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**DEVELOPMENT OF CONVECTIVE TESTING
METHODS FOR LOW-RISE MULTIFAMILY BUILDINGS**

Report 96-11

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**DEVELOPMENT OF CONVECTIVE TESTING METHODS FOR
LOW-RISE MULTIFAMILY BUILDINGS**

Final Report

Prepared for

**THE NEW YORK STATE
ENERGY RESEARCH AND DEVELOPMENT AUTHORITY**

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ABSTRACT

This report describes convective testing methods and protocols developed for use in weatherizing low-rise multifamily buildings. The methods can lead to controlling internal air movement and preventing leakage to the exterior by estimating the magnitudes of air leakage pathways in garden and town house apartments. The four methods cited are referred to descriptively as: the After-a-Retrofit; Equivalent Interfaces; Open-a-Door; and Add-a-Pathway. The report finds that, because of modern interior finishing practices, convective problems tend to be more associated with indoor air quality than loss of space conditioning energy. The After-a-Retrofit method is the easiest to integrate into current diagnostic practices. In some cases, the Equivalent Interfaces method may be used on a production basis. The methods are an advance on current field practices that do not quantify the leakage pathways and research practices that require extensive equipment.

Key Words: Multifamily buildings, pressure diagnostics, weatherization, air leakage, convective pathways

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SUMMARY

The objective of this project was to develop convective testing methods and protocols for small- to mid-sized multifamily buildings. These methods and protocols are needed as diagnostic aids for guiding air-sealing work. Controlling internal air movement, and preventing its leakage to the exterior, are two primary goals in weatherizing buildings.

The blower door is becoming an essential tool for weatherization professionals who work on multifamily buildings. As it is presently used, it provides data on whole-apartment leakage. However, the present blower door techniques cannot distinguish infiltration to the exterior from infiltration to adjacent zones within the building.

Air that leaks to the exterior wastes space conditioning energy, which needlessly increases an apartment's energy consumption. Air leakage among apartments is an important factor for the quality of air inside the building. There has thus been a great interest in the development of test procedures for estimating the magnitudes of these two different types of air leakage.

Research was conducted to provide weatherization professionals with at least one test procedure for estimating the magnitudes of air leakages to the exterior and between adjacent apartments. The aim is to be able to distinguish external leakage from internal leakage routinely, in order to perform the most appropriate types of weatherization work on a building. The same test procedures can be used to verify the quality of weatherization work. This project was initiated specifically in response to the need for test procedures that can be performed quickly, without extensive laboratory equipment, and as a variation of present field practices.

The stock that was tested during the project consisted of garden-style and town house complexes in western New York State. Anecdotal evidence suggests that these modern styles of construction are prevalent in upstate New York.

The highlights of the project's results include:

- The development of four methods for estimating the magnitudes of air leakage pathways in apartments (the After-a-Retrofit, Equivalent Interfaces, Open-a-Door, and Add-a-Pathway methods);
- An arrival at a few easy-to-use methods for production-oriented work; and,
- The development of more detailed methods for use in future research and stock characterizations.

A brief description of each of the test methods follows. They are given in order of increasing complexity, and hence, of decreasing ease with which they might be adopted into current weatherization practices.

The After-a-Retrofit method is the easiest, because it does not require the measurement of any pressure differentials other than the one established by the blower door between an apartment and the exterior. A series of blower door tests on different days are required.

An initial measurement of the flow through the blower door is made prior to any retrofit measures. This measurement is repeated each time a weatherization measure (or group of measures) is implemented. The reduction in flow through the blower door can be attributed directly to the most recent treatment of the structure.

The major advantages of the After-A-Retrofit method are that it requires no assumptions about the natures of the convective pathways, and that it may be used in almost any type of multifamily structure. Depending on the layout of the structure, however, it may not be possible to generalize test results from one apartment to the whole building.

If the apartments in a given multifamily structure are very similar to each other in construction, the Equivalent Interfaces method can be used to characterize air leakage in a typical apartment in the complex. The test procedure for this method begins by setting up and turning on a blower door in an apartment. The flow through the blower door is measured. Using a micromanometer, the pressure differential is then measured between the apartment and its interior borders--the floor, ceiling, and the walls that border adjacent apartments.

The analysis is based on the assumption that the convective characteristics of all of the interfaces between adjacent apartments are more or less the same. The total flow through the blower door is taken to be the sum of the leakage flows from the exterior and the leakage flows from adjacent zones in the building.

Under the assumptions for this method, the flow from an apartment occurs through its leakage pathways to the exterior and through its pathways to the adjacent apartments. It is possible to write a series of simultaneous equations for flows across the interfaces, and to solve them by invoking these assumptions.

The Equivalent Interfaces method is most applicable to complexes where no more than a few apartments are adjacent to the one where the blower door is operating. The advantage of the method is that it allows for quantitative estimates of the magnitudes of leakage pathways for several convective interfaces from relatively few measurements of pressure differentials.

The method may not be applicable if the intervening zones are partially connected to many apartments as well as to the exterior. Additionally, the results of the method may be difficult to interpret if there are structures like cantilever sections along the exterior walls of an apartment.

If diagnostic tests and visual inspection reveal that there are only one or two convective interfaces between adjacent apartments, and if access can be gained into adjacent apartments, the Open-a-Door method may be appropriate. All of the measurements for the Equivalent Interfaces method are performed. The next step for the Open-a-Door method is to take a reading of pressure differentials between the adjacent apartments and the exterior.

If an adjacent apartment develops a pressure differential that is within the range of 10-40 pascals (when the blower door apartment is at 50 Pa with respect to the exterior), a second test condition is set up where the adjacent apartment is completely opened to the exterior. The blower door is then adjusted to keep a 50 Pa pressure differential between its apartment and the outside, and the new value of its flow is recorded. A measurement of the new pressure differential at the interface bordering the opened apartment is taken.

The results from these two test conditions are subject to further constraints, but in certain cases they can be used to solve a set of equations for flows across the interfaces. A spreadsheet application was developed for on-line checking of the field data for this method, as well as for computing the magnitudes of the flows along the various air leakage pathways of the test apartment.

A sensitivity analysis shows that the Open-a-Door method is applicable only when the blower door's apartment is fairly leaky, and when the interface between apartments is much leakier than the interfaces to the exterior. If these conditions are not true for a given set of apartments, the Equivalent Interfaces method may be used instead.

The Add-a-Pathway method requires the most amount of hardware and added labor in the field. The added pathway can be supplied in the form of a flexible duct mounted in the windows of two adjacent apartments. The blower door is set up, and all of the measurements for the Equivalent Interfaces method are taken. The ducted pathway is introduced between apartments, and the measurements are repeated. Equations for flows across the interfaces are then solved using this information.

The Add-a-Pathway method is extremely difficult if the test apartments are more than a few stories high. There are also constraints on the method's applicability that are similar to those for the Open-a-Door method. It might be useful in the more research-oriented types of field programs, but it is not suitable for most production work.

The Equivalent Interfaces method was applicable in all three of the buildings studied in the project. Test results showed that the apartments studied in this project are fairly tight, largely due to modern interior finishing practices. Leakage to adjacent building spaces ranged from 20% to 54% of total apartment leakage. Convective problems thus include those associated with indoor air quality, because these apartments require more air changes per hour than they presently get.

The testing methods are the basis for new tools for use by air sealing crews and auditors. They represent an intermediate step in the evolution of convective building science, appearing between the present field practices that do not quantify the leakage pathways at all, and the present research practices that require extensive equipment and specialized training.

The After-a-Retrofit and Equivalent Interfaces methods are recommended for field implementation in the New York State Weatherization Assistance Program (WAP). These methods can provide first-order estimates of the magnitudes of leakage pathways without requiring extensive departures from present field practices. The Open-a-Door method is also recommended for field implementation, but its applicability depends on convective characteristics that weatherization personnel may need special training to recognize.

If tight construction is observed in garden-style apartments and town house stock, the Equivalent Interfaces method may be used on a production basis. The present retrofit practices for air sealing and insulating this stock (side wall and attic insulation) are probably very adequate as energy conservation measures.

Based on the results of the methods developed for this project, no significant changes in these weatherization practices can be recommended at this time. However, the practice of venting bathroom fans into attic spaces should be discouraged. This practice has been implicated in the transport of large quantities of moisture to the underside of roof decks.

Although natural infiltration does not appear to impose significant energy losses, there are a variety of issues of air quality in the modern stock. The magnitude of these air quality problems should be investigated. The question also arises as to how fresh-air ventilation (more air changes per hour) can be provided cost-effectively.

The more-elaborate methods developed in the project might be useful for future research, particularly in older stock. An extensive survey of the construction would be helpful for planning technology transfer curricula for different areas in the state.

Section 1

INTRODUCTION

BACKGROUND

The blower door is becoming an essential tool for weatherization professionals who work on multifamily buildings. As it is presently used, it provides data on whole-apartment leakage. However, the present blower door techniques cannot distinguish infiltration to the exterior from infiltration to adjacent zones within the building.

Air that leaks to the exterior wastes space conditioning energy, which needlessly increases an apartment's energy consumption. Air leakage among apartments is an important factor for the quality of air inside the building. There has thus been a great interest in the development of test procedures for estimating the magnitudes of these two different types of air leakage.

In a very recent article about low-rise multifamily stock (1), the following observations appeared, which concur with many of this project's findings:

- It is important to distinguish between high-rise buildings and the low-rise stock; the latter often resembles single units stacked one on top of the other.
- Low-rise apartments often have tight inner skins, and building cavities included between apartments and into the attic are inaccessible. Such cavities provide opportunities for convective loops to occur, and they can act like unconditioned spaces.
- The pressure barrier often consists of the attic floor and the exterior walls.
- Special areas that need attention are overhangs, cantilevers, and ducts.

The article noted that blower door and pressure diagnostic testing has not yet evolved significantly for use in low-rise multifamily buildings. While research progresses on several fronts, production-level testing methods have not yet appeared.

Part of the problem of expanding the repertoire of diagnostic measures for multifamily buildings is their complexity. For example, blower door testing will not reveal convective problems within open cavities surrounding apartments. Infra-red scanning is a better method for finding such spaces in a building (1).

The thrust of the present work has been to adapt pressure diagnostic methods to low-rise multifamily structures. The project began with an exploration of the options for convective testing and for analytical procedures. Preparations were made for subsequent field work, including the documentation of detailed and systematic instructions for conducting the tests and for handling the field measurements. A number of the methods were then implemented in three different apartment complexes near Syracuse, New York.

OBJECTIVE

The purpose of this project was to develop convective testing methods and protocols for small to mid-sized multifamily buildings. These methods and protocols are needed as diagnostic aids for guiding air-sealing work. Controlling internal air movement and preventing its leakage to the exterior are two primary goals in weatherizing these buildings. The emphasis was placed on creating testing methods that can be implemented on a production-level basis.

The research in this project was conducted to provide weatherization professionals with at least one test procedure for estimating the magnitudes of air leakages to the exterior and between adjacent apartments. The aim is to be able to distinguish external leakage from internal leakage routinely, in order to perform the most appropriate types of weatherization work on a building. The same test procedures can be used to verify the quality of weatherization work. This project was initiated specifically in response to the need for test procedures that can be performed quickly, without extensive laboratory equipment, and as a variation of present field practices.

RESEARCH PLAN

The objective was achieved by way of the following eight tasks:

1. Develop protocols for at least one test procedure.
2. Identify and select three multifamily buildings having structural characteristics suitable for testing with the protocols.
3. Adapt instrumentation for implementing test procedures.
4. Prototype and test the hardware.
5. Conduct field tests.
6. Estimate how much of the air leakage of each apartment is to the exterior and how much is between adjacent apartments.
7. Produce a final report.
8. Make recommendations for technology transfer.

The first task was structured to allow for the development of a range of test procedures. The easiest protocols to implement required no more instrumentation than what is currently used by weatherization professionals—a blower door and a micromanometer. More elaborate protocols, which required further instrumentation or manipulations of the building's structure, were also developed.

The multifamily structures selected for this study met the following minimum criteria.

- The structure was of the small to mid-sized range, with at least six units per building.
- The structure was comprised of apartment units that had a door that opened to the outside, or had a common area that opened to the outside.
- The apartment units were within distances of nearby zones that could be traversed by plastic tubes for purposes of micromanometer pressure measurements.

Two of the selected multifamily buildings that met these criteria were provided by a private owner. One was in the Maplewood Complex in Syracuse, New York, and the other was in the Walnut West Complex in Camillus, New York. A third building was investigated in conjunction with the ongoing work of SyrEsco, of Syracuse, New York. This third building was in the Westminster Complex in Liverpool, New York.

A number of modifications were made during the course of the project. The research plan originally called for the testing of two apartments in each of two different buildings, at two different complexes. The two buildings in each complex were to have been selected on the basis of substantial differences in their heating bills. However, detailed examination of historical billing data did not reveal consistent differences in energy consumption among buildings. Hence, it was decided to select one structurally representative building for testing at each complex.

The research design included provisions for short-term monitoring of test apartment energy consumption. The goal was to correlate level of energy consumption with apartment air leakage characteristics. However, the similarity of construction from one complex to the next, and the fact that there were no a priori methods for determining convective characteristics before the test protocols were developed, prohibited short-term monitoring.

The final version of the research plan called for the convective characterization of adjacent apartments in three buildings, one from each of three different complexes. The goal of the data analysis was focused on obtaining estimates of the magnitudes of air leakage along several pathways in each apartment. An option was reserved for testing one or more apartments before and after an air sealing retrofit, but this opportunity did not arise during the course of the project. The lack of opportunity for collecting pre- and post-retrofit data was another reason why short-term monitoring was not implemented.

The stock that was tested consisted of garden-style and town house complexes. Anecdotal evidence suggests that these modern styles of construction are prevalent in upstate New York.

This sample of buildings was adequate for implementation of the range of protocols developed under the first task. However, the applicability of some of the protocols was determined largely by the limitations of the available instrumentation. A single protocol was developed that was applicable to a total of four apartments and their adjacent apartments.

The field tests were comprised of a structural inspection for determining applicability of a given method, and of a number of measurements of pressure differentials and blower door flows. Analysis of the data taken in the field produced estimates of how much of a given apartment's air leakage was to the exterior, and how much was to its adjacent spaces. The minimum complement of data taken for each apartment consisted of one blower door flow measurement, one measurement of pressure differential between the

interior of the apartment and the exterior, and at least one measurement of a pressure differential with respect to each neighboring apartment.

Confirmation of the results of analysis was readily accomplished in cases where there was little or no air leakage through a particular boundary in a given apartment. In such cases, visual inspection showed the boundary to be tight.

Finally, each of the protocols was reviewed in terms of its complexity and the degree to which it resembled current practices. This allowed for a ranking of the protocols from the most readily adaptable for weatherization practices, to the least.

Section 2

ANALYTICAL METHODS

The whole success of pressure diagnostic methods in single family dwellings depends on a practical understanding of the physical relationships between pressure differentials and leakage air flows. During a blower door test, there is often one or more compartments within this type of dwelling through which air from the outside must pass before entering the conditioned space (2).

For example, air passing from the exterior into a basement encounters a second barrier: the one between the basement and the interior. The magnitude of the flow across this series of barriers can be inferred from a few measurements taken during some easy manipulations of the building. What was discovered in the course of this project was that the pressure diagnostic methods developed for single-family dwellings can be adapted for use in certain types of low-rise multifamily structures.

Many of the low-rise structures in upstate New York are very similar to each other in construction and layout. These buildings are not unduly large or complicated, and it is possible to identify the potential pathways through which air might leak into and out of the apartments. Most of the analytical work in the project was thus a matter of re-interpreting the single-family pressure diagnostic methods for the slightly more complicated cases represented by the low-rise multifamily buildings.

This section reports the underlying physical principles of the testing methods that evolved during the course of the project. A few of these methods are generally applicable to the stock that was encountered in the field work. The details of construction that define this stock are discussed. The adaptations of the relevant test methods to this stock are then presented.

OVERVIEW OF THE TESTING METHODS

Testing methods were sought that required only a blower door, a micromanometer, and possibly a spreadsheet application. Further, the testing methods had to be restricted to procedures that can be performed in only one or a few apartments at any one time, to keep the size of the auditing crew down to a few individuals.

The description of the diagnostic methods uses some terminology from building science. The two key terms are defined below.

Convective Interface: A barrier or partition within a building through which air may flow. In a multifamily apartment, the typical convective interfaces are the walls, the ceiling, and the floor.

Intervening Zone: A space within a building that is partially, but not completely, open to at least two other adjacent zones. Typical examples of intervening zones are the spaces between the ceiling and the floor of two stacked apartment units; partition walls; fire walls; and attics and basements that span more than one apartment.

It has been discovered that intervening zones can present significant challenges to managing or sealing air leakage pathways. First, they are fairly common in multifamily structures. Second, unless you are looking for them, you may not suspect that they are there. Third, they can provide leakage pathways between apartments as well as to the exterior. Fourth, they can be interconnected in ways that confound our best attempts to trace them.

The presence of intervening zones is a problem because the original analytical techniques for estimating leakage flows assumed a direct connection between zones (2). The derivations of analytical models that take intervening zones into account are presented in Appendix A. Appendix A also covers the theory behind all of the methods developed during the course of the project.

A straight-forward procedure has been developed for establishing whether an intervening zone is present between an apartment and adjacent space in the building. To determine this, a minimum of two pressure differentials must be measured:

- (1) Between the blower door apartment and a wall, ceiling, or floor, and,

- (2) Between the blower door apartment and the adjacent apartment.

The rule of thumb for deciding whether there is an intervening zone is:

If the two measured pressure differentials are different by more than 5 pascals, there is probably an intervening zone.

If an intervening zone is present, it must be taken into account when analyzing and quantifying the leakage pathways that may be present through it.

Most of the methods rely on a single equation for relating a flow across an interface with the measured pressure differential that the blower door establishes across that interface, namely,

$$Q = K P^n \quad (2-1)$$

where

Q = air flow, in cubic feet per minute (cfm)

K = the flow coefficient

P = pressure differential (pascals, Pa)

n = the flow exponent

The relationship expressed by Equation (2-1) has been successfully applied in convective diagnostics using the blower door (2). Practical application of Equation (2-1) is limited by the fact that pressures cannot be measured to any better than ± 5 pascals and that blower door flows cannot be measured to any better than ± 100 cfm. There is thus a lower limit on the magnitude of leakage air flow that can be estimated by these diagnostic methods.

Prior to analyzing the results of the field work, the planning of blower door testing must be thought out ahead of time. The field team was granted written permission to work in a complex by the owners, and test dates and times were arranged. If the apartment to be tested was occupied, the owners notified the tenants and gained their permission as well. After testing was completed, the site was restored to its original condition, the tenants were thanked for their cooperation, and any keys that were borrowed were returned.

Given this general background, it is possible to introduce the four testing methods developed during the course of the project. They are presented below in order of increasing complexity.

The After-a-Retrofit Method

This method is the easiest because it does not require the measurement of any pressure differentials other than the one established by the blower door between an apartment and the exterior. However, a series of blower door tests on different days are required.

The idea is to take an initial measurement of the flow through the blower door prior to any retrofit measures, and then repeat the test each time a measure (or group of measures) is implemented. The reduction in flow through the blower door can be attributed directly to the most recent treatment of the structure.

The major advantages of the method are that it requires no assumptions about the natures of the convective pathways, and that it may be used in almost any type of multifamily structure. Depending on the layout of the structure, however, it may not be possible to generalize test results from one apartment to the whole building. In such cases, this method is primarily useful for estimating air leakage reduction on a per-unit basis.

The Equivalent Interfaces Method

Pathways for air leakage depend on the details of construction. If the apartments in a given multifamily structure are very similar to each other in construction, this method can be quickly used to characterize air leakage in a typical apartment in the complex.

The test procedure for this method begins by setting up and turning on a blower door in an apartment. The flow through the blower door is determined. Using a micromanometer, the pressure differential is then measured between the apartment and its interior borders--the floor, ceiling, and the walls that border adjacent apartments.

The analysis is based on the assumption that the convective characteristics of all of the interfaces between adjacent apartments are more or less the same. The total flow through the blower door is taken to be the sum of the leakage flows from the exterior with the leakage flows from adjacent zones in the building.

Under the assumptions for this method, the flows from adjacent apartments occur through their leakage pathways to the exterior and through their pathways to the next neighboring apartment, and so on. It is possible to write a series of simultaneous equations for flows across the interfaces, based on Equation (2-1), and to solve them by invoking these assumptions (see Appendix A).

The method distinguishes between leakage pathways that include intervening zones and those that do not. It is most applicable to complexes where no more than a few apartments are adjacent to the one where the blower door is operating. The advantage of the method is that it allows for quantitative estimates of the magnitudes of leakage pathways for several convective interfaces from relatively few measurements of pressure differentials.

The method may not be applicable if the intervening zones are partially connected to many apartments as well as to the exterior. Additionally, the results of the method may be difficult to interpret if there are structures like cantilever sections along the exterior walls of an apartment.

Given this general background, it is possible to introduce the four testing methods developed during the course of the project. They are presented below in order of increasing complexity.

The Open-a-Door Method

This is a method that was originally created for single-family structures (2). However, its underlying principles have been re-interpreted for multifamily structures (see Appendix A). Because the procedures are almost universally applicable to low-rise construction, a full set of field protocols has been developed for this method. They are presented in Appendix B.

If diagnostic tests and visual inspection reveal that there are only one or two convective interfaces between adjacent apartments, and if access can be gained into adjacent apartments, this method may be

appropriate. All of the measurements for the Equivalent Interfaces method are performed. The next step for the Open-a-Door method is to take a reading of pressure differentials between the adjacent apartments and the exterior.

There are two ways to accomplish this step while the blower door is in operation. First, a series of plastic tubes can be initially laid out between the blower door apartment and the neighboring apartments. In this case, the low port of the micromanometer is connected to a tube to an adjacent apartment, and the high port is connected to a tube to the exterior.

The second way is to have a second auditor in the adjacent apartment take the measurement. This second approach is best taken when there is a way for the operator of the blower door to communicate with the person in the neighboring apartment (by way of walkie-talkies, for instance).

The key finding that makes the Open-a-Door method applicable is a pressure differential between an adjacent apartment and the exterior in the range of 10-40 Pa (when the blower door apartment is at 50 Pa with respect to the exterior). It has been found that the accuracy of the blower door prevents it from yielding trustworthy results when the adjacent zone develops less than 10 Pa, or more than 40 Pa, with respect to the exterior under these test conditions; changes in blower door flow should be several hundreds of cfm (2).

If an adjacent apartment develops a pressure differential that is within the useful range, a second test condition is set up where the adjacent apartment is completely opened to the exterior. The blower door is then adjusted to keep a 50 Pa pressure differential between its apartment and the outside, and the new value of its flow is recorded. A measurement of the new pressure differential at the interface bordering the opened apartment is taken.

The results from these two test conditions are subject to further constraints, but if they pass, they can be used to solve a set of equations based on Equation (2-1) for the interfaces. A sensitivity analysis shows that the Open-a-Door method is applicable only when the blower door apartment is fairly leaky, and when the interface between apartments is much leakier than the interfaces to the exterior (see Appendices A and B). If these conditions are not true for a given set of apartments, the Equivalent Interfaces method may be used instead.

The Add-a-Pathway Method

Requiring the most amount of hardware in the field, this method is analogous to the "Add a Hole" diagnostic method developed for single family dwellings (2). In the original method, blower door flow and the pressure differential across a given convective interface are measured. An opening of at least a few square feet in area is then introduced in the interface, and the measurements are re-taken. This information can then be used to quantify the magnitude of the leakage pathways in the interface when the added hole is not present (2).

It is not feasible to introduce a hole between apartments. An alternative way of enhancing flow between apartments was devised. This added pathway can be supplied in the form of a flexible duct mounted in windows of two adjacent apartments. Details of the measurements and computations needed for this method are given in Appendix A.

The blower door is set up, and all of the measurements for the Equivalent Interfaces method are taken. The ducted pathway is introduced between apartments, and the measurements are repeated. A series of equations based on Equation (2-1) are then solved using this information.

Of all of the methods developed for pressure diagnostic testing in this project, this one is the most cumbersome. The construction and transportation of the added pathway can be problematic. The method is extremely difficult if the test apartments are more than a few stories high. There are also constraints on the method's applicability that are similar to those for the Open-a-Door method. It might be useful in the more research-oriented types of field programs, but it is not suitable for production work.

TESTS ADAPTED TO THE SELECTED SITES

The preceding section notes that there are restrictions and limitations for each of the testing methods. In the development of a testing protocol—a set of procedures for evaluating which method is most applicable in an efficient way—the current state of the science does not permit broad generalizations. It is therefore necessary to examine some of the prevalent features of the stock under consideration in order to recommend the most appropriate methods.

Garden-style apartments and town house complexes are a prevalent stock in upstate New York. Thanks to modern practices of sheet rocking and interior finishing, the interiors of the apartments in this construction are fairly air-tight. In fact, most of the leakage sites can be found by visual inspections. Typical pathways are summarized in Table 2-1.

Table 2-1.
Typical Convective Pathways
in Garden-Style and Town House Construction.

Adjacent Zone	Typical Convective Pathways
exterior	around windows and doors; kitchen vent
attic	ceiling cracks; bathroom vent; chase ways
neighboring apartment(s)	chase ways through otherwise tight fire walls or floor decks

The question still remains, however: What are the magnitudes of leakage pathways among apartments and to the outside? Using the identified pathways listed in Table 2-1, it is possible to examine the corresponding interfaces for purposes of implementing one or more of the test methods. This may be done with the help of the sketches in Figure 2-1.

Figure 2-1 shows the three types of construction encountered in the project. Anecdotal evidence suggests that these types of multifamily stock are often encountered in weatherization work in upstate New York (3). Figure 2-1(a) shows a simple type of building in which apartments are stacked vertically but are separated from each other horizontally by substantial passages, such as breeze ways.

In this type of construction, there are three major convective interfaces. Apartments may exchange air with the exterior, or with apartments above or below them. The flow coefficients for those two interfaces are labeled K_e and K_v , respectively, in Figure 2-1(a). There is also the possibility of leakage from the top-story apartment to what is usually an attic that is well-vented to the exterior. This third pathway's flow coefficient is denoted as K_a .

A second type of construction is somewhat more complicated, where there are adjacent apartments both horizontally and vertically. This situation is sketched in Figure 2-1(b). As in the first case, the attic tends

to be well ventilated to the exterior. There are horizontal leakage pathways in Figure 2-1(b), and the corresponding flow coefficient is labeled K_h .

In the second type of construction, fire walls are built (by code) as intervening spaces between horizontally adjacent apartments. The fire walls are of masonry construction, with mortar applied between blocks and at the base. The tops of the fire walls tend to be capped tightly as well. In this type of construction, the predominant leakage pathways are thus horizontally among apartments and not to the exterior.

A third type of construction, that of town or row houses, is sketched in Figure 2-1(c). The fire walls between apartments extend from grade to the roof. They are tightly sealed by mortar on the sides and by roofing materials at the top. The principle convective pathways of the apartments are horizontally and to the exterior.

Given this information about the construction of this stock, it is possible to devise a protocol for deciding which of the first three methods described in the preceding section is most applicable. An outline of this protocol is given in flow chart form in Figure 2-2.

The protocol starts with a few visual inspections and ends with a decision for selecting a diagnostic method. Note that one of the options that can be taken early in the process is a decision that the testing methods do not apply in a given building. This could be the decision for any number of reasons, such as damage done to a building sometime after its construction¹.

The recommended procedures for a garden-style complex include installation of the blower door in a top story apartment, and the measurement of total leakage areas in the ceiling. These procedures allow for an estimate of the flow coefficient K_a shown in Figures 2-1(a) and (b). If the attic is well-ventilated to the outside, it can be assumed that the leakage pathways in the ceiling of the top-story apartment are to the exterior. In this case, Equation (2-1) assumes a form for leakage through orifices (2):

$$Q = 1.06 A P^{0.5} \quad (2-2)$$

¹ Note that the attic leakage term, Equation (2-2), must be modified in those cases where partition walls in the top story apartment are substantially opened to the attic.

(a)

TYPE OF CONSTRUCTION:
Stacked apartments, separated horizontally by breeze ways; two to four stories; unfinished attic

PRINCIPAL CONVECTIVE BOUNDARIES:
Vertically between apartments; flow coefficient = K_v

Between top story and attic; flow coefficient = K_h

Net leakage per apartment to exterior; flow coefficient = K_e

(b)

TYPE OF CONSTRUCTION:
Blocks of adjacent apartments separated horizontally by fire walls; two to four stories; unfinished attic common to several apartments

PRINCIPAL CONVECTIVE BOUNDARIES:
Vertically between apartments; flow coefficient = K_v

Between top story and attic; flow coefficient = K_h

Net leakage per apartment to exterior; flow coefficient = K_e

Between top story and attic; flow coefficient = K_a

(c)

TYPE OF CONSTRUCTION:
Town house and row house apartments separated by fire walls

PRINCIPAL CONVECTIVE BOUNDARIES:
Between top story and attic; flow coefficient = K_h

Net leakage per apartment to exterior; flow coefficient = K_e

Figure 2-1. Test Site Stock.

Figure 2-2. Flow Chart for Selecting Test Methods.

where A is the measured (or estimated) leakage area in the top-story ceiling, in square inches. In other words, for the attic leakage pathway, the flow coefficient is $K_a = 1.06 A$, and the flow exponent is $n = 0.5$.

The result of computing Equation (2-2) is a term for the attic leakage flow. It can be subtracted from the total flow through the blower door. The flow coefficients for the interfaces to the exterior and to neighboring apartments must then be computed using one or more methods.

The Open-a-Door method, if appropriate, can be performed according to the protocol given in Appendix B. Specific considerations for using the After-a-Retrofit and the Equivalent Interfaces methods are given below.

The After-a-Retrofit Method for the Sites

Air sealing and insulation typically occur in two stages in this stock. The first round of work is on the side walls, and the second is in the attic (3). This suggests that a total of three blower door tests should be performed:

1. A pre-retrofit blower door test.
2. A blower door test following side wall treatments. The difference in flow between the first and second tests is due to side wall treatments alone.
3. A blower door test following attic treatments. The difference in flow between the second and third tests is due to the attic treatments alone.

To maintain analytical consistency in these tests, it is important to establish the same apartment-to-exterior pressure differential in all three blower door tests. For example, if the first test cannot be performed at 50 Pa, the highest pressure differential that can be established in the first test should be used in the subsequent tests.

The Equivalent Interfaces Method for the Sites

The following five-part procedure is applicable to the construction depicted in Figures 2-1(a) and (b) for low-rise garden-style complexes.

1. Set up the blower door in a top-story apartment.
2. Solve Equation (2-2) for attic leakage flow according to the procedure outlined above.
3. The difference between the blower door flow and the attic leakage flow is set equal to the sum of the exterior flow with the flows from adjacent apartment(s).
4. If intervening zones are present, no flow is assumed to go between it and the exterior; the flow across one interior side of the intervening zone is assumed to be equal to the flow across the other interior side.
5. Assume that all of the leakage flow induced by the blower door through an adjacent apartment passes directly from the exterior through the adjacent apartment. Further, assume that this leakage flow develops a pressure differential between the adjacent apartment and the exterior of a few pascals.

The two assumptions suggested in this procedure bear further explanation. For part (4), recall that the intervening zones between apartments in this type of construction are mostly tight except where chase ways penetrate. It is a fair assumption to say that there is little leakage between these particular intervening zones and the exterior.

In part (5), the assumption lumps all of the leakage flows across a wall between adjacent apartments into one source, namely, the apartment most immediately adjacent to the blower door apartment. Further, it is assumed that the adjacent apartment gets its make-up air flow directly from the outside. This assumption is based on the tendency of leakage flows to seek the path of least resistance.

While it is true that the adjacent apartments have their own leakage pathways to other apartments, these pathways have several serial barriers to the exterior. The most direct pathway is the one to the exterior from the adjacent apartment, which is the path of least resistance to the flow.

It is further assumed that the adjacent apartment does not develop a pressure differential with respect to the exterior in the 10-40 Pa range. Otherwise, the Open-a-Door method should be applied. The

assumption that a few pascals of pressure develop is a convenience for solving the set of flow equations required for the Equivalent Interfaces method.

For town or row house construction (see Figure 2-1(c)), the testing procedures are based on similar assumptions:

1. Set up the blower door in an apartment near the middle of the building.
2. Open all interior doors in the blower door apartment and in the two adjacent apartments.
3. Take the average of the pressure differentials measured across the blower door apartment's walls that border the adjacent apartments.
4. Set the flow through the blower door equal to the leakage flow to the exterior and through the two walls bordering the neighboring apartments.
5. Assume that none of the flow through intervening zones is from the exterior.
6. Assume that all of the leakage flow induced by the blower door through an adjacent apartment passes directly from the exterior through the adjacent apartment. Further, assume that this leakage flow develops a pressure differential between the adjacent apartment and the exterior of a few pascals.

These procedures are the basis for obtaining the information needed to set up and solve the equations for the Equivalent Interfaces method. All leakage flows other than that to the attic in garden-style buildings are assumed to be described by Equation (2-1) with a flow exponent $n = 0.65$ (2). It is then possible to solve for the flow coefficients of the interfaces between adjacent apartments and to the exterior².

Using these assumptions, estimates of the magnitude of leakage flow across specific interfaces can be computed. These are, however, only estimates. The results of the computations should always be checked against what is visually observed at the site.

For example, it is common in the types of construction depicted in Figure 2-1 for there to be leakage areas between apartments on the order of 5-10 square inches. The Equivalent Interfaces method should produce results indicating that the majority (> 50%) of total blower door flow is not through any single interface

² If the *cfm50* of the interface is a number of interest, it can be obtained by multiplying the flow coefficient by $50^{0.65}$.

between apartments. If the computed results do not agree with common sense and observations, the After-a-Retrofit method should be used.

Section 3

RESULTS

DESCRIPTION OF TEST SITES

At least one of the test methods was applied at each of three different complexes in the greater Syracuse, New York, area. The blower door was set up in at least one apartment in each of the buildings. The buildings in these complexes represent the styles of construction depicted in Figure 2-1.

Apartments in the Maplewood Complex are stacked with breezeways separating them horizontally, as shown in Figure 2-1(a). Apartments were built on three floors, with a well-ventilated attic that spans multiple units. None of the units was weatherized. One of the issues explored in the field work was an examination of moisture damage to the roof decks of several of the buildings in the complex. A single unoccupied apartment was tested at Maplewood by way of the Equivalent Interfaces method.

The apartments in the Westminster Complex resembled those illustrated in Figure 2-1(b)³. At each end of the buildings, there are two apartments, one on each of two floors. In the middle, there is a block of eight apartments, divided into two groups of four, one group on each of two floors. Continuous fire walls separate the horizontally adjacent apartments in this central block. The apartments on the ends are separated from the block in the middle by breeze ways. Well-ventilated attics span each quarter of the top story apartments.

The Equivalent Interfaces method and the Open-a-Door method were implemented in one apartment at Westminster. The apartment was tested between the time of side wall retrofits and the time of attic retrofits. It was not possible to arrange a post-retrofit testing session following the attic treatments.

³ The author thanks the personnel at Syracuse Energy, Syracuse, NY, for their invaluable assistance in securing test apartments at the Westminster Complex, and for assistance and feedback in the field work.

A total of six town houses comprise the test building at the Walnut West Complex. Each unit is three floors in height, with fire walls separating adjacent units. There are no attic spaces, and each unit has a small utility room on the ground floor for the furnace and hot water heater.

Two unoccupied and unweatherized units were tested at Walnut West following general painting and maintenance in the building. Three methods were used in each apartment--Equivalent Interfaces, Open-a-Door, and Add-a-Pathway.

The apartments in the Maplewood and Westminster complexes occupy a single story, are less than 900 square feet in floor area, and have blower door flows at 50 Pa of about 1,000 cfm. The Walnut West units occupy three stories, have a floor area of about 1,000 square feet, and a blower door flow at 50 Pa of about 2,400 cfm. By the ventilation standards used in multifamily weatherization, the units studied in this project are fairly tight (1,3).

LEAKAGE MEASUREMENTS

Neither the Open-a-Door nor the Add-a-Pathway method was applicable in any apartment that was tested. This suggests that the leakage to the exterior is much greater than the leakage between apartments in these buildings.

The Equivalent Interfaces method gave quantitative results for each of the three complexes. Figure 3-1 summarizes the measurements of pressure differentials and blower door flow found at the Maplewood Complex.

Working from the top story, the leakage flow to the attic is estimated first. The remainder of the analytical steps are presented in Figure 3-1, leading to two equations containing the two unknowns, K_e and K_f . Referring to the measured pressure differentials shown in Figure 3-1,

(Total blower door flow) - (Attic leakage flow) = (Flow from the exterior) + (Flow across the floor from the second story apartment), or,

$$\begin{aligned}
 Q - Q_a &= 1050 - 191 = 895 \text{ cfm} \\
 &= K_e (50 \text{ Pa})^{0.65} + K_v (43 \text{ Pa})^{0.65}
 \end{aligned}
 \tag{3-1a}$$

and

(Flow across the floor of the third story apartment) = (Flow into the second story apartment from the exterior), or,

$$K_v (43 \text{ Pa})^{0.65} = K_e (7 \text{ Pa})^{0.65} \tag{3-1b}$$

The measurements taken at the Westminster Complex, in an apartment in the central block, are shown in Figure 3-2. No intervening zone was found between the first and second story apartments. The fire wall was the intervening zone between the two second story apartments. Four flow coefficients are identified for the interfaces sketched in Figure 3-2. The figure also contains the four equations and the values of the pressure differentials needed to solve for the four flow coefficients:

(Total blower door flow) - (Attic leakage flow) = (Flow from the exterior) + (Flow across the floor from the first story apartment) + (Flow through the fire wall from the horizontally adjacent apartment), or,

$$\begin{aligned}
 Q - Q_a &= 1100 - 397 = 703 \text{ cfm} \\
 &= K_e (50 \text{ Pa})^{0.65} + K_v (45 \text{ Pa})^{0.65} + K_{hl} (36 \text{ Pa})^{0.65}
 \end{aligned}
 \tag{3-2a}$$

and

(Flow across the floor of the second story apartment) = (Flow into the first story apartment from the exterior), or,

$$K_v (45 Pa)^{0.65} = K_e (5 Pa)^{0.65} \quad (3-2b)$$

and

(Flow through the blower door apartment side of the fire wall) = (Flow into the fire wall from the adjacent apartment), or,

$$K_{hl} (36 Pa)^{0.65} = K_{h2} (12 Pa)^{0.65} \quad (3-2c)$$

and

(Flow into the fire wall from the adjacent apartment) = (flow into the adjacent apartment from the exterior), or,

$$K_{h2} (12 Pa)^{0.65} = K_e (2 Pa)^{0.65} \quad (3-2d)$$

Finally, the field measurements and the definitions of the flow coefficients for a unit at the Walnut West Complex are given in Figure 3-3. The three equations for solving for the three flow coefficients for this site are:

(Total blower door flow) = (Flow from the exterior) + (Flow from the two horizontally adjacent apartments), or,

$$\begin{aligned} Q &= 2386 \text{ cfm} \\ &= K_e (50 Pa)^{0.65} + 2 K_{hl} (31 Pa)^{0.65} \end{aligned} \quad (3-3a)$$

(Flow across the blower door apartment side of a fire wall) = (Flow into the fire wall from the adjacent apartment), or,

$$K_{hl} (31 Pa)^{0.65} = K_{h2} (17 Pa)^{0.65} \quad (3-3b)$$

and

(Flow into a fire wall from the adjacent apartment) = (flow into the adjacent apartment from the exterior), or,

$$K_{h2} (17 Pa)^{0.65} = K_e (2 Pa)^{0.65} \quad (3-3c)$$

It is a simple matter to solve the systems of equations presented above for the values of the flow coefficients. For example, they can be put into matrix form and solved with the determinant functions available in most spreadsheet applications.

There are a variety of forms for expressing the results of solving Equations (3-1) through (3-3). One useful form is the fraction of the total blower door flow that was due to air leakage at specific interfaces, for each test site.

This fraction was computed by substituting the solutions for the values of the flow coefficients back into Equations (3-1a), (3-2a), and (3-3a) for the Maplewood, the Westminster, and the Walnut West complexes, respectively. The product of the flow coefficient and the exponentiated pressure differential measurement gives the value of the flow for a specific interface. The ratio of that flow to the total blower door flow is the percentage through the given interface.

Results in this form are given in Table 3-1. Note that the absence of a numerical result in a cell means that the corresponding interface was not present at the given site.

Table 3-1.
Air Leakage Across Specific Interfaces,
Given as Percentage of Blower Door Flow.

Test Site	To Exterior	Through Ceiling (to Attic)	Through Floor	Through Interior Walls
Maplewood	64%	18%	18%	--
West-minster	46%	36%	10%	8%
Walnut West	80%	--	--	20%

The Equivalent Interfaces method suggests, from the results shown in Table 3-1, that the predominant leakage pathways are to the exterior in all three cases tested. This result agrees with the results from the Add-a-Pathway and the Open-a-Door methods, as well as with visual inspections. The field results suggest that there is little inter-apartmental air leakage in the units that were tested.

In the case of the results from the Westminster apartment presented in Table 3-1, a certain amount of stack effect convection to the attic might be expected. This supposition was verified by the presence of stains on the very loosely packed fiberglass batting lying on the attic floor over the apartment.

The source of the moisture problem at the Maplewood complex was found based on field investigations. The roof deck was damaged in several buildings in the complex, even though the attics are well ventilated to the exterior. The results shown in Table 3-1 suggest that very little moisture should be able to leak from the top story apartments to the attics, and, if that were the case, the moisture had to come from some other source.

Inspections at the Maplewood complex revealed that the flues for the bathroom vents in the apartments were terminated inside the attics. They should have been terminated above the outer surface of the roof. In the winter, these flues deliver highly concentrated moisture to the cold underside of the roof decks, creating condensation and water damage.

**DEFINITION OF
INTERFACES FOR
FLOW COEFFICIENTS**

Ke: From apartment
to the exterior

Kv: From apartment
to its floor deck

Step (1): Flow to attic (Q_a)

Estimated leakage area = 26 sq. in.

$$Q_a = 1.06 (26 \text{ sq. in.}) [48 \text{ Pa}]^{0.5} \\ = 191 \text{ cfm}$$

Step (2): Flow equation for top story

$$Q - Q_a = 1050 - 191 = 859 \text{ cfm}$$

$$= K_e (50)^{0.65} + K_v (43)^{0.65}$$

Step (3): Flow equation for second story

o Assume that the make-up flow to the top story is from the exterior through the second story apartment (single pathway as opposed to serial paths, the path of least resistance)

o Assume that K_v and K_e do not change from apartment to apartment

$$K_v (43)^{0.65} = K_e (7)^{0.65}$$

Step (4) Solve for the flow coefficients using the two equations from steps 2 and 3

Figure 3-1. The Equivalent Interfaces Method at the Maplewood Complex.

DEFINITION OF INTERFACES FOR FLOW COEFFICIENTS

Ke: From apartment to the exterior

Kv: From apartment to floor deck (no intervening zone was present)

Kh1: From blower door apartment to fire wall

Kh2: From fire wall to adjacent (east) apartment

LEAKAGE FLOW TO ATTIC

Estimated leakage area = 54 sq. in.

$$Q_a = 1.06 (54 \text{ sq. in.}) [48 \text{ Pa}]^{0.5} = 397 \text{ cfm}$$

ADDITIONAL EQUATIONS

$$Q - Q_a = K_e (50)^{0.65} + K_v (45)^{0.65} + K_{h1} (36)^{0.65}$$

$$K_v (45)^{0.65} = K_e (5)^{0.65}$$

$$K_{h1} (36)^{0.65} = K_{h2} (12)^{0.65}$$

$$K_{h2} (12)^{0.65} = K_e (2)^{0.65}$$

Figure 3-2. The Equivalent Interfaces Method at the Westminster Complex.

DEFINITION OF INTERFACES FOR FLOW COEFFICIENTS

Ke: From apartment to the exterior

Kh1: From blower door apartment to fire walls

Kh2: From fire walls to adjacent apartments

FLOW EQUATIONS

$$Ke (50)^{0.65} + 2 Kh1 (31)^{0.65} = 2386 \text{ cfm}$$

$$Kh1 (31)^{0.65} = Kh2 (17)^{0.65}$$

$$Kh2 (17)^{0.65} = Ke (2)^{0.65}$$

Figure 3-3. The Equivalent Interfaces Method at the Walnut West Complex.

Weatherization and rehabilitation practices for this type of stock currently re-route bathroom vents to the outside when necessary. These practices do not, however, include extensive inter-apartment air sealing efforts (3). Based on the results of the pressure diagnostic methods developed in this project, there is no need for inter-apartment air sealing in most cases.

The evidence that suggests that there is little air flow between apartments in this particular stock does not agree with some assumptions common among weatherization crews. A common rule of thumb is that there is just as much leakage to the exterior as there is among apartments (3). This does not appear to be the case. In this type of housing stock, inter-apartment air-sealing needs to be performed only if gross air leakage sites are seen (e.g., structural damage).

Section 4

CONCLUSIONS AND RECOMMENDATIONS

The main goal of this project was to develop convective diagnostic methods for low-rise multifamily structures. Four such methods were developed. They represent an intermediate step in the evolution of convective building science, appearing between the present field practices that do not quantify the leakage pathways at all, and the present research practices that require extensive equipment (such as multiple blower doors and tracer gas devices) (1,3).

The four methods were developed in multifamily housing stock which is, according to colleagues in the weatherization profession, prevalent in upstate New York. In garden-style apartments and town house stock, if tight construction is found by visual inspection and blower door testing, the Equivalent Interfaces method may be used on a production basis. The method estimates leakage flows across specific convective interfaces of the apartments.

The After-a-Retrofit and Equivalent Interfaces methods are recommended for field implementation in the New York State Weatherization Assistance Program (WAP). These methods can provide first-order estimates of the magnitudes of leakage pathways without requiring extensive departures from present field practices. The Open-a-Door method is also recommended for field implementation, but its applicability depends on convective characteristics that weatherization personnel may need special training to recognize.

Toward the end of promoting the transfer of technology developed during this project, a copy of this report has been forwarded to staff members of the WAP, as well as to Professional Skills Development personnel. This material is being evaluated for inclusion in state training programs. One of the key factors under consideration is the adaptation of the test methods to the various types of multifamily structures encountered in different areas of the state.

The present retrofit practices for air sealing and insulating the upstate stock (side wall and attic insulation) are probably very adequate as energy conservation measures. Based on the results of the methods developed for this project, no significant changes in these practices can be recommended at this time.

Top-story apartments with tight interior skins are not likely sources for moisture problems in attics, by way of natural infiltration. Bathroom fans should never be vented into the attic space, even though in this type of construction, it is not a significant pressure barrier to the outside.

It would be useful for energy auditing purposes to incorporate the estimated interface leakage values in whole-building simulations of the prevalent stock, in order to quantify the convective energy losses. Modification of presently existing auditing software to accommodate these simulations was beyond the scope of the present project.

Although natural infiltration does not appear to impose significant energy losses, there are a variety of issues of air quality in the prevalent stock. The magnitude of these air quality problems should be investigated. The question also arises as to how fresh-air ventilation (more air changes per hour) can be provided cost-effectively.

The more elaborate methods developed in the project might be useful for future research, particularly in older stock. It has been noted that the older stock is less prevalent in upstate New York and more prevalent in large urban areas (3). An extensive survey of the construction would be helpful for planning technology transfer curricula for different areas in the state.

Section 5

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Appendix A

THEORY OF THE LEAKAGE FLOW ESTIMATION METHODS

INTRODUCTION

This appendix gives the derivations of the equations for the Open-a-Door, Add-a-Pathway, and Equivalent Interfaces methods. The derivations are treated in a general way, and, as Sections 2 and 3 show, some care must be taken when applying the resulting equations to specific types of multifamily construction. The theory is presented here to facilitate applications to other types of stock.

PROCEDURES AND APPARATUS

Administrative and Tenant Amenities

The field team must be granted permission to work in a complex by the owners, and test dates and times must be arranged. If the apartments to be tested are occupied, the owners should notify the tenants and gain their permission as well. After testing is completed, the site must be restored to its original condition, the tenants must be thanked for their cooperation, and any keys that were borrowed must be returned.

Error Limits on Pressure and Flow Terms

Two of the methods are intended to induce significant changes in certain measured quantities. The following guidelines apply to these efforts:

- 1) All pressure measurements are assumed to have an error of ± 5 Pa. A change in a pressure differential following experimental manipulation must be 10 Pa or greater to be considered significant.

- 2) The error of flow measurements through the blower door is assumed to be ± 100 cubic feet per minute (cfm). A change in blower door flow following experimental manipulation must be 200 cfm or greater to be considered significant.
- 3) Test conditions are implemented under the assumption that the blower door can be adjusted to keep its apartment at a pressure differential of 50 Pa with respect to the exterior. Experimental manipulation of one convective interface should not induce significant changes in the pressure differentials across the other interfaces if there are no convective pathways among the adjacent zones. The exceptions are for intervening zones, and they are discussed in detail below.

For example, if two apartments adjoin the blower door apartment, opening one of the adjacent apartments to the exterior should not result in a significant change in the pressure differential of the blower door apartment with respect to the other apartment. (This of course assumes that the blower door fan is adjusted to maintain a 50 Pa pressure with respect to the exterior.) If there is a significant change in the pressure differential with respect to the non-manipulated zone, the methods discussed in this appendix do not apply.

- 4) If the blower door apartment is at 50 Pa with respect to the exterior, then the pressure differentials from that apartment across any set of serial interfaces to the exterior should add up to within a few pascals of 50.
- 5) Control measurements of pressure differentials are performed preceding and following experimental manipulations of zones. The values obtained after restoration of conditions should not be significantly different from those obtained before the manipulations.

Identification and Monitoring of Intervening Zones

It was found that at least two plastic tubes should be run across an apparent convective interface bordering the blower door apartment. One of these tubes should be run directly to a neighboring apartment. The other tube should be attached to a small penetration in the interior wall of the interface. The pressure differentials to these two zones are measured with respect to the blower door apartment. If the pressure differentials measured through these two routes differ significantly, there is at least one intervening zone.

The intervening zones themselves may be composed of several smaller compartments that may or may not be interconnected. For first-order characterization of leakage flows, only one penetration has to be made for measuring pressure differential.

A more complete approach would be to connect three or four tubes through small punctures in the inner wall of the interface to the intervening zone. If possible, the penetrations should be evenly spaced across the surface of the interface. All of the tubes tapped into the intervening zone should be connected to a single tube, which is then connected to a port of the pressure gauge. In this way, the sub-zone pressure differentials are spatially averaged and a much more stable measurement is obtained. Pressure measurements taken in this way should conform to all of the error limits and data checks described above.

Lower Limits on the Size of the Added Pathway

One of the methods calls for the addition of a temporary convective pathway between zones. One of the easiest materials for this added pathway is flexible aluminum duct. Some design calculations were performed to explore how big this pathway should be in order to accommodate a significant amount of air flow.

Standard duct design equations were invoked (4). The case of a straight run of flex duct 30 feet long was examined. To handle more than 300 cfm of flow at 20-45 Pa of pressure drop between the ends of the pathway, the duct should be 10 inches in diameter or more.

The presence of elbows and bends in the duct increases the frictional factors, and it is usually necessary to bend the added pathway near its connection in a window or blower door frame. It is therefore advisable to use a duct of not less than 20 inches in diameter. An example of such a pathway is the flex duct used to provide forced air down manholes.

ANALYTICAL METHODS

Quantitative Relationships

There are two mathematical underpinnings to all of the analytical approaches discussed below:

- (1) All of the air flow entering a convective zone is equal to all of the air flow leaving the convective zone (and vice versa). If this were not true, there would be a steady accumulation (or, depletion) of air in the zone. This is a result of the principle of

conservation of mass in the air flows. The mathematical counterpart of this principle takes the form of a summation notation.

- (2) Flow and pressure across a given convective interface are assumed to be related by the following power law:

$$Q = K P^n \quad (A-1)$$

where

Q = air flow across the interface (cfm)
K = the flow coefficient
P = pressure differential across the interface (Pa)
n = the flow exponent.

Further, leakage through cracks is assumed, for which the flow exponent is taken as $n = 0.65$ (2). Characterization of the leakage pathways in the interface is taken to be the estimation of the flow coefficient (K) for that interface. Once an estimate of the flow coefficient is obtained, the measured pressure differential across the interface can be used in Equation (A-1) to estimate the leakage flow across that interface.

Intervening Zones

The presence of an intervening zone introduces a level of complexity that must be taken into account. It will be seen that flow and pressure conditions two zones away from the blower door apartment need to be analyzed. A set of conventions for discussing such situations is presented in Figure A-1.

There are eight representative zones shown in each of the top, middle and bottom sketches of Figure A-1.

A blower door pressurizes the zone labeled A. To simplify the analysis, only the leakage flows to the right (through zones B and C) will be considered.

All of the flow entering Zone A through the blower door (Q) leaves through the leakage pathways in the apartment. Net leakage to the exterior is designated as Q_e . Leakage through interior pathways--those in the interfaces with adjacent zones--are numbered (Q_1 , Q_2 , etc.). These pathways are in interior walls, ceilings, and floors. Air moving through these pathways leaks into adjacent zones.

The consequence of the leakage flow across the convective interface of interest is shown in the middle sketch of Figure A-1. A portion of the blower-door's flow that is labeled Q_1 in the figure becomes the source of air movement through the adjacent zone B. In the example, flow Q_1 pressurizes Zone B, and all of the leakage flow leaving this adjacent zone must be equal to Q_1 . Air flows that leak from Zone B are labeled with primes (Q'_0 , Q'_1 , etc.).

The leakage flow labeled Q'_1 enters the next zone over, Zone C, as shown in the bottom sketch of Figure A-1. All of the flow from Zone C must be equal to Q'_1 . The flows leaving Zone C are labeled with double primes (Q''_0 , Q''_1 , etc.).

It can be imagined that leakage flows propagate across intervening zones in all directions from the zone in which the blower door operates¹. Further, if all of the eight zones represented in Figure A-1 should be convectively connected, modeling efforts become complicated. For purposes of the work reported here, cases of parallel leakage among the adjacent zones will not be considered. Serial leakage flows like those shown among zones A, B, and C in Figure A-1 are analyzed for purposes of modeling.

The details of implementation of this approach depend on the configuration of a given multifamily structure. The actual apartments first analyzed by this approach were selected on the basis of having as few convective interfaces as possible in order to reduce the complexity of protocol development. One of the goals of developing field procedures is to find a method of characterizing leakage pathways that requires the least effort to identify and label the important flows and pressures. This will be especially important in those multifamily structures in which apartments border each other on two or more sides, as well as above and below.

Most of the testing methods presented below require two different test configurations, the results of which are combined to yield an estimate of the flow coefficient of the interface under consideration. Once the relevant quantities are identified in each analytical model, they are used in an appropriate set of equations that can be solved for the relevant flow coefficient.

¹ Note that in practical applications, the only air leakage of concern may come from, at most, two zones over. Refer to the discussion of the Equivalent Interfaces method in Section 2.

PROPAGATION OF BLOWER-DOOR INDUCED FLOWS

Apartment in which
blower door is operating

$$Q = Q_0 + \sum_{i=1}^N Q_i$$

Most adjacent zone

$$Q'_1 = Q'_0 + \sum_{i=1}^{N'} Q'_i$$

Next zone over

$$Q''_1 = Q''_0 + \sum_{i=1}^{N''} Q''_i$$

Figure A-1. Serial Leakages.

Three Methods for Estimating Flow Coefficients

The flow estimation techniques in low-rise multifamily structures can be organized into procedures for three different methods. They are presented in order of increasing complexity, both in terms of analysis and field procedures.

Equivalent Interface Method--Without Intervening Zones. This method was first proposed by Michael Blasnik for adjacent apartments without intervening zones (5). It is the most approximate of the three methods presented here, and it is best applied in apartments that have relatively few convective interfaces, all of which are the same kind.

An example of row or town house construction without intervening zones is illustrated in Figure A-2. The apartment units are side-by-side, with a single solid wall separating a given apartment from each of its neighbors. In the blower door apartment, all of the leakage to the exterior is lumped into the quantity called Q_e , and the flows across each of the walls to the adjacent apartments are labeled Q_1 and Q_2 , respectively. It is apparent by inspection of the figure that:

$$Q = Q_e + \sum_{i=1}^{N=2} Q_i \quad (A-2)$$

From inspection of Figure A-2, the following equation may be written for the adjacent zone:

$$Q_1 = Q'_e + \sum_{i=1}^{N'=1} Q'_i \quad (A-3)$$

Four assumptions are made in order to write two simultaneous equations to characterize the convective interfaces:

- Each apartment has the same flow coefficient across its interface to the exterior, K_e .
- The flow coefficient for all apartment-to-apartment interfaces is the same, K .
- A pressure differential can be measured for all the interfaces shown in Figure A-2 that are labeled with a flow value.

EQUIVALENT INTERFACE METHOD

No Intervening Zones

Assumptions

- (1) Apartment-to-apartment and apartment-to-exterior leakage pathways are identical from one apartment to another.
- (2) The pressure differentials can be measured across the convective interfaces where flow (Q) terms are labelled.
- (3) No sources of flow or pressure other than those created by the blower door are present.
- (4) Flow balance equations are:

$$Q = Q_e + \sum_{i=1}^{N=2} Q_i$$

$$Q_1 = Q'e + \sum_{i=1}^{N'=1} Q'i$$

Figure A-2. Equivalent Interfaces without Intervening Zones.

- There are no sources of flow (or pressure) other than those created by the operation of the blower door.

If all four assumptions are met, Equations (A-2) and (A-3) can be re-written in the form of Equation (A-1), and the measured pressure differentials can be inserted. The result is the following pair of simultaneous equations:

$$K_e P_e^n + K \sum_{i=1}^{N=2} (P_i)^n = Q \quad (A-4a)$$

$$K_e (P'_e)^n + K \left[\left(\sum_{i=1}^{N'=1} (P'_i)^n \right) - (P'_1)^n \right] = 0 \quad (A-4b)$$

Equations (A-4a) and (A-4b) may be solved for K_e and K , which characterizes the convective interfaces between the apartment and the exterior, and between adjacent apartments, respectively.

Equivalent Interface Method—With Intervening Zones. A relatively simple example of row or town house construction with intervening zones between apartments is illustrated in Figure A-3. The apartment units are side-by-side, with a single zone separating a given apartment from each of its neighbors. The assumptions made for this situation are substantially the same as those made in the absence of the intervening zone. The major difference is that the flow coefficient K is now taken at the interface between an apartment and its adjacent intervening zone.

The equations that describe the balances of flows are given at the bottom of Figure A-3 and are similar in form to Equations (2) and (3). If the appropriate pressure differentials can be measured, a set of simultaneous equations may be derived:

$$K_e P_e^n + K \sum_{i=1}^{N=2} (P_i)^n = Q \quad (A-5a)$$

$$K_e (P''_e)^n + K \left[\left(\sum_{i=1}^{N'=1} (P''_i)^n \right) - (P'_1)^n \right] = 0 \quad (A-5b)$$

The result is the same as that for Equation (A-4), which is a solution for K_e and K .

EQUIVALENT INTERFACE METHOD

Intervening Zones

Assumptions

- (1) Apartment-to-zone and apartment-to-exterior leakage pathways are identical from one apartment to another.
- (2) The pressure differentials can be measured across the convective interfaces where flow (Q) terms are labelled.
- (3) No sources of flow or pressure other than those created by the blower door are present.
- (4) Flow balance equations are:

$$Q = Q_e + \sum_{i=1}^{N=2} Q_i$$

$$Q'_1 = Q''_e + \sum_{i=1}^{N''=1} Q''_i$$

Figure A-3. Equivalent Interfaces with Intervening Zones.

Open-a-Door Method--Without Intervening Zones. The basic analysis for this method was first introduced by Blasnik and Fitzgerald (2) for the case of no intervening zones. The method is adapted below for use in multifamily structures, and a new analytical treatment is derived for the case of an intervening zone.

This method is useful for estimating the value of the flow coefficient for a single convective interface. However, the zone separated from the blower door apartment by the intervening zone must have a doorway or several windows to the exterior. This method is therefore convenient for testing apartments that are bordered by three or more apartments.

Figure A-4 illustrates the application of this method in the case of no intervening zones. At the left of the figure, the blower door operates while the next door apartment is closed to the exterior. The flow through the blower door is labeled as the quantity Q_a (taken during test condition "a"). The convective interface through which the leakage labeled Q_{1a} flows is the interface of interest. There is a pressure differential P_{1a} across this interface.

Under the assumption that the apartments bordering the blower door apartment are not convectively coupled to one another, all other leakage flows beside Q_{1a} can be modeled as a single quantity, so that under test condition "a":

$$Q_a = Q_{1a} + \sum_{i \neq 1} Q_{ia} \quad (A-6)$$

where the Q_i terms are all of the leakage flows from the blower door apartment except for Q_{1a} . Note that in this formulation, one of the Q_i terms includes leakage to the exterior.

It is assumed that the pressure differentials across all other relevant interfaces are monitored for stability as part of this method. When the apartment next door is opened to the exterior, as on the right side of Figure A-4, the only pressure differential that should change significantly in this new condition is the one across the interface to the opened apartment. The flow equations resulting from test condition "b" with the adjacent apartment open to the exterior are:

OPEN-A-DOOR METHOD

No Intervening Zone

Adjacent apartment closed
to exterior

Test condition "a"

$$Q_a = Q_{1a} + \sum_{i \neq 1} Q_{ia}$$

... $\sum_{i \neq 1} Q_i$ is the sum of flows through
all leakage routes except for Q1's
(including leakage to exterior).

Adjacent apartment open
to exterior

Test condition "b"

$$Q_b = Q_{1b} + \sum_{i \neq 1} Q_{ib}$$

$$P_{1b} = 50 \text{ Pa}$$

Assumption: $\sum_{i \neq 1} Q_{ia} = \sum_{i \neq 1} Q_{ib}$

Computation: $Q_b - Q_a = Q_{1b} - Q_{1a}$

Figure A-4. Open-a-Door Without Intervening Zones.

$$Q_b = Q_{1b} + \sum_{i=1} Q_{ib} \quad (A-7a)$$

$$\sum_{i=1} Q_{ia} = \sum_{i=1} Q_{ib} \quad (A-7b)$$

Subtracting Equation (A-6) from Equation (A-7a) gives a result that can be put into the form of the power law of Equation (A-1):

$$Q_b - Q_a = Q_{1b} - Q_{1a} = K_1 (P_{1b}^n - P_{1a}^n) \quad (A-8)$$

from which the flow coefficient for the interface of interest is obtained:

$$K_1 = \frac{Q_b - Q_a}{(P_{1b}^n - P_{1a}^n)} \quad (A-9)$$

Open-a-Door Method—With Intervening Zones. An example is shown in Figure A-5 of leakage flows through the convective interface between the blower door apartment and an intervening zone. As shown at the bottom of the figure, it is the next apartment past the intervening zone that is opened to the exterior. Equations are given in the figure that are similar to Equations (A-6) and (A-7a), with the pressure differential P_1 now being measured between the blower door apartment and the intervening zone. These equations can be manipulated into a form like Equation (A-9)'s, leading to a computation of K_1 for the interface between the blower door apartment and the intervening zone.

Once a value for the coefficient K_1 has been obtained, it is possible (with the appropriate measurements of pressure differentials) to estimate the flow coefficients for the other two interfaces of the intervening zone. The flow equations are given in Figure A-5 for test conditions "a" and "b." Putting those equations in the power-law form of Equation (A-1) results in the following pair of simultaneous equations:

OPEN-A-DOOR METHOD

Intervening Zone

Adjacent apartment closed
to exterior

$$Q_a = Q_{1a} + \sum_{i \neq 1} Q_{ia}$$

$$Q_{1a} = Q'_{ea} + Q'_{1a}$$

... $\sum_{i \neq 1} Q_i$ is the sum of flows through
all leakage routes except for Q_1 's
(including leakage to exterior).

Adjacent apartment open
to exterior

$$Q_b = Q_{1b} + \sum_{i \neq 1} Q_{ib}$$

$$Q_{1b} = Q'_{eb} + Q'_{1b}$$

Assumption: $\sum_{i \neq 1} Q_{ia} = \sum_{i \neq 1} Q_{ib}$

Figure A-5. Open-a-Door with Intervening Zones.

$$K_1 P_{1a}^n = K'_e (P'_{ea})^n + K'_1 (P'_{1a})^n \quad (A-10a)$$

$$K_1 P_{1b}^n = K'_e (P'_{eb})^n + K'_1 (P'_{1b})^n \quad (A-10b)$$

where K'_e and K'_1 are the flow coefficients for the intervening zone's convective interfaces to the exterior and to the next neighboring apartment, respectively.

Add-a-Pathway Method--Without Intervening Zones. The elements of this method were developed by Synertech in a recent study of convective zones that included forced-air distribution systems (6). The most appropriate use of this method is in cases where an adjacent zone cannot be opened to the exterior or to an apartment, such as an unfinished attic. In such cases, a temporary hatch must often be made in order to accommodate the added pathway.

Because of its invasive nature, and because setting up a temporary pathway can be challenging, this is the most cumbersome of the three methods for characterizing leakage pathways. Accordingly, there must be adequate justification for implementing this method.

Figure A-6 illustrates the method when there are no intervening zones. The same assumptions are made in this method as in the Open-a-Door method (compare with Figure A-4), with the following two exceptions:

- The flow going through the added pathway must be of sufficient strength to change the pressure differential across the interface at which the pathway is added. In the illustration of Figure A-6, the pressure differential P_{1b} must be significantly different from P_{1a} .
- When taking a difference in system flow equations in the spirit of Equation (A-8), there is an additional term Q_p to take into account. This computation is shown at the bottom of Figure A-6.

The flow coefficient for the interface of interest that is illustrated in Figure A-6 can thus be determined from the following equation:

ADD-A-PATHWAY METHOD

No Intervening Zone

Assumptions: (1) Qp makes P1b significantly different from P1a

$$(2) \sum_{i \neq 1} Q_{ia} = \sum_{i \neq 1} Q_{ib}$$

Computation: $Q_b - (Q_a + Q_p) = Q_{1b} - Q_{1a}$

Figure A-6. Add-a-Pathway without Intervening Zones.

$$K_I = \frac{Q_b - (Q_a + Q_p)}{(P'_{1b} - P'_{1a})} \quad (A-11)$$

Add-a-Pathway Method--With Intervening Zones. An equation of the form of Equation (A-11) can be used in the case where there is an intervening zone. There are three principle differences between the two cases in the Add-a-Pathway method when an intervening zone is present:

- The interface of interest is the one between the blower door apartment and the intervening zone, as indicated in Figure A-7.
- The flow going through the added pathway must be of sufficient strength to change the pressure relationships of the intervening zone across which the pathway is added. For example, in the illustration of Figure A-7, the pressure differential P'_{1b} must be significantly different from P'_{1a} .
- Values of the flow coefficients of the interfaces between the intervening zone and the exterior, and between the intervening zone and the next neighboring apartment, may be computed using equations of the form of (10a) and (10b).

ADD-A-PATHWAY METHOD

Intervening Zone

No Added Pathway

$$Q_a = Q_{1a} + \sum_{i \neq 1} Q_{ia}$$

$$Q_{1a} = Q'_{ea} + Q'_{1a}$$

... $\sum_{i \neq 1} Q_i$ is the sum of flows through all leakage routes except for Q_{1a} 's (including leakage to exterior).

With Added Pathway

$$Q_b = Q_p + Q_{1b} + \sum_{i \neq 1} Q_{ib}$$

Q_p : Flow through added pathway

$$Q_{1b} = Q'_{eb} + Q'_{1b}$$

Assumptions:

(1) Q_p makes P'_{1b} significantly different from P'_{1a}

$$(2) \sum_{i \neq 1} Q_{ia} = \sum_{i \neq 1} Q_{ib}$$

Figure A-7. Add-a-Pathway with Intervening Zones.

Appendix B

PROTOCOLS FOR THE OPEN-A-DOOR METHOD

INTRODUCTION

Multifamily buildings come in a wide variety of shapes and sizes. They range from garden-style apartments that are much like detached single-family structures, to high-rises. Controlling internal air movement, and preventing its leakage to the exterior are two primary goals in weatherizing these buildings. However, when it comes to identifying air leakage sites, the complexity of the job can literally get as big as the building.

There is not a lot of information available yet concerning air leakage in multifamily structures. There is much we do not understand. However, the tools for diagnosing air leakage are getting better all the time. And the better you can track air leakage pathways, the better you can treat them and understand the impacts on the building.

This document introduces a method for tracking air leakage in multifamily structures that are in the small to mid-sized range. A previous study (7) has characterized these types of structures as follows:

Multifamily Structural Type #1: Row house configurations--typically one- or two-story apartment units connected side-by-side, most often with individual heating systems. These units, although they may include five or more apartments in a complex, have much in common with single-family structures, town houses and side-by-side duplexes. This is a low-cost housing model and is often used as Section 8 subsidized housing. These units are typically built with low structural investment and are often of cement block construction or wood frame. Heating systems are based commonly on gas furnaces or on electric baseboards.

Multifamily Structural Type #2: Five-to-twenty unit, two- or three-story cluster housing with a central hall/stairway surrounded by two to six apartments per floor. These units are quite common, often of masonry construction with a flat or slightly pitched roof. Heat and hot water are usually supplied from a central boiler.

The few studies that have been done on air leakage in these types of multifamily structures suggests that there is often at least as much air leakage among apartments as there is to the outside. Sometimes most of the air leakage is between apartments (8).

There must be coordination between the ventilation needs of a building and air sealing efforts. The issues of concern thus include indoor air quality as well as energy losses in the building. In fact, it may be more important to control air leakage within a building than it is to try to eliminate it.

The method introduced in this document specializes in tracking down air leakage paths within a multifamily structure. It is done on an apartment-by-apartment basis. As such, the method provides a step forward in the effort to identify, understand, and manage air movement in multifamily structures.

The method will not work in all cases, but there are usually enough clues to decide whether or not it is applicable. These clues are provided by the measurements that are taken in the method. However, even for the simplest of multifamily structures, there can be a lot of numbers to keep track of.

Because keeping track of all of the numbers can be time consuming in the field (and confusing), an electronic spreadsheet application was developed. The spreadsheet performs data-checking procedures and computes the results. The spreadsheet makes the method practical for field work.

Of course, some level of personal judgment is required when using the method--no spreadsheet will ever replace careful observation. A spreadsheet cannot think on its feet.

This assumes the availability of a computer that can run the spreadsheet application. Computer skills are becoming increasingly valuable in weatherization work. The proper use of diagnostic instrumentation allows quick and efficient collection and analysis of measurements.

The method also assumes familiarity with the evolving field of pressure diagnostics with a blower door and with gauges for measuring pressure differentials. The basic principles presented here were pioneered by Michael Blasnik and James Fitzgerald, mainly for single-family detached structures. Their work is recommended reading (2).

Attending a mini-course in pressure diagnostics at a weatherization/building science training center or conference might be helpful. These workshops demonstrate what the diagnostic equipment is, how to use it, and how to make sense out of the measurements.

This method presented in this document applies the basic principles of pressure diagnostics to multifamily structures. The method was developed in parallel with field work. This work has revealed features of

multifamily structures that can be radically different from what is found in single-family detached structures. The result is a field-tested approach to tracking air leakage in some of the trickier building configurations often found in multifamily apartments.

OVERVIEW OF THE DIAGNOSTIC METHOD

Definitions and Terminology

This description of the diagnostic method uses some terminology from building science. The two key terms are defined below.

Convective Interface: A barrier or partition within a building through which air may flow. In a multifamily apartment, the typical convective interfaces are the walls, the ceiling, and the floor.

Intervening Zone: A space within a building that is partially, but not completely, open to at least two other adjacent zones. Typical examples of intervening zones are the spaces between the ceiling and the floor of two stacked apartment units; partition walls; fire walls; and attics and basements that span more than one apartment.

It has been discovered that intervening zones can present significant challenges to managing or sealing air leakage pathways. First, they are fairly common in multifamily structures. Second, unless you are looking for them, you may not suspect that they are there. Third, they can provide leakage pathways between apartments as well as to the exterior. Fourth, they can be inter-connected in ways that confound our best attempts to trace them.

There is no known comprehensive way to trace all air leakage pathways in multifamily buildings with a single blower door and a pressure gauge. This section covers the tests that can be done with these simple tools, and how to tell whether to trust your results.

At the end of the section, a flow chart is given that summarizes the major steps in the method. The next section covers the details of the procedures.

Preliminary Procedures

As always, it is a good idea to look around before setting up the test equipment. Visual inspection can provide insights that will aid in your planning of test procedures. The lay out of the apartment should be noted. You should identify the neighboring apartments, hallways, attic(s), and other spaces that border the apartment you are about to test. A quick sketch of the apartment and its bordering spaces may be of value in mapping potential leakage pathways.

While looking for details relating to convective diagnostic procedures, you might also get some initial ideas about your air-sealing strategy. Where are the most obvious air leakage routes? Are there fire and building codes that need to be observed? Will what you are about to do interfere with intentional ventilation strategies?

Next, determine from the appropriate people whether you may drill small openings in the walls, ceiling, and floor for tubes to connect to your pressure gauge. Such openings are usually made with a 1/16" drill bit. If the tenant or building owner objects to this, you may not be able to perform the diagnostic work.

Care must be used in the placement of drilled openings. They should be as unobtrusive as possible. Be careful to not drill into duct work, plumbing, or electrical lines.

Plastic tubes connected to a pressure gauge are used to measure pressure differentials between apartments. Good routes for these tubes must be selected. You must also secure these tubes so that they will not be underfoot or become dislodged during testing.

Before setting up the blower door, you should decide whether to pressurize or depressurize the apartment. Experience and common sense should be your guides in making this decision.

If the tenant does not want frigid outside air to be pumped into the apartment, you should consider depressurization. If there is the possibility of spreading lead paint dust from around window sills, you will want to consider pressurization. The decision should be an informed one, with the option to include the tenant in the decision making process.

Finally, unless the building is unoccupied, you will have to interact with the tenants in the apartments surrounding the unit being tested. It is a good idea to introduce yourself to the tenants. Explain the purpose and methodology of the procedures. Answer any questions that they might have.

Testing for Intervening Zones

The distribution of intervening zones in a building may make the entire test procedure inapplicable. The idea is to characterize them as early in the procedure as possible, so you will not waste your time in unproductive efforts. At the very least, the method gives you a systematic way to examine the leakage pathways in the apartment.

In practice, there is an easy way to tell whether there is an intervening zone between the blower door apartment and an adjacent apartment (or attic, hallway, etc.). Recall that an intervening zone is partially, but not completely, open to at least two other zones in the building. The blower door creates a leakage flow on one side of the intervening zone. The physical laws governing the leakage flow then determine what happens inside the intervening zone.

All of the leakage flow at the interface in the blower door apartment must flow to somewhere else in the building and, eventually, back to the outside. If this was not the case, a building cavity beyond the interface would either eventually explode (in pressurization mode) or cave in (in depressurization mode).

An intervening zone presents at least two opportunities for there to be a leakage flow: one at the interface to the blower door apartment, and the other at the interface to the next adjacent zone in the building. The two leakage flows create two distinct pressure differentials, one at each of the interfaces.

Pressure differentials add together across successive interfaces. This rule means that when there is an intervening zone, there is a certain pressure differential from the blower door apartment to the intervening zone. There is another pressure differential between the intervening zone and the adjacent apartment. The sum of these two pressure differentials must be equal to the pressure differential between the blower door apartment and the adjacent apartment.

On the other hand, if there is only a single interface, there can be only a single pressure differential. The pressure differential from the blower door apartment is then the same to the interior of the interface as it is to the adjacent apartment.

These principles are illustrated in Figure B-1. Figures B-1(a) and B-1(b) are floor plan views of two adjacent apartments, one of which has a blower door installed and operating at 50 pascals with respect to the exterior. Between the apartments is an interior wall. The challenge in this example is to tell whether there is an intervening zone inside the interior wall. To determine this, a minimum of two pressure differentials must be measured:

- (1) Between the blower door apartment and the interior wall space, and,
- (2) Between the blower door apartment and the adjacent apartment.

The rule of thumb for deciding whether there is an intervening zone is:

If the two measured pressure differentials are different by more than 5 pascals, there is probably an intervening zone.

To measure the pressure differential between the blower door apartment and the interior wall cavity, one port of the pressure gauge must be open to the blower door apartment. The other port must be connected by a plastic tube to the interior wall cavity.

Figure B-1 shows two tubes inserted into the interior wall. They are connected to a single tube that leads to a port on the differential pressure gauge. This is a pressure-measuring technique known as spatial averaging. It is used because there can be partitions behind the interior wall if it does indeed conceal an intervening zone.

Spatial averaging gives you a quick and representative measurement. The alternative is to find where the partitions within the cavity are and measure the pressure differentials across each of them.

To keep life as simple as possible, the goal is to take the space inside of the interior wall cavity as a single convective zone. It should be tapped for pressure measurement in at least two places, in the manner shown in Figure B-1. The tubes between the pressure gauge and the wall should be about the same length. The tubes should enter at evenly-spaced intervals from each other on the interior wall.

ANALYSIS:

Pressure measured with respect to interior wall: 35 Pa

Pressure measured with respect to adjacent apartment: 33 Pa

The pressures do not differ by more than 5 pascals.

There is probably no intervening zone in the interior wall.

(a)

ANALYSIS:

Pressure measured with respect to interior wall: 20 Pa

Pressure measured with respect to adjacent apartment: 33 Pa

The pressures differ by more than 5 pascals.

There is probably an intervening zone in the interior wall.

(b)

Figure B-1. Testing for the Presence of an Intervening Zone.

To measure the pressure differential between the blower door apartment and the adjacent apartment, one port of the pressure gauge must be open to the blower door apartment. The other port must be connected to a plastic tube that runs directly into the other apartment (for example, under the doors).

In the example shown in Figure B-1(a), the pressure differential with respect to the interior wall cavity is shown as 35 pascals. The pressure differential with respect to the adjacent apartment is 33 pascals. These two measurements are not more than 5 pascals apart. There is probably not an intervening zone in the interior wall cavity.

Figure B-1(b) shows an example of pressure readings that are different by more than 5 pascals. This indicates the presence of an intervening zone. The basic set-up illustrated in Figure B-1 is also be used for the floor and the ceiling of the blower door apartment.

As a check on the collected data, the pressure differentials between the intervening zone and the adjacent apartment, and between the adjacent apartment and the outside, should also be measured. The pressure differentials across each of the following interfaces should be summed:

- Between the blower door apartment and the intervening zone
- Between the intervening zone and the adjacent apartment
- Between the adjacent apartment and the exterior.

These are a full set of successive interfaces between the blower door apartment and the exterior. The sum of the pressure differentials across them all should be equal to the pressure differential established directly between the blower door apartment and the exterior.

Air Leakage through Intervening Zones

An intervening zone makes for complex convective pathways. The progression of air leakage through these pathways is illustrated by the fairly straight-forward example shown in Figure B-2. Serial row- or town-house apartments are separated from each other by party walls. A blower door is shown pressurizing one of these apartments. There is a flow of leakage air from this apartment directly out to the exterior, as well as into both party walls bordering it. We will consider the progress of air leakage only to the right of the blower door apartment.

The chain of induced air flows starts with the leakage represented by the empty arrow in Figure B-2(a). This is the air leakage into the party wall on the right. If the leakage into the party wall is substantial, the pressure differential between the apartment and the party wall may be much less than the one between the apartment and the exterior.

Figure B-2(b) shows that the air leaking into the party wall can go in two directions. A fraction of the air pushed into the party wall can escape to the exterior. The remainder of the air pushed into the party wall leaks into the next apartment.

By the time the air currents originating in the blower door apartment reach the next apartment over, there might be a flow of several hundred cfm. This amount of flow might pressurize the adjacent apartment with respect to the exterior by anywhere from a few to perhaps tens of pascals. However, much depends on the physical details of the leakage pathways taken by the air flows.

The ratio of the pressure differential at one interface to that at the next interface is determined by the ratio of the effective leakage areas in those interfaces. These leakage areas can have significant energy and air quality implications for multifamily buildings under normal operating conditions. During the test procedures, the pressure differentials are determined by the conditions created by the blower door.

Figure B-2(c) shows the propagation of air into and out of the next adjacent apartment. This apartment will develop its own pressure differentials with respect to the exterior and with respect to the party walls that border it.

In summary, the pressures and flows that are induced by the blower door when there is an intervening zone depend on the relative leakiness of each of the following interfaces:

- Between the blower door apartment and the intervening zone
- Between the intervening zone and the exterior
- Between the intervening zone and the adjacent apartment (or attic, hallway, etc.)
- Between the adjacent apartment and all of its other interfaces.

(a)

Flows into and out of
the apartment in which
blower door is operating

Empty arrow: Air leakage
flow into party wall

(b)

Flows into and out of
an intervening party wall

Empty arrow: Air leakage
flow from party wall into
adjacent apartment

(c)

Flows into and out of
adjacent apartment

Empty arrow: Air leakage
flow from adjacent
apartment into next
party wall over

Figure B-2. Progression of Flows Induced by a Blower Door.

Introduction to the Method

To keep track of all of the pathways for air leakage, you would have to measure the flows across all of the interfaces illustrated in Figure B-2. However, the aim of the method is to estimate the amount of the leakage flow between the blower door apartment and its immediately adjacent zones. In Figure B-2, we would only be interested in estimating the air leakage to the exterior and into the spaces of the bordering party walls.

There are many approaches to this complicated problem, and only the easiest-to-implement is presented in this document. In particular, only one blower door and a moderate number of pressure measurements are required by the method. Other approaches require more instrumentation, more measurements of pressure differentials, and/or greater complexity of analysis.

The method is basically comprised of six parts:

- (1) Setting up a blower door and the pressure-measuring apparatus
- (2) Determining whether there is a likely intervening zone between the blower door apartment and an adjacent zone
- (3) Taking pressure readings when a zone of the building on the other side of an interface is closed to the exterior
- (4) Re-taking the pressure readings when a zone on the other side of an interface is opened to the exterior
- (5) Entering data into a spreadsheet and determining whether the leakage flow can be estimated with the information entered
- (6) Performing a number of data quality-checking procedures to ensure that the method has been applied properly.

Limits of the Method

If all goes well, the method is capable of estimating the magnitudes of leakage flows through the convective interfaces bordering an apartment in a multifamily structure. However, even in the simplest of cases, such as the one illustrated in Figure B-2, there are limits to the applicability of the method.

The limits to the method are determined by how well the instrumentation can measure pressures and flows. If the method cannot be used in a given circumstance, it does not necessarily mean that the convective interface is air-tight. It may mean that the equipment is not sensitive enough to provide the kind of information needed to determine the leakage flow.

Fortunately, it turns out that the leakier a convective interface is, the better the method is. When you encounter tight interfaces, automatic data-checking routines in the spreadsheet tell you whether the method is applicable. These checking features were included in the spreadsheet because there can be a lot of numbers to keep track of. Keeping an eye on them electronically saves a lot of time in the field.

Always keep in mind that the construction of a building can be too complicated to analyze. It may be impossible to make sense out of the leakage patterns that you come across. The method does not apply to every multifamily building.

The method's limits depend on both the precision of the instrumentation and the building's characteristics. These two factors are discussed below.

Limits Due to the Instrumentation. The precision of an instrument's measurement capabilities is important when you compare measurements taken under two different test conditions. In steps (3) and (4) of the method (see above), the difference in test conditions comes from opening an adjacent apartment to the exterior. You need to know if the pressure and flow measurements change significantly from the first condition to the second.

The following rules of thumb regarding significant changes in measurements have evolved from convective diagnostic research:

- Two blower door flow measurements are significantly different from each other if they differ by at least 200 cfm.
- Two pressure measurements are significantly different from each other if they differ by at least 5 pascals.

These two rules of thumb express the limits of the method's ability to detect leakage flows. Without going too deeply into the theoretical reasons for this, some examples can be given of how complicated the situation can become. These examples are provided in Figure B-3.

Figure B-3(a) shows the two conditions of the method--the adjacent apartment is first closed to the exterior (top) and later opened to the exterior (bottom). In both cases, the pressure differential between the blower door apartment and the exterior is 50 pascals.

Before the adjacent apartment is opened, there is air leakage at a rate labeled Q_1 through the interior wall's interface. There is also a pressure differential across that interior wall, labeled P_1 . Air flows through the blower door at a rate that is labeled BD_1 .

When the adjacent apartment is opened to the exterior, the pressure across the interior wall's interface is at a value labeled P_2 , and the corresponding flow through that interface is labeled Q_2 . The flow through the blower door is labeled BD_2 .

As shown in the equations in Figure B-3(b), the change in flow through the blower door due to opening the adjacent apartment must exceed 200 cfm. The change in the pressure across the interior wall's interface must exceed 5 Pa. Both of these conditions must be met for the method to work, regardless of whether or not there is an intervening zone behind the interior wall.

Mathematical analysis reveals the limits of the method, and representative examples are plotted in the graph of Figure B-3(b). On the horizontal axis, the original pressure differential across the interior wall, P_1 , is given. On the vertical axis, the minimum value of P_2 for the method to work is given.

Two examples are plotted. In one, the rate of air flow prior to opening the adjacent apartment, Q_1 , is 200 cfm. Three things are apparent. First, the method applies in this case only when P_1 is in the range of 5-10 Pa. Second, as the value of P_1 increases, so does the method's minimum value of P_2 . Third, the maximum pressure P_2 is given as 40 Pa.

The other example is for a value Q_1 of 800 cfm. The workable range of P_1 is 15-25 Pa.

What these examples show is that if the pressure differential P_1 happens to be outside of a certain range based on the actual leakage flow, the method will not be able to estimate the amount of that leakage flow. The problem is that you cannot know what the amount of leakage flow is until you have tried both parts of the procedure, as shown in Figure B-3(a).

Condition 1:
 Adjacent apt closed to exterior
 (floor plan view)
 BD1: Flow through blower door
 Q1: Flow through interface to
 interior wall
 P1: Pressure drop across
 interior wall

Condition 2:
 Adjacent apt opened to exterior
 BD2: Flow through blower door
 Q2: Flow through interface to
 interior wall
 P2: Pressure drop across
 interior wall

(a)

**Instrumental Limitations
 for Using the Test Method**

$BD2 - BD1 \geq 200 \text{ cfm}$

$P2 - P1 \geq 5 \text{ Pa}$

(b)

Figure B-3. Examples of Instrumental Limits of the Test Method.

The computations operating behind the scenes in the spreadsheet do all of the checking of the numbers. As soon as the numbers are entered, you are notified as to whether the method is applicable or not. And remember, just because the method does not apply, it does not mean that a convective interface is air-tight. All it means is that the capabilities of the available instruments are limited.

Limits Due to Building Characteristics. There are several ways in which the building itself can outsmart the method. The method cannot be applied if you cannot get to the other side of a convective interface with a pressure probe. However, it is usually possible to at least drill into a closed-off space to insert a pressure probe.

A much bigger problem happens when you cannot completely open an adjacent building space to the exterior. This situation prevents you from setting up the second test condition needed to estimate leakage flows. The method does not apply in such cases.

The biggest problem of all is when the pressure differential changes across more than one interface in the blower door apartment when an adjacent building space is opened to the exterior. If two pressure differentials change from the same starting value to the same new value, they may both be part of a single intervening zone. However, if they change by different amounts, they are probably only partially connected to each other, and are really two separate interior zones.

This can get very complicated very fast. If you cannot convince yourself that two different interfaces share the same intervening zone, do not try to use the method. When intervening zones are only partially interconnected to each other, you have to do some creative thinking and testing.

For example, partition walls may have leakage pathways into common attic spaces. When the attic is opened to the exterior, the pressure differentials across the ceiling and across the partition walls might change in a top-story apartment. You would have to account for the leakage flows through the ceiling and through the partition walls at the same time.

You might be able to see whether the leakage to the attic is through chase ways in a partition wall and not through the ceiling. You might not. These situations cannot be readily reduced to a spreadsheet or to a simple set of rules.

Sometimes the only way around this problem is to seal as many of the leaks as you can find at one interface, and re-test with the blower door. The change in blower door flow is then an indication of how much leakage there was through the interface that you just sealed.

Research continues on diagnostic methods for analyzing complicated leakage pathways. For the time being, the method cannot be used reliably when the pathways are complex. The method allows for the pressure at only one convective interface to change when you open its adjacent building space to the exterior.

Discussion

Figure B-4 is a flow chart of the steps of the method. These steps are the basis for the spreadsheet application. The spreadsheet takes you through all of the places in the flow chart where a yes or no decision must be made.

As the flow chart suggests, the procedures are really for a process of elimination. The goal is to not waste time testing an interface if the method does not apply to it. The first two yes/no decisions can disqualify a convective interface from further testing. If you make it past the first two decisions for yes, you can proceed to apply the method.

You then go through several more procedures, measurements, and decisions for a given interface. If all goes well, you will get an estimate of the leakage flow across the interface.

Note that in the flow chart, cases of intervening zones are treated in much the same way as cases without them. It turns out that if you get to the stage of estimating an interface's leakage flow, you can get further information about an intervening zone. However, this fact is not on the flow chart in order to keep it straight-forward.

Recall that the intervening zone may leak to the exterior as well as to an adjacent building space. If the method works for the interface to the blower door apartment, the spreadsheet can estimate the intervening zone's other leakages as well.

Figure B-4. Flow Chart of the Diagnostic Method.

Even if leakage into an intervening zone is successfully estimated, you will want to know how much of the leakage is to the exterior. This is an issue of loss of conditioned air and its energy. You will also want to know how much of the leakage is to the adjacent building space. This is an issue of indoor air quality and the management of the building's internal ventilation.

Keep in mind that this is not the end of the story of managing air leakage in multifamily structures.

The flow chart in Figure B-4 leads to a different set of procedures for air sealing the leakage pathways that you find. The method cannot tell you, for example, which side of an intervening zone would be the most advantageous to air-seal. You must rely on other information gathered in a particular building, and on your own experience, for determining where to air-seal and why.

Drawing a distinction between air sealing for energy conservation and air sealing for managing indoor air quality is a matter of ongoing research. For example, the present methods cannot tell you whether a building with an average apartment cfm_{50} of 2,000 is too tight.

The advancement offered by the method outlined in Figure B-4 is a relatively simple and systematic attempt to trace air leakage pathways. It is but one step in the larger effort of managing air flows in multifamily structures.

When the method applies in cases of intervening zones, there is a lot of information that a few measurements can reveal. The big advantage is that this information can be obtained from inside one apartment, using a single blower door and a pressure gauge.

PROCEDURES

Introduction

This section gives the step-by-step procedures for using spreadsheet applications together with some field practices. The method covers diagnostic procedures for estimating air leakage across the convective interfaces in an apartment.

The details of air sealing are not covered. Refer to the literature in Section 5 for further information about materials and practices that are recommended for good air sealing.

You should, however, perform the testing procedures given in this section twice: once before you begin air sealing, and once after. At the very least, the pressure differential across each interface that you seal should increase.

Tools

The following minimum equipment is needed in the method:

- Standard audit tools, for example, a smoke stick
- A blower door
- A gauge for measuring pressure differentials down to one pascal (more than one gauge is helpful; the best is a digital micromanometer)
- Plastic tubing and T-joint connectors for the tubing
- Needle probes--like the kind of needle used to inflate basket balls. This is for inserting into walls, floors and ceilings.
- A drill with 1/16", 1/8", and 1/4" bits
- Masking tape
- A computer with the spreadsheet applications
- Patching material to repair holes
- Air-sealing materials and tools.

Gaining Access

It is assumed that you are taking part in the auditing phases of a larger weatherization effort. As such, the administrative, logistical, and legal aspects of your job should be set up before you arrive on site.

There are, however, a few things that you should do yourself to ensure that your part of the job goes smoothly.

- Give your contact at the job site a phone call before you arrive. Make sure you will have access to all of the areas that you will need to enter, and that the clients are aware that you are coming.
- Make sure that the list of names and apartment numbers that you have is accurate.
- Verify that written authorization from the building's owner or manager has been submitted.
- Verify that the tenants have received formal notification from your agency as well as from the building owner.
- Verify that you have permission to enter the apartments of any client who will not be there during the testing.
- Find out who is going to introduce you to the clients and when. Make sure you are introduced to everyone involved.

Preliminary Inspection / Spreadsheet #1

A shell of the first application spreadsheet is given in Figure B-5. All of the places where you can enter information are shown as solid lines. All of the places where the computer will respond are filled in with the symbols #####.

Column 1: Identification of Convective Interfaces. As you are performing your first round of inspections, use this column to keep track of all convective interfaces except for exterior walls.

Note that it is possible for the cavities within the exterior walls to connect to other zones in the building. These cavities may be part of a complicated network of intervening zones, especially if the building has a balloon frame.

However, as the next several columns in this spreadsheet indicate, the method requires there to be a clearly identifiable building space on the other side of a wall in the blower door apartment. This is not the case for exterior walls. The method is not applicable to the exterior walls.

Column 2: Major Building Space Adjacent to Interface. The next column is for entering what is on the other side of each convective interface--the neighboring apartment, the hallway, the attic, etc.

MULTIFAMILY AIR LEAKAGE TESTS

APPLICATION SPREADSHEET #1

PRELIMINARY INSPECTION OF CONVECTIVE INTERFACES

Identification of Convective Interfaces	Major Building Space Adjacent to Interface	Can Adjacent Space Be Accessed for Pressure Measurements (Y or N)?	Can Adjacent Space Be Completely Opened to the Exterior (Y or N)?	Is the Test Method Applicable?
(1) _____	_____	_____	_____	#####
(2) _____	_____	_____	_____	#####
(3) _____	_____	_____	_____	#####
(4) _____	_____	_____	_____	#####
(5) _____	_____	_____	_____	#####
(6) _____	_____	_____	_____	#####
(7) _____	_____	_____	_____	#####
(8) _____	_____	_____	_____	#####
(9) _____	_____	_____	_____	#####
(10) _____	_____	_____	_____	#####

Figure B-5. Preliminary Inspection Spreadsheet.

Column 3: Can Adjacent Space Be Accessed for Pressure Measurements? If you can get a probe into the major building space on the other side of an interface, enter a "Y" for yes. Otherwise, enter a "N" for no.

Column 4: Can Adjacent Space Be Completely Opened to the Exterior? Enter a "Y" for yes or a "N" for no.

Column 5: Is the Test Method Applicable? The spreadsheet determines this for you. Basically, if you answered no to either of the two questions (columns 3 and 4), the method is not applicable. If the method is not applicable, you need not perform further tests on the interface.

Setting Up the Equipment

The Blower Door. It is assumed that you are familiar with the basics of blower door installation and use. You must have the necessary equipment and tables to determine the flow through the blower door.

Some points to keep in mind are:

- Are all combustion appliances turned down or off so that they will not back-draft or otherwise be disturbed?
- Are all windows, vents, and other intentional sources of outside air closed up?
- Are all interior (bedroom, bathroom, closet, etc.) doors in the apartment to be tested open?
- Are all interior doors in the adjacent apartments open?
- Can you leave the apartment once the blower door is installed to open the adjacent apartments to the outside later in the tests? (Alternatively, you must make some other arrangements, such as working with a partner, for doing this.)

Pressure Gauges. These are used to measure the pressure differentials between the various spaces within the building.

The apartment-to-exterior pressure differential is used to establish the blower door flow. Various other pressure differentials are called for in the next set of spreadsheets.

The pressure gauge is connected to a building space (except for the blower door apartment) by way of plastic tubing. Make sure you observe the following rules:

- If you are using more than one pressure gauge, make sure that they are all calibrated against each other.
- One plastic tube must be run to the exterior, at the same distance from the ground as the blower door.
- Label all tubes before starting your tests! This will allow you to make the pressure measurements quickly and accurately.
- Keep track of which building space is connected to the "low" port on the gauge as well as which is connected to the "high" port.
- When connecting to a convective interface inside the apartment, access at least two points that are equally spaced from each other in the middle of the interface. Drill a 1/16" hole where appropriate, insert a pump needle, and connect the other end of the needle securely to a plastic tube. Connect the free ends of the plastic tubes together with T-junctions, making sure that all tubes are about the same length (within about a foot). Connect the other end of the T-junction to a single tube, which will be connected to the pressure gauge.
- When running tubes to spaces in the building outside the blower door apartment, make sure the tubes are not under foot and are securely fastened. Run the tubes to all of the "Major Building Spaces" listed in the second column of the first spreadsheet. A good place to run them outside of the blower door apartment is between the blower door and its fan.

Testing for Intervening Zones / Spreadsheet #2

A shell of the second application spreadsheet is provided in Figure B-6. The places where you enter data are shown as blank lines. The places where the computer responds to your inputs are labeled with the symbols #####.

Note that you can test up to 10 convective interfaces. Each of these might have an intervening zone behind it. The spreadsheet will automatically keep track of the interfaces where the method might apply. In fact, the spreadsheet fills in the name of the interface for you and sets up directions for measuring pressure differentials.

In the intervening zones sheet (#2), you will find that all of the interfaces to be tested go across the spreadsheet. The first interface that you will test begins all the way to the left, at the "A" column. The second one begins at the "AA" column. The third one begins at the "BA" column, and so on.

You may want to preview this arrangement. You can do this by using the left and right arrow keys. This will get you back and forth in the second application spreadsheet.

For each interface to test, there is a place to fill in the pressure differential between the apartment and the exterior, and the flow through the blower door. In the test sequence for each interface, the order of the procedures is as follows:

- (1) With the blower door off, make the pressure gauge connections listed in the first two columns, one by one. Record the measurements.
- (2) Turn on the blower door and establish a pressure differential of 50 Pa between the apartment and the exterior. Re-do the pressure measurements according to the pressure gauge connections listed in the first two columns.
- (3) Turn the blower door back off, and repeat step (1).

Go back and perform step (3) as a way to check on your measurements. If the pressure measurements in steps (1) and (3) differ by more than 5 pascals, there is something going on that you should investigate. For example, someone might have turned on mechanical ventilation in the building.

With this outline of the procedures in mind, here are the details of the second spreadsheet:

Columns 1 and 2: Low Port and High Port. The spreadsheet copies the appropriate sequences of names of interfaces and adjacent building spaces to these columns. These are the directions for setting up your pressure gauge.

MULTIFAMILY AIR LEAKAGE TESTS

APPLICATION SPREADSHEET #2

TESTING FOR INTERVENING ZONES

PRESSURE FROM BLOWER DOOR APT TO EXTERIOR: _____ Pa

FLOW THROUGH BLOWER DOOR: _____ cfm

@ Interface #		<i>BLOWER DOOR OFF</i>	<i>BLOWER DOOR ON</i>	<i>BLOWER DOOR OFF</i>	Data Quality Checks	
Connections to Pressure Gauge:		Pressure	Pressure	Pressure	With Blower Door	Without Blower Door
Low Port	High Port	Differential (Pa)	Differential (Pa)	Differential (Pa)		
blower door apt	#####	_____	_____	_____	####	####
#####	#####	_____	_____	_____	####	####
blower door apt	#####	_____	_____	_____	####	####
#####	exterior	_____	_____	_____	####	####

Does Interface #

Have a Transitional

Zone?

#####

Figure B-6. Intervening Zones Spreadsheet.

Column 3: BLOWER DOOR OFF. As the heading states, the blower door should be off. For each of the low and high port connections, record the corresponding pressure differential that you measure in this column. These are the natural pressures across the various interfaces during normal conditions of the building.

Column 4: BLOWER DOOR ON. Turn on the blower door. Record the actual pressure differential between the apartment and the exterior. Record the flow through the blower door. For each of the low and high port connections, record the corresponding pressure differential that you measure in this column.

Column 5: BLOWER DOOR OFF. Turn the blower door off again. For each of the low and high port connections, record the corresponding pressure differential that you measure in this column. This is a check on the naturally-occurring pressures across the various interfaces.

Column 6: Data Quality Checks / With Blower Door. There are spreadsheet routines that examine the numbers that you entered in Column 4. These routines will tell you if there are some obvious problems.

For example, say that the pressure differential between the apartment and the exterior is 50 Pa. The pressure differentials across any series of convective zones between the apartment and the exterior should then add up to 50 Pa. If this is not the case, the "Data Quality Checks" will inform you, and you might want to go back and re-take the suspect measurement.

Column 7: Data Quality Checks / Without Blower Door. There are spreadsheet routines that examine the numbers that you entered in columns 3 and 5. These routines will tell you if there was a significant change in baseline pressure differentials during the checking conditions.

Column 8: Does Interface # Have a Transitional Zone? The routines in the spreadsheet will fill in the name of the interface and replace the # symbol. They will also give you a yes or a no for an answer.

Estimating Leakage Air Flows / Spreadsheet #3

The shell of the third spreadsheet is shown in Figure B-7. This shell must be filled out for each convective interface that may be tested by the method.

As before, the places where you have to fill in with measurements are shown as blank lines. The places where the computer responds are marked with the ##### symbols.

Like the shells for Spreadsheet #2, the series for #3 go across the screen. You may want to preview the series.

When testing each interface and using this spreadsheet, there are two important requirements:

- Only one adjacent building space at a time is opened to the exterior
- All other adjacent building spaces are exactly as you had them when filling out spreadsheet #2.

You will notice in Figure B-7 that there are only three types of information that you have to enter:

- (1) The pressure from the blower door apartment to the exterior. THIS MUST BE THE SAME (TO WITHIN A FEW PASCALS) AS IT WAS WHEN YOU PERFORMED THE TESTS FOR SPREADSHEET #2!
- (2) The flow through the blower door (once the adjacent zone is opened to the exterior).
- (3) The pressure differentials between the blower door apartment and each interface listed in the first column. (The spreadsheet automatically fills in the first column for you.)

The pressure differentials are entered in the second column.

The third column will contain the results of the spreadsheet's data checks. There are too many checks and counter-checks to describe in detail here. The data checks will fill in "OK" if all is well and there are no discrepancies. Otherwise, specific comments will appear.

In the far right column of Figure B-7, there is a question, "Is Method Applicable?" The spreadsheet checks the numbers that you have entered and tells you either yes or no.

MULTIFAMILY AIR LEAKAGE TESTS

APPLICATION SPREADSHEET #3

ESTIMATION OF LEAKAGE AIR FLOWS

Pressure Gauge Low Port: Blower Door Apt

Zone Opened to Exterior: #####

PRESSURE FROM BLOWER DOOR APT TO EXTERIOR: _____ Pa

FLOW THROUGH BLOWER DOOR (adjacent zone opened): _____ cfm

Figure B-7. Leakage Air Flow Spreadsheet.

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Pressure Gauge High Port	Pressure Differential (Pa)	Data Quality Checks	ANALYSIS
(1) #####	_____	#####	<i>Is Method Applicable?</i> #####
(2) #####	_____	#####	
(3) #####	_____	#####	
(4) #####	_____	#####	RESULTS
(5) #####	_____	#####	Blower door apt's cfm50 is: ##### cfm
(6) #####	_____	#####	Air leakage through #####: ##### cfm
(7) #####	_____	#####	
(8) #####	_____	#####	Flow from ##### to exterior: ##### cfm
(9) #####	_____	#####	Flow from ##### to #####: ##### cfm
(10) #####	_____	#####	

If the method is applicable and leakage flows have been estimated, the results appear in the lower right corner. Otherwise, "NA" appears there, indicating that the method is not applicable.

Reviewing Results / Spreadsheet #4

The summary sheet (#4) is represented in Figure B-8. As you can see, you enter nothing here. The spreadsheet summarizes the following information for you:

- Each convective interface that you identified
- Whether or not each interface has an intervening zone behind it
- The percentage of the blower door's flow going through that interface, if the method applied.

Removing Equipment and Departing

After you have completed your air sealing job, it is time to repeat the method. You may want to repeat it several times for interfaces that are very leaky in order to check your progress.

Once you've sealed the leakage pathways to your satisfaction, be sure to take care of the following before leaving:

- Open all vents and flues that were shut during testing
- Remove all tools, materials, and other equipment, including all the plastic tubes
- Relight pilot lights and turn combustion appliances back on
- Patch your drill holes
- Clean up all debris
- Save your spreadsheet records and make back-up copies as needed
- Thank the tenants for their cooperation
- Check out with the appropriate management personnel, and be sure to return all keys.

MULTIFAMILY AIR LEAKAGE TESTS

APPLICATION SPREADSHEET #4

SUMMARY

Interface	Intervening Zone Present?	% of Blower Door Apt's Flow Through Interface
(1) #####	#####	#####
(2) #####	#####	#####
(3) #####	#####	#####
(4) #####	#####	#####
(5) #####	#####	#####
(6) #####	#####	#####
(7) #####	#####	#####
(8) #####	#####	#####
(9) #####	#####	#####
(10) #####	#####	#####

Figure B-8. Summary Spreadsheet.

A WORKED-OUT EXAMPLE

Preliminary Inspection

A two-story building has ten apartments in it--five on the first floor and five on the second. Each apartment spans the width of the building. Access to the second-story apartments is by stairway to an open-air common porch, similar to those found on two-story motel units.

You are auditing Apartment B3, which is three apartments from one end of the building, on the second floor. The tenant does not like the drafts coming from outside in the winter. Once in awhile, cooking odors come in from neighboring apartments.

Apartment B3 is bordered by two other apartments on the second story--Apartment B2 on the west side and B4 on the east side. Apartment A3 is directly below it. There are maybe a few inches of sub-roof space above B3. The north and south walls in B3 are exterior walls, and there are exterior doors in each.

Preliminary inspection shows cracks around the frames of the windows and exterior doors. There are plumbing chase ways in the bathroom and kitchen, but they seem tightly plugged with rodent barrier material. There is a large closet in the wall adjoining Apartment B4. You note that there is a similar closet in B4, and that the two closets are back-to-back.

Figure B-9 shows how you fill out spreadsheet #1 for Apartment B3. You decide to regard the ceiling as an interface to the exterior. This leaves you with interfaces to three building spaces: apartments B2, B4, and A3.

The west wall is a party wall to Apartment B2. The east wall is a party wall to Apartment B4. The floor is the interface between apartments B3 and A3.

You have complete access to all three of the other apartments, and you can open each one completely to the exterior. The test method is therefore applicable to all three of the interfaces listed in Column 1.

You set up your equipment and install the blower door in the south exterior door. This leaves you the north exterior door for getting to the neighboring apartments.

MULTIFAMILY AIR LEAKAGE TESTS
APPLICATION SPREADSHEET #1
PRELIMINARY INSPECTION OF CONVECTIVE INTERFACES

Identification of Convective Interfaces	Major Building Space Adjacent to Interface	Can Adjacent Space Be Accessed for Pressure Measurements (Y or N)?	Can Adjacent Space Be Completely Opened to the Exterior (Y or N)?	Is the Test Method Applicable?
(1) west party wall	apt B2	y	y	yes
(2) floor	apt A3	y	y	yes
(3) east party wall	apt B4	y	y	yes
(4)				
(5)				
(6)				
(7)				
(8)				
(9)				
(10)				

Figure B-9. Example of Preliminary Inspection Spreadsheet.

Testing for Intervening Zones

Figure B-10(a) is a filled-out Spreadsheet #2 for the west party wall. There are no "blower door off" pressure differentials to speak of either before you operate the blower door or after.

The apartment pressurizes 50 pascals with respect to the outside easily, and a flow of 1,850 cfm is measured. With the blower door operating, the pressure differential between B3 and the west party wall is 48 pascals, which is virtually identical to the pressure differential of 49 pascals between apartments B3 and B2. There is probably no intervening zone between apartments B3 and B2.

Figure B-10(b) is Spreadsheet #2 for the floor of Apartment B3. There are no significant "blower door off" pressure differentials. The fact that a pressure differential of 49 pascals develops between apartment B3 and its floor suggests that there is no intervening zone under the floor. The other measurements you take confirm this.

Figure B-10(c) shows the numbers entered into Spreadsheet #2 for the east party wall, adjacent to B4. The pressure differential between B3 and the east party wall is 13 pascals, but the pressure differential between B3 and B4 is 22 pascals. There is an intervening zone between B3 and B4. The other numbers go through their data checks without any problems.

Measuring Leakage Air Flows

You proceed to open Apartment B4 up to the exterior, and you proceed to use Spreadsheet #3 for the east party wall in B3. The entries into Spreadsheet #3 are shown in Figure B-11. You start the blower door, and at a 50 pascal pressure differential with respect to the outside, you get 2,100 cfm through the blower door.

You note that the flow through the blower door increased by 250 cfm after you opened B4 to the exterior. This is a significant change in the air flowing through the blower door.

You measure a pressure differential of 26 pascals now between Apartment B3 and the east party wall. This is an increase of 13 pascals over the previous condition, which is significant.

MULTIFAMILY AIR LEAKAGE TESTS

APPLICATION SPREADSHEET #2

TESTING FOR INTERVENING ZONES

PRESSURE FROM BLOWER DOOR APT TO EXTERIOR: 50 Pa

FLOW THROUGH BLOWER DOOR: 1850 cfm

@ Interface west party wall		BLOWER DOOR OFF	BLOWER DOOR ON	BLOWER DOOR OFF	Data Quality Checks	
Connections to Pressure Gauge:		Pressure Differential (Pa)	Pressure Differential (Pa)	Pressure Differential (Pa)	With Blower Door	Without Blower Door
Low Port	High Port					
blower door apt	west party wall	1	48	0	OK	OK
west party wall	apt B2	0	0	1	OK	OK
blower door apt	apt B2	2	49	2	OK	OK
apt B2	exterior	0	1	0	OK	OK

Does west party wall

Have a Transitional

Zone?

NO

Figure B-10(a). Example of Intervening Zone Spreadsheet.

To the right of Figure B-11, the spreadsheet tells you that 415 of Apartment B3's cfm_{50} of 1,850 cfm was leaking through the east party wall. Of that 415 cfm, about 116 cfm leaked to the exterior and about 299 cfm leaked to apartment B4.

SUMMARY

Figure B-12 is the summary spreadsheet, #4. The first two interfaces that you tested have no intervening zones behind them. The spreadsheet cannot determine the leakage flow through those interfaces.

The east party wall does have an intervening zone. The percentage of leakage flow through this interface is listed as 22.4%. One would suspect that a significant amount of air is exchanged between apartments B3 and B4.

The tenants in Apartment B4 say that they often cook spicy meals. This was probably the source of the cooking odors that made their way into B3.

You check the east wall carefully in B3, and you find that there are at least a hundred square inches of open gap in the wall in the closet. There are major holes in the adjoining closet in B4 as well. The smoke stick confirms that there is a lot of flow coming through the closet when the blower door is running.

You then seal the cracks around the door and window frames, and you plug up the gaps in the closet. You attend to the other air sealing details.

When you start up the blower door again, the apartment's cfm_{50} is now 975. This turns out to give barely the required number of natural air changes per occupant. You discuss the possible need for additional ventilation in that apartment with the building's owner.

Going through the spreadsheets for the second time, you only check the east party wall. The method no longer applies to the interface. Only a small amount of air leakage may still be present after you took care of the major leakage pathway. Because the new apartment cfm_{50} is only 975, you decide to stop air sealing.

Now it is time to move on to Apartment B4....

MULTIFAMILY AIR LEAKAGE TESTS

APPLICATION SPREADSHEET #2

TESTING FOR INTERVENING ZONES

PRESSURE FROM BLOWER DOOR APT TO EXTERIOR: 50 Pa

FLOW THROUGH BLOWER DOOR: 1850 cfm

Figure B-10(b).

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@ Interface floor		<i>BLOWER DOOR OFF</i>	<i>BLOWER DOOR ON</i>	<i>BLOWER DOOR OFF</i>	Data Quality Checks		
Connections to Pressure Gauge:		Pressure Differential (Pa)	Pressure Differential (Pa)	Pressure Differential (Pa)	With Blower Door	Without Blower Door	
Low Port	High Port						
blower door apt	floor	0	49	0	OK	OK	Does floor
floor	apt A3	0	1	0	OK	OK	Have a Transitional
blower door apt	apt A3	0	49	0	OK	OK	Zone?
apt A3	exterior	0	1	0	OK	OK	NO

MULTIFAMILY AIR LEAKAGE TESTS

APPLICATION SPREADSHEET #2

TESTING FOR INTERVENING ZONES

PRESSURE FROM BLOWER DOOR APT TO EXTERIOR: 50 Pa

FLOW THROUGH BLOWER DOOR: 1850 cfm

Figure B-10(c).

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@ Interface east party wall		BLOWER DOOR OFF	BLOWER DOOR ON	BLOWER DOOR OFF	Data Quality Checks	
Connections to Pressure Gauge:		Pressure	Pressure	Pressure		
Low Port	High Port	Differential (Pa)	Differential (Pa)	Differential (Pa)	With Blower Door	Without Blower Door
blower door apt	east party wall	0	13	1	OK	OK
east party wall	apt B4	1	9	0	OK	OK
blower door apt	apt B4	0	22	0	OK	OK
apt B4	exterior	1	28	1	OK	OK

Does east party wall

Have a Transitional

Zone?

YES

Figure B-11. Example of Leakage Air Flow Spreadsheet.

MULTIFAMILY AIR LEAKAGE TESTS

APPLICATION SPREADSHEET #3

ESTIMATION OF LEAKAGE AIR FLOWS

Pressure Gauge Low Port: Blower Door Apt

Zone Opened to Exterior: apt B4

PRESSURE FROM BLOWER DOOR APT TO EXTERIOR: 50 Pa

FLOW THROUGH BLOWER DOOR (adjacent zone opened): 2100 cfm

Pressure Gauge
High Port

Pressure
Differential (Pa)

Data Quality Checks

ANALYSIS

(1) west party wall

47

OK

Is Method Applicable? YES

(2) floor

50

OK

(3) east party wall

26

OK

RESULTS

(4)

Blower door apt's cfm50 is: 1850 cfm

(5)

Air leakage through east party wall: 415 cfm

(6)

(7)

Flow from east party wall to exterior: 116 cfm

(8)

Flow from east party wall to apt B4: 299 cfm

(9)

(10)

MULTIFAMILY AIR LEAKAGE TESTS

APPLICATION SPREADSHEET #4

SUMMARY

Interface	Intervening Zone Present?	% of Blower Door Apt's Flow Through Interface
(1) west party wall	NO	can't compute it
(2) floor	NO	can't compute it
(3) east party wall	YES	22.4
(4)		
(5)		
(6)		
(7)		
(8)		
(9)		
(10)		

Figure B-12. Example of Summary Spreadsheet.

AIR SEALING REFERENCES

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