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BUILDING TECHNOLOGIES PROGRAM

# Case Study of Envelope Sealing in Existing Multiunit Structures

Jordan Dentz, Francis Conlin, and David Podorson
*ARIES Collaborative*

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# Case Study of Envelope Sealing in Existing Multiunit Structures

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Office of Energy Efficiency and Renewable Energy

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Golden, CO 80401

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Prepared by:

ARIES Collaborative

The Levy Partnership, Inc., 1776 Broadway, Suite 2205

New York, NY 10019

NREL Technical Monitor: Michael Gestwick

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# Definitions

| | |
|---|---|
| $ACH_{50}$ | Air changes per hour at 50 pascals |
| BEopt | Building Energy Optimization |
| BPI | Building Performance Institute |
| CEC | California Energy Commission |
| CFA | Conditioned floor area |
| $cfm_{50}$ | Cubic foot per minute of air at 50 pascals |
| ESF | Envelope square foot |
| $ft^2$ | Square foot |
| IEQ | Indoor environmental quality |
| $in^2$ | Square inch |
| GWB | Gypsum wall board |
| MBtu | Thousand British thermal units |
| NREMD | National Residential Efficiency Measures Database |
| RECS | Residential Energy Consumption Survey |
| yr | Year |

# Executive Summary

Sealing envelope air leakage in occupied multiunit buildings is difficult and costly to implement,[1] particularly when compared to single-family detached homes. Working around tenants complicates implementation as does the more complex nature of air pathways in multiunit buildings. In addition, because of the smaller surface to volume ratio of multiunit buildings, the cost effectiveness of air sealing is presumably lower than for single-family detached homes.

The literature, however, underscores the importance of controlling air leakage in multifamily buildings. For example, a Lawrence Berkeley National Laboratory study concluded that multiunit residential buildings and commercial buildings "seem to be about twice as leaky as single-family detached homes, per unit of building envelope area," indicating that substantial energy savings might be associated with air sealing these types of buildings (California Energy Commission, 2006). The study also concluded that transport of pollutants between apartments and within mixed-use buildings has health consequences. Furthermore, sealing these buildings from outside air infiltration without reducing the internal transport of air could exacerbate indoor air quality problems.

There are a number of reasons to air seal a multiunit building, all of which further the goals of the Building America Program. Foremost among these is controlling heat loss and gain through the building envelope to save energy and improve comfort by eliminating drafts and temperature swings. Other important reasons include avoiding moisture problems that can result when uncontrolled air leaks introduce humid air into building cavities; minimizing air movement between apartments and other spaces (including crawlspaces and attics), which prevents contaminant transfer and improves indoor environmental quality; reducing air movement through insulation, which reduces its insulating benefit; and allowing the use of lower capacity heating and cooling equipment by reducing thermal loads.

The research questions addressed by this work include the following:

1. What reduction in leakage can be obtained and how much energy can be saved by production-scale air sealing in low-rise multiunit buildings?

2. What is the cost per unit of leakage reduction as measured by pressurization testing?

3. What are the most significant leakage sites and how much do they contribute to total leakage?

The research described in this report identified air leakage pathways in a low-rise, multiunit building type commonly found in mixed-humid climates. The report recommends corrective actions for cost-effectively remediating this leakage.

These research findings are based on the retrofit of a 236-unit, low-rise (two-story), wood frame, multiunit building complex in North Carolina (climate zone 4). A comprehensive program of air

[1] Multiunit buildings as used in the report include townhomes and low-rise (two-story) apartment buildings.

sealing was part of a more extensive retrofit effort. Pre- and post-retrofit enclosure leakage tests were conducted on 51 units and detailed diagnostics were performed on 16 units. On average, based on unguarded testing, total leakage was reduced by nearly half, from 19.7 $ACH_{50}$ to 9.4 $ACH_{50}$. Costs for air sealing were \$0.31/$ft^2$ of conditioned floor area, lower than estimates found in the literature. These lower costs are due, in part, to the relatively large scale of the project, allowing for the efficient use of labor. The lower costs also might suggest that the data contained in the National Residential Efficiency Measures Database are not an appropriate basis for estimating multiunit building costs.

Modeling of the North Carolina project using Building Energy Optimization software was conducted to project the resulting space conditioning energy cost savings. Using an average of 85% of the envelope air leakage going to the outside (based on guarded tests performed at the site), an annual return on investment of 8% to 33% was projected to result from the air sealing retrofit, suggesting that air sealing multiunit buildings can be cost effective even in relatively mild climates.

# 1 Introduction

Sealing envelope air leakage in existing multiunit buildings and individual apartment units is typically more difficult and costly than for single-family detached homes. For multiunit buildings, air movement between individual units, between units and the outdoors (including often dirty crawlspaces and attics), and between units and common areas, complicate the task of characterizing and sealing air leakage pathways. According to the California Energy Commission (CEC), retrofit air sealing techniques for multiunit buildings are not as well documented or developed as those for single-family construction (California Energy Commission, 2006). The ranges of construction methods (wood frame, light-gauge steel, and concrete block), styles of buildings, and construction details unique to multiunit structures contribute to greater variability in air leakage pathways.

This report identifies the most important air leakage pathways found in a two-story townhouse and apartment style development, a building type commonly found among the affordable housing stock in the mixed-humid climate. The study includes recommendations for cost-effectively identifying and correcting air leakage in these buildings.

## 1.1 Background

According to the *American Housing Survey for the United States: 2005,* there are approximately 25.8 million multifamily units in the United States. Eighteen million of these units are in buildings with fewer than 20 units and are most likely low-rise buildings (U.S. Census Bureau, 2006).

Limited information is currently available on air leakage in multiunit buildings. The CEC compiled and analyzed available data on indoor/outdoor air leakage rates and building leakiness parameters for commercial buildings and apartments in the United States and other developed countries. Data for only 78 multiunit residential buildings in North America were found. The proportion of high-rise buildings to low-rise buildings in the study was not reported. The CEC concluded that multiunit residential buildings and commercial buildings "seem to be about twice as leaky as single-family detached homes, per unit of building envelope area" (California Energy Commission, 2006). Although surface to volume ratio is lower for multiunit buildings, this nevertheless suggests the potential for substantial energy savings resulting from air sealing these building types. The CEC study observed little systematic variation in envelope leakage with construction type, activity type, height, size, or location. The study authors concluded that a more important issue, which needs further investigation, might be the transport of pollutants between units in apartment and mixed-use buildings, which may expose occupants to high levels of tobacco smoke or a mixture of commercial air contaminants including nail polish, dry-cleaning fumes, or other volatile organic compounds.

Several green programs and building standards have established airtightness targets.[2] Among these, only *LEED 2009 for Existing Buildings: Operations & Maintenance Rating System* offers

[2] In new residential construction (not specific to multifamily), ENERGY STAR® Version 3 requires a maximum infiltration level of 3 to 6 $ACH_{50}$ depending on climate (U.S. Department of Energy and U.S. Environmental Protection Agency 2011). For commercial buildings, ASHRAE 189.1 sets the upper limit of whole building leakage

guidance specifically for multifamily buildings (U.S. Green Building Council, Inc., 2008). The LEED standard requires control of environmental tobacco smoke transfer between residential units, limiting the air leakage area of each unit to 1.25 $in^2$ per 100 $ft^2$ of enclosure area (i.e., the sum of all wall, ceiling, and floor areas).

Although specific leakage locations and their severity vary greatly from building to building, the literature indicates that the following leakage areas are among the most significant in multifamily structures, and are often worthy of sealing (Brabon, undated; Hayes, 1995; Keefe, 1995; Steven Winter Associates, Inc., 2010; Oregon Department of Energy, 2008; Genge, 2009; Feustel, 1985, Lowe, 2007):

- Attic bypasses, such as through common walls, chases, dropped soffits, open core block walls, and overhangs
- Intersections of floors, walls, and ceilings, especially where structural members extend across multiple units
- Central shafts and mechanical chases/rooms between units
- Plumbing penetrations and the common wall between bathrooms of adjoining units, especially underneath bathtubs and showers, and at heating pipe penetrations
- Electrical panel, gas line, and other penetrations into the conditioned space
- Space between window/door jambs and the framing, and door latch holes through the door frame
- Cutouts in the drywall around the perimeter of fans, vents, duct shafts, air-conditioner sleeves, and medicine cabinets
- Wall and ceiling penetrations such as electrical outlets, recessed lighting, thermostats, and intercoms
- Any areas where renovations have altered the original construction.

This research documents total enclosure air leakage, estimates leakage amounts by site, and measures the improvement in airtightness and the cost of production-scale remediation in affordable, low-rise, wood frame, multiunit housing stock.

## 1.2 Importance and Risks of Air Sealing Existing Low-Rise Multiunit Buildings

Most older buildings were built with little attention to enclosure tightness. Air sealing alone can save 10% to 20% of single-family home energy use (U.S. Department of Energy, 2010) and is therefore an essential ingredient to the Building America goal of 30%–50% energy savings retrofits. Comparable data are not available for multiunit buildings. Reducing heat loss or gain from uncontrolled infiltration is the first necessary step in a retrofit, and a prerequisite for implementing other energy savings measures, such as adding insulation or upgrading equipment.

There are several reasons for air sealing in a multiunit building, including the following:

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to 0.4 cfm/$ft^2$ of envelope area tested at 75 Pa (ASHRAE, 2009), and the U.S. Army Corps of Engineers has specified 0.25 $cfm_{75}$/ envelope square foot (Zhivov, et al., 2010).

- To control heat loss and/or gain through the envelope to save energy
- To improve comfort by eliminating drafts and temperature swings
- To avoid moisture problems that can form when uncontrolled air leaks bring moisture into building cavities
- To reduce air movement through insulation, which reduces its insulating benefit
- To minimize air movement between apartments and other spaces (including crawlspaces and attics), preventing transfer of contaminants and improving indoor environmental quality (IEQ)
- To improve equipment performance.

All these reasons further Building America's goals.

Energy savings from air sealing for this project is discussed later in this report. The potential effects and related risks of air sealing with respect to moisture, IEQ, and equipment performance are discussed in the following sections.

### *1.2.1 Moisture*

Moisture problems can arise when unintended air infiltration brings moisture into building cavities. Air sealing can avert moisture problems such as the accumulation of moisture in materials that can result in material deterioration (Zhivov and Anis, 2010). Another benefit of air sealing is the potential to reduce duct loss to the outside and mitigate moisture problems in semiconditioned spaces where cooling ducts are located.

Many multiunit buildings that were not originally built with central cooling have uninsulated ducts located in floor cavities between units. These cavities can have a great deal of outside air infiltration and therefore high humidity levels much of the year. Moisture-laden air in the vicinity of the now cold ducts can result in condensation. Air sealing of the band joists and other areas that reduce air infiltration into the floor cavity reduces the risk of condensation on the ducts. Additionally, proper air sealing brings the ducts more within the conditioned space, reducing the need for remedial duct sealing in these difficult-to-access areas (Zhivov and Anis, 2010).

### *1.2.2 Indoor Air Quality*

Envelope air sealing can minimize air movement between apartments and other spaces, preventing transfer of contaminants and maintaining better IEQ. Even though interunit air leakage might not result in significant energy loss compared to leakage to the outside, it is generally recognized that preventing interunit leakage by compartmentalizing living units is desirable from an IEQ perspective. A study in Minnesota revealed that almost 50% of renters said that secondhand smoke gets into their apartment from somewhere else in the building. Of those surveyed, more than one-quarter said that smoke bothers them "a lot" or "so much I'm thinking of moving" (Center for Energy and Environment [CEE], 2004).[3]

[3] Note that management policy at the test site described in this report prohibits smoking within the buildings.

Most older multiunit buildings do not have a mechanical ventilation system; instead, unintended infiltration brings in outside air. Because it is uncontrolled, this results in an energy penalty. If significant infiltration reductions are achieved through an air sealing retrofit, the amount of infiltrating outside air could be inadequate for fresh air needs and a new fresh air ventilation system might be required. This could add to the cost of a retrofit. Furthermore, if pressure balances change, combustion safety (i.e., draft of flue gases) can be affected. This might require alterations to the equipment or combustion appliance zone to maintain adequate flue draft.

Improving IEQ by reducing air leakage between living units is important for occupant health and comfort (including preventing odor transmission). Its cost, however, cannot be recouped by energy savings because sealing between conditioned spaces does not save significant amounts of energy.

It is important to note, though, that reducing air infiltration from the outside without adding mechanical ventilation, reducing the transport of air between units, or both, risks exacerbating IEQ problems (California Energy Commission, 2006). When conducting air sealing retrofits, post-retrofit ventilation levels should be assessed for compliance with the relevant standards such as those of the Building Performance Institute (BPI). The BPI standard for single-family homes (Building Performance Institute, 2005) applies to buildings up to four units and to all townhome (single-family attached) units (Peters, 2012) such as those retrofit in this project. The Building Airflow Standard (based on ASHRAE ventilation standard 62-89) (AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS, 1989) should be calculated to determine the minimum allowable infiltration. If post-retrofit infiltration is measured at below the allowable threshold, a fresh air ventilation system should be added, if it does not already exist. If a ventilation system exists, it should be evaluated for effective operation and improved if necessary for code compliance. In all cases, if controllable indoor pollution sources are identified, these should be mitigated at the source.

### *1.2.3 Equipment Performance*

Space heating, cooling, and ventilation systems perform better when they are not contending with excessive air infiltration. Reducing air infiltration correspondingly reduces the quantity of particulate matter being brought into the building and the HVAC system. This will reduce the frequency of filter changes that are required and prevent particulate matter from fouling heat exchangers and other equipment. Overall, the HVAC system will perform better and require less maintenance.

Air sealing can also reduce a building’s heating and/or cooling load, resulting in the need for less expensive, lower capacity equipment at the time of replacement. If equipment is not being replaced when air sealing is performed, however, the lowered leakage rate can result in oversizing of the HVAC equipment. This can reduce both the efficiency of the cooling equipment and its ability to provide adequate dehumidification.

# 2 Experiment

The ARIES Collaborative partnered with Ginkgo Residential, a developer and owner of affordable low-rise apartment, townhome, and other multiunit properties across the southern United States, to improve enclosure airtightness of a recently acquired apartment complex in North Carolina (climate zone 4). The air sealing work was done as part of a general rehabilitation of the approximately 40-year-old property.

Researchers hypothesized that air sealing these units could be cost effective from an energy savings standpoint. The purpose of ARIES's involvement was to answer the following questions:

1. What is the air leakage as measured by pressurization tests for these units? What reduction in leakage can be obtained through air sealing by a low-cost contractor? And how much energy can be saved through this measure as estimated through modeling?
2. What is the cost per unit of leakage reduction as measured by pressurization testing? The literature on cost effectiveness of air sealing low-rise multiunit structures is limited. This research attempts to address this gap.
3. What are the most significant leakage sites and how much do they contribute to total leakage as measured by pressurization?

To answer these questions, 51 units in low-rise multiunit buildings were tested before and after air sealing. All units were tested for total envelope leakage in $cfm_{50}$; 16 units were subject to more involved testing to identify leakage sites and leakage to outdoors. Two typical units were modeled to estimate the annual energy savings resulting from air sealing. The short duration of the project did not permit collection of utility bills. The results of this research are only applicable to low-rise, wood frame, multiunit buildings. Applicability might be further limited because, although units were tested from 25 buildings of varying age ranges, they were all in the same development (although constructed at different times). Cost data might not be representative of all areas in the country or all market conditions.

In addition to answering these questions, this report also contains specifications and illustrations created to assist the air sealing contractors with their work.

# 3 Retrofit

The test site was in North Carolina in the mixed-humid climate (Figures 1 and 2). There are 236 apartments in 30 two-story brick and siding clad buildings constructed between 1968 and 1970. The buildings include both townhome and apartment style units, with some being built on slabs and others over crawlspaces. Figure 3 shows the floor plans. The average unit floor area is approximately 1,400 $ft^2$.

**Figure 1. Townhome units**

**Figure 2. Apartment units**

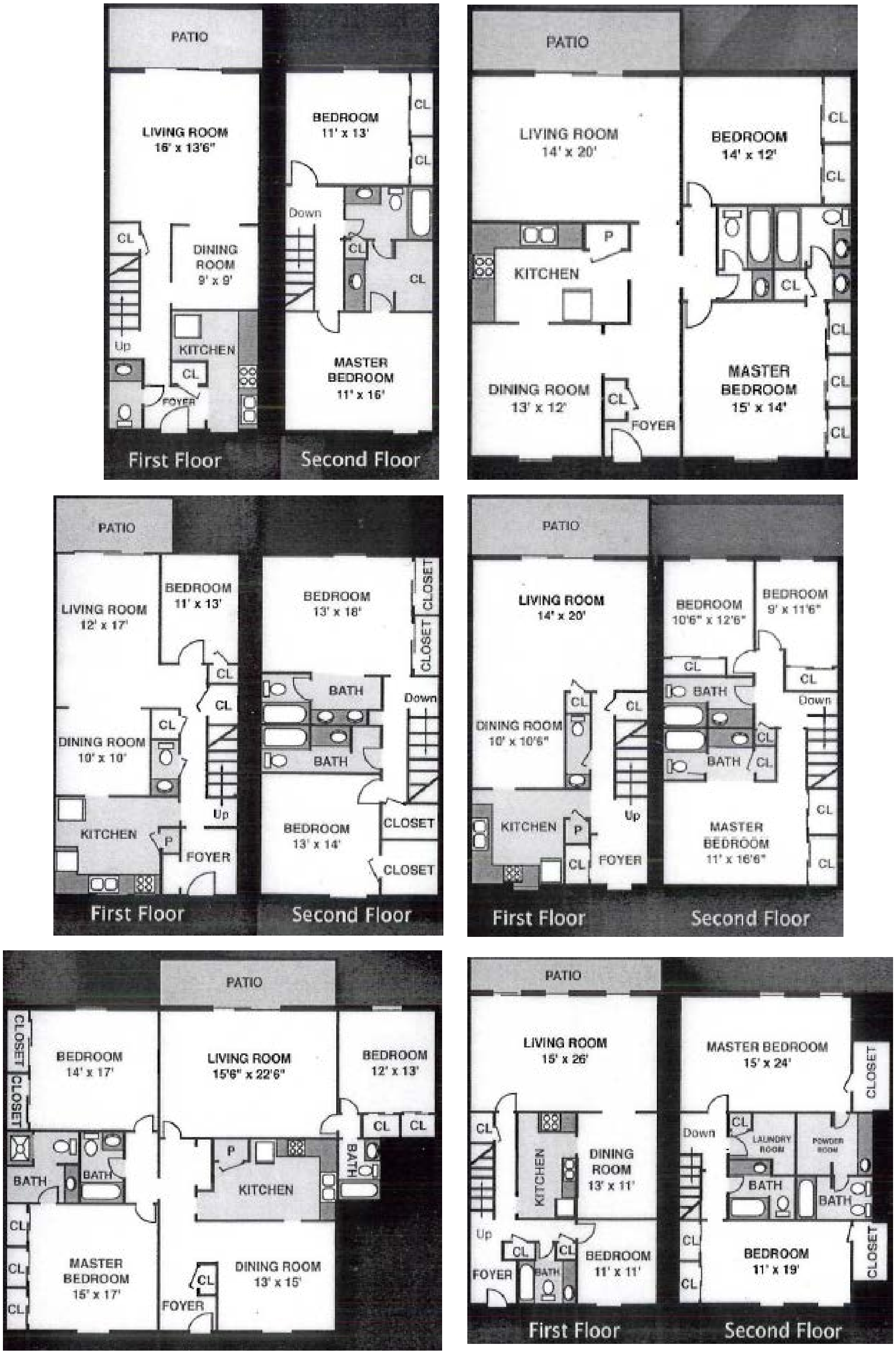


**Figure 3. Floor plans**

The apartments are typical of low-rise affordable multifamily housing stock throughout the Southeast and lower Midwest region. According to the Residential Energy Consumption Survey (RECS) database, there are more than nine million low-rise multifamily living units in RECS climate zones 2, 3 and 4 (Figure 4; U.S. Energy Information Administration, 2009).

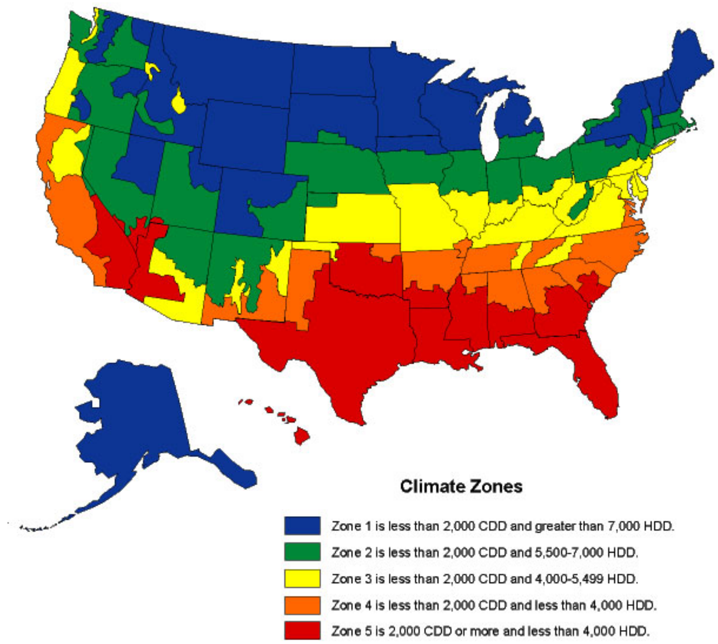


**Figure 4. Climate zone map used by RECS database**
***(U.S. Energy Information Administration, 2009)***

Ginkgo Residential retained a contractor to perform air sealing in all units in compliance with the specification and instructions developed by ARIES (see Appendix A and B). Work progressed as units became available during occupancy changes. Work was not performed on occupied units. Units were sealed from the inside without opening walls or moving cabinets; townhome style and second-floor apartment style units were also sealed from the attic. Crews used canned spray foam and caulk. For larger openings, sheet goods such as wall board were used in combination with caulk and foam. Ginkgo's goal was to reduce leakage by approximately 50%, a level of airtightness that would not require the addition of new fresh air ventilation. Blower-door guided air sealing was employed. A blower door was set up and running during air sealing to assist crews in identifying leaks and to measure the ongoing reduction in air leakage.

The following photographs (Figure 5 through Figure 26) illustrate common leakage sites that were found and sealed during the work.

**Figure 5. Before: Disconnected duct boot behind floor register**

**Figure 6. After: Boots sealed to subfloor**

**Figure 7. Before: Openings in walls above dropped ceiling in kitchen**

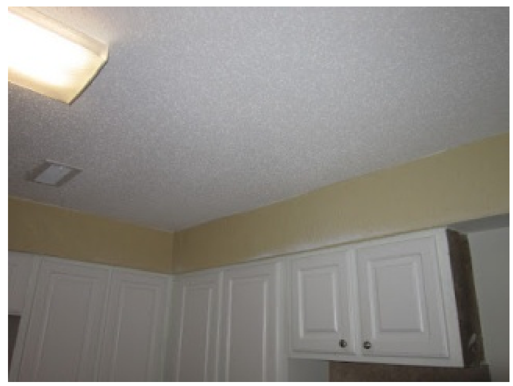

**Figure 8. After: New gypsum board ceiling in kitchen isolates wall penetrations from living space**

**Figure 9. Before: Opening in wall above dropped ceiling**

**Figure 10. After: Sealed wall above dropped ceiling**

**Figure 11. Before: Poorly patched plumbing opening in wall above dropped ceiling**

**Figure 12. After: Opening in wall above dropped ceiling patched and sealed**

**Figure 13. Before: Gaps around window sill resulting from poor installation of windows**

**Figure 14. After: Window sill sealed to wall with caulk**

**Figure 15. Before: Old windows not closing tightly**

**Figure 16. After: New tightly closing windows**

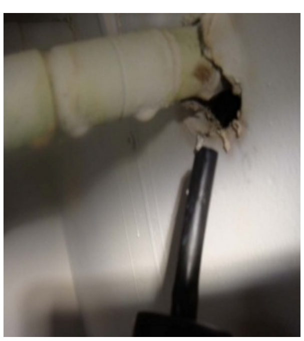

**Figure 17. Before: Opening in wall around pipe being tested with smoke stick reveals air pathway**

**Figure 18. After: Plumbing penetrations sealed around pipes and behind escutcheons with foam and caulk**

Figure 19. Before: Openings around water heater pipe penetrations

Figure 20. After: Water heater pipe penetrations sealed with foam

Figure 21. After: Outlet sealed to wallboard around perimeter

Figure 22. After: New door sweep and sill sealed to brick

Figure 23. After: Dryer exhaust duct sealed to wall with caulk

Figure 24. After: Gap around supply duct sealed with foam

**Figure 25. After: Crack under wall in mechanical space sealed to floor with foam**

**Figure 26. After: Crack at bottom of door jamb sealed to floor with caulk**

# 4 Results

The following four types of testing were conducted to evaluate the condition of the existing units and effects of the air sealing retrofit:

1. Total unit enclosure leakage
2. Temporary air sealing tests
3. Pressure mapping
4. Guarded envelope leakage.

A description, the purpose, and the results of each test type follow.

## 4.1 Total Unit Enclosure Leakage

Total enclosure leakage was measured for all units as they were retrofit. Table 1 shows overall average post-air sealing leakage reduction. The complete test results for 51 living units are included in Appendix C: Unguarded Envelope Testing Results

**Table 1. Average Total Envelope Leakage and Reduction From Retrofit**

| Unit | Pre-Retrofit Average | Average Reduction | Average % Leakage Reduction[a] |
|---|---|---|---|
| cfm/Conditioned Floor Area (CFA) | 2.6 | 1.4 | –50% |
| $ACH_{50}$ | 19.8 | 10.4 | –50% |

[a] Average improvement of each of the 51 cases. Note that this differs from the average reduction divided by the pre-retrofit average.

## 4.2 Temporary Air Sealing Tests

One goal of the project was to determine which leakage locations contributed the most to total unit air leakage. During blower door testing, leakage sites were successively sealed using tape and the resulting change in air leakage was recorded. Table 2 gives the results. Consistent sources of envelope leakage included duct leaks, penetrations in kitchens (primarily soffits and dropped ceilings), and windows (windows had recently been replaced but were improperly sealed between the frame and rough opening).

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**Table 2. Temporary Air Sealing Results**

| Building | Unit | CFA ($ft^2$) | Base Leakage (ACH50) | Base Leakage (cfm) | Reduction in Leakage (% of Base) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Ducts | Kitchen | Bath | Windows | Outlets | Plumbing | Other | Total |
| **2030** | 8 | 1,500 | 52.7 | 10536 | | 76[a] | 7 | 0.2 | 0.4 | | | 84 |
| **2030** | 10 | 2,200 | 9.5 | 2798 | 20[b] | 3 | | | | 3 | 1[c] | 27 |
| **2117** | 16 | 1,700 | 15.5 | 3515 | 19 | 32 | | 3 | 6 | | | 60 |
| **2117** | 2 | 1,200 | 10.5 | 1674 | 17 | | | 14 | 3 | 1 | 2[d] | 37 |
| **2117** | 3 | 1,200 | 12.7 | 2039 | 12 | | | 10 | 10 | 0.2 | 5[e] | 37 |
| **2309** | 16 | 1,500 | 27.5 | 5492 | 1[f] | 0.5[g] | 65[h] | 5 | | | | 72 |
| **2330** | 7 | 2,000 | 15.8 | 4201 | 8 | 33[a] | | 11 | 3 | | | 55 |
| **Average (%)** | | | | | 13 | 29 | 36 | 7 | 4 | 1 | 3 | 53 |

[a] The large leakage reduction in 2030 unit 8 and 2330 unit 7 when the kitchen was sealed off was caused by the fact that the space above the dropped ceiling in the kitchen was completely open to the wall cavity.
[b] Including mechanical closet
[c] Electrical penetrations
[d] Access panel
[e] Hatch to plumbing
[f] Return only
[g] Penetrations only
[h] The large leakage reduction in the bathroom of 2309 unit 16 results from large voids in the bathroom wall.

## 4.3 Pressure Mapping

During pressurization testing of four units, the pressure with reference to outdoors was measured in selected building cavities to assess the degree to which those cavities were connected to the outside via air pathways. Table 3 gives the results of this pressure mapping. The Average Ratio Connected to Outside column indicates the degree to which the location is outside of the pressure boundary of the unit. A ratio of 100% indicates that the location is completely outside the pressure boundary, and a ratio of 0% indicates that it is completely inside. For example, if a wall cavity measures –20 Pa with respect to outside while the unit is being depressurized to –50 Pa with respect to outside, that wall cavity would be considered 60% connected to outside (((–20) – (–50)) / (–50) = 0.60). Appendix D contains the complete pressure mapping data.

Pressure mapping was used to characterize leakage pathways. It also indicated that much of the leakage from the units was to the outside, which was consistent with the guarded testing results described next. Most interstitial spaces (common walls and ceilings) were far more connected to outside the apartments than to inside. This also has important implications for duct leakage when the ducts are in these spaces. Leakage from these ducts will be mostly to the outside.

**Table 3. Average of Pressure Mapping Results (Number of Locations Investigated)**

| | Location (number of cases) | Average Ratio Connected to Outside (%) |
|---|---|---|
| Intended Interior Space | Interior living area | 0 |
| | Common wall cavity (6) | 75 |
| | Exterior wall cavity (6) | 61 |
| | Interior wall cavity (2) | 52 |
| | Ceiling cavity between floors (1) | 70 |
| | Kitchen chase (1) | 55 |
| | Kitchen soffit (1) | 88 |
| | Ducts (4) | 69 |
| Intended Exterior Space | Dropped ceilings (3) | 73 |
| | Crawlspace (1) | 55 |
| | Attic (4) | 73 |

## 4.4 Guarded Envelope Leakage

Table 4 summarizes the results of guarded testing of six units. A guarded test is conducted by depressurizing (or pressurizing) adjacent living units to the same pressure, thereby eliminating any driving force and leakage between the two (or more) adjacent units. Guarded tests can be used to determine the portion of air leakage that goes to conditioned versus unconditioned spaces.

Because the dwellings were occupied, guarded testing was only conducted where access to neighboring units was available. In all but one case, only one unit neighboring the subject unit was accessible. As a result, the tests were partially guarded, meaning that leakage between units was cancelled out on only one side. The total leakage to outside was estimated by multiplying the leakage reduction achieved by guarding (as compared to an unguarded test) by the ratio of the total wall area to the guarded wall area.

For example, in a townhome unit with 1,200-$ft^2$ wall area that was guarded to one side comprising 400 $ft^2$ of wall area, the leakage reduction would be multiplied by 1,200/400, or 3. If the unguarded test resulted in 2,000 $cfm_{50}$ leakage and the guarded test resulted in 1,900 $cfm_{50}$ leakage, the 100 $cfm_{50}$ reduction would be multiplied by three and then deducted from the unguarded test result, yielding an estimated 1,700 $cfm_{50}$ leakage to the outside. Note that this method only yields a gross estimate and does not consider differences in wall construction. It is used here only to obtain a general idea of the level of leakage to outside and for modeling inputs.

The low leakage reductions seen in the guarded tests are consistent with the pressure mapping results, which suggested that building cavities are well connected to outdoors. Taken together they suggest that, at least under test conditions, air infiltrating through common walls and ceilings is more likely being drawn from the outside than from an adjacent unit. The average leakage to outside of the six guarded tests was 85% of total leakage when adjusted as described previously.

**Table 4. Guarded Test Results**

| Building | Unit | Pre- or Post-Test | Adiabatic sides | Guarded sides | Type | Unguarded Leakage ($cfm_{50}$) | Guarded Leakage ($cfm_{50}$) | Leakage Reduction ($cfm_{50}$) | Guarded Area ($ft^2$) | Total Leakage Area to Inside ($ft^2$) | Total Leakage Area to Outside ($ft^2$) | Interpolated total leakage to conditioned space ($cfm_{50}$) | Estimated leakage to outside as percentage of unguarded |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1800** | 15 | Pre | 2 | 1 | Twn | 2,412 | 2,339 | 73 | 675 | 1,710 | 1,860 | 185 | 92 |
| **2030** | 6 | Pre | 3 | 1 | Apt | 2,685 | 2,528 | 157 | 356 | 2,211 | 2,184 | 976 | 64 |
| **2132** | 23 | Pre | 1 | 1 | Twn | 2,302 | 2,224 | 78 | 774 | 1,800 | 1,452 | 181 | 92 |
| **1800** | 12 | Post | 2 | 2 | Twn | 1,782 | 1,720 | 62 | 1350 | 1,710 | 1,860 | 79 | 96 |
| **1800** | 17 | Post | 1 | 1 | Twn | 1,394 | 1,091 | 303 | 675 | 1,035 | 1,785 | 465 | 67 |
| **2030** | 6 | Post | 3 | 1 | Apt | 1,546 | 1,546 | 0 | 356 | 2,211 | 2,184 | 0 | 100 |
| **Average** | | | | | | 2,020 | 1,908 | 112 | 698 | 1,780 | 1,888 | 314 | 85 |

## 4.5 Leakage Locations

Based on inspections and the testing, the major areas of envelope leakage were found to be (in approximate sequence from most to least significant): plumbing and electrical penetrations, soffits/dropped ceilings, ducts, windows, and floor–wall intersections.

- **Plumbing and electrical penetrations**. Original plumbing, electrical and appliance installation, and subsequent repair work were completed without an air sealing protocol in effect. Little attention was paid to sealing gaps between plumbing and electrical penetrations and the air barrier material. At some locations, sections of the air barrier material—interior gypsum wallboard (GWB) in this case—were completely removed to allow repair access and were not replaced after the repairs were completed. Unsealed penetrations of this type were most commonly found in HVAC closets, above dropped ceilings, under/inside cabinets, and behind appliances, but were also present in the living space.
- **Soffits/dropped ceilings**. Dropped ceilings were found to conceal a variety of air barrier deficiencies. The air barrier material above the dropped ceiling was not air sealed at material intersections, permitting air leakage between the living space and the vented attic. Plumbing and electrical penetrations hidden by the dropped ceiling were not air

sealed. Often, large sections of the air barrier material were removed to permit repair access and were not replaced or sealed after repairs were completed. For the dropped ceiling condition in top-floor locations, the missing sections of air barrier material resulted in direct (visible) connectedness to the vented attic and strong connection to the outdoors. Blower door testing while temporarily sealing the kitchen from the rest of the apartment with adhesive films illustrated profound air leakage into these areas.

- **Ductwork**. Duct leakage to the outside was substantial because of improper installation, deterioration over time, or other causes.[4] According to property management, leakage was great enough to significantly increase utility bills and decrease occupant comfort. Missing or deteriorated duct boots resulted in exchange of air between the living area and the crawlspaces and attic where air quality is relatively poor. Duct leakage within wall cavities sometimes resulted in moisture signatures inside the living space where cool, uninsulated ducts and contact with outside air resulted in condensation and water staining. Accessible ducts were replaced before the air sealing retrofit. Information on mitigating duct leakage can be found in *Measure Guideline: Sealing and Insulating Ducts in Existing Homes* (Aldrich & Puttagunta, 2011).
- **Windows**. The original windows had reached the end of their serviceable life. Closing/sliding/locking mechanisms, weather stripping, and the panes themselves had broken or deteriorated over time to such an extent that gaps of 1 in. or greater were common. The deteriorated state of the windows increased heating/cooling costs, negatively affected occupant comfort, allowed pest infiltration, and posed a potential security problem. Windows were replaced shortly before air sealing work began.
- **Floor-to-wall intersections**. During original construction, bottom plates were not sealed or gasketed to subflooring, resulting in greater than expected air leakage into wall cavities at the floor-to-wall intersections. GWB interior walls generally do not completely reach the subflooring material. The gap created by the installation of the GWB, combined with the lack of bottom plate sealing, resulted in voids that permitted air leakage into the unconditioned space of the wall cavities.

[4] Duct testing by ARIES confirmed high levels of leakage.

# 5 Modeled Energy Savings

To quantify the energy cost savings resulting from the air sealing, pre- and post-retrofit conditions were modeled using Building Energy Optimization (BEopt) software. Separate models were created for a typical apartment and a typical townhome unit. The models project the energy and cost savings for three climate locations using the average pre- and post-retrofit air leakage results found in the field. Locations in the mixed-humid and the cold climate were selected because of the prevalence of these building types in those climates.

Two adjustments were made to the BEopt models to simulate dwellings in multiunit buildings. First, demising walls, floors, and ceilings were modeled as windowless and with an R-value of 100 to replicate the adiabatic condition. Because walls cannot be modeled individually, the total UA value of the dwelling was calculated using R-100 for the demising walls and common ceilings/floors, and the actual insulation level for the outer walls.[5] This value was then averaged per square foot of wall area for entry into BEopt. Secondly, air infiltration levels were multiplied by the 85% leakage to outside ratio calculated from the guarded tests to account only for the leakage to the outside. (Air leakage between conditioned spaces does not affect total energy consumption of the building). Table 5 shows the air leakage values used for modeling. Although the apartments have newly installed heat pumps (heating seasonal performance factor 8.6, seasonal energy efficiency ratio 14), the savings are shown for both heat pumps and electric furnaces with central air conditioning (seasonal energy efficiency ratio 14).

**Table 5. Leakage to Outside and Percentage Reduction From Retrofit**

| Unit | Pre-Retrofit Average | Average Reduction | Average % Leakage Reduction |
|---|---|---|---|
| cfm/CFA | 2.2 | 1.2 | 50 |
| $ACH_{50}$ | 16.7 | 8.7 | 50 |

Table 6 presents the modeled savings of the air sealing retrofits using the reductions in leakage from Table 5. Table 7 presents the savings in modeled total home energy consumption in percentage terms.

**Table 6. Average Modeled Savings per Unit**

| Location | Townhome | | | | Apartment | | | |
|---|---|---|---|---|---|---|---|---|
| | Heat Pump | | Electric Furnace | | Heat Pump | | Electric Furnace | |
| | MBtu/yr | $/yr | MBtu/yr | $/yr | MBtu/yr | $/yr | MBtu/yr | $/yr |
| Durham, NC | 7.9 | 60.53 | 20.2 | 154.70 | 5.0 | 38.67 | 10.0 | 76.56 |
| Cincinnati, OH | 14.6 | 116.77 | 31.0 | 247.95 | 10.2 | 81.52 | 16.6 | 132.74 |
| Indianapolis, IN | 28.9 | 203.63 | 48.6 | 342.87 | 21.2 | 149.77 | 30.9 | 218.14 |

[5] This method was recommended by BEopt developers at the National Renewable Energy Laboratory..

**Table 7. Percentage Energy Savings**

| Location | Townhome | | | | Apartment | | | |
|---|---|---|---|---|---|---|---|---|
| | Heat Pump | | Electric Furnace | | Heat Pump | | Electric Furnace | |
| | % total | % space conditioning | % total | % space conditioning | % total | % space conditioning | % total | % space conditioning. |
| Durham, NC | 5 | 17 | 9 | 21 | 3 | 15 | 5 | 16 |
| Cincinnati, OH | 7 | 19 | 11 | 21 | 6 | 19 | 7 | 18 |
| Indianapolis, IN | 12 | 25 | 15 | 25 | 10 | 25 | 12 | 23 |

# 6 Cost Effectiveness

Enclosure air sealing activities can be judged on cost effectiveness based on space conditioning energy saved; however, this does not factor in two other major air sealing benefits—moisture control and IEQ. A literature search for cost effectiveness of air sealing in multiunit buildings revealed limited results. Studies of retrofits in other building types, though, indicate that air sealing can often be cost effective in older buildings. The following sources provide cost estimates for air sealing and are summarized in Table 8.

The National Residential Efficiency Measures Database (NREMD) is a publicly available, centralized resource of residential building retrofit measures and costs for the U.S. building industry.[6] The database is intended to help users determine the most cost-effective retrofit measures for improving energy efficiency of existing homes. It is accessible to software programs that evaluate the cost effectiveness of retrofit measures to improve the energy efficiency of residential buildings, as well as to home performance contractors and manufacturers of residential materials and equipment. NREMD contains cost data for residential air sealing retrofits estimated in dollars per square foot of CFA at a range of specified leakage reduction levels (U.S. Department of Energy and National Renewable Energy Laboratory, 2011). Leakage is assumed to be to the outside because of the presumed single-family detached focus of the database. BEopt uses building envelope leakage reduction estimates and costs derived from the NREMD (National Renewable Energy Laboratory, 2011).

CEE conducted research on tobacco smoke transfer in six multifamily buildings in Minnesota in an effort to quantify air sealing measures to reduce contaminant transfer between units. Five of the buildings were 4 stories or shorter; one was 11 stories. The results showed a post-retrofit median leakage reduction of 139 $cfm_{50}$—or 18% of the total air leakage of the unit—at an average cost of $0.046/ft$^2$ of CFA per 1% reduction in air leakage (CEE, 2004). This is on the high end of the NREMD estimates. Because this effort was focused on controlling air transfer between units (i.e., total leakage), it cannot be judged solely by energy costs saved.

Table 8 compares the cost estimates from the cited literature to the results of the retrofit, based on the air sealing contract amount and the total floor area of the retrofit project. The actual costs incurred were significantly lower than those cited by the sources mentioned. Based on an average of 1,400-ft$^2$ floor area, typical per-apartment costs for air sealing alone were $441.

Reasons for the lower costs might include the production nature of the work (large volume, repetitive); the competitive bid process used by the owner; the rough condition of the units at the time of retrofit (yielding “lower hanging fruit”); and the slow construction market conditions during the project. Note that the air sealing contractor was also retained to conduct other work including insulation, which might have helped the owner obtain a lower price than if the contract was for air sealing alone. In addition, the work was conducted on vacant units as part of a large rehabilitation of the property. Air sealing occupied units as a stand-alone measure would likely cost more.

[6] Although not explicitly stated in public documentation, it is presumed that the NREMD data are derived from single-family home measures.

**Table 8. Cost per Square Foot of CFA per Leakage Reduction**

| Source | Leakage Reduction Total (%) | Leakage Reduction to Outside (%) | Cost in $/CFA |
|---|---|---|---|
| NREMD | 25 | 25 | 0.23–0.6 |
| | 40 | 40 | 0.4–2.2 |
| | 50 | 50 | 0.51–3.80 |
| | 60 | 60 | 1.1–4.7 |
| CEE | 18 | – | 0.828 |
| BEopt | 22 | 22 | 0.36 |
| | 29 | 29 | 0.63 |
| | 45 | 45 | 1.61 |
| | 49 | 49 | 2.30 |
| | 60 | 60 | 2.90 |
| Test Site Average | 50% | 50% (estimated) | 0.31 |

A study of nonresidential buildings in northern climates indicated that a 40% to 70% reduction in infiltration commonly yields a 15% to 25% reduction in heating costs, or a 9% to 15% reduction in overall energy expenditure, with a payback period of less than 2 years (Kokko, 2010). Modeling of the estimated 50% leakage to outside reduction at the test site yields a 15% to 25% reduction in space conditioning costs, or a 3% to 15% reduction in overall energy expenditure, with a payback period of 1.4–12.2 years, depending on climate location. Table 9 shows the return on investment based on the modeled savings. These savings and returns are for envelope air sealing alone and do not include savings resulting from other measures implemented at the test site.

**Table 9. Return on Investment**

| Location | Townhome | | Apartment | |
|---|---|---|---|---|
| | Heat Pump (%) | Electric Furnace (%) | Heat Pump (%) | Electric Furnace (%) |
| Durham, NC | 13 | 33 | 8 | 16 |
| Cincinnati, OH | 25 | 53 | 17 | 28 |
| Indianapolis, IN | 43 | 73 | 32 | 46 |

# 7 Conclusion

The approximately 40-year old low-rise multiunit affordable rental buildings studied in this project were found to have very leaky enclosures. The vast majority of the leakage was to the outside. Major leakage locations found were plumbing and electrical penetrations, dropped ceilings/soffits, windows, and floor-to-wall intersections. Previous repair locations were also a major source of leakage. Air sealing costs per unit of air leakage reduction were lower than typically cited in the literature, possibly because of the repetitive, production-scale nature of the project as compared to smaller, on–off jobs. Reductions in air leakage of greater than 50% were consistently obtained without highly invasive measures, in part because of the poor existing conditions.

The low air sealing costs contributed to an attractive return on investment in the North Carolina climate and would be even more attractive in colder climates based on the results of modeling in BEopt.

Specific recommendations for others embarking on similar projects include the following:

- When contracting for air sealing work it is important to establish requirements with a set of written specifications that align with leakage reduction goals. Detailed guidelines including graphics can also improve results by setting expectations.
- During the project an owner's representative should inspect air sealing contractor work to ensure neat and clean installation.
- Testing is important to ensure that leakage reduction goals are met. Ginkgo insisted on 100% testing by the contractor. If a third party is used, a random sampling approach could also be effective.
- Doing air sealing in conjunction with other retrofit work can reduce costs. Work should be sequenced, however, to reduce the likelihood that following contractors will undo air sealing measures by disturbing foam seals or other repairs to perform their own work.
- Duct leakage is also an important contributor to enclosure leakage, but is not typically addressed by air sealing work. Depending on duct materials and accessibility, it might be cost effective to repair ducts during accession of the attics for ceiling air sealing.
- Finally, when general repairs/upgrades are made to a building, contracts should include specifications for restoring the air barrier. Inspections should verify these, particularly in concealed locations such as air handler enclosures and behind dropped ceilings.

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# Appendix A: Specifications

GENERAL

1.1 SUMMARY

A. This specification includes the following:

1. Air sealing techniques, priorities and products specific to the air sealing project.

B. Related Sections

1. NOT USED

1.2 DEFINITIONS

A. Air Barrier: An element or assembly which controls air movement into and out of a structure

1.3 PERFORMANCE REQUIREMENTS

A. Air Sealing Assemblies shall be capable of accommodating substrate movement, joints and intersections, construction material, and other transitions without deterioration or air leakage exceeding specified limits.

1.4 ACTION SUBMITTALS

A. Product Data: Include manufacturer's written instructions for evaluating, preparing, and treating substrate, technical data, and tested physical and performance properties of air barrier.

B. Shop Drawings: Include details for substrate joints and cracks, penetrations, voids, and attic assemblies.

1.5 INFORMATIONAL SUBMITTALS

A. NOT USED

1.6 QUALITY ASSURACE

A. Applicator Qualifications: Installer is to be experienced in applying air barrier materials similar in material, design, and extent to those indicated for this Project, whose work has resulted in applications with a record of successful performance.

B. Blower-Door Testing: Identify location of Air Barrier material throughout the unit to be sealed. Test all units for leakage to outside before beginning any air sealing strategy. Pressurize to 50 Pa and record leakage, or extrapolate to leakage at CFM50. After completing air sealing tasks, provide follow-up blower door test to assure that owner's reduction requirement has been met.

C. Pre Installation Conferences: Review air sealing requirements including surface preparation, substrates, curing/drying periods, installation procedures, repairs and protection. Coordinate air sealing strategies and sequencing with HVAC contractor to ensure that no work is duplicated or neglected.

1.7 DELIVERY, STORAGE, AND HANDLING

A. Store materials in their original undamaged packages in a clean, dry, protected location and within temperature range required by product manufacturer.

B. Remove and replace liquid materials that cannot be applied within their stated shelf life. Protect stored materials from sunlight.

1.8 PROJECT CONDITIONS

A. Environmental Limitations: Apply air sealing materials within the range of ambient temperatures recommended by the product manufacturer.

PRODUCTS

1.9 RIGID AIR BARRIER MATERIALS

A. Gypsum Wall Board (GWB)

B. Oriented Strand Board (OSB)

C. Rigid Faced Insulation Board

1.10 POLYURETHANE SPRAY FOAM

A. Single-part Spray Foam (Expanding and non-expanding)

B. Two-part Spray Foam

1.11 CAULKS AND JOINT SEALANTS

A. Silicone or polyurethane caulk

B. Latex, expanding foam

1.12 FLUID APPLIED AIR BARRIERS

A. Liquid Air Barrier Membranes and Mastics

1.13 AUXILARY MATERIALS

A. General: Employ auxiliary materials recommended by manufacturer for intended use and compatible with substrates and membranes.

B. Transition reinforcing strips: Glass fiber mesh tapes approved by Air Barrier Manufacturer at voids with spans greater than ¼”.

C. Backer Rod: Compressible foam backer rod to be installed before applying sealants and mastics at areas with cracks larger than ¼”.

D. Mechanical Fasters: Provide wood or gypsum board screws as needed of length necessary to securely fasten rigid air barrier materials to structure.

E. Weatherstripping: Provide flexible weatherstripping around doors and attic accesses to reduce air infiltration

EXECUTION

1.14 EXAMINATION

A. Examine substrates areas and conditions, with installer present, for compliance with requirements and other conditions affecting performance.

   1. Verify that substrates are sound and free of oil, grease, dirt, excess mortar and other contaminants.

1.15 SURFACE PREPARATION

A. Provide clean, dust-free, and dry substrate for air barrier application.

B. Mask off adjoining surfaces to be covered by air barrier to prevent spillage and overspray in the visible living area.

C. At changes in substrate plane, apply sealant or mastic at sharp corners and edges to form a smooth transition from one place to another

D. Where rigid materials are to be fastened, provide clean adjacent edges to create a flush or near flush (within ¼”) transition between existing and new rigid materials. Cut away jagged edges to create a regular surface before inserting patches. Ensure that structural base for rigid air barrier material will adequately support the material to be fastened. Cut patches to dimensions to minimize unnecessary use of backer rod, tapes, and strips.

1.16 PRIORITY

A. General: Air Sealing tasks are to be prioritized to maximize results over time. Seal largest areas of compromised air barrier first, and then work toward locations with smaller air leaks.

B. Primary Areas

   1. Missing Sheathing: Install/repair air barrier above dropped ceilings in kitchens. Provide and install rigid air barriers and sealing products to complete airtight assembly above dropped ceiling. Prepare surfaces to receive rigid air barrier panels, patches, and plugs. Mechanically fasten OSB or GWB to structure and seal all joints and intersections with joint sealants or fluid applied membranes. Seal existing and newly installed rigid air barriers to make a complete air barrier.
   2. Plumbing, Electrical, Mechanical penetrations: Seal and make airtight all penetrations through the air barrier, including (not limited to): Plumbing penetrations around pipes, drains and vents; Mechanical penetrations around supply ducts, returns, and exhaust fans; Electrical penetrations surrounding outlets, conduits and wiring. For air leaks around penetrations which are greater than ¼”, rigid plugs or mesh transition reinforcement strips should be used to bridge gaps and allow for full sealing of penetrations.
   3. HVAC Closets: Completely seal perimeter and voids in HVAC closets with caulk to ensure that no air leaks between outside and mechanically depressurized closets.

4. Other voids: Air seal all other voids present in vertical and horizontal air barrier assemblies using appropriate products to complete an air tight boundary.

C. Secondary Leakage Areas

1. Attic access: Provide and install perimeter weatherstripping to reduce air infiltration around attic hatch.
2. Ceiling-to-wall and floor-to-wall: Provide and install air sealing materials to create an airtight boundary between the floor and ceiling surfaces and the vertical walls.
3. Exterior Doors: Provide and install flexible weatherstripping to ensure a tight seal around all exterior doors. Ensure that exterior doors fit snugly in their openings and adjust placement to maintain air tightness on all sides.
4. Windows: Apply sealants and necessary backers to ensure that window installation forms a tight air barrier. Be sure that sealant connects window to wall air barrier. Windows generally have a primary exterior weather barrier that often does not serve as an air barrier Electrical Fixtures: Apply sealant to all fixtures which penetrate the air barrier, or completely remove fixture and repair air barrier.

1.17 FIELD QUALITY CONTROL

A. Testing Agency: Owner may engage a qualified testing agency to perform random inspections and air leakage testing, and prepare reports detailing the findings.

B. Inspection: Installation and products are subject to inspection for compliance with the owner’s and manufacturer’s requirements. Inspections may include:

1. Continuity of repairs has been achieved with no voids, gaps, or holes unsealed.
2. Laps in transitions have been layered in the correct direction, or mastic has been applied to exposed edges.
3. Sealants and strips have been firmly adhered or fastened to the substrate material
4. Compatibility of materials.
5. All penetrations have been sealed.

C. Testing: Provide evidence of reduced air leakage using blower door testing and smoke visualization inspection.

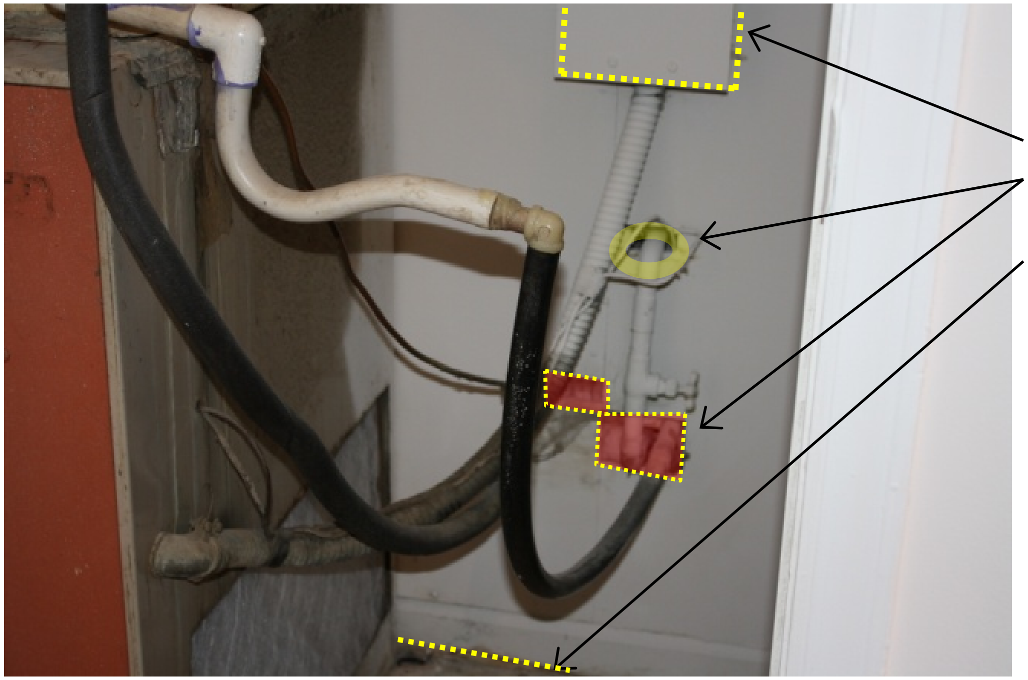
D. Remove and replace deficient air sealing components and retest.

1.18 CLEANING AND PROTECTION

A. Clean spills, stains, and soiling from construction that would be exposed in the completed work using cleaning agents and procedures recommended by the manufacturer of the affected construction.

B. Remove masking materials after installation.

## Appendix B: Air Sealing Instructions

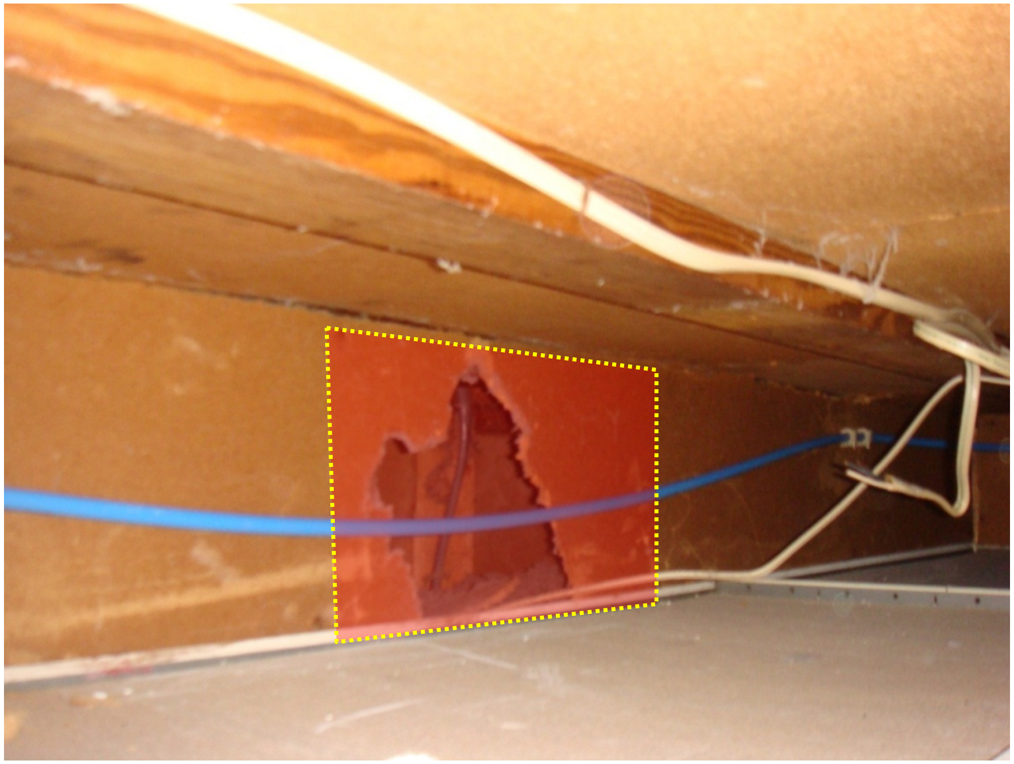


**Typical electrical and mechanical piping penetration in HVAC return closet**

1. Seal electrical boxes to wallboard with foam or caulk.
2. Make piping penetrations airtight, using sealants, foam, and plugs.
3. Seal all transitions in HVAC return closet between floor and wall and ceiling and wall

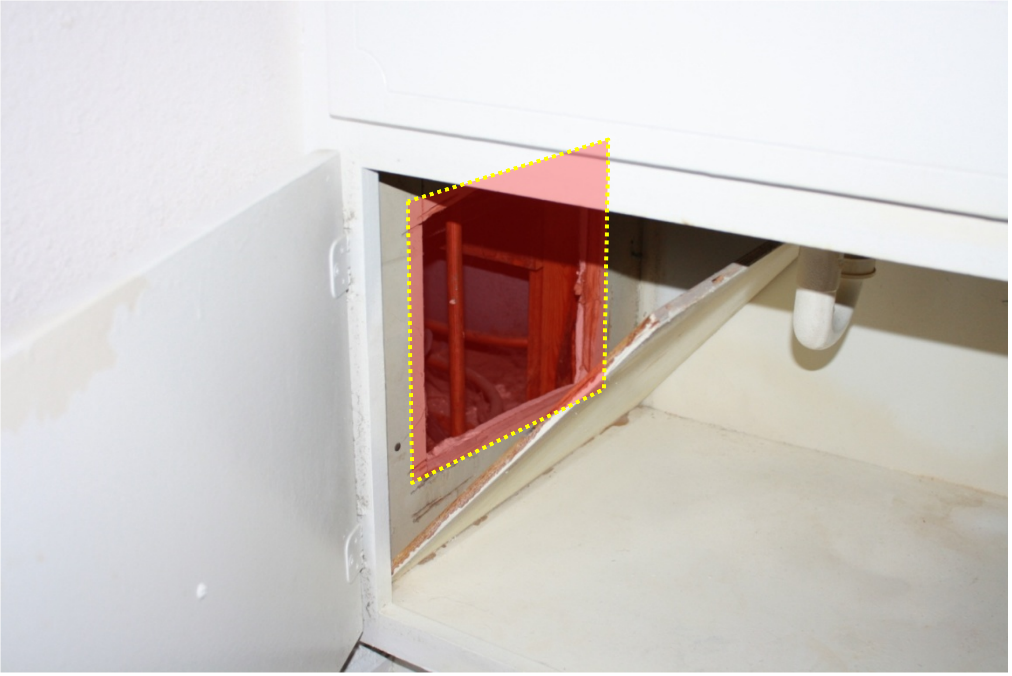
**Typical electrical fixture penetration**

1. Seal can lights and ceiling fan to air barrier or remove completely and repair air barrier. Seal entire perimeter of fan. Air leakage within the fixture assemblies might require installing airtight enclosures on the attic side, and then sealing them to the ceiling air barrier with foam, caulk, or gaskets depending on air barrier and enclosure material.
2. Seal intersection of HVAC supply duct with ceiling air barrier.



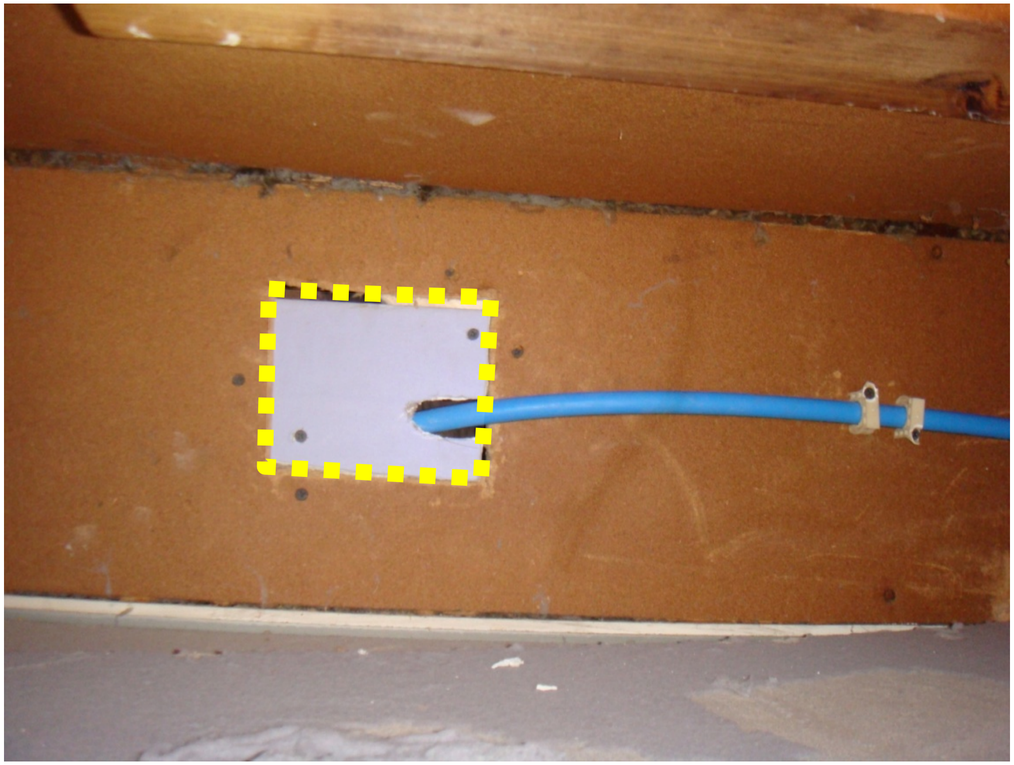
**Typical void above kitchen area dropped ceiling**

Install patch or plug and mechanically fasten to substrate, then make airtight with sealant or fluid-applied membrane around perimeter.



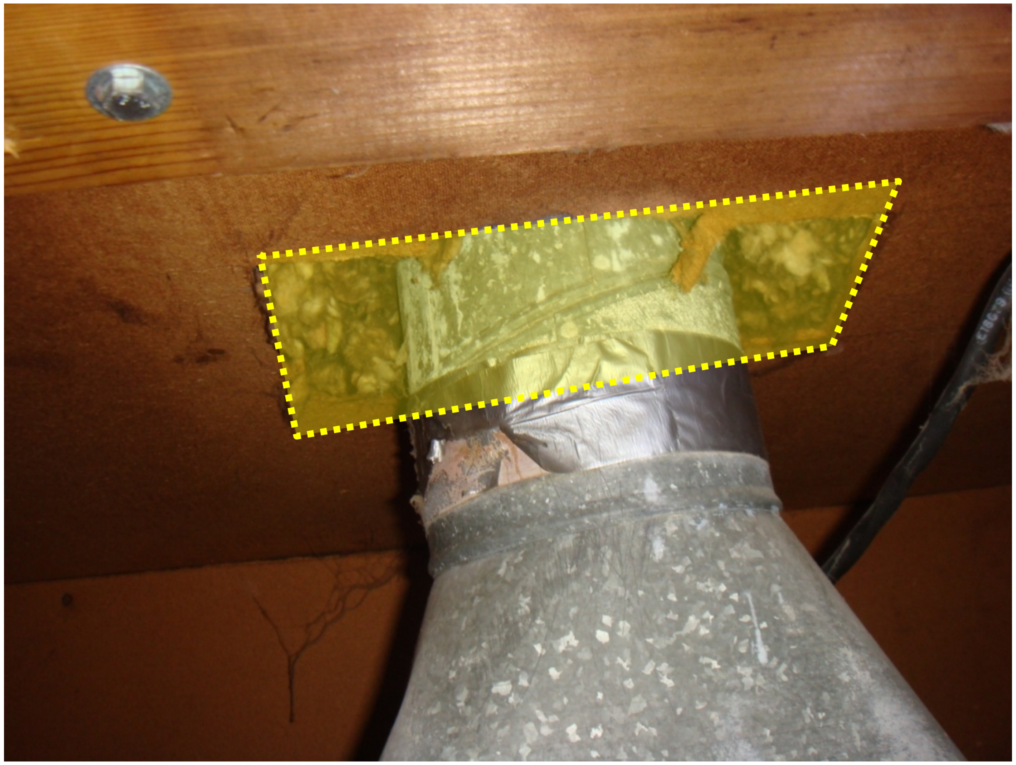
**Typical access void behind tub in bathroom**

Install patch or plug and mechanically fasten to substrate, then make airtight with sealant or fluid-applied membrane around perimeter.



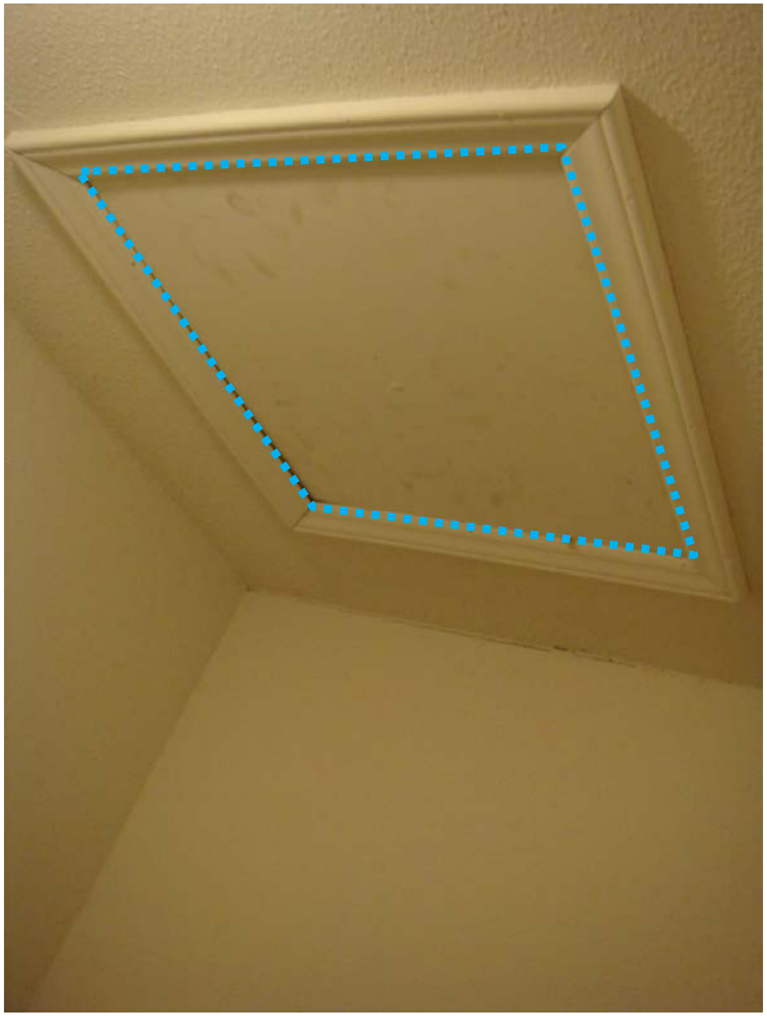
**Incomplete air sealing patch**

The hole has been prepared and a plug inserted and mechanically fastened. Sealant requirements have not been met. Use spray foam, caulk, or fluid-applied membrane to make penetrations airtight.



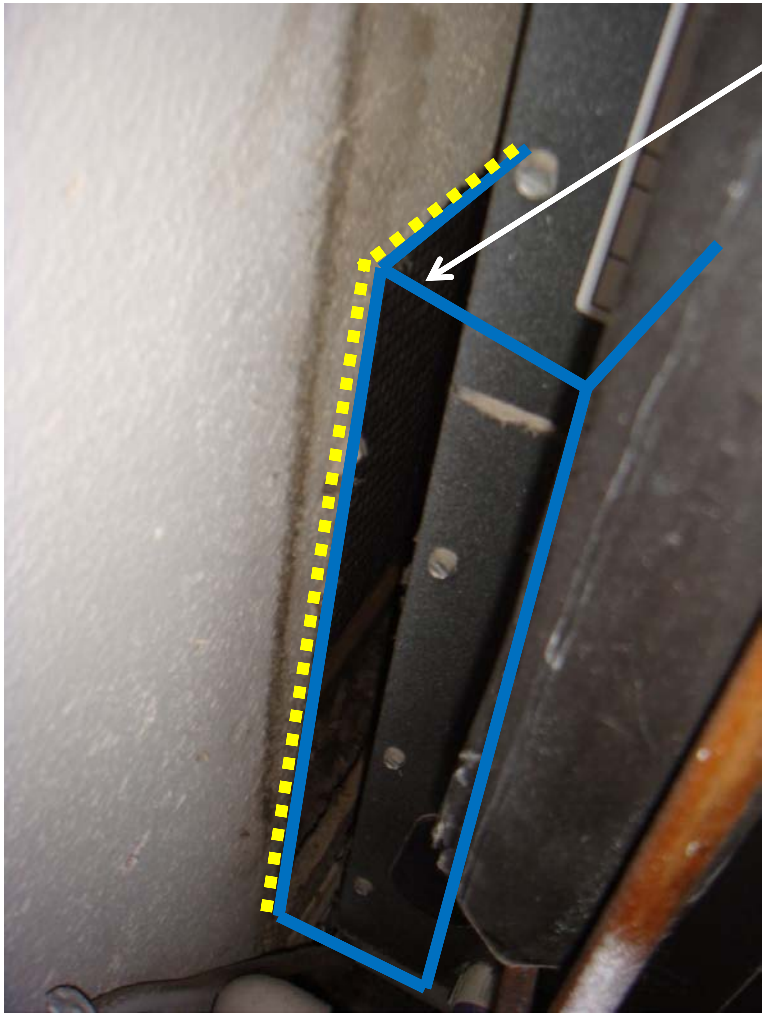
**Typical unsealed duct penetration**

Apply spray foam or sealant/membrane with transition strips around HVAC penetration to make airtight.



**Typical attic scuttle**

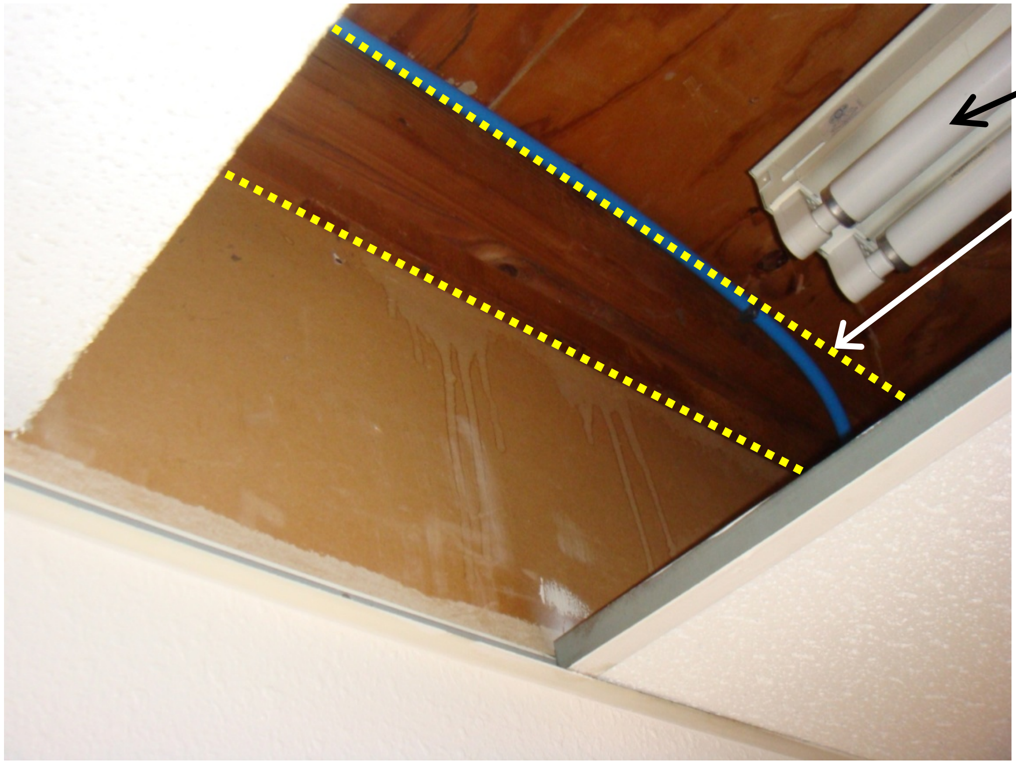
Install weather stripping to create snug seal between ceiling and attic scuttle.



**Unsealed HVAC return**

Install return duct between air handler and grill (HVAC scope).

Make airtight with sealant or membrane.



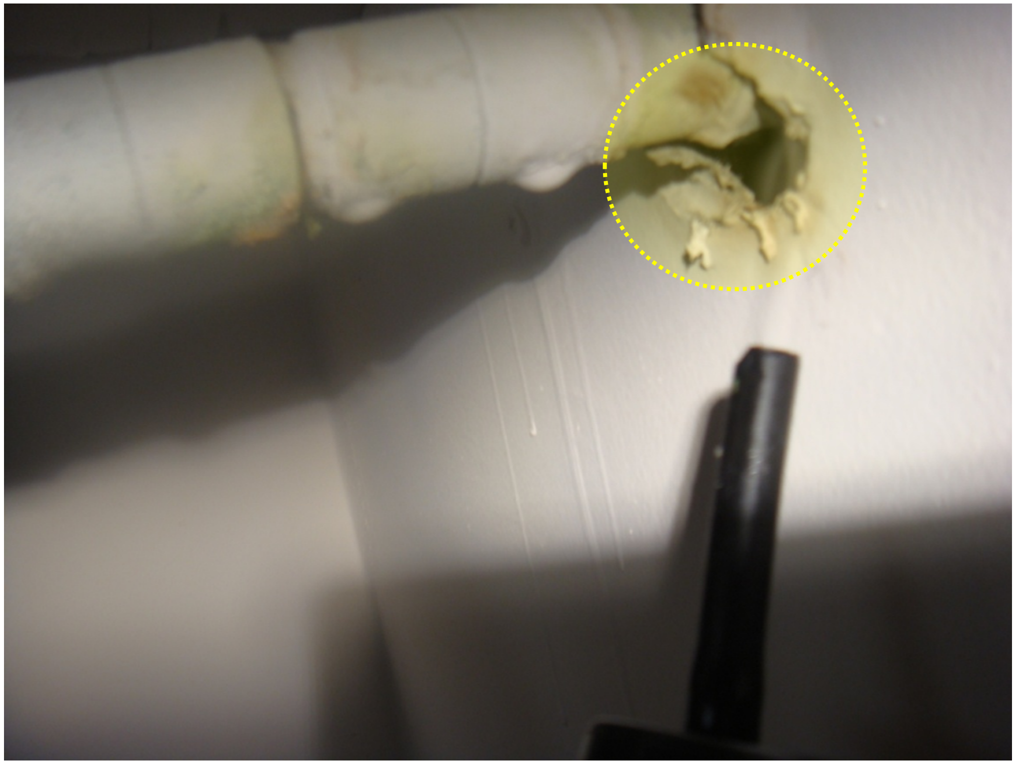
**Typical kitchen area above dropped ceiling**

Seal attic penetrations for light fixture above dropped ceiling, or remove fixture entirely and repair air barrier.

Seal drywall and ceiling lid to structure with a continuous bead of caulk or joint sealant.

**HVAC duct penetration through air barrier**

Install sealants or membranes with backer rod or transition strips as necessary to make duct penetration airtight.



**Typical unsealed plumbing penetration under sink**

Air seal between the plumbing penetration and the GWB air barrier using continuous beads of spray foams or fluid membrane with transition strips.

**Floor to wall transition**

Pull carpeting away from wall. Clean area to ensure sealant adhesion and install a continuous bead of sealant to make floor-to-wall intersection airtight. Use backer rod to support sealant at openings greater than ¼ in., or the distance described in the sealant manufacturer's installation instructions.

**Typical bathroom electrical fixture penetration**

Make fixture airtight by installing an airtight enclosure on the inside-wall side of the air barrier and sealing the enclosure to the inside-wall side of the air barrier. Alternatively, remove the fixture, install “Air Barrier Rated” lighting fixture, and caulk rated fixture to GWB air barrier to ensure airtight seal.

# Appendix C: Unguarded Envelope Testing Results

| Building | Unit | CFA ($ft^2$) | Pre-Retrofit Leakage ($cfm_{50}$) | Post-Retrofit Leakage ($cfm_{50}$) | Pre-Retrofit Leakage ($cfm_{50}$/CFA) | Post-Retrofit Leakage ($cfm_{50}$/CFA) | Pre-Retrofit Leakage ($ACH_{50}$) | Post-Retrofit Leakage ($ACH_{50}$) | Change (%) |
|---|---|---|---|---|---|---|---|---|---|
| **1700** | 2 | 1,500 | 3,295 | 1,644 | 2.20 | 1.10 | 16.5 | 8.2 | –50 |
| **1700** | 7 | 1,500 | 7,023 | 2,078 | 4.68 | 1.39 | 35.1 | 10.4 | –70 |
| **1700** | 9 | 1,500 | 2,330 | 1,512 | 1.55 | 1.01 | 11.7 | 7.6 | –35 |
| **1700** | 12 | 1,500 | 2,634 | 2,042 | 1.76 | 1.36 | 13.2 | 10.2 | –22 |
| **1700** | 14 | 1,500 | 4,035 | 1,993 | 2.69 | 1.33 | 20.2 | 10.0 | –51 |
| **1700** | 15 | 1,500 | 3,420 | 1,693 | 2.28 | 1.13 | 17.1 | 8.5 | –50 |
| **1800** | 2 | 1,500 | 3,166 | 1,632 | 2.11 | 1.09 | 15.8 | 8.2 | –48 |
| **1800** | 4 | 1,500 | 3,499 | 2,189 | 2.33 | 1.46 | 17.5 | 10.9 | –37 |
| **1800** | 9 | 1,500 | 3,913 | 1,993 | 2.61 | 1.33 | 19.6 | 10.0 | –49 |
| **1800** | 10 | 1,500 | 3,399 | 1,926 | 2.27 | 1.28 | 17.0 | 9.6 | –43 |
| **1800** | 11 | 1,500 | 3,637 | 1,746 | 2.42 | 1.16 | 18.2 | 8.7 | –52 |
| **1800** | 12 | 1,500 | 3,030 | 1,560 | 2.02 | 1.04 | 15.2 | 7.8 | –49 |
| **1800** | 14 | 1,500 | 4,000 | 1,715 | 2.67 | 1.14 | 20.0 | 8.6 | –57 |
| **1800** | 16 | 1,500 | 2,905 | 1,864 | 1.94 | 1.24 | 14.5 | 9.3 | –36 |
| **1800** | 17 | 1,500 | 2,474 | 1,324 | 1.65 | 0.88 | 12.4 | 6.6 | –46 |
| **1800** | 18 | 1,500 | 2,934 | 1,412 | 1.96 | 0.94 | 14.7 | 7.1 | –52 |
| **1800** | 19 | 1,500 | 2,900 | 1,419 | 1.93 | 0.95 | 14.5 | 7.1 | –51 |
| **1800** | 21 | 1,500 | 6,516 | 1,928 | 4.34 | 1.29 | 32.6 | 9.6 | –70 |
| **1800** | 22 | 1,500 | 3,684 | 1,778 | 2.46 | 1.19 | 18.4 | 8.9 | –52 |
| **1920** | 14 | 1,200 | 3,956 | 1,865 | 3.30 | 1.55 | 24.7 | 11.7 | –53 |
| **1920** | 15 | 1,200 | 4,119 | 2,171 | 3.43 | 1.81 | 25.7 | 13.6 | –47 |
| **1920** | 19 | 1,200 | 3,039 | 2,039 | 2.53 | 1.70 | 19.0 | 12.7 | –33 |
| **2011** | 1 | 1,500 | 2,661 | 1,611 | 1.77 | 1.07 | 13.3 | 8.1 | –39 |
| **2029** | 8 | 1,500 | 3,462 | 1,720 | 2.31 | 1.15 | 17.3 | 8.6 | –50 |
| **2030** | 4 | 1,500 | 3,834 | 1,965 | 2.56 | 1.31 | 19.2 | 9.8 | –49 |
| **2030** | 5 | 1,500 | 3,176 | 1,687 | 2.12 | 1.12 | 15.9 | 8.4 | -47 |
| **2030** | 10 | 2,200 | 5,035 | 1,727 | 2.29 | 0.79 | 17.2 | 5.9 | –66 |
| **2117** | 2 | 1,200 | 2,233 | 1,648 | 1.86 | 1.37 | 14.0 | 10.3 | –26 |
| **2117** | 23 | 2,000 | 4,210 | 2,106 | 2.11 | 1.05 | 15.8 | 7.9 | –50 |
| **2132** | 4 | 1,200 | 3,634 | 1,756 | 3.03 | 1.46 | 22.7 | 11.0 | –52 |
| **2132** | 10 | 1,500 | 2,438 | 1,263 | 1.63 | 0.84 | 12.2 | 6.3 | –48 |
| **2132** | 15 | 1,200 | 4,218 | 2,172 | 3.52 | 1.81 | 26.4 | 13.6 | –49 |
| **2132** | 22 | 1,200 | 3,023 | 1,643 | 2.52 | 1.37 | 18.9 | 10.3 | –46 |
| **2132** | 23 | 1,200 | 2,627 | 1,345 | 2.19 | 1.12 | 16.4 | 8.4 | –49 |
| **2219** | 1 | 1,500 | 4,950 | 2,032 | 3.30 | 1.35 | 24.8 | 10.2 | –59 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **2219** | 5 | 1,500 | 3,709 | 1,907 | 2.47 | 1.27 | 18.5 | 9.5 | –49 |
| **2235** | 2 | 1,200 | 5,671 | 2,408 | 4.73 | 2.01 | 35.4 | 15.1 | –58 |
| **2235** | 4 | 1,200 | 3,846 | 1,748 | 3.21 | 1.46 | 24.0 | 10.9 | –55 |
| **2247** | 2 | 1,200 | 3,664 | 1,618 | 3.05 | 1.35 | 22.9 | 10.1 | –56 |
| **2247** | 5 | 1,200 | 2,345 | 1,461 | 1.95 | 1.22 | 14.7 | 9.1 | –38 |
| **2309** | 3 | 1,200 | 3,927 | 1,817 | 3.27 | 1.51 | 24.5 | 11.4 | –54 |
| **2309** | 7 | 1,200 | 4,076 | 1,667 | 3.40 | 1.39 | 25.5 | 10.4 | –59 |
| **2309** | 16 | 1,500 | 3,727 | 1,679 | 2.48 | 1.12 | 18.6 | 8.4 | –55 |
| **2309** | 17 | 1,500 | 2,737 | 1,718 | 1.82 | 1.15 | 13.7 | 8.6 | –37 |
| **2309** | 20 | 1,200 | 5,586 | 1,250 | 4.66 | 1.04 | 34.9 | 7.8 | –78 |
| **2309** | 25 | 1,200 | 6,646 | 1,742 | 5.54 | 1.45 | 41.5 | 10.9 | –74 |
| **2314** | 4 | 1,500 | 2,932 | 1,972 | 1.95 | 1.31 | 14.7 | 9.9 | –33 |
| **2330** | 4 | 1,500 | 3,834 | 1,965 | 2.56 | 1.31 | 19.2 | 9.8 | –49 |
| **2330** | 9 | 1,500 | 4,094 | 1,641 | 2.73 | 1.09 | 20.5 | 8.2 | –60 |
| **2330** | 15 | 1,500 | 4,218 | 2,172 | 2.81 | 1.45 | 21.1 | 10.9 | –49 |
| **2330** | 21 | 2,000 | 3,541 | 1,876 | 1.77 | 0.94 | 13.3 | 7.0 | –47 |
| **Average** | | | | | 2.64 | 1.26 | 19.8 | 9.4 | –50 |
| **Median** | | | | | 2.46 | 1.27 | 18.4 | 9.5 | –49 |
| **Standard deviation** | | | | | 0.89 | 0.25 | 6.7 | 1.9 | 11 |

# Appendix D: Pressure Mapping Data

| Building, Unit | Test Pressure (Pa) | Location | Pressure Reading (Pa) | Pressure Difference (Pa) | % Inside |
|---|---|---|---|---|---|
| 2117, Apartment 2 | 50 | Common wall | 45 | 5 | 10 |
| | | Kitchen soffit | 44 | 6 | 12 |
| | | Common wall under stair | 40 | 10 | 20 |
| | | Exterior wall | 46 | 4 | 9 |
| | | Attic | 51 | –1 | –2 |
| 2309, Apartment 16 | 40 | Exterior wall | 23 | 17 | 41 |
| | | Common wall | 20 | 20 | 51 |
| | | Dropped ceiling | 20 | 20 | 50 |
| | | Exterior wall | 16 | 24 | 61 |
| | | Exterior wall | 26 | 14 | 36 |
| | | Interior wall | 29 | 11 | 29 |
| 2117, Apartment 3 | 40 | Common wall | 33 | 7 | 18 |
| | | Common wall | 27 | 13 | 33 |
| | | Kitchen chase | 22 | 18 | 45 |
| | | Ceiling bet floors | 28 | 12 | 30 |
| | | Dropped ceiling | 39 | 1 | 3 |
| | | Crawl | 22 | 18 | 45 |
| | | Attic | 29 | 11 | 28 |
| | | Supply duct | 28 | 12 | 30 |
| | | Return duct | 25 | 15 | 38 |
| | | Supply duct | 29 | 11 | 28 |
| 2030, Apartment 8 | 22 | Attic | 22 | 0 | 0 |
| | | Supply duct | 16 | 6 | 27 |
| | | Dropped ceiling | 16 | 6 | 27 |
| | | Common wall | 18 | 4 | 18 |
| | | Attic | 4 | 18 | 82 |
| | | Interior wall | 7 | 15 | 68 |
| | | Exterior wall | 9 | 13 | 59 |
| | | Exterior wall | 16 | 6 | 27 |

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