage Area	**** External Leakage Area	External Leakage as Fraction of Total Apt. Leakage
			Single-Door, Multi-Zone Method #1	Two-Door Multi-Zone	Tracer-Gas Assisted			
2R	187.6	1L	* AF			0	99.1	0.53
		1R	26.5	21.5	19.8	20.7		
		2L	11.6	19.8	16.6	18.2		
		3R	3.1			3.1		
		Stairwell	** N/A	N/A	N/A	46.5		
		Interstitial to floor	AF	N/A	N/A	0		
		Interstitial to dumbwaiter	AF	N/A	N/A	0		
		Interstitial to 2L	AF	N/A	N/A	0		
		Interstitial to above	AF	N/A	N/A	0		

* The AF indicates that measurements were made, but that the analysis failed to determine the leakage area of this site. An empty cell indicates that no measurement was made.

** N/A indicates that a specific type of measurement cannot be applied to the site. For instance, since the blower door is positioned in the apartment entry door, one cannot use the blower door to measure the leakage area of the entry door. This leakage area is estimated by measuring the door undercut with a graduated ruler or with a measuring tape. Similarly, the two-door method cannot be used to measure leakage areas to interstitial spaces, since one cannot mount a blower door on an interstitial space. Finally, the tracer gas technique cannot be applied to interstitial spaces since one cannot sample tracer gas from interstitial spaces.

*** The "Best Estimate" of the interzonal leakage area for 2R-1R and 2R-2L is calculated by taking the average of the tracer-gas measurement and the two-door measurements. If properly applied, these measurements are more accurate than the multi-zone single-door measurements. The interzonal leakage area for 2R-3R is obtained with multi-zone single-door measurements. Please refer to page 4-2, second, third and fourth paragraphs, for further discussion.

**** The external leakage area is calculated by subtracting the sum of interzonal leakage areas from the total leakage area of the apartment. The latter is measured with the single-door, single-zone method.

In this building, all methods yielded similar results. The multi-zone single-door version #1 produced results in two instances because of the generally larger leakage fraction between zones.

Testing was discontinued after one day because part of the plaster ceiling in a bedroom was sucked off during depressurization. The background for this incident is as follows: The original plaster was in poor condition and had been removed in all other rooms. The ceilings had been replaced either with gypsum board or with hung tiles. Both new ceiling types were in good condition at the time of the tests. In that bedroom, however, the plaster ceiling had been only *partially* removed and a hung ceiling had been placed underneath, masking the existence of the damaged plaster areas. Although there was no other damage to personnel or property, tests were discontinued because of concern regarding other possible hidden flaws.

In general, the interzonal partitions in the Grove Street building can be characterized as loose. First, the hung tile ceilings account for a large fraction of the ceiling area in these apartments. The tile ceilings pose very little resistance to air movement. Consequently, horizontal air tightness between 1st and 2nd, and between 2nd and 3rd floor apartments is achieved primarily by subflooring and flooring.

Next, the plaster-on-wood lath walls evidenced cracks. This indicates a relatively large leakage area between the apartments on the same floor.

Finally, the interior wall cavities communicate to some extent with the ceiling cavities. Consequently, wall cracks can also result in larger air leakage to the apartments above.

This generally loose condition of interior walls and ceilings is often encountered in older, low-income housing built with stud walls and joist floors. The collapse of a plastered area is an extreme event, but it did not affect the results, since (a) the cracked plaster is unlikely to have posed any significant resistance to pressurization and (b) that plaster should have been cleared in the bedroom anyway as it had been cleared in the rest of the building.

Section 5

POST-WEATHERIZATION TESTS

Section 4 and Section 5 list the test data. A discussion of these data follows in Section 6.

Each building was tested using a two-blower-door technique and the second version of the multi-zone single-blower-door technique (see Version 2 in Appendix B). The first version was not attempted any longer because of its poor performance in the pre-weatherization tests. No tracer-assisted tests were undertaken in the post-weatherization tests because they were too time consuming. The two-door technique was used instead for a more direct comparison with the multi-zone single-door technique #2. No measurements to interstitial spaces were attempted because the first series of tests did not yield useful data. The emphasis in this series of tests was on determining the feasibility of the second version of the multi-zone single-door technique. The technique yielded results that compare favorably with the two-door results (see Table 6-3 on page 6-11).

Also, because of complete measurements, the sum of the exterior ELAs of each apartment could be compared against the directly-measured ELA of all exterior surfaces of the Grove building (whole-building pressurization). The two figures are within 12% of each other, indicating good agreement and suggesting that version two of the multi-zone single-door method can be developed into an effective and practical energy auditing technique.

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The only retrofitting performed in this building was for apartment 1L, where the air tightening was done by the occupant *before* the first set of tests. None of the other apartments were retrofitted before retesting, because the replacement windows were not available. (The factory was several months late in the delivery of the windows.) For this reason, the set of tests discussed here is referenced as the "set of tests #2," in order to avoid the impression that weatherization was systematically performed. Please refer to Table 5-1 for test results.

As noted in Section 4, all results are presented with one digit after the decimal point to allow the reader to follow the calculations. The uncertainty in the measurements and method would require reporting by at least rounding to the nearest 5 in^2.

When reading this table note that the "best estimate" for single-door measurements is an average of two values. For example, the interzonal leakage between 1L and 1R is 6.0 in² when 1L is the main zone and 2.6 in² when 1R is the main zone. The average of the two measurements is 4.3 in², which is entered as "best estimate" twice: for the 1L-1R cell and for the 1R-1L cell.

TABLE 5-1: Effective Leakage Area [in²] of 1348 Willoughby: Set of Tests #2

Zone Name	Total Apt. Leakage Area Measured with Single-Door, Single-Zone Method	Neighbor Zone Name	Interzonal Leakage Measurements		*** Best Estimate of Interzonal Leakage Area	**** External Leakage Area	External Leakage as Fraction of Total Apt. Leakage
			Single-Door, Multi-Zone Method #2	Two-Door Multi-Zone			
1L	30.2	1R	6.0		4.3	7.4	0.25
		2L	6.4	4.2	4.2		
		Stairwell	** N/A	N/A	0.8		
		Basement	18.1		13.5		
1R	96.7	1L	2.6		4.3	37.5	0.39
		2R	12.2		7.3		
		Stairwell	N/A	N/A	25.6		
		Basement	24.8		22.0		
2L	128.8	1L	2.5	4.2	4.2	83.0	0.64
		2R	18.3	13.5	13.5		
		3L	10.5	2.5	2.5		
		Stairwell	N/A	N/A	25.6		
2R	123.4	1R	2.5		7.3	71.1	0.58
		2L	12.9	13.5	13.5		
		3R	2.5		5.9		
		Stairwell	N/A	N/A	25.6		
3L	116.7	2L	8.4	2.5	2.5	79.0	0.68
		3R	11.0		9.6		
		Stairwell	N/A	N/A	25.6		
3R	106.8	2R	9.3		5.9	65.7	0.62
		3L	8.4		9.6		
		Stairwell	N/A	N/A	25.6		
Basement	247.7	1L	8.8		13.5	160.7	0.65
		1R	19.4		22.0		
		Stairwell	N/A	N/A	51.5		
Stairwell	200.9	1L			0.8	20.8	0.10
		1R			25.6		
		2L			25.6		
		2R			25.6		
		3L			25.6		
		3R			25.6		
		Basement			51.5		

Please see footnotes on next page.

* An empty cell indicates that no measurement was made.

** N/A indicates that a specific type of measurement cannot be applied to the site. For instance, since the blower door is positioned in the apartment entry door, one cannot use the blower door to measure the leakage area of the entry door. This leakage area is estimated by measuring the door undercut with a graduated ruler or with a measuring tape. Similarly, the two-door method cannot be used to measure leakage areas to interstitial spaces, since one cannot mount a blower door on an interstitial space. Finally, the tracer gas technique cannot be applied to interstitial spaces since one cannot sample tracer gas from interstitial spaces.

*** The "Best Estimate" of the leakage area in this table is obtained from the two-door measurements, where available. If properly applied, these measurements are more accurate than the multi-zone single-door measurements. Where two-door measurements were not performed, the single-door measurements are used instead. For further discussion of "Best Estimate" please refer to page 4-2, second, third and fourth paragraphs. Also paragraph on top of page 5-2 and paragraph following the footnotes, on page 5-3.

**** The external leakage area is calculated by subtracting the sum of interzonal leakage areas from the total leakage area of the apartment. The latter is measured with the single-door, single-zone method.

When a two-door measurement was made, that measurement was taken as the "best estimate" and the single-door value was ignored, since, in principle, single-door measurements are less accurate.

The changes in total leakage area between the two tests (set of tests #1 of Table 4-1 and set of tests #2 of Table 5-1) need to be explained because there were no retrofits performed in this building between the two sets of measurements. For 2L, the measured total leakage dropped by 5%, which is well within expected noise and may be due to seasonal changes in leakage. Apartment 3R apparently had a 37% drop, which is much larger than expected for seasonal changes. It was observed during the pre-retrofit measurements that the windows in this apartment were in particularly poor condition. One window had tape holding the glass panes together and other windows were held in place using scrap lumber to push against the window frames. One reason why the leakage of the windows in 3R changed significantly between the pre- and post-retrofit measurements is because the broken glass pane was retaped. Also, the position of scrap lumber may have changed, reducing the crack width. Note: The poor condition of this window is uncommon, but not exceptional for low-rise, privately-owned, low-income housing.

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The retrofitting consisted of new windows, caulking at window jambs and weatherization of all doors. The entry door to Apartment 1L was also replaced. Table 5-2 lists the test results of these "post-weatherization" tests, also designated as "set of tests #2".

In this case there is almost a complete set of measurements of the building. This allows a comparison of the measured total leakage area to outside (using a whole-building, single-zone, single-door test) with the sum of the estimated leakage areas to outside from each zone (using the two-door and single-door multi-zone method).

Enough data exist for this building to compare the ELA estimated with one direct measurement of the entire building -- designated the "total ELA" -- with the sum of the ELAs to outside of individual zones -- designated the "sum ELA". Based on the whole-building pressurization tests, the total equivalent leakage area of this building was calculated as 250 in^2 (1616 cm^2). However, this total was made with the doors to apartment 3L and the basement closed. The contribution of these two zones to the total is their internal ELA. The pressure across the internal walls of these zones during pressurization tests was 12.2 Pa, while the external pressure difference during the whole-building test was 27.5 Pa. As a result, the internal ELA of the two zones cannot be simply added to the total ELA. The internal ELA of these zones is recalculated for 27.5 Pa using the equation below:

ELA of 3L and basement at 27.5 Pa =
ELA of 3L and basement at 12.5 Pa * $(27.5/12.5)^{0.67}$ (EQ 1)

With this correction, the measured total increases to 306 in^2 (1973 cm^2). The sum of the leaks to outside (inside for Apartment 3L and the basement) is 343 in^2 (2214 cm^2), which is 12% larger than the measured total. Considering all the assumptions and measurements errors, and the 5-15% accuracy of the individual blower door measurements, this is as good an agreement as can be expected. Please note that the analysis of Section 6 shows a 20 to 25% theoretical uncertainty in the average of leakage areas to the outside from each apartment.

TABLE 5-2: Effective Leakage Area [in²] of 347 Grove: Post-Weatherization Tests

Zone Name	Total Apt. Leakage Area Measured with Single-Door, Single-Zone Method	Neighbor Zone Name	Interzonal Leakage Measurements		*** Best Estimate of Interzonal Leakage Area	**** External Leakage Area	External Leakage as Fraction of Total Apt. Leakage
			Single-Door, Multi-Zone Method #2	Two-Door Multi-Zone			
1L	88.0	1R	8.4		7.6	28.6	0.33
		2L	7.8		10.4		
		Stairwell	** N/A	N/A	15.7		
		Basement	18.1		25.7		
1R	71.6	1L	6.8		7.6	15.5	0.22
		2R	13.5	8.1	8.1		
		Stairwell	N/A	N/A	12.2		
		Basement	23.6	28.2	28.2		
2L	89.3	1L	13.0		10.4	46.0	0.52
		2R	8.4	11.3	11.3		
		3L	9.8		9.8		
		Stairwell	N/A	N/A	11.8		
2R	113.8	1R	10.4	8.1	8.1	63.8	0.56
		2L	14.0	11.3	11.3		
		3R	9.3	7.8	7.8		
		Stairwell	N/A	N/A	22.8		
3L	***** 68.2	2L	9.8		9.8	41.0	0.60
		3R	4.7		4.7		
		Stairwell	N/A	N/A	12.7		
3R	68.2	2R	8.4	7.8	7.8	43.0	0.63
		3L	4.7		4.7		
		Stairwell	N/A	N/A	12.7		
Basement	235.9	1L	33.3		25.7	125.2	0.54
		1R	30.8	28.2	28.2		
		Stairwell	N/A	N/A	51.5		
Stairwell	160.4	1L	15.7		15.7	21.0	0.13
		1R	12.2		12.2		
		2L	11.8		11.8		
		2R	22.8		22.8		
		3L	13.0		12.7		
		3R	12.7		12.7		
		Basement	51.5		51.5		

Please see footnotes on next page.

*	An empty cell indicates that no measurement was made.

**	N/A indicates that a specific type of measurement cannot be applied to the site. For instance, since the blower door is positioned in the apartment entry door, one cannot use the blower door to measure the leakage area of the entry door. This leakage area is estimated by measuring the door undercut with a graduated ruler or with a measuring tape. Similarly, the two-door method cannot be used to measure leakage areas to interstitial spaces, since one cannot mount a blower door on an interstitial space. Finally, the tracer gas technique cannot be applied to interstitial spaces since one cannot sample tracer gas from interstitial spaces.

***	The "Best Estimate" of the leakage area in this table is obtained from the two-door measurements, where available. If properly applied, these measurements are more accurate than the multi-zone single-door measurements. Where two-door measurements were not performed, the single-door measurements are used instead. For a discussion on "Best Estimate" please refer to page 4-2, second, third and fourth paragraphs. Also refer to the text on page 5-2 (top) and page 5-3 (after footnotes).

****	The external leakage area is calculated by subtracting the sum of interzonal leakage areas from the total leakage area of the apartment. The latter is measured with the single-door, single-zone method.

*****	The total ELA of 3L is estimated as being equal to that of 3R ($68.2 in^2$) and the single-door method #2 uses this estimate for calculating the leakage between zones.

Section 6
SUMMARY AND DISCUSSION OF MEASUREMENTS

The study used several techniques to measure a selection of different apartments, pre- and post-weatherization, for two sites in New York City. Although there is substantial variation between individual measurements, it is instructive to condense them into two estimates (unweatherized and weatherized) to derive typical cases.

External Leakage Area

Multi-zone measurements are important only if there is significant interzonal leakage. Otherwise one can assume that single-zone measurements give a good indication of external leakage. The following discussion shows that the external leakage area expressed as a fraction of the total leakage area is about 0.4 to 0.7. Consequently, interzonal air leakage and multi-zone measurements are important.

TABLE 6-1: Interzonal & External Leakage Area (in²) of Unweatherized Apartments

(1) Building	(2) Apt.	(3) Test #	(4) Total Leakage Area	(5) Total Interzonal Leakage Area	(6) Total Interzonal Leakage Area as a Fraction of Total Leakage Area (5)/(4)	(7) External Leakage Area	(8) External Leakage Area as Fraction of Total Leakage Area (7)/(4)	(9) Uncertainty in External Leakage Area as % of External Leakage Area *	(10) Mean of External Leakage Area as Fraction of Total Leakage Area	(11) Standard Error of the Mean as Fraction of Total Leakage Area
1348 Willoughby	1R	2	96.7	59.2	0.61	37.5	0.39	86%	0.63	0.05
	2L	1	134.9	34.4	0.26	100.5	0.74	25%		
	2L	2	128.8	45.8	0.36	83.0	0.64	25%		
	2R	2	123.4	52.3	0.42	71.1	0.58	36%		
	3L	2	116.7	37.7	0.32	79.0	0.68	27%		
	3R	1	170.5	37.1	0.22	133.4	0.78	20%		
347 Grove	2R	1	187.6	88.5	0.47	99.1	0.53	35%		

* A discussion of these values is presented on page 6-5, eq. 4 & 5.

Table 6-1 includes all tests performed on the Willoughby building, except the sole test on apartment 1L and the second test on apartment 3R. As noted above, apartment 1L had been thoroughly weatherized by the tenant before any tests were performed. Apartment 3R had been weatherized to some extent by its tenant after the first set of tests.

The total leakage area (col. 4) and the external leakage area (col. 7) are directly extracted from Tables 4-1 and 5-1. The total interzonal leakage area (col. 5) is obtained by adding all "best estimate of interzonal leakage area" for each apartment in Tables 4-1 and 5-1. The "mean of external leakage area as fraction of total leakage area" (col. 10) is obtained by dividing the sum of external leakage areas (col. 7) to the sum of total leakage areas (col. 4).

The 0.05 standard error of the mean (col.11) was calculated with the formula:

$$\sigma_{\bar{x}}=\sigma_x/(N-1)^{0.5} \qquad \text{(EQ. 2)}$$

where:

σ_x is the sample standard deviation calculated as:

$$\sigma_x= [\Sigma(x_i-\bar{x})^2/(N-1)]^{0.5} \qquad \text{(EQ. 3)}$$

x_i is an individual measurement, $\bar{x}$ is the mean and N is the number of measurements.

The use of (N-1) rather than N in the denominator makes these formulas conservative.

By examining Table 6-1 it can be seen that the mean, or average external leakage area of the apartments before weatherization is expressed as 0.63 of the total leakage area, if the total leakage area is considered the unit (1.0). There is about *seventy percent probability* that a new set of measurements on these apartments, using the same apparatus and the same techniques under the same weather conditions, will yield a mean fractional value of between 0.63+0.05 and 0.63-0.05, i.e., between 0.58-0.68 (when total leakage area is 1.0). Further, there is a *ninety-five percent probability* that the mean external leakage area calculated based on another set of tests can be expressed as a fractional value between 0.63+0.10 and 0.63-0.10 of a unitary total leakage area, i.e., between 0.53-0.73. It is assumed that the measurements did not have systematic errors, i.e., that there was nothing systematically and significantly skewing the results, such as faulty instrumentation or inherent bias in the measurement techniques.

<u>Uncertainty in Total Leakage Area</u>

The next question is how accurate the 0.63 fraction is. While from a statistical standpoint such tests will generally yield an external leakage area between 0.58 and 0.68, we also need to know what is the uncertainty in calculating the mean leakage area itself. This uncertainty depends on the accuracy of blower door measurements and on error propagation as calculations are performed with the results of these measurements.

The method for calculating the external leakage area uses two types of measurements: (a) single-door, single-zone measurements used to determine the total leakage area of the apartment, and (b) single-door, multi-zone or two-door, multi-zone measurements used to quantify interzonal leakage.

The uncertainty in the total leakage area estimate is determined by single-zone single-blower-door uncertainties[15]. These, in turn, are dominated by uncertainties in the measurement of pressure, both for the estimation of flows through the fan as well as for the driving pressure. Accuracies of 5-15% for the total flow rates are reasonable estimates for blower door technologies when the test is performed according to ASTM E 779.

Wind speed during the Willoughby and Grove tests was generally below 5 mph (2 m/s), as required by ASTM E 779. Occasional, brief wind puffs during the measurement period exceeded the limit and could have caused some errors in the calculations for that particular measurement. This is not of particular concern for the measurements as a whole. For this experiment, post-processing data treatment was used to extract useful information from the noise. The multiple measurement techniques enabled consistency checks and cancellation of errors. However, the potential for common biases still exists.

In general, the calculated effective leakage area of the entire apartment will be within 10% when using single-zone, single-blower-door techniques.

<u>Uncertainty in Interzonal Leakage Area</u>

The interzonal leakage area is important because it is subtracted from the total leakage area to obtain the external leakage area. The following discussion lays the premises for the calculation of uncertainty in the external leakage area.

Multi-zone measurements have similar uncertainties as single-zone measurements with respect to the blower doors, i.e., 5-15% of the flow rates. Also, the wind speed limitations that exist for single-zone, single-blower-door tests also limit the multi-zone techniques used to determine the interzonal leakage areas. Any multi-zone method needs to analyze the difference either between two measurements or two-measurement series. Bias in the measurements due to wind may cancel, but uncertainty due to changes in wind speed and direction probably increase the uncertainty in the calculated leakage areas for any multi-zone situation to about twice as much as for single-zone measurements. Herrlin and Modera[12] found that the uncertainty of two-door leakage measurements due to wind at 5 mph to be 2-3%, but that, when combined with other measurement uncertainties, the error, in the leakage area for a single apartment could increase up to 40% of that leakage area. If the error were to be expressed as a percentage of the *total* leakage area of the apartment, the figure decreases in the 5-15% range.

In general, the leakage between two zones will have a minimum uncertainty of 5% of the *total* leakage area when using the two-door technique and of 10% of the *total* leakage area when using the second version of the multi-zone single-door technique. The interzonal leakage areas (Tables 4-1, 4-2, 5-1, 5-2) were derived as follows:

- Single-door results were not used if two-door or tracer gas results were available.
- When both two-door and tracer gas results were available, these results were averaged.
- When only tracer gas results were available or only two-door results were available (regardless of availability of single-door data), those results were used directly.
- When only single-door results were available (two per apartment), these results were averaged and used.

For many apartment-to-apartment interzonal leakage areas, an uncertainty of 5-10% of the *total* leakage area results in an uncertainty of close to or even over 50% of the interzonal leakage area itself. Therefore, the confidence in any one interzonal leakage area is low, since these areas are characterized by small numbers and small numbers have large percentage uncertainties.

For instance, the interzonal leakage area between apartments 2L and 2R of Willoughby is estimated as 13.5 in^2 using a two-door test (Table 5-1). The total leakage area of apartment 2R, where the primary blower door was installed, is 128.8 in^2. The uncertainty in the interzonal leakage area is 6.5 in^2, if one assumes 5% uncertainty of total leakage area (5% of 128.8 in^2) when performing two-door tests. This uncertainty is 48% of the interzonal leakage area.

However, if all internal measurements are examined the uncertainty decreases rapidly. For example, instead of focusing on the leakage area between two apartments, the analysis can take the broader view of the *total interzonal leakage area* of each apartment (i.e., the leakage area between that apartment and all other adjacent spaces). This single value is more useful for practical purposes, since it is the value that determines the external leakage area.

Table 6-1 shows in col. 5 the total interzonal leakage areas and in col. 4 the total leakage areas (interzonal plus external). By dividing the sum of the leakage areas in col. 5 to the sum of leakage areas in col. 4 we obtain a fraction of 0.37. Consequently, it can be stated that for all unweatherized apartments the total interzonal leakage is a fraction of 0.37 of the total leakage. An error propagation analysis yields an uncertainty of about 17% for the total interzonal leakage, i.e., 0.37±17%. A similar calculation for weatherized apartments yields an uncertainty of about 12%. These interzonal uncertainties are presented here to understand their order of magnitude, but are not the focus of the research. Rather, the uncertainty in the external leakage area is of highest interest. This uncertainty is discussed in detail below.

Uncertainty in the External Leakage Area

The external leakage is found by subtracting the interzonal leakage from the total leakage; therefore, it has the largest uncertainty of all the leakage paths. Whereas the uncertainties associated with single-zone measurements are assumed to be about 10% of the total leakage area, the uncertainties of external leakage areas in multi-zone measurements were calculated for the unweatherized apartments to be about 20%-86% of the external leakage area. (The 86% is an extreme case, as will be shown below, since it involves a very conservative estimate of uncertainty).

The external leakage area uncertainty was calculated as follows:

$$\delta_{ext} = [(\delta^2_{ss}) + \Sigma(\delta^2_{ms})]^{0.5} \qquad \text{(EQ. 4)}$$

when only single-door data were available

$$\delta_{ext} = [(\delta^2_{ss}) + \Sigma(\delta^2_{mt})]^{0.5} \qquad \text{(EQ. 5)}$$

when tracer gas and/or two-door data were available

where:

δ_{ext} is the uncertainty in the external leakage area. This uncertainty is expressed as a percentage of the external leakage area.

δ_{ss} is the uncertainty in the total leakage area when measured with single-zone, single-door technique. In this error propagation analysis the uncertainty is assumed to be 10% of the total leakage area.

δ_{mt} is the uncertainty in the interzonal leakage area when measured with a multi-zone two-door technique or with a tracer gas technique. In this error propagation analysis the uncertainty is assumed to be 5% of the total leakage area.

δ_{ms} is the uncertainty of the interzonal leakage area when measured with version two of the multi-zone single-door technique. In this error propagation analysis the uncertainty of the average of the two single-door measurements is assumed to be 10% of the total leakage area. The total leakage area used in the calculation was conservatively taken as the largest of the areas of the two zones separated by the partition.

The results are shown in Table 6-1, column 9. The uncertainty in the external leakage areas of the apartments varies from 20% to 86% of their external leakage areas, with 86% an extreme case. The 86% uncertainty results from the fact that the larger leakage area tested (the basement) is double the smaller one tested (apartment 1R). As a result, the conservative assumption that the 10% error applies to the larger leakage area has a major effect, especially since the interzonal leakage area between basement and 1R is small. In a more typical example, in the Willoughby apartment 2L, test 1, the external leakage area could be expressed as the fraction 0.74±25%, with the total leakage area being 1.0. Even so, this uncertainty is fairly large.

However, for weatherization purposes, the value of highest interest is the uncertainty in the mean (average) of the external leakage areas of *all* apartments. The mean is obtained by summing all external leakage areas and by dividing the result to the sum of all total leakage areas. Table 6-1 shows this mean value to be 0.63 for unweatherized apartments. Equation 6 below yields an *uncertainty for the mean of all external leakage areas of about 19%,* as shown below.

$$\delta_{\bar{ext}} = [\Sigma(\delta^2_{total})]^{0.5}/\Sigma(L_{total}) + [\Sigma(\delta^2_{ext})]^{0.5}/\Sigma(L_{ext}) \qquad \text{(EQ. 6)}$$

Where:

$\delta_{\bar{ext}}$ is the uncertainty for the mean of all external leakage areas. The uncertainty is expressed as a percentage of the mean.

δ_{total} is the uncertainty in the total leakage area of each measurement (in^2).

δ_{ext} is the uncertainty in the external leakage area of each measurement (in^2).

L_{total} is the total leakage area for each measurement (in^2).

L_{ext} is the external leakage area for each measurement (in^2).

Equation 6 will overpredict the uncertainty δ_{ext}, since it adds the uncertainty in the total leakage area to the uncertainty in the individual external leakage areas. This simple addition presents a worst-case scenario, but it was used because a reliable method to derive a more accurate figure for the uncertainty has not yet been developed. As such, the 19% uncertainty is conservative.

In summary, the tests on unweatherized apartments yielded a mean external leakage area expressed as 0.63 fraction of the unitary total leakage area. Statistically, any new set of tests of the same type, performed with the same instrumentation under the same conditions will yield a mean external leakage area between 0.58 and 0.68. We can state this with seventy percent confidence. At the same time we can reasonably state that the uncertainty in this mean external leakage area, wherever it may fall within the 0.58-0.68 interval, is about 19%. For the 0.63 mean calculated in this study the result is expressed as $0.63 \pm 19\%$. If the mean were 0.60, the result would be expressed as $0.60 \pm 19\%$, etc.

The tests did have other potential sources for uncertainties that cannot be quantified. One potential bias was induced by the assumption that the flow exponent was equal to 0.67. While there is good evidence that this is reasonable for single-zone buildings, it may not be appropriate for the kind of leaks found between zones. Leaving the exponent as a free parameter has been determined by LBL to induce unacceptable variations in the results, thus making the potential bias of fixing the exponent a worthwhile trade. A detailed study of these kinds of leaks could determine the best choice for the flow exponent and the size of the induced bias. Such study was not within the scope of this project, and no other applicable data are available.

Another source of uncertainty is due to the behavior of the occupants during the tests. Many of the tests had to be repeated because a door or window was opened by an occupant at a bad time. It is possible that some of these events were not noted at the time and could have an adverse affect on the results. However, in general it can be assumed that behavior-related uncertainties were low.

The same analysis techniques are applied to the weatherized apartments, summarized in Table 6-2. This table includes the second set of tests at Grove Street and two sets of tests at the Willoughby building: the only test on apartment 1L which had been weatherized by its tenant, and the second test on apartment 3R which had been weatherized by its tenant after the first set of tests were completed.

TABLE 6-2: External Leakage Area of Weatherized Apartments

(1) Building	(2) Apt.	(3) Test #	(4) Total Leakage Area	(5) Total Interzonal Leakage Area	(6) Total Interzonal Leakage Area as Fraction of Total Leakage Area (5)/(4)	(7) External Leakage Area	(8) External Leakage Area as Fraction of Total Leakage Area (7)/(4)	(9) Uncertainty in External Leakage Area as % of External Leakage Area *	(10) Mean of External Leakage Area as Fraction of Total Leakage Area	(11) Standard Error of the Mean as Fraction of Total Leakage Area
1348 Willoughby	1L	2	30.2	22.8	0.75	7.4	0.25	375%	0.49	0.06
	3R	2	106.8	41.1	0.38	65.7	0.62	35%		
347 Grove	1L	2	88.0	59.4	0.68	28.6	0.32	69%		
	1R	2	71.6	56.1	0.78	15.5	0.22	91%		
	2L	2	89.3	43.3	0.48	46.0	0.52	41%		
	2R	2	113.8	50.	0.44	63.8	0.56	30%		
	3L	2	68.2	27.2	0.40	41.0	0.60	33%		
	3R	2	68.2	25.2	0.37	43.0	0.63	30%		

* The method of calculation is explained on page 6-5, equation 4 & 5

The mean, or average leakage area of the weatherized apartments is expressed as a fraction 0.49 of the total leakage area (1.0). There is about *seventy percent probability* that any new set of measurements on these apartments will yield a mean value between 0.49+0.06 and 0.49-0.06, i.e., between 0.43-0.55 of the total leakage area (expressed as 1.0). There is a *ninety-five percent probability* that any new set of measurements will yield a mean value between 0.49+0.12 and 0.49-0.12, i.e., 0.37-0.61 of the total leakage area (expressed as 1.0). The above ranges express a statistical probability that the results of the calculations will fall within the 0.43-0.55 or 0.37-0.61 ranges. However, the uncertainty in the results themselves, based on the accuracy of tests and method, needs also to be calculated. *The uncertainty in the 0.49 mean external leakage area fraction, calculated as shown for Table 6-1, is about 22%.* In this study the mean external leakage area can be presented as 0.49±22%. Another set of experiments with the same methods and under the same conditions might yield a mean external leakage area of 0.51, which is in the 0.41-0.53 statistical interval. This result would be presented as 0.51±22%, etc.

By comparing the mean external leakage areas of unweatherized and weatherized apartments (column 10 of Tables 6-1 and 6-2), one can see a decrease from 0.63 to 0.49 expressed as fractions of unitary total leakage area. This decrease could be accounted for by the fact that weatherization generally affects more the exterior envelope than interior partitions. However, since the unweatherized data is dominated by Willoughby apartments while the weatherized data is dominated by Grove apartments, this comparison is not reliable. Instead of attempting to quantify the reduction in fractional leakage area, a better approach is to describe the range of these fractions for all apartments tested. For all apartments, the external leakage area is, in average, 0.4-0.7 of the total leakage area. The 0.4-0.7 range is within one standard deviation (seventy percent confidence).

The theoretical uncertainty in the *mean* external leakage area for the two tests is 19% and 22%. Therefore, one can assume a 20-25% uncertainty in deriving such a value for other similar tests. The 20-25% uncertainty does not apply to the external leakage area of any single apartment; for individual predictions the uncertainty can be much higher. However, a determination of external leakage areas for each apartment in a building is not practical and is not performed for energy auditing or for weatherization purposes. It is the mean value, representative of all apartments (and therefore of the entire building) that matters most. From this perspective, the 20-25% uncertainty is good.

One important question is whether the 20-25% uncertainty is attainable only with research personnel and research equipment, or whether the uncertainty could be attained by auditing and weatherization crews during production work. The data collected during this research allowed a direct comparison between the sum of external leakage areas calculated for each apartment of the Grove Street building and the total external leakage area of the building when obtained with a single, direct pressurization test. As shown in page 5-4, the sum of external leakage areas, calculated with the multi-zone method, was within 12% of the measured total leakage area of the building. The 12% deviation is half the 20-25% uncertainty range and indicates that research-grade testing and analysis can be much more accurate than predicted by the error propagation analysis.

(Note that Eq. 6 used for this analysis was conservative in its estimate of uncertainty.) Therefore, it could be assumed that weatherization work is no more than twice as inaccurate as the research work, i.e., in the 20-25% range.

Single-Door vs. Two-Door Accuracy

When examining the ratios between the interzonal leakages obtained with the single-door and two-door methods, one should refer to the previous discussion of Section 6 on the uncertainty of interzonal leakage areas. These uncertainties are often as high as or higher than the leakage area itself, since small numbers have large percentage errors. As a result, it cannot be stated that a large discrepancy between individual measurements exists unless the data are far apart.

For instance, out of eight single-door/two-door comparisons in Table 6-3, six have ratios below 1.5. The measurement between the Willoughby apartments 3L and 2L has a ratio of 3.8. The average of the single-door measurements is 9.5 in^2 with an uncertainty of 12.9 in^2 (10% of 128.8 in^2 total building leakage area of the primary zone 2L, per Table 5-1). The two-door measurement is 2.5 in^2 with an uncertainty of 6.4 in^2 (5% of 128.8 in^2 total leakage area of 2L, per Table 5-1). Therefore, the single-door measurement could be 0 in^2 to 22.4 in^2, while the two-door measurement could be 0 in^2 to 8.9 in^2. The two ranges overlap. Similar results are obtained for the comparison between apartments 2L and 3L in Grove where the ratio single-door/two-door leakage area is 2.5: the range of both single-door and two-door uncertainties extend to 0 and therefore overlap.

Since the *individual* measurements are not good indicators of the fit between single-door and two-door techniques, it is better to look at the *mean* of these measurements. The mean interzonal leakage area calculated with the single-door technique is 12.41 in^2 versus 9.98 in^2 using the two-door technique. The ratio between the two is 1.24. This correlation is within the range of accuracy of both methods and shows that, *when applied over many apartments, the multi-zone single-door technique can yield useful results.*

<u>Summary</u>

The multi-zone measurements show a range of 0.4-0.7 mean (average) external leakage area for the apartments, where the total leakage area is expressed as 1.0. The fraction for mean external leakage area has a calculated uncertainty of about 20%-25%. However, a comparison of the sum of external leakage areas calculated with the multi-zone method vs. a direct measurement of the external leakage area of the entire Grove building shows agreement within 12%.

These results were obtained over a relatively small sample of apartments and can be applied to three-story, walk-up turn-of-the-century buildings. Nonetheless, the measurements are in line with other LBL research which shows that the external leakage area is often in a 0.4-0.7 range of the total leakage area (with the latter expressed as 1.0). Therefore, one cannot assign the entire leakage area calculated with a single-zone single-door ASTM test to the exterior envelope. There is a need to develop a simple multi-zone method and/or to develop rules-of-thumb based on building type.

As noted in the previous section, the multi-zone single-door method no. 2 holds the promise of quick results with reasonable accuracy in the estimate of the external leakage area. The accuracy for the mean of all external leakage values (not of each individual value) would probably be in the 25%-30% range if all measurements were performed using the single door method only. Please refer to section 9, "Implications for Weatherization Programs," for a discussion on how the multi-zone, single-door technique could be applied in weatherization of multi-family housing.

TABLE 6-3: Comparison of Interzonal Leakage (in²) Obtained with Single- and Two-Door Techniques, Post-Retrofit

Building	(1) Multi-zone Single-Door Method #2		(2) Multi-zone Two-Door Method	(1)/(2)
1348 Willoughby	1L-2L	6.4	4.2	**1.1**
	2L-1L	2.5		
	Average	**4.5**		
	2L-2R	18.3	13.5	**1.2**
	2R-2L	12.9		
	Average	**15.6**		
	2L-3L	10.5	2.5	**3.8**
	3L-2L	8.4		
	Average	**9.5**		
347 Grove	1L-2L	7.8	4.2	**2.5**
	2L-1L	13.0		
	Average	**10.4**		
	1L-2R	13.5	8.1	**1.5**
	2R-1R	10.4		
	Average	**12.0**		
	1R-Basement	23.6	28.2	**1.0**
	Basement-1R	30.8		
	Average	**27.2**		
	2L-2R	8.4	11.3	**1.0**
	2R-2L	14.0		
	Average	11.2		
	2R-3R	9.3	7.8	**1.1**
	3R-2R	8.4		
	Average	**8.9**		
Both Bldgs.	Mean	12.41	9.98	1.24

Section 7
IMPLICATIONS FOR STANDARDS AND PROTOCOLS

Given the size of the induced pressures and the wind effects, it appears that the first version of the multi-zone single-door method will never be suitable for use by weatherization crews. For some situations and with trained research personnel, it is possible to glean information from the first multi-zone single-blower-door method, but the uncertainty of doing so makes it unattractive as a field protocol.

In general, the second multi-zone single-blower-door method gives results of the correct order of magnitude (see Table 6-3) if a comparison is made between the *average* of the two multi-zone single-door measurements and the two-door measurement. Moreover, the second multi-zone single-door method yielded very good results when used to calculate the exterior ELA (see Section 5).

The second version of the multi-zone single-blower-door method is faster than the two-door method and does not require as much simultaneous access to apartments. (A tube can be inserted below the door into a locked apartment to measure pressures.) It is possible that this version may eventually become an ASTM Standard, but the two-door method will probably be a Standard first (see below). However, the second version of the multi-zone single-door method could be developed into a field protocol to augment the extant single-door method (ASTM E 779-88).

The two-door test is the more reliable method for making these measurements. The method used here*, which assumes a fixed flow exponent, needs only a few measurement points while using the second door. Based on the error analysis it is necessary to have good measurement conditions and calibrated equipment for reasonable accuracy in the predicting interzonal flows.

The two-door method appears to be appropriate for development as an ASTM standard. There could be two levels to the standard, one for measurements where the primary intended result is the leakage to outside, and a more rigorous standard where more detailed information on the interzonal leaks is desired. The data taken in this project will be helpful in that development.

The tracer-assisted technique appears to work well where it was used, but suffers from the rather long time it takes to make repeated measurements. It may still be a valuable technique where multiple tracer gases could be used, thus eliminating the time it takes to flush the building between tests with a single-tracer gas.

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* The more complete deduction method as developed by Feustel[4] should be used for obtaining more detailed information for computer models.

Section 8
AIR FLOWS AND EFFECT ON ENERGY USE

Computer analyses were performed to examine the effect that reductions in external and interzonal leakage areas have on annual air infiltration rates and on annual heating loads. Air flows have been modeled for the Willoughby and Grove apartment buildings using COMIS,[11] a multi-zone infiltration and ventilation modeling program. The results were used to calculate the heating load due to infiltration for each zone. These values were calculated assuming an inside temperature of 68°F for all zones, including the stairwell and basement. An analysis of Willoughby with the basement at 50°F instead of 68°F has also been done to assess the importance of this temperature assumption.

The following tables show the air flow rates and heating loads due to air infiltration for each zone for each month. These values are smaller than the total air flow and heating loads for the zone. It should be noted that, in all cases, the measurement of leakage areas was incomplete and it was necessary to impose assumptions. In general, if an apartment was not measured, then it was assumed to have the same leakage values as its horizontal neighbor; or if that information was not available, an average unit of the building. Where no leakage measurements of the stairwell or basement were made, measurements from the other building were used. If a pre- or post-retrofit leakage value was missing, the retrofit measures were assumed to have the same percentage change in each apartment for external leakage (35% reduction in external leakage area due to the retrofit). The only internal leakage that changed because of the retrofits was the leakage of the door from each apartment to the stairwell. This was estimated to be 11 in^2 (15% reduction in interzonal leakage area).

For these reasons, the results only suggest the magnitude of air leakage reduction. However, the results clearly indicate that significant decreases in external and interzonal leakage areas yield significant decreases in air infiltration rates and heating loads.

Tables 8-1, 8-2 and 8-3 present Willoughby data, with the basement assumed at 68°F. The leakage values used are the best estimate from the first round of measurements (those designated as pre-retrofit).

Table 8-1: Willoughby Basement at 68°F; Monthly Average Infiltration Rate (cfm)

Zone	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Basement	304	262	276	204	160	130	114	94	137	222	265	271
Stairwell	26	27	26	18	11	6	9	6	10	24	31	28
1L	13	11	12	9	8	7	7	5	7	11	12	12
1R	74	63	68	51	42	37	34	28	38	58	67	66
2L	131	108	123	94	81	80	78	65	78	112	124	115
2R	118	98	111	85	74	73	72	59	71	102	112	103
3L	106	85	103	80	75	81	84	70	77	103	108	92
3R	94	75	90	71	67	72	75	62	69	91	96	81
Apartments Total	536	440	508	390	347	350	350	291	340	476	519	470
Building Total	866	730	809	611	518	487	472	391	488	722	815	769

TABLE 8-2: Willoughby Basement at 68°F; Monthly Average Infiltration Rate (ach)

Zone	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
Basement	1.75	1.51	1.59	1.17	0.93	0.75	0.66	0.54	0.79	1.28	1.53	1.56
Stairwell	0.32	0.34	0.32	0.23	0.13	0.07	0.11	0.08	0.13	0.29	0.39	0.36
1L	0.18	0.15	0.17	0.13	0.11	0.10	0.09	0.07	0.10	0.15	0.17	0.16
1R	1.01	0.86	0.93	0.70	0.57	0.51	0.47	0.39	0.52	0.79	0.91	0.90
2L	1.79	1.48	1.68	1.28	1.11	1.09	1.07	0.89	1.07	1.53	1.69	1.57
2R	1.61	1.34	1.52	1.16	1.01	0.99	0.98	0.81	0.97	1.38	1.53	1.41
3L	1.45	1.16	1.40	1.10	1.02	1.11	1.14	0.96	1.05	1.40	1.47	1.26
3R	1.28	1.02	1.23	0.97	0.91	0.98	1.02	0.85	0.94	1.24	1.30	1.11
Apartments Average	1.22	1.00	1.15	0.89	0.79	0.80	0.79	0.66	0.77	1.08	1.18	1.07
Building Average	1.25	1.05	1.17	0.88	0.75	0.70	0.68	0.56	0.70	1.04	1.18	1.11

TABLE 8-3: Willoughby Basement at 68°F; Monthly Average Heating Load Due to Infiltration (Btu/hr)

Zone	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
Basement	994	872	739	360	145	N/A	N/A	N/A	N/A	267	558	818
Stairwell	96	95	78	35	11	N/A	N/A	N/A	N/A	30	73	89
1L	43	37	33	16	7	N/A	N/A	N/A	N/A	13	26	35
1R	241	210	182	88	37	N/A	N/A	N/A	N/A	69	140	198
2L	420	359	324	156	69	N/A	N/A	N/A	N/A	131	257	344
2R	379	324	293	141	62	N/A	N/A	N/A	N/A	118	233	310
3L	335	279	265	127	59	N/A	N/A	N/A	N/A	116	222	275
3R	295	245	234	112	52	N/A	N/A	N/A	N/A	103	196	242
Apartments Total	1713	1455	1331	639	287	N/A	N/A	N/A	N/A	550	1073	1403
Building Total	2803	2423	2149	1039	449	N/A	N/A	N/A	N/A	851	1705	2311

Tables 8-4 through 8-6 present data for Willoughby, with the basement at 50°F instead of 68°F.

TABLE 8-4: Willoughby Basement at 50°F; Monthly Average Infiltration Rate (cfm)

Zone	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Basement	301	259	273	201	156	127	111	90	133	219	262	268
Stairwell	26	27	26	18	11	6	9	6	10	24	31	28
1L	13	11	13	9	8	7	7	6	7	11	12	12
1R	75	64	69	52	43	38	35	29	39	58	67	66
2L	131	109	124	94	82	80	79	66	79	113	125	115
2R	119	99	112	85	75	73	72	60	72	102	113	104
3L	106	85	103	81	76	82	84	71	77	103	108	93
3R	94	75	91	71	67	73	75	63	69	91	96	81
Apartments Total	538	442	510	392	351	354	353	295	344	479	522	472
Building Total	866	730	809	611	518	487	472	391	488	722	815	769

TABLE 8-5: Willoughby Basement at 50 F; Monthly Average Infiltration Rate (ach)

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Basement	1.74	1.50	1.58	1.16	0.90	0.73	0.64	0.52	0.77	1.26	1.51	1.55
Stairwell	0.33	0.34	0.32	0.23	0.13	0.07	0.11	0.08	0.13	0.30	0.39	0.36
1L	0.18	0.15	0.17	0.13	0.11	0.10	0.09	0.08	0.10	0.15	0.17	0.16
1R	1.02	0.87	0.94	0.70	0.58	0.52	0.47	0.40	0.53	0.80	0.92	0.90
2L	1.79	1.48	1.69	1.28	1.12	1.10	1.08	0.90	1.08	1.54	1.70	1.57
2R	1.62	1.34	1.53	1.16	1.02	1.00	0.98	0.82	0.98	1.39	1.54	1.42
3L	1.45	1.16	1.40	1.10	1.04	1.12	1.15	0.96	1.06	1.40	1.48	1.26
3R	1.28	1.02	1.24	0.97	0.92	0.99	1.02	0.86	0.94	1.24	1.31	1.11
Apartments Average	1.22	1.01	1.16	0.89	0.80	0.80	0.80	0.67	0.78	1.09	1.19	1.07
Building Average	1.25	1.05	1.17	0.88	0.75	0.70	0.68	0.56	0.70	1.04	1.18	1.11

TABLE 8-6: Willoughby Basement at 50 F; Monthly Average Heating Load due to Infiltration (Btu/hr)

Zone	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
Basement	506	431	334	111	28	N/A	N/A	N/A	N/A	95	252	371
Stairwell	96	96	79	36	12	N/A	N/A	N/A	N/A	30	74	90
1L	44	38	33	16	7	N/A	N/A	N/A	N/A	13	26	36
1R	243	212	183	89	38	N/A	N/A	N/A	N/A	70	141	200
2L	421	361	325	157	69	N/A	N/A	N/A	N/A	131	258	345
2R	380	325	294	141	63	N/A	N/A	N/A	N/A	119	234	311
3L	336	280	266	127	60	N/A	N/A	N/A	N/A	117	222	276
3R	296	246	235	112	53	N/A	N/A	N/A	N/A	103	196	243
Apartments Total	1720	1462	1336	643	289	N/A	N/A	N/A	N/A	553	1077	1410
Building Total	2300	1989	1739	774	303	N/A	N/A	N/A	N/A	627	1348	1863

Tables 8-7 through 8-9 present the Grove building in the pre-retrofit condition.

TABLE 8-7: Grove Pre-Retrofit Monthly Average Infiltration Rate (cfm)

Zone	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
Basement	280	243	253	187	145	116	100	82	123	202	242	251
Stairwell	26	26	25	18	11	6	9	6	10	24	30	28
1L	145	124	134	101	83	74	69	57	75	114	132	129
1R	49	42	45	33	27	24	22	18	25	38	44	43
2L	149	124	141	107	94	92	91	76	90	129	143	131
2R	175	145	165	126	110	108	107	89	106	152	167	154
3L	106	85	103	80	76	81	84	71	77	103	109	93
3R	111	89	107	84	78	84	87	73	80	107	113	97
Apartments Total	735	608	695	531	467	464	461	383	454	643	707	646
Building Total	1041	877	973	735	623	586	569	471	587	868	980	924

TABLE 8-8: Grove Pre-Retrofit Monthly Average Infiltration Rate (ach)

Zone	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
Basement	1.62	1.40	1.46	1.08	0.84	0.67	0.58	0.47	0.71	1.16	1.40	1.45
Stairwell	0.32	0.33	0.31	0.22	0.13	0.07	0.11	0.08	0.13	0.29	0.38	0.35
1L	1.98	1.69	1.83	1.37	1.13	1.00	0.94	0.78	1.02	1.56	1.80	1.76
1R	0.66	0.57	0.61	0.45	0.37	0.33	0.30	0.25	0.33	0.52	0.60	0.59
2L	2.03	1.69	1.92	1.46	1.28	1.25	1.24	1.03	1.23	1.76	1.95	1.79
2R	2.39	1.98	2.25	1.71	1.50	1.48	1.46	1.22	1.45	2.07	2.28	2.10
3L	1.45	1.16	1.40	1.10	1.03	1.11	1.15	0.96	1.06	1.41	1.48	1.26
3R	1.51	1.21	1.46	1.14	1.06	1.15	1.18	0.99	1.09	1.46	1.54	1.32
Apartments Average	1.67	1.38	1.58	1.21	1.06	1.05	1.05	0.87	1.03	1.46	1.61	1.47
Building Average	1.50	1.26	1.40	1.06	0.90	0.85	0.82	0.68	0.85	1.25	1.41	1.33

TABLE 8-9: Grove Pre-Retrofit Monthly Average Heating Load due to Infiltration (Btu/hr)

Zone	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
Basement	920	809	679	332	133	N/A	N/A	N/A	N/A	243	511	758
Stairwell	93	93	77	34	11	N/A	N/A	N/A	N/A	29	72	87
1L	472	411	358	173	74	N/A	N/A	N/A	N/A	136	276	388
1R	158	138	119	58	24	N/A	N/A	N/A	N/A	45	91	130
2L	479	410	370	178	79	N/A	N/A	N/A	N/A	150	296	392
2R	562	480	435	209	92	N/A	N/A	N/A	N/A	176	347	460
3L	336	280	266	127	59	N/A	N/A	N/A	N/A	117	223	275
3R	350	292	277	132	62	N/A	N/A	N/A	N/A	122	232	287
Apartments Total	2357	2010	1825	877	390	N/A	N/A	N/A	N/A	746	1465	1932
Building Total	3370	2911	2582	1249	540	N/A	N/A	N/A	N/A	1023	2049	2777

Tables 8-10 through 8-12 present data on the Grove building assuming a post-retrofit condition.

TABLE 8-10: Grove Post-Retrofit Monthly Average Infiltration Rate (cfm)

Zone	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
Basement	276	238	250	185	146	120	104	86	125	201	240	246
Stairwell	24	25	24	17	10	6	10	7	10	23	30	26
1L	78	66	73	54	45	41	39	32	42	62	71	69
1R	26	22	24	18	15	14	13	11	14	21	24	23
2L	80	66	76	58	52	52	51	43	50	70	77	70
2R	94	77	89	68	61	61	61	51	59	83	91	82
3L	56	44	54	43	41	46	48	40	43	56	58	49
3R	58	46	56	45	43	47	49	41	44	58	60	51
Apartments Total	392	320	372	286	256	260	260	217	252	350	381	343
Building Total	692	583	646	488	413	386	375	310	387	575	650	616

TABLE 8-11: Grove Post-Retrofit Monthly Average Infiltration Rate (ach)

Zone	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
Basement	1.59	1.37	1.44	1.07	0.84	0.69	0.60	0.50	0.72	1.16	1.38	1.42
Stairwell	0.30	0.31	0.30	0.21	0.13	0.07	0.12	0.09	0.13	0.29	0.37	0.33
1L	1.06	0.90	0.99	0.74	0.62	0.56	0.53	0.44	0.57	0.85	0.97	0.94
1R	0.35	0.30	0.33	0.25	0.21	0.19	0.17	0.15	0.19	0.28	0.32	0.31
2L	1.09	0.90	1.03	0.79	0.70	0.70	0.70	0.58	0.68	0.96	1.05	0.96
2R	1.28	1.05	1.22	0.93	0.83	0.84	0.83	0.70	0.81	1.13	1.24	1.12
3L	0.76	0.60	0.74	0.59	0.56	0.62	0.65	0.54	0.59	0.76	0.80	0.66
3R	0.79	0.62	0.77	0.61	0.58	0.64	0.67	0.56	0.60	0.79	0.82	0.69
Apartments Average	0.89	0.73	0.84	0.65	0.58	0.59	0.59	0.49	0.57	0.80	0.87	0.78
Building Average	1.00	0.84	0.93	0.70	0.59	0.56	0.54	0.45	0.56	0.83	0.94	0.89

TABLE 8-12: Grove Post-Retrofit Monthly Average Heating Load due to Infiltration (Btu/hr)

Zone	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
Basement	903	792	670	327	132	N/A	N/A	N/A	N/A	242	505	744
Stairwell	89	87	74	33	11	N/A	N/A	N/A	N/A	29	70	82
1L	252	219	192	93	40	N/A	N/A	N/A	N/A	74	149	207
1R	84	73	64	31	13	N/A	N/A	N/A	N/A	24	49	69
2L	256	217	198	95	43	N/A	N/A	N/A	N/A	81	159	209
2R	300	254	233	112	50	N/A	N/A	N/A	N/A	96	187	245
3L	176	144	140	67	32	N/A	N/A	N/A	N/A	63	119	144
3R	182	150	145	69	33	N/A	N/A	N/A	N/A	65	123	149
Apartments Total	1250	1057	972	466	210	N/A	N/A	N/A	N/A	404	785	1023
Building Total	2241	1936	1716	831	358	N/A	N/A	N/A	N/A	678	1361	1850

TABLE 8-13: Grove Reduction in Average Infiltration Rate due to Weatherization (ach)

Zone	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
Basement	.03	.03	.03	.01	.00	-.02	-.02	-.03	-.01	.00	.02	.03
Stairwell	.02	.02	.01	.01	.00	.00	-.01	-.01	.00	.00	.01	.02
1L	.92	.79	.84	.63	.51	.44	.41	.34	.45	.71	.83	.82
1R	.31	.27	.28	.20	.16	.14	.13	.10	.14	.24	.28	.28
2L	.94	.79	.89	.67	.58	.55	.54	.45	.55	.80	.90	.83
2R	1.11	.93	1.03	.78	.67	.64	.63	.52	.64	.94	1.04	.98
3L	.69	.56	.66	.51	.47	.49	.50	.42	.47	.65	.68	.60
3R	.72	.59	.69	.53	.48	.51	.51	.43	.49	.67	.72	.63
Apartments Average	.78	.65	.74	.56	.48	.46	.46	.38	.46	.66	.74	.69
Building Average	.50	.42	.47	.36	.31	.29	.28	.23	.29	.42	.47	.44

TABLE 8-14: Grove Reduction in Monthly Average Heating Load due to Weatherization (Btu/hr)

Zone	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
Basement	20	17	9	5	1	N/A	N/A	N/A	N/A	1	6	14
Stairwell	4	6	3	1	0	N/A	N/A	N/A	N/A	0	2	5
1L	220	192	166	80	34	N/A	N/A	N/A	N/A	62	127	181
1R	74	65	55	27	11	N/A	N/A	N/A	N/A	21	42	61
2L	223	193	172	83	36	N/A	N/A	N/A	N/A	69	137	183
2R	262	226	202	97	42	N/A	N/A	N/A	N/A	80	160	215
3L	160	136	126	60	27	N/A	N/A	N/A	N/A	54	104	131
3R	168	142	132	63	29	N/A	N/A	N/A	N/A	57	109	138
Apartments Total	1107	953	853	411	180	N/A	N/A	N/A	N/A	342	680	909
Building Total	1129	975	866	418	182	N/A	N/A	N/A	N/A	345	688	927

Figure 8-1 shows the estimated infiltration rates as calculated by the COMIS program for the post-retrofit Grove building. The line through the data points is the weekly average. While the hourly averages vary from 0.005 ach to over 4.0 ach, the weekly averages vary from 0.38 ach to 1.23 ach.

The effect of the assumption of 68°F for all zones has been tested by modeling the case where the Willoughby basement is given a temperature of 50°F. *There is insignificant change in the heating load of the apartments* due to air infiltration. However, the overall building heating load due to air infiltration decreases by 18%. This indicates that the basement temperature is important for the total heating load due to air infiltration, and therefore for the total heating energy use of the building.

The findings suggest that it could be worthwhile to perform air tightening measures on the basement during any retrofit process, so that the only air admitted in the basement is that required for combustion. Best results will be obtained if the boiler uses a separate fresh air intake. Alternately, the boiler and the hot water pipes could be better insulated so that most of the heat produced goes to the apartments. If furnaces heat the apartments, the furnaces and ducts could be better insulated, and the ducts could be air-sealed. Note, however, that any retrofit measures that significantly decrease the heat gain from the heating system into the basement must ensure that low temperatures in winter do not result in pipe freezing.

The analyses show that, for a building similar to that on Grove Street, a 35% reduction in the external leakage area coupled with a 15% reduction in interzonal leakage area can bring significant decreases in air infiltration rates and in heating loads. Heating season air infiltration rates in apartments (November through March) decreased by about 25% from an average of 1.54 ach to 1.13 ach.

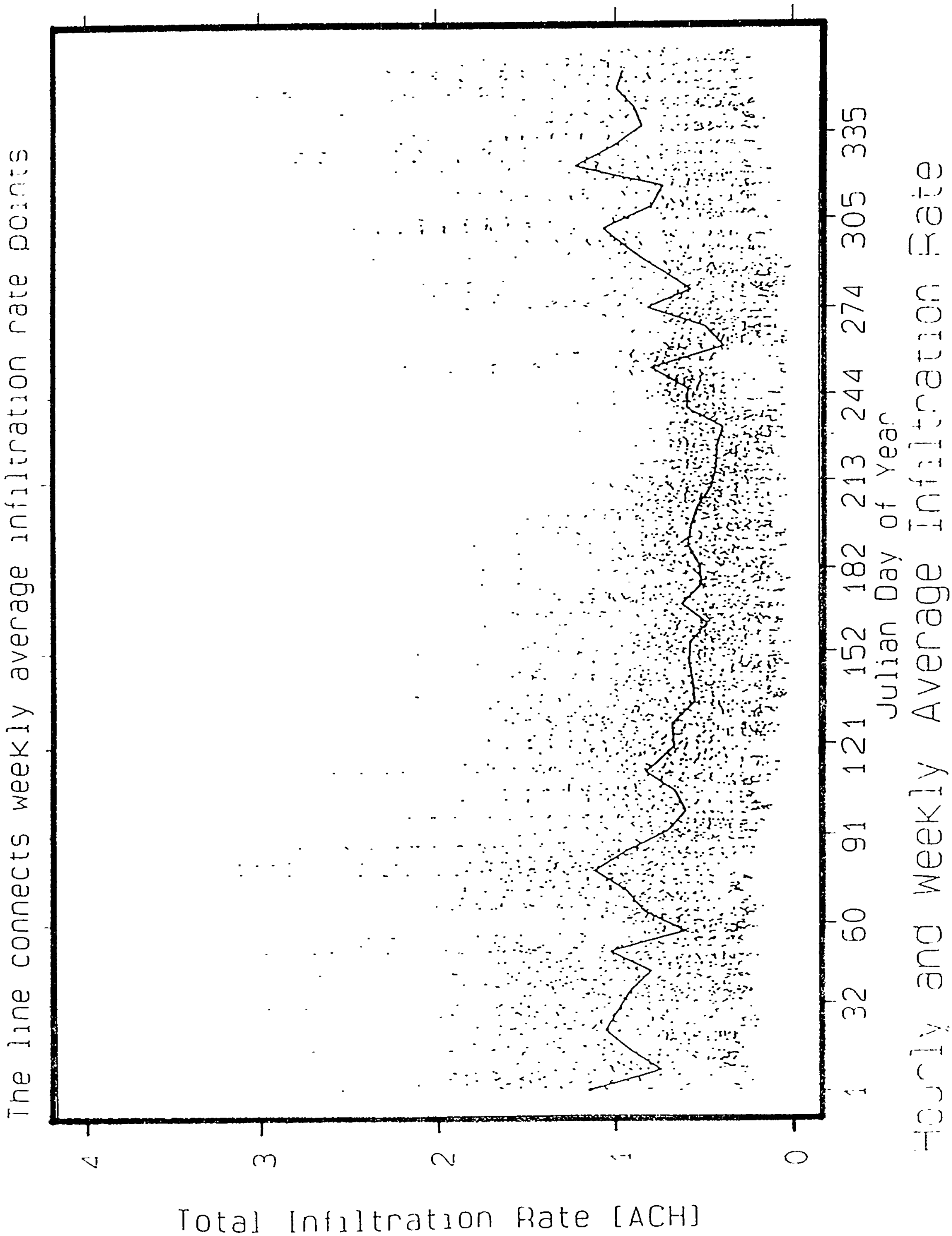

Figure 8 -1: Air Infiltration Plot

Section 9

IMPLICATIONS FOR WEATHERIZATION PROGRAMS

This study presents information suggesting that weatherization is effective in reducing the annual air leakage through the building envelope. The most significant findings of the study are in two domains: (a) fraction of external leakage area and (b) methods to determine the external leakage area.

Fraction of External Leakage Area

It is important to note that the external leakage area is comparable in size to the interior leakage area. The data in this research (see Table 6-1 and 6-2) confirm results from earlier tests performed by Lawrence Berkeley Laboratory and by Steven Winter Associates, Inc. Consequently, the contribution of interzonal ELA air infiltration should not be neglected during weatherization, especially since internal air leakage has an effect not only on energy use but also on indoor air quality.

The Multi-zone Single-door Method

One conclusion that can be drawn from this study is that the first version of the multi-zone single-blower-door method cannot be reliably used to determine the interzonal and outdoor leakage, whereas the second version of the multi-zone single-door method is effective for practical purposes in determining exterior and interzonal leakages. The single-door method no. 2 yields numerical data on interior air leakage only when this leakage is a significant fraction of the external air leakage. In practical terms, this may be all that is required for weatherization work. The single-door method also yielded good results for the exterior ELA (see sections 5 and 6).

It is likely the multi-zone single-door method will become suitable for use by energy auditors. However, some additional development work is still required before its use can be supported. Because a full implementation of the multi-zone single-door technique requires that *all* apartments be tested, it is more expensive than current weatherization, which uses spot-testing. Consequently, weatherization work on *all* apartments using the multi-zone single-door method is unlikely. However, the full method could be used to characterize one building that is representative of several being weatherized (e.g., 3-story, wood frame, row housing).

A spot-application of the multi-zone single-door could be used more successfully in routine weatherization work. In this scenario the crew would spot-check only several apartments, to get an idea whether internal leakage is dominant, significant or unimportant. This information is valuable, since there always are typical buildings and buildings which depart widely from the norm. The latter types of buildings can be most affected by incorrect weatherization. Further, the spot-application method could be used to investigate problems such as soot in apartments, fuel smell or visual evidence of poor fire-stopping. Spot application of the single-door method could substantially enhance the tools available to the weatherization personnel without a major increase in time expended on tests.

The Two-door Method

The two-door technique appears to work well when compared to tracer gas tests, and according to analysis of the test data. This technique requires good access to neighboring apartments. Because it is relatively time-consuming, we envision that two-door measurements have the primary application for research purposes (e.g., determining the air leakage characteristics of the building stock).

Conclusion

In conclusion, the multi-zone single-door method is not fully developed but shows good promise for weatherization application. The two-door method is probably too expensive to apply in a routine manner. However, the questions on the air leakage characteristics of multi-family buildings need not remain unanswered.

An approach to consider is to carry out a survey of typical apartment types, using research-grade instrumentation. This survey would use the two-door technique to determine ranges of leakage area parameters. Version two of the multi-zone single-door technique could also be tested in one or two instances for fine-tuning. If, as anticipated, similarly constructed building types have similar leakage characteristics, one could develop simplified rules to be combined with a traditional ASTM E 779 test of an apartment to estimate weatherization effects.

Section 10
CONCLUSIONS

Tests were performed on two walk-up, three-story, turn-of-the-century apartments in Brooklyn, New York. The tests performed on both unweatherized and weatherized apartments showed that the average external leakage area is a fraction of about 0.4-0.7 of the total leakage area, when the latter is expressed as a unit (1.0). Another way of interpreting this result is to say that if many such apartments are tested, their external leakage areas will likely be only 40% to 70% of their total leakage areas. As a result, the interzonal leakage is confirmed to be significant.

An error propagation analysis showed that the average external leakage area can be calculated with a 20-25% uncertainty when two doors are used. This is a good result, when accounting for the fact that single-zone single-door measurements can be performed with about 10% uncertainty. For tests using only single doors, this uncertainty is probably in the 25-30% range.

The two-door technique is fully developed and yields good results. The technique can be used for research-type projects, which would catalog the leakage areas of various construction types. However, this technique is too expensive to be used for routine weatherization work.

Version 2 of the multi-zone single-door compared favorably with the two-door technique. Its interzonal leakage areas are in average within 25% of the leakage areas calculated with the two-door method. This difference in results is within the accuracy range of the two methods. The single-door technique is relatively fast. If spot-applied to a sample of apartments in a building, it can give a good indication of the airtightness of the exterior envelope relative to interior partitions. This can, in turn, help the weatherization crews decide if internal air tightening is a priority. The single-door technique can also be used to detect reasons for soot, odors, CO_2 and CO migration within buildings.

Finally, computer analyses showed that significant reductions in external and interzonal leakage areas result in significant decreases of both annual air infiltration and annual heating load.

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APPENDIX A:
PROTOCOL FOR TWO-DOOR FAN PRESSURIZATION MEASUREMENTS

The two-door fan pressurization technique has been used to directly measure the total and interzonal leakage of a set of zones as in a multi-family building. Although ASTM Committee E6 is in the process of developing a test method, no agreed-upon standard method yet exists. This appendix describes the basic method used for this project. Appendix D describes the detailed field procedure followed for this test.

INSTRUMENTATION

The instrumentation used in this procedure consists of the following:

- One set of equipment that meets the full requirements of ASTM Standard E 779-88[1], including a blower door, a flow measuring device, a pressure measuring device and auxiliary instrumentation.

- A second blower door capable of moving as much air as the first. Although this blower door need not have flow measuring capability to use the protocol, it is much more convenient if it is meets the requirements of E 779 in terms of flow and pressure measurement. For this project we used two equivalent (E 779) blower doors.

- An additional pressure measurement device to measure the pressure between the main zone and the second zone. Since the purpose of the measurement is verify a pressure differential close to zero, a digital manometer that reads down to 0.1 Pa was used.

Because on the research nature of this project, the data were collected on a computer using a data acquisition system developed at LBL. In practice this is not necessary. The data can be collected using two digital manometers, one of which verifies the zero pressure differential between the two zones that are pressurized, and the second which is part of the blower door installed in the primary zone. No pressure measurement for the second blower door is need, unless if two doors are required to pressurize the entire building; however, pressurizing the whole building is a desirable check but not essential. Refer to Appendix D for a step-by-step description of test procedure.

BASIC PROCEDURE

The basic two-door procedure uses the deduction method developed by Feustel[4] and the error analysis developed by Herrlin and Modera[5,6]. It uses a second blower door to control the pressure difference between the second zone and the main zone. From that data set, the total leakage and the interzonal leakage can be estimated. The method is repeated for each neighboring zone of interest. The leakage to outside is the total leakage minus the leakage to each neighbor.

$$Q_{BD}=K_t\Delta P^n_e \qquad \text{(EQ 7)}$$

where $\Delta P_w=\Delta P_e$

$$Q_{BD}=K_e\Delta P^n_e \qquad \text{(EQ 8)}$$

where $\Delta P_w=0$

If it is assumed that the flow exponent, n, is a constant for all leaks then

$$K_w=K_t - K_e \qquad \text{(EQ 9)}$$

In practice, one makes a blower door measurement of the main zone with the neighboring zones open to the outside (either directly or through a stairwell that is well coupled to the outside, in this case opened at first and the last floor levels). The data are fitted to the power law equation with the flow exponent, n, forced to a specific value, in this case n=0.67. This is the total leakage.

A second measurement is then made while keeping the pressure difference between the two zones as close to zero as possible. Several attempts may be needed to obtain the desired pressure difference. The blower door data with no pressure between the zones is then fitted to the power law equation with n=0.67. The leakage obtained is the leakage of all but the partitions (walls, ceiling or floor) between the main zone and second zone*. The difference between the two measurements is the leakage of the wall.

The method used varied from that of Herrlin and Modera in several respects. The electronic pressure gages used averaged readings over 30 seconds. The flow exponent (n) of the leak between two zones was assumed to be 0.67. The outside reference used was located at one wall rather than averaging three (or four) walls. In the post-retrofit measurements, the outside reference used was the stairwell (open to outside) for all pressures, except when the stairwell itself was measured. It is believed that these changes make the analysis of leakage to the outside more robust and the measurements easier to obtain. The assumption of an interzonal flow exponent may not be appropriate where the goal of the measurements is to provide detailed inputs to model a specific building. The uncertainty of the interzonal flow coefficient should be somewhat improved over the 63% found by Herrlin and Modera[5].

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* This assumes there is no interstitial leakage (i.e., to spaces other than measured zones).

APPENDIX B:
PROTOCOL FOR MULTI-ZONE SINGLE-DOOR FAN PRESSURIZATION MEASUREMENTS

Various suggestions for using a single blower door to measure interzonal leakage have been put forth, but little work has been done on any of them. This appendix describes the basic method and the two versions that were used for this project.

INSTRUMENTATION

The instrumentation used in this procedure consists of the following:

- One set of equipment that meets the full requirements of ASTM Standard E 779-88[1], including a blower door, a flow measuring device, a pressure measuring device and auxiliary instrumentation.

- Additional pressure measurement devices to measure the pressures between the main zone and all of the adjacent zones. This may be done with multiple devices or with a single device and a suitable multiplexer.

BASIC PROCEDURE

The single-zone single-door technique (ASTM E 779-88) measures the pressures induced in adjacent zones with the building in different leakage configurations, while keeping the main zone at a reference pressure (approximately 50 Pa) by varying the flow through the blower door installed in the zone. Two versions of the single-door technique were used in this project for multi-zone testing. These versions are described below.

Version 1

In the first round of measurements, the leakage configuration of the building was varied by opening the doors of neighboring zones to the hallway one at a time or in different combinations. The hallway was brought to outdoor conditions by opening the large set of entry doors as well as the roof aperture (a door in Willoughby and a large hatch in Grove). The test was done in the depressurization mode only. The procedure yields a data set that consists of air flows into the main zone at various pressures from its neighbors. The flow coefficients are found by solving a system of equations

$$\hat{K} = \hat{Q} \times \hat{P}^{-1} \qquad \text{(EQ 10)}$$

where these symbols are interpreted as matrices.

A simple two-zone problem has three unknowns, i.e., the two flows from the first and second zone to outside and the flow between the zones. A two-zone case where there is an interstitial space has six flows and requires at least four different blower door measurements. More complex situations quickly make for a large number of blower door measurements.

The measurement method for a single blower door can be explained by considering the case of a simple four-zone building with no interstitial spaces. (See Figure B-1 on next page.) The target apartment is designated as Zone I. It is assumed that there are no wind or stack pressures present, or that the effect of such pressures has been eliminated based on measurements made before the blower door was installed.

Setup:
A single blower door in Zone I with pressure sensors to each exterior wall and to every other zone in the building that connects to Zone I.

Initially the doors of zones II, III and IV are open to effectively make these zones equivalent to the outside; the multi-zone problem is therefore reduced to a single zone one. By performing an ASTM E 779 blower door test on Zone I, we obtain the airflow out of Zone I, the flow coefficient K, and the flow exponent n.

$$Q = K * \Delta P^{n} \qquad \text{(EQ 11)}$$

The flow equation for this multi-zone experiment is:

$$Q=A*Pa^{n} + B*Pb^{n} + C*Pc^{n} + D*Pd^{n} \qquad \text{(EQ 12)}$$

The flow exponent n is known from the first test and is assumed to be the same for all walls. If the flow coefficient A is determined, the leakage area of zone I to outside can be calculated. To separate the terms (A,B,C,D), the pressures Pa, Pb, Pc and Pd must be varied without allowing them to correlate; one cannot separate the leakage paths without changing something about them. In the single-door tests, the pressures are varied by selectively closing the doors of the surrounding zones, according to various combinations.

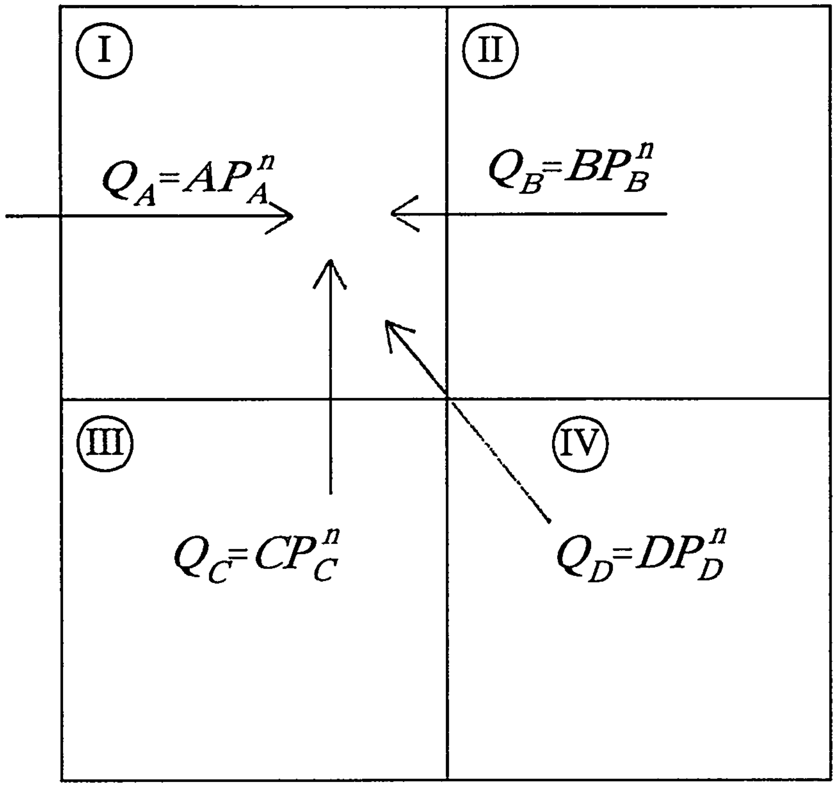

Figure B-1: Single-Blower-Door Measurement with Four Zones.

The tests are performed at a single reference pressure (approximately -50 Pa to outside) for different configurations of window openings. The blower door flow (Q) and the pressure difference between Zone I and its surroundings (Pa, Pb, Pc, Pd) are defined as follows:

Q = blower door flow
Pa = Outside pressure - Pressure in Zone I
Pb = Pressure in Zone II - Pressure in Zone I
Pc = Pressure in Zone III - Pressure in Zone I
Pd = Pressure in Zone IV - Pressure in Zone I
n = Flow exponent found from the full blower door test (Test 1)

Test #	Zone configuration: I	II	III	IV	{0 = doors open, 1 = doors closed}
1	1	0	0	0	$Q = (A + B + C + D) * Pa^n$
2	1	0	1	1	$Q = (A + B) * Pa^n + C * Pc^n + D * Pd^n$
3	1	1	0	1	.
4	1	1	1	0	.
5	1	0	0	1	.
6	1	0	1	0	.
7	1	1	0	0	.
8	1	1	1	1	$Q = A*Pa^n + B*Pb^n + C*Pc^n + D*Pd^n$

The tests yield eight equations with four unknowns (A, B, C, D); however, some of the equations may be identical (e.g., if there is no leakage from Zone IV to Zone I, tests 5 and 1 are identical). In cases where there is only a very small leakage area between zones, Q (the airflow) is also very small, but is obtained by subtracting relatively large numbers. Consequently, the calculation of Q between such tightly separated zones has a high uncertainty level and cannot be used for determining the other flow coefficients. For these reasons it is good to have an over-determined system of equations.

The interstitial spaces add more unknowns to the above conditions; the solution of the set of equations is less over-determined and therefore less well determined. In the example Figure B-2 on next page, three interstitial spaces are added around Zone I.

The general system of equations is:

$$Q = A*Pa^n + B*Pb^n + C*Pc^n + D*Pd^n + E*Pe^n + F*Pf^n + G*Pg^n \qquad \text{(EQ 13)}$$

The same eight tests yield a system of eight equations with seven unknowns.

It is *unlikely* that there is any direct leakage from Zone IV to Zone I.

It is *likely* that the interstitial zones, if they leak at all, connect to other zones, such as the basement. As a result, it may not be possible to obtain much variation in the pressure differentials between Zone I and the interstitial zones; larger uncertainties may result in the calculation of the leakage areas between Zone I and these zones.

Where a physically impossible K value is calculated (see EQ 10), such as a negative one or one bigger than the total measured for a zone, one flow path and one equation are eliminated and the calculation is repeated. In practice it is difficult to determine which flow path is the offending one. In this research the interstitial flows and flows from zones that are diagonally arranged from the zone with the blower door were the first to be eliminated.

During the analysis of the data collected in Brooklyn, it was commonly necessary for all flows, except the flow to outside, to be eliminated before the calculated K values made physical sense. A simple error analysis suggested that neighboring zones must have a pressure of about 10% of the main zone pressure for the signal to be large enough to be useful. This would be the case where the leakage is about 20% of the total into the zone. The interzonal leakage of the zones in the buildings in this study was too small to use this analysis technique.

This technique is the only one attempted that might be able to determine interstitial leakage. Although it was not useful in this study because of the overall tightness of the interzonal leaks, it may be useful in another type of building.

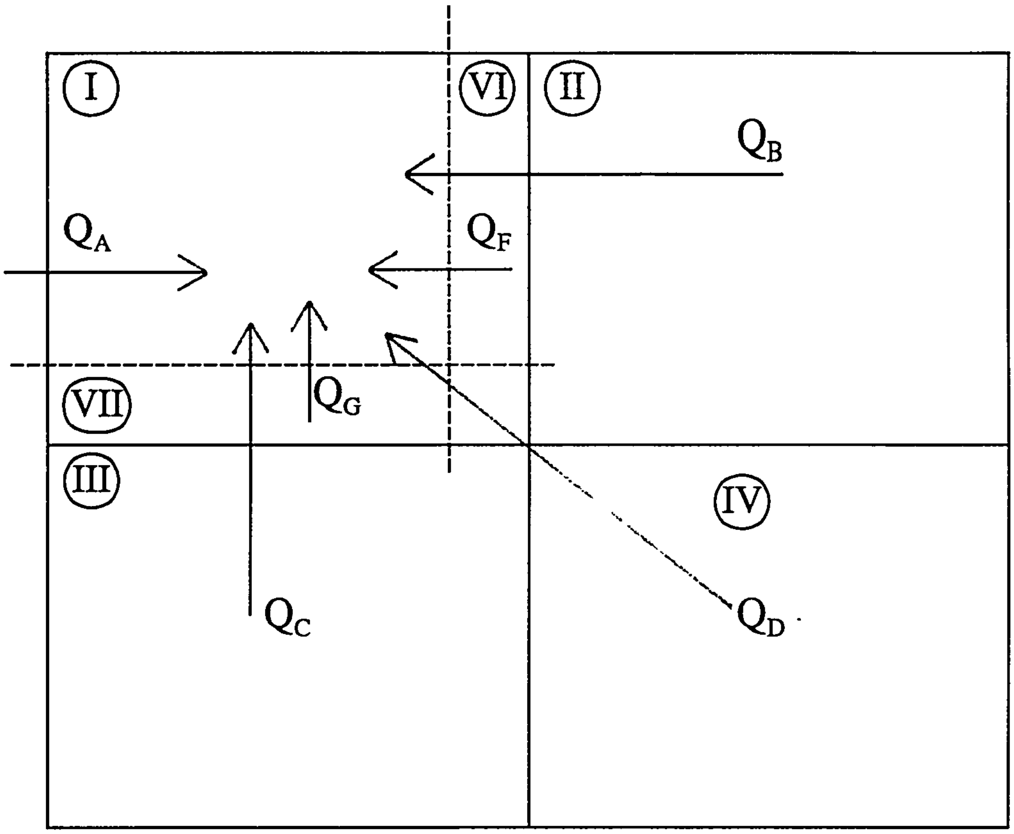

Figure B-2: Single-Blower-Door Measurement with Interstitial Spaces.

<u>Version 2</u>
In this version, a single blower door is used to measure the total leakage of all zones in the building one at a time. (This is part of the two-door test as well.) An additional measurement is made at the maximum pressure with the doors and windows of the neighboring zones closed. Assuming that there is no interaction between neighbors, the flow from the main zone to the neighbor is equal to the flow from that neighbor to outside. For each neighbor, then

$$K_w \Delta P_w^n = K_e \Delta P_e^n \qquad \text{(EQ 14)}$$

where the subscript "w" refers to the wall between the zone with the blower door and the neighbor, and the subscript "e" is the neighbor to outside. If, as in the two-door test, the flow exponent is assigned a constant value, n=0.67, then the following equation can be written:

$$K_w = K_t - K_e \qquad \text{(EQ 15)}$$

Solving Equation 14 for Ke, substituting Ke into Equation 15 and solving for Kw yields:

$$K_w = \frac{K_t \Delta P_e^n}{\Delta P_e^n + \Delta P_w^n} \qquad \text{(EQ 16)}$$

where the subscript "t" refers to the total leakage measurement in the neighboring zone (not the zone with the blower door).

The case of an interfering neighbor is only slightly more complex:

$$K_w = K_t - K_e - K_{w2} \qquad \text{(EQ 17)}$$

$$K_w = \frac{K_t \Delta P_e^n - K_{w2}\ (\Delta P_e^n + \Delta P_{w2}^n)}{\Delta P_e^n + \Delta P_w^n} \qquad \text{(EQ 18)}$$

The subscript "w2" refers to the wall between the two neighbors obtain the value of K_{w2} from either earlier measurements or to estimate it. In either case it is not usually a large source of uncertainty. Only when the blower door is in the stairwell are there significant neighbor-to-neighbor interactions. It is estimated that the uncertainty of K_w is 5% of K_t.

In the post-retrofit measurements, the one-door method was limited to two configurations: (1) all doors of neighbors open to the hallway (which in turn was open to outside at both ends; or (2) all doors of neighbors closed. Both pressurization and depressurization modes were employed to maximize the changes in pressure of the neighboring zones.

APPENDIX C:
PROTOCOL FOR TRACER-ASSISTED PRESSURIZATION MEASUREMENTS

Tracer gas technology is ideal for measuring air flows when the air flows paths are either inaccessible or unknown. The tracer system can substitute for direct air flow measurement instrumentation and have a much larger dynamic range.

INSTRUMENTATION

The instrumentation used in this procedure consists of the following:

- One set of equipment that meets the full requirements of ASTM Standard E 779[1], including a blower door, a flow measuring device, a pressure measuring device and auxiliary instrumentation.
- One set of instrumentation that meets ASTM Standard E 741[1] including a tracer gas analyzer, a source and injections means for tracer gas, and a sampling and distribution system.

BASIC PROCEDURE

The tracer assistance procedure involves depressurizing a zone while injecting a suitable tracer gas into one adjacent zone and measuring its concentration in both zones. At equilibrium, the tracer gas concentration ratio is the ratio of the flows between the zones to the total flow of the main zone.

$$K_w = K_t \frac{C_{zone}}{C_{neighbor}} \qquad \text{(EQ 19)}$$

where C_{zone} is the concentration of tracer gas in the zone with the blower door, and $C_{neighbor}$ is the concentration of the tracer gas in the neighboring zone.

Ideally, this measurement is made at equilibrium but it is sufficient that the concentration of the adjacent zone be constant while determining the concentrations. It is assumed that the tracer gas is well mixed in both zones. This may require the use of several fans to mix the air in the adjacent zone, preferably with tracer being injected into the air flow at each fan.

These tests are time consuming because it may take quite some time for the adjacent zone to come to equilibrium. After one measurement it is necessary to flush the building of tracer gas before the next measurement is made. This is difficult in occupied apartments during winter.

APPENDIX D:
FIELD PROCEDURES FOR TWO-DOOR TESTS

This appendix shows how the two-door tests were performed and serves as a guide for other auditors. Note that an ASTM Standard for the double-blower-door method has not been yet promulgated, and therefore the procedures may be refined at a later date.

The following text explains the rationale of the measurements taken. A detailed enumeration of all steps is presented later in this appendix.

I. SUMMARY

The tests were performed during 2 days. The first day was used for single-door tests. The single-door tests complement the two-door tests. Part of the information obtained with the single-door is required (test with all doors open). The other results are desirable, albeit not intrinsic to the two-door procedure. Two-door tests were performed the second day.

Preparation

Section IIA: Preparation describes the setup, which was especiall_ useful for this research where the results had to be thoroughly documented. In practice, the auditors will be able to simplify the setup. Specifically, there will be no need to use a computer and a data acquisition system (daq). Instead the data can be collected using two digital manometers, one of which measures the zero pressure differential between the two zones that are pressurized, and the second of which is part of the blower installed in the primary zone. No pressure measurement for the second blower door is need, except if two doors are required to pressurize the entire building; however, the whole building pressurization is a desirable check but not essential.

Single door tests

Once the preparation is complete, each apartment is tested with one blower door (starting with Section IIB). The stairwell is open to the outside (in this research, by opening entry and roof doors). Two sets of tests are performed (see steps B, C, D, E, F, G):

- Adjacent apartments have all doors to the stairwell closed while the test apartment is pressurized* and depressurized at several pressures up to 45 Pa. The basement door is also closed. This test is desirable for checking two-door results but not necessary.

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* In this research the maximum pressure was 45 Pa for the following reason: The sensors were selected to measure low pressures; therefore, the high pressure on the sensor scale was only 50 Pa. Readings very close to the boundary of 50 Pa could introduce bias. As a result, the maximum pressure measured was selected about 10% smaller than 50 Pa, at 45 Pa.

In general, other maximum pressures between 40 and 75 Pa are acceptable. A maximum pressure below 40 Pa may be too small to accurately analyze the results given the pressure background induced by wind. A maximum pressure above 75 Pa may be dangerous. (Actually, a maximum pressure not exceeding 60 Pa is more prudent.) The choice for the maximum pressure is made in accordance with the tightness of the apartment. A tight apartment yields a higher maximum pressure.

- The second set of tests is the same as above, but adjacent apartments have all doors open to the stairwell, bringing them to approximately the same pressure as the outside. The basement door is also open. (Note: The basement door could be closed if site conditions require it, although the analysis becomes somewhat more complicated.) This test is necessary because it yields the total ELA of the apartment and the coefficients for the airflow equation (Equation 11). The data are needed for the two-door analysis.

A baseline comparison is made between the results of pressurization and depressurization. If the two results are close, the tests thereafter are all done with pressurization only (or depressurization only). This simplification is important, because the two-door method is more time consuming than the extant ASTM E 779-88 single-door method and requires greater cooperation from tenants.

The airflow coefficients are also calculated for use with the two-door analysis (see Equation 11).

The next step is to perform a pressurization test on the entire building (step II H). The purpose of this test is to obtain a total ELA of the exterior surfaces in the building. To this end, all apartment doors are open. The sum of the ELAs of exterior surfaces in each apartment, as obtained with the two-door method, will be compared for reasonableness against this value.

Step H is a recommended check but is not intrinsic to the two-door procedure.

Two-door tests

Section III of this appendix presents the two-door tests. These tests are conducted at one pressure. The principle is as follows:

Theoretically, several pressures could be used instead of one (e.g., 20 Pa, 30 Pa, 40 Pa, 45 Pa). If the data were good, both the flow coefficient (k) and the flow exponent (n) for the wall between the apartments could be obtained ($Q = k + \Delta P^n$). However, tests at LBL have shown that even under low wind conditions there is so much fluctuation in readings that the k and n coefficients cannot be predicted with any degree of confidence for each wall. Instead, the more practical and reasonable method is to use the k and n coefficients for the entire apartment as determined with the single-blower-door.

The apartment tested, and one of the adjacent apartments, are pressurized 45 Pa (or other pressure between 40 and 75 Pa). The other adjacent apartments and the basement are unpressurized and have the doors open to the stairwell to obtain a pressure approximately equal to the outdoors.

This is repeated by moving the blower door.

II. DAY ONE -- SINGLE-DOOR TESTS

A. Preparation

1. Inform apartment occupants of arrival.
2. Ask for cooperation for the day to open and close their doors.
3. Set up on second floor of the three-floor building (or, in general, on the floor of interest).
4. Run power cable.
5. Set up computer and daq suitcase (N/A for practitioner).
6. Run pressure box cable, extensions to front door of each apartment (six total in this specific project).
7. Use No. 75 pressure sensors on each apartment (high side in hallway). This configuration only applies to the apartment building tested.
   a) P75_0 to apt. 1L, voltage channel 2
   b) P75_1 to apt. 1R, voltage channel 3
   c) P75_2 to apt. 2L, voltage channel 4
   d) P75_3 to apt. 2R, voltage channel 5
   e) P75_4 to apt. 3L, voltage channel 6
   f) P75_5 to apt. 3R, voltage channel 7
   g) Make sure pressure sensors are not in front of blower door fan flow.
8. Run pressure box cable or tube to roof for outside reference pressure.
9. Run pressure box cable or tube to basement. This measurement is important for both energy use and pollutant propagation reasons.

10. Use No. 75 pressure sensors (high side in hallway).
    a) P75_6 to outside, voltage channel 8
    b) P75_7 to basement, voltage channel 9
11. Determine where other pressure sensors may be located (one 125, and two 25 Pa).
12. Make sure all pressure sensor boxes are powered.
13. Make sure both pressure zeroing lights go on.
14. Connect pressure cable to spider box and suitcase.
15. Hook up thermistors to measure outside, hallway and apartment temperature.
16. Make necessary adjustments in data acquisition program.
17. Close basement door.
18. Open top and bottom stairwell doors. This step is essential to bring the stairwell to outside pressure.

B. Set blower door in first apartment

This procedure comprises steps that should be taken for any test using blower doors (single, double or multiple).

1. Check to make sure there is access to one apartment and all other apartments around the one tested.
2. Install blower door for pressurization.
   a) Use P750 pressure sensor to measure fan pressure, voltage channel 1
      (1) Make sure to get positive pressures

3. Close all windows in apartments.
4. Make sure all pressure sensors in other apartments have been installed.
5. Make a table in notebook, make headings of time, blower door pressure and apartment pressure and notes for observations.
   a) Note which flow ring used.
   b) Not if doors are opened during tests.
6. General notes on flow ring:
   a) Use the smallest ring possible.
   b) ΔP fan must be greater than 20 Pa or rings should be switched.
7. Baseline pressures need not be measured each time if wind is calm.
8. Measure ΔP between stairwell and outside with blower door off.

C. **Pressurization test - doors closed**
1. Make sure high side (reference pressure) of P750A is upstream of the fan.
2. Make sure all windows and doors in other apartments are closed.
3. Check interstitial pressures at various places using hand held sensor and drill recording interesting data in notebook. Means to determine whether the zone connects to the interstitial space include (a) smoke stick tests and (b) comparisons of pressures recorded during preliminary blower door tests. In this latter case the target zone is pressurized and the pressure in the adjacent zone measured. If the adjacent zone does not increase its pressure relative to the outside, it is unlikely that there is any significant leakage between two zones.
4. Record time and blower door fan and apartment pressure in notebook. Record also any observations during tests (i.e. doors opening and closing etc.).
5. Turn off blower door fan.
6. Seal fan with cover plates.
7. Measure baseline pressure for doors-closed configuration

D. **Depressurization test - doors closed**
1. Make sure high side (reference pressure) of P750A is upstream of the fan.
2. Set up for depressurization.
   a) Turn fan around.
3. Depress to 45 Pa.
   a) Record pressures.
4. Record time, blower door fan and apartment pressure and notes during test.

E. **Depressurization Test - doors open**
1. Make sure high side (reference pressure) of P750A is upstream of the fan.
2. Make sure doors to all other apartments are **open**.
3. Measure ΔPs between the other apartments and outside (or corridor) when the fan is off.
4. Depressurize.
   a) Record pressures.
5. Record time, blower door fan and apartment pressure and notes during test.

F. Pressurization test - doors open

1. Make sure high side (reference pressure) of P750A is upstream of the fan.
2. Turn fan around.
3. Pressurize in steps of 10Pa first apartment.
   a) Record pressures for each step (~20 sec averages).
4. Record time, blower door fan and apartment pressure and notes during test.
5. Turn off blower door fan.
6. Seal fan with cover plates.
7. Measure baseline pressure for doors to stairwell open.

G. Move blower door to next apartment, until all apartments are tested

1. Repeat procedure, from Step C through Step F.

H. Building total test (if not enough time, do first in the morning)

1. Install blower door in hallway to outside.
2. Open all apartment doors, close all apartment windows.
3. Install second blower door if necessary.
4. Pressurize in steps up to 45 Pa.
   a) Run both doors at approximately the same flowrate.
5. Record time, both blower door fan pressure, building pressure and notes during test.

Throughout the test procedures measure indoor and outdoor temperatures, and outdoor wind speed.

III. DAY TWO -- TWO-DOOR TESTS

A. Set up pressure sensors in same way as Day 1.

B. Make sure windows are closed in all apartments, and that doors to the stairwell are open in apartments without blower doors (a neighboring apartment will also have a blower door, see below).

C. Set up blower door in primary apartment.

1. Use apartment where we have access to adjacent apartments (in case we do not get to all apartments in the time we are there).
2. Seal fan with cover plates.
3. Measure baseline pressure for door-open configuration.

D. Set secondary blower door in adjacent apartment (next door or directly below primary apartment) or seal if already installed.

1. Set up 125 Pa sensor between two apartments.

E. Pressurize both apartments to 45 Pa.

1. Pressurize primary apartment to maintain constant pressure.
2. Pressurize neighboring apartment to 70 Pa by reading 25 $\pm$ 1 Pa on the 125 Pa sensor

(if cannot reach 70, use highest possible).
   a) Record the data.

3. Pressurize neighboring apartment to 45 Pa by reading 0 ± 1 Pa on the 125 Pa sensor.
   a) Record the data.
4. Turn fan off, should be reading 45 ± 1 Pa on the 125 Pa sensor.
   a) Record the data.

F. Move secondary blower door to next adjacent apartment (directly below or next door to primary apartment).

1. Move 125 Pa sensor to measure pressure between the two apartments.
2. Repeat from Step C, Section 1.

G. Move primary blower door to new primary apartment.

H. Repeat from Step C above (measure baseline).

1. Repeat for as many apartments as possible.

I. Pack up.

Throughout the test procedures, measure indoor and outdoor temperatures, and outdoor wind speed.

APPENDIX E: BUILDING DESCRIPTION

BUILDING AT 1348 WILLOUGHBY AVENUE

The building at 1348 Willoughby Avenue is a three-story multi-family residential building in Brooklyn, NY. There are six apartments in the building having an area of approximately 635 square feet each. The floor-to-floor height is 9.5 feet between 1st and 2nd floor, and 10.5 feet between other floors. The apartments are identified by a combination of a number followed by a letter. The number denotes the floor and the letter indicates the position, thus 2L defines an unit on the second floor on the left side when looking from Willoughby Avenue. Further details of the building are described below:

Exterior wall	Masonry construction, plaster inside and face brick outside (1-foot thick)
Interior walls	Brick wythe and plaster on both sides, tight construction
Ceilings	Plaster on lath inside apartments and stamped metal ceiling in corridor
Doors	Wooden; 6.66 feet high x 2.66 feet wide
Basement	Leaky; access hatches fit poorly on the frames
Floor	Vinyl tiles or carpet on plywood subfloor
Windows	As per following table

TABLE E-1: Window Description at 1348 Willoughby Avenue

Apt #	Qty	Location	Size in feet		Type	Condition / Additional Comments
			Width	Height		
1L	1	Kitchen	3.33	5.58	Double hung	Good, storm window
	1	Bathroom	1.58	4.08	Double hung	Good, paint on panes
	2	Bedroom	2.58	5.75	Double hung	Good
	2	Front room	3.3	5.5	Double hung	Good
1R	1	Kitchen	3.5	5	Double hung	Fair, storm window
	1	Bathroom	2	4.08	Double hung	Fair
	2	Bedroom	2.66	5.75	Double hung	Loose, storm window
	2	Front room	2.5	5.66	Double hung	Loose, no storm window
2L	1	Kitchen	3.5	5	Double hung	Fair
	1	Bathroom	2	4.08	Double hung	Fair
	2	Bedroom	2.66	5.75	Double hung	Fair
	2	Front room	2.5	5.66	Double hung	Loose, storm window broken
2R	1	Kitchen	3.5	5	Double hung	Loose, broken pane
	1	Bathroom	2	4.08	Double hung	Fair, lower pane boarded
	2	Bedroom	2.66	5.75	Double hung	Good
	2	Front room	2.5	5.66	Double hung	Good
3L	1	Kitchen	3.5	5	Double hung	Fair, no storm window
	1	Bathroom	2	4.08	Double hung	Fair, no storm window
	2	Bedroom	2.66	5.75	Double hung	Loose
	2	Front room	2.5	5.66	Double hung	Loose, storm window broken
3R	1	Kitchen	3.5	5	Double hung	Fair
	1	Bathroom	2	4.08	Double hung	Fair, screen on storm window
	2	Bedroom	2.66	5.75	Double hung	Loose, good storm window
	2	Front room	2.5	5.66	Double hung	Fair, good storm window

* Front room refers to the room on Willoughby Avenue

BUILDING AT 347 GROVE STREET

The building at 347 Grove Street is a three-story multi-family residential building in Brooklyn, NY. There are six apartments in the building, having an area of approximately 630 square feet each. The floor-to-floor height is 10.5 feet, and the apartments are identified by a combination of a number followed by a letter. The number denotes the floor and the letter indicates the position, thus 2L defines an unit on the second floor on the left side when looking from Grove Street. Further details of the building are described below:

Exterior wall	Masonry construction, plaster inside and face brick outside
Interior walls	Plaster-on-wood lath on wood studs, loose construction
Ceilings	Varies; acoustic tile drop ceiling, sheetrock and plaster on lath, or any combination of above
Doors	Wooden; 6.66 feet high x 2.66 feet wide
Basement	Fair; less leakier than Willoughby Two windows, one of the window panes dislocated
Floor	Vinyl tiles on plywood subfloor
Windows	As per following table

TABLE E-2: Window Description at 347 Grove Street

Apt #	Qty	Location	Size in feet		Type	Condition / Additional Comments
			Width	Height		
1L	2	Kitchen/dining	3.5	5	Double hung	Fair, storm window
	1	Bathroom	2	4.08	Double hung	Fair, paint on window
	2	Bedroom	2.66	5.75	Double hung	Loose
1R	2	Kitchen/dining	3.5	5	Double hung	Fair, storm window
	1	Bathroom	2	4.08	Double hung	Fair
	2	Bedroom	2.66	5.75	Double hung	Loose, storm window
2L	2	Kitchen/dining	3.5	5	Double hung	Good, new double pane, no storm window
	1	Bathroom	2	4.08	Double hung	Good, new double pane, no storm window
	2	Bedroom	2.66	5.75	Double hung	Good, new double pane, storm window
2R	2	Kitchen/dining	3.5	5	Double hung	Loose, no storm window
	1	Bathroom	2	4.08	Double hung	Loose, no storm window
	2	Bedroom	2.66	5.75	Double hung	Loose, storm window open
3L	2	Kitchen/dining	3.5	5	Double hung	Fair, no storm window
	1	Bathroom	2	4.08	Double hung	Fair, no storm window
	2	Bedroom	2.66	5.75	Double hung	Loose
3R	2	Kitchen/dining	3.5	5	Double hung	Fair
	1	Bathroom	2	4.08	Double hung	Fair, screen on storm window
	2	Bedroom	2.66	5.75	Double hung	Loose, good storm window