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# Leveraging Limited Scope for Maximum Benefit in Occupied Renovation of Uninsulated Cold Climate Multifamily Housing

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Abstract:

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U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

BUILDING TECHNOLOGIES PROGRAM

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*Building Science Corporation*

March 2012

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*Unless otherwise noted, all tables were created by BSC.*

## Definitions

| | |
|---|---|
| BA | Building America Program |
| BSC | Building Science Corporation |
| CFM50 | Air flow, usually through an enclosure or assembly induced by a relative pressure difference of 50 Pascals |
| CMU | Concrete masonry unit |
| CSTO | Castle Square Tenants Organization |
| DHW | Domestic hot water |
| EF | Energy factor |
| ELA | Effective leakage area. |
| HVAC | Heating, ventilation, and air conditioning |
| IAQ | Indoor air quality |
| Pa | Pascals (unit of pressure) |
| USGBC | U.S. Green Building Council |
| Winn | WinnDevelopment |

## Executive Summary

This project examines a large-scale renovation project in a 500-unit, 1960s era subsidized urban housing community. The development comprises low-rise and mid-rise structures, both of which exhibit exposed concrete frames with uninsulated masonry infill walls. The project has a particular focus on indoor environmental quality and energy performance. The nature of occupied rehabilitation necessarily limited the scope of work implemented within apartment units. This research focuses on the airflow control and window replacement measures implemented as part of the renovations to the low-rise apartment buildings.

The window replacement reduced the nominal conductive loss of the apartment enclosure by approximately 15%; air sealing measures reduced measured air leakage by approximately 40% on average. The full scope of renovation work, which includes mechanical system upgrades in addition to the air sealing and window replacement measures, is expected to achieve energy savings of approximately 30% relative to existing conditions.

The window replacement measure and much of the air sealing correspond to typical building upkeep and component replacement activity. The research provides specific findings relative to window details and effective air sealing strategies. It also aims to convey broader lesson in leveraging upkeep and maintenance activities to benefit durability, comfort, indoor air quality, and energy performance.

# 1 Introduction

This project examines performance measures in the context of a large-scale renovation project. Castle Square Apartments is a 500-unit, 1960s era subsidized urban housing community in Boston. Castle Square Apartments is owned by the Castle Square Tenants Organization (majority owner, hereinafter CSTO) and by WinnDevelopment (Winn). The development includes low-rise and mid-rise structures. The wall assemblies for both types of structures consist of exposed concrete frames with uninsulated masonry infill. Existing fenestration is nonthermally broken aluminum-framed double-pane windows.

The renovation has a particular focus on indoor environmental quality (thermal comfort, odor control, and ventilation) and energy performance. In the low-rise (two- to four-story) apartment buildings, these goals will be pursued through a renovation project involving kitchen replacement, window replacement, mechanical system upgrade, and a limited scope of remediation air sealing that is implemented mostly in the kitchen and mechanical room areas.

The research project focuses on evaluation of the air sealing measures and window replacement implemented as part of the renovation scope. The iterative nature of the measures implemented in a large number of apartment units suggests the opportunity to assess the effectiveness of various airflow control, air sealing, and air quality measures implemented at a large scale within occupied residences.

The Castle Square Apartments community represents a type of building construction and situation of building occupancy/ownership that presents acute challenges to high performance retrofit. These construction types and situations are also reasonably common, particularly in metropolitan areas across the heating dominated climates of the United States.

The limited scope of engagement within the apartments and, in particular, the limited scope applied directly to energy and indoor air quality (IAQ) measures necessitated carefully targeted measures. This project provides the opportunity to assess the effectiveness of various airflow control, air sealing, and air quality measures implemented at a large scale within occupied residences in uninsulated masonry and concrete structures.

# 2 Project Context

**Figure 1. Castle Square low-rise or "garden" apartments.**

## 2.1 Background

### 2.1.1 Midcentury Subsidized Housing

Across the country, and particularly in the Northeast and upper Midwest, a multitude of uninsulated masonry structures were built to provide durable and functional subsidized housing. Many of these structures were built in an era when it was acceptable cold climate practice to provide a building enclosure with no added insulation. Although considerable expense may have been applied toward making the buildings hardened and abuse resistant, comfort did not appear to have been a priority. To say that aesthetics are often sparse would be an understatement. Approaches to IAQ have evolved considerably in the time since these buildings were built.

Despite the compromises of comfort, charm, and healthful interior environments, the need for affordable housing is so acute that vacancies in subsidized housing developments are often scarce in major metropolitan areas. The uninsulated enclosures and sometimes arcane mechanical infrastructure drive many of these buildings toward being unaffordable for the housing authorities, community development agencies, and tenants' organizations that operate them.

Clear guidelines about effective and technically sound retrofit strategies are needed that can be implemented in occupied housing. The sustained viability of these buildings may also require strategies to significantly improve aesthetics, comfort, water management, and energy performance.

### 2.1.2 Castle Square Apartment Renovations

In preparation for regular and periodic refinancing, the CSTO and Winn sought to develop a plan to address ongoing performance concerns and substantially modernize the facility. Surveys of residents and frequent resident input meetings found that improving IAQ (reducing transmission of odors) and thermal comfort are top priorities (see Appendix A). The CSTO and Winn also expressed a strong desire that the renovations to the community be as "green" as possible and that energy costs be reduced as much as possible. Because of the acute need for affordable housing in the area, the high cost of relocating residents, and the extremely low vacancy rate, it was determined that the renovations must take place without displacing residents.

The CSTO-Winn joint venture hired an Architect, Elton + Hampton Associates, an engineer, Petersen Engineering, and Building Science Corporation (BSC) as building science and enclosure consultants, to assist in developing project directions. Initially, the joint venture aspired to implement a Passive House-level retrofit. Although the goals did need to adjust to financial circumstances, CSTO and Winn maintained a firm commitment to super-insulation of the mid-rise buildings.

The scope of renovations in the low-rise apartments comprises kitchen replacement, window replacement, provision of kitchen and bath exhaust, and replacement of the furnaces and water heaters. This scope is representative of what may be included in a typical "modernization" or upgrade of housing units for nonenergy reasons. The scope also replaces components that would need to be replaced multiple times over the normal service life of a concrete and masonry building. The renovation project at Castle Square Apartments seeks to leverage this rather generic scope for maximum energy and IAQ benefit.

A significant portion of the design development for this project occurred prior to the start of the present Building America (BA) project. BSC had worked with the project team under prior BA program years as well as under direct contract with the project team. During this earlier phase, BSC contributed to the development of air sealing strategies and of performance specifications. Investigations and diagnostic testing were conducted in vacant apartment units designated as mock-up/investigation units. During the present BA program period, BSC contributed to the refinement of pertinent performance details and assessment of performance specifications. After the contract for implementation of the renovation was awarded, an additional vacant apartment was made available for investigations and measurements. BSC worked with the architect and selected general contractor to refine strategies based on work conducted in this apartment unit.

### 2.2 Relevance to Building America's Goals

The goal of the U.S. Department of Energy's (DOE) BA program is to reduce energy use for existing homes by 15% (compared to pre-retrofit energy use). Based on estimates of the design team, the renovations to the low-rise buildings are expected to yield energy use savings of approximately 30%.[1]

The measure examples and guidelines produced by this research project will be applicable to uninsulated masonry multifamily structures in heating-dominated climates. Of particular interest is that the lessons learned will be representative of the context of subsidized housing and occupied renovation. Furthermore, measures implemented in the low-rise apartment renovations

[1] The design team used input from a variety of analyses to arrive at energy reduction estimates. BSC provided modified heat flux analysis to reduction in enclosure heating load. The mechanical engineer prepared estimates of reductions in energy use of the mechanical systems relative to loads. The estimates of relative reductions could then be applied to historical consumption data to arrive at estimates of the value of energy savings.

address components that typically will need to be replaced or assemblies that will need to be refurbished during the service life of buildings. Measures guidance for these measures provides support for building owners/operators to capitalize on performance improvement opportunities represented by regular maintenance and replacement activities.

# 3 Data Sources and Methods

## 3.1 Review and Observation

In the capacity of a technical support consultant, BSC reviewed shop drawings pertaining to window installation and other measures affecting either water management or airflow control. BSC suggested changes through the project architect.

BSC also reviewed implementation of work in the field and participated in refinement of details with involvement of the implementing trade contractors, general contractor, architect, and owners' representative. In-field observation of work involved visual observation and documentation by digital photographs. In some cases, BSC reviewed photographs and documentation provided by persons in the field.

## 3.2 Measurements

Air leakage performance was measured via multipoint blower door testing. Total apartment enclosure air leakage performance was assessed by testing apartments in a fully unguarded configuration, that is, with neighboring apartments open to the exterior. During initial stages of the renovation project, some iterations of guarded blower door testing were performed as well. During initial construction stages of project, we performed air leakage testing at a small sample of apartment units at intermediate stages of scope to assess success of implementation and help the contractor understand air sealing measures.

Total apartment enclosure air leakage performance after completion of the renovation scope was measured in a 10% sample (31 apartment units) of the renovated apartment units. Pre-renovation measurements were taken in a smaller sample of units. It was generally not practical to directly measure pre- and post-renovation air leakage within specific apartments.

## 3.3 Analysis

The performance specification referenced in the project specification is expressed in terms of an effective leakage area (ELA) ratio where the calculated effective leakage area is normalized to 100 $ft^2$ of enclosure/boundary surface area. This ratio is given the shorthand ELA/100. The ELA is defined as the area of a special nozzle-shaped hole (similar to the inlet of the blower door fan) that would leak the same amount of air as the building does at a pressure of 4 Pa.[2]

The TECtite software was used to calculate the ELA based on multipoint air leakage tests. BSC performed area and volume takeoffs of the apartment unit plans to be able to normalize the air leakage measurements in terms of ELA/100, ACH50, and CFM50/$ft^2$ of enclosure area.

[2] ELA was developed by Lawrence Berkeley National Laboratory. Under less than optimal testing conditions, coefficients and exponents derived from multipoint testing can be relatively unstable resulting in extrapolations to airflow at lower pressures that are also unstable. The measurement of air leakage flow at 50 Pa, where 50 Pa is near the upper end of the test pressure range, is taken to provide a more stable measure of air leakage. Extrapolation using fixed coefficient and exponent values applied to the calculated cfm50 measurement is believed to provide a more repeatable and stable measure of effective leakage area.

Because it was generally not practical to directly measure pre- and post-renovation air leakage within specific apartments, reduction of air leakage performance is taken from a statistical analysis of pre- and post-retrofit air leakage measurements. Normalized measurements for the pre-retrofit sample are compared to normalized measurements of the post-retrofit sample.

# 4 Retrofit Measures

The retrofit measures impacting energy performance include air sealing, window replacement, and replacement and reconfiguration of the mechanical system. This research addresses the air leakage control and window replacement measures. It does not assess the reconfiguration of the heating and water heating systems.

## 4.1 Air Sealing

A major component of BSC's contribution to the project plan was development of air sealing scopes of work and performance specifications for the apartment renovations. The air sealing scope and performance specifications are aimed at compartmenting and odor control as well as infiltration/exfiltration control. The development of air sealing scopes necessarily employed destructive investigation to confirm construction of assemblies. Blower door diagnostics were also used to guide development of air sealing measures and to establish reasonableness of performance targets.

During design development, the architect proposed an air leakage target of 1.25 ELA/100. This target was initially selected to align with a U.S. Green Building Council (USGBC) LEED prerequisite path for multifamily residential projects. It was hoped that air sealing implementation and air leakage testing in a mock-up apartment would determine whether this target was appropriate for the project. For reasons discussed in Section 5.1, it proved impractical to provide a determination of the appropriateness of the target prior to full-scale construction.

Based on support provided by BSC, the architect developed an air sealing scope for the apartment renovations. The scope of renovation work within the apartment outside the kitchen was limited; therefore, opportunities for air-sealing measures were limited. The kitchen cabinets and fixtures to be replaced in the kitchen were on a demising wall; therefore the kitchen renovation provided opportunities to address air leakage between apartments. The air leakage scope for the apartments is as follows:

### *4.1.1 General Air Sealing*

- Seal the gap around the duct plenums (both supply and return) connecting the apartment to the mechanical closet (see Figure 2).
- Remove register grilles throughout the apartment and seal from the inside of the duct to the face of the drywall with appropriate tape. Trim the tape at the face of the drywall so that the register flanges will conceal the tape (see Figure 3).
- Caulk the steel frame of the entry door to the drywall; replace door gasketing where it does not provide a good seal.
- Seal the demising wall to exterior wall. At the corner of the demising wall and the exterior wall, remove a 2- to 4-in. wide strip of drywall from exterior wall to allow the drywall of the demising wall to be sealed to the exterior wall (concrete frame or concrete masonry unit [CMU] backup) (see Figure 4).[3]

[3] Ultimately, this measure was removed from the scope for the low-rise apartments.

- Seal accessible plumbing, electrical, and other penetrations through the drywall with appropriate sealant; e.g., if plumbing penetrations are accessible beneath a bathroom sink.
- Where soffits (bulkheads) are opened, seal all penetrations and connections to adjacent units and the surface of the demising wall; otherwise, make it continuous and seal it to the underside of the deck above.[4]

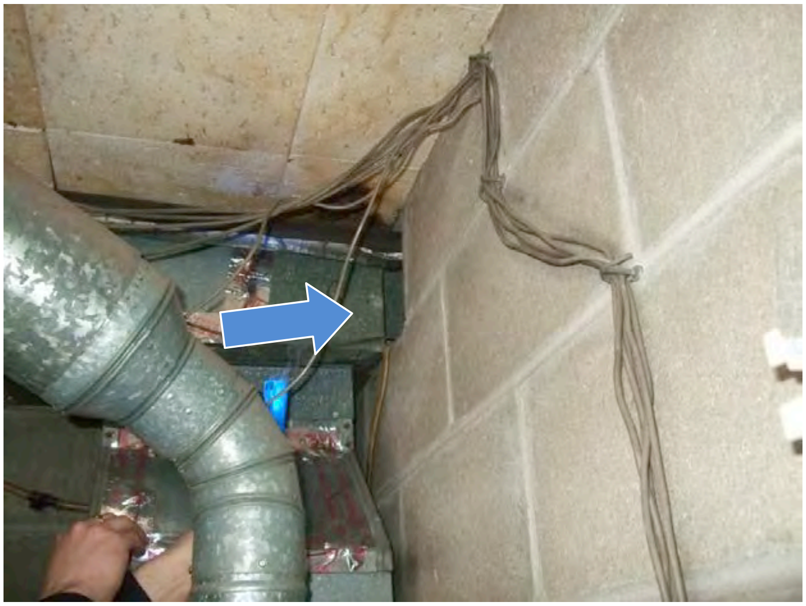

**Figure 2. Typical gap around supply plenum in separation between mechanical room and apartment.**

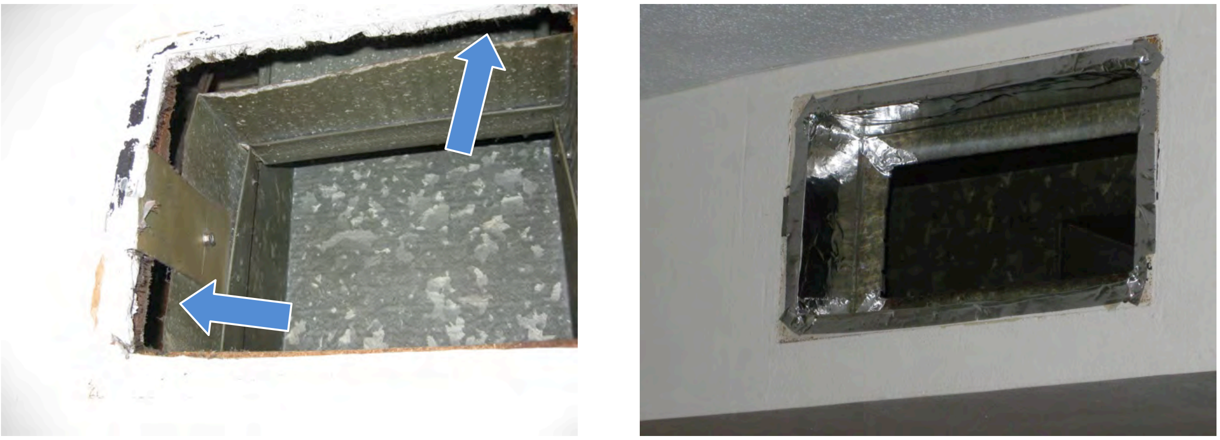

**Figure 3. Left: Gaps between duct boot and drywall created a bypass for heating distribution and also represented significant leakage pathways into the demising wall and, consequently, between apartments; Right: The work scope called for metal extension sleeves and foil mastic tape to seal from the existing duct, over the extension sleeve to the face of the drywall.**

[4] Because of the cost, disruption to residents, and risk of hazardous materials, the contractor avoided situations that would open or compromise the duct soffit enclosure.

**Figure 4. Furring cavity of exterior wall communicates with demising wall. Left: Drywall removed at section of exterior wall adjacent to demising wall; Right: Close-up of connection between furring cavity of exterior wall and demising wall.**

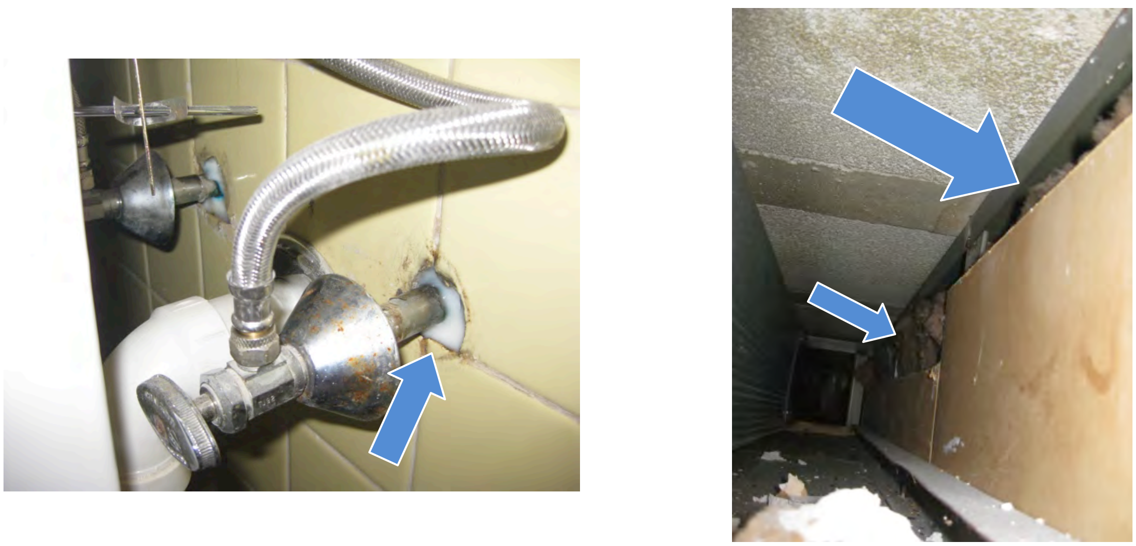

**Figure 5. Left: Annular seal at easily accessible plumbing penetration; Right: Within the duct soffit enclosure, the demising wall is not continuous to the ceiling.**

### *4.1.2 Air Sealing at the Location Affected by the Kitchen Remodeling Scope*

- Seal around all plumbing, electrical, and other penetrations at the wall surface with appropriate sealant.
- Seal between the bottom of the wall and the floor.
- Extend the top of the wall to meet the ceiling/floor assembly and seal between the top of the wall and the ceiling/floor assembly above.

- Where the base of the exterior wall is exposed, clean the floor-exterior wall junction and apply a liquid-applied waterproof membrane to seal the block wall to the floor slab.
- Connect and seal the drywall of the demising wall to the exterior wall at the side of the kitchen adjacent to the exterior wall.
- Where the unused duct stub penetrates the surface of the demising wall, cut back the duct to allow the drywall to extend and seal to the floor/ceiling assembly, then cap and seal the duct.
- Provide airtight electric boxes throughout or seal each electric box with appropriate sealant.
- Where CMU backup wall of exterior wall is exposed, apply mastic over accessible cracks or minor holes. Patch major holes (broken block) in CMU wall.

**Figure 6. Left: Large discontinuities in demising wall surface round plumbing and other services above the soffit. Drywall surface is not sealed to floor/ceiling above; Right: Demising wall surface is not sealed to floor slab.**

**Figure 7. Left: Where work exposes the joint between the exterior wall and floor slab, there is an opportunity to ensure a robust air seal at this joint; Right: As seen in this exposed section above the kitchen soffit, the demising wall does not connect to the exterior wall structure. This leaves a path for airflow around the demising wall.**

**Figure 8. Dead-end stub of supply plenum extends through demising wall. Left: View of supply plenum with kitchen soffit and cabinets removed; Right: View into demising wall cavity through large opening around dead-end stub of supply plenum.**

**Figure 9. Left: Small hole in mortar joint of exterior wall; Right: Large existing hole in CMU of exterior wall apparently created to accommodate electrical and communication services.**

The architect conveyed this air sealing scope in construction drawings reserved exclusively for air sealing details (see Figure 10). In addition to the explicit air sealing scope, other scopes of work impacted air leakage control. The window details in particular were developed to provide robust air leakage control. The air sealing objectives were also reinforced throughout the project specification. BSC and the architect wrote a performance testing quality assurance protocol that was written into the project specifications (see Appendix B). The owner's representative also employed an air-sealing checklist that was completed for each of the 308 apartments in the low-rise portion of the project (see Appendix C).

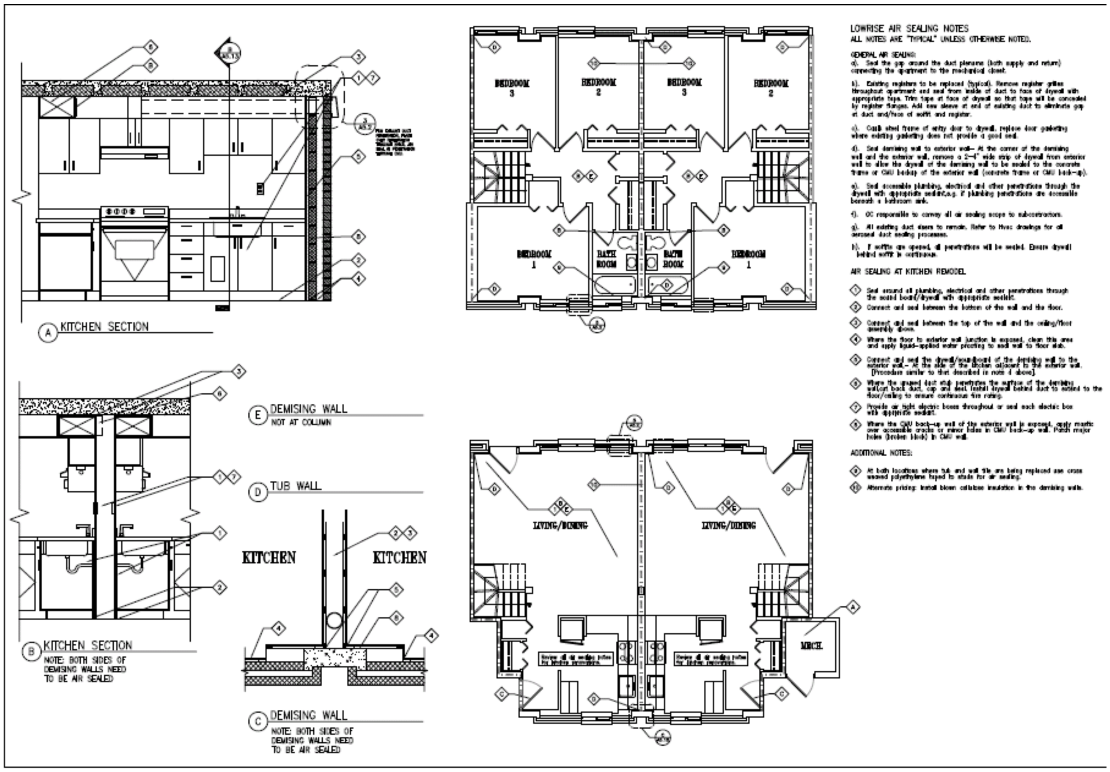


**Figure 10. Air sealing scope in construction drawings.**

(Image courtesy of Elton + Hampton Architects, used with permission.)

Although most of the explicit air sealing scope fell within the drywall division and under the obligation of the drywall subcontractor, the work also overlapped with other specification divisions and subcontractor scopes of work. Plumbing, heating, ventilation, and air conditioning (HVAC), and electrical subcontractors were responsible for some of the air sealing scope. During initial mobilization of the construction effort, the architect, BSC and the general contractor conducted meetings to review with construction personnel the air sealing scope, the need for and expected benefit of the air sealing, and the testing and verification protocol. Presentations given by the architect and BSC at these meetings included images of air leakage conditions (such as those above) from earlier investigations. These meetings were mandatory for all subcontractor foremen whose work would impact the air leakage performance.

## 4.2 Window Replacement

### *4.2.1 Development of Window Replacement Details*

During the prior phase of work, BSC developed schematic details for the retrofit window replacement at the low-rise buildings. Within the limited scope of the low-rise renovations, the window replacement represents one of the most significant opportunities to address air leakage to the exterior.[5] To understand conditions the window installation would need to mitigate, BSC conducted destructive investigation into the construction of the low-rise apartments.

The window replacement represents an important opportunity to address airflow control because of the large openings in the airflow control layer observed around the window openings. The windows had been installed to wood bucks. A large (but, as discovered later, variable) gap existed between the wood buck and the CMU opening. In Figure 11, the back of the brick veneer is clearly visible through the gap between the sill buck and the CMU. Because the CMU backup wall, with its dampproof coating on the interior side, was the primary infiltration control layer for the apartments, the window replacement details and installation sequence needed to provide a means to seal between the wood bucks and the CMU opening.

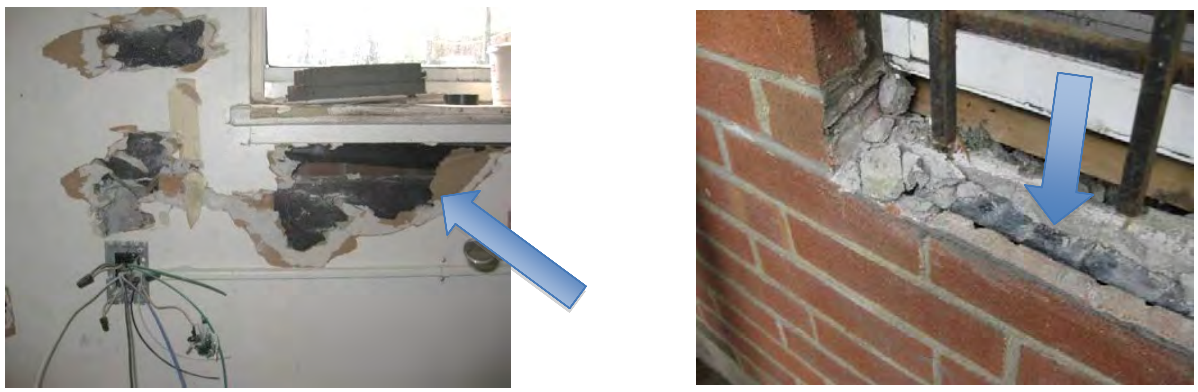

**Figure 11. Destructive investigation into existing window assembly and installation. Left: Interior view of existing window installation in mock-up unit. Note the gap between masonry opening and sill; Right: Exterior view of existing window installation in mock-up unit. Note the sill membrane forming a trough that is filled with mortar.**

[5] The other major opportunity to address air leakage to the exterior is represented by the mechanical system work. The mechanical system work scope provides access to both the supply and return plenum penetrations into the apartment enclosure. Early investigations revealed significant gaps around these duct penetrations, which effectively connected the apartment environment to the mechanical closet.

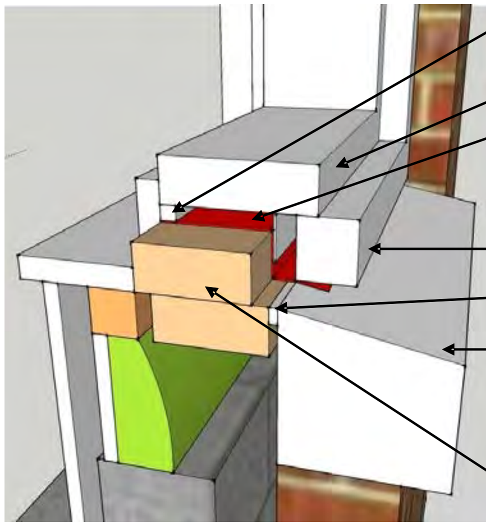


**Figure 12. Early schematic detail for low-rise window replacement**

BSC provided comment and review of architectural details, including those for the window. As details evolved in the course of the design process, BSC provided technical guidance to ensure that critical control functions were evinced in the details.

Window installation was also carefully studied in the mock-up apartment. Details and implementation processes needed to be well resolved to allow the work to proceed rapidly once the project started in earnest. The window supplier, installation subcontractor, general contractor, architect, and BSC were involved in evaluation of windows in the mock-up apartment unit. As a result of this work, the manufacturer made changes to the window and installation details were revised.

During the mock-up installations, the installing subcontractor's personnel were able to identify areas where the installation process could be improved to achieve better performance results. BSC incorporated the subcontractor's improvements into revisions to a window installation "recipe" developed by the general contractor (see Appendix D).

The window installation details in the construction bid documents called for drilling the wood bucks at regular intervals and injecting a foam sealant into the gap. This was a less-than-desirable solution because it did not offer the opportunity to visually verify a continuous seal. The window installation subcontractors devised and demonstrated an alternate approach involving cutting the wood bucks to allow access to the gap to be sealed. The wood buck is cut approximately flush with the face of the CMU backup wall. The gap between the wood buck and the CMU opening is then accessible through the cavity between the brick and the CMU.

**Figure 13. Left: Wood jamb buck being cut to allow access to joint between buck and masonry opening; Right: Wood jamb buck cut showing both working and visual access to the gap to be sealed.**

**Figure 14. Foam sealant being applied between off-cut wood buck and CMU**

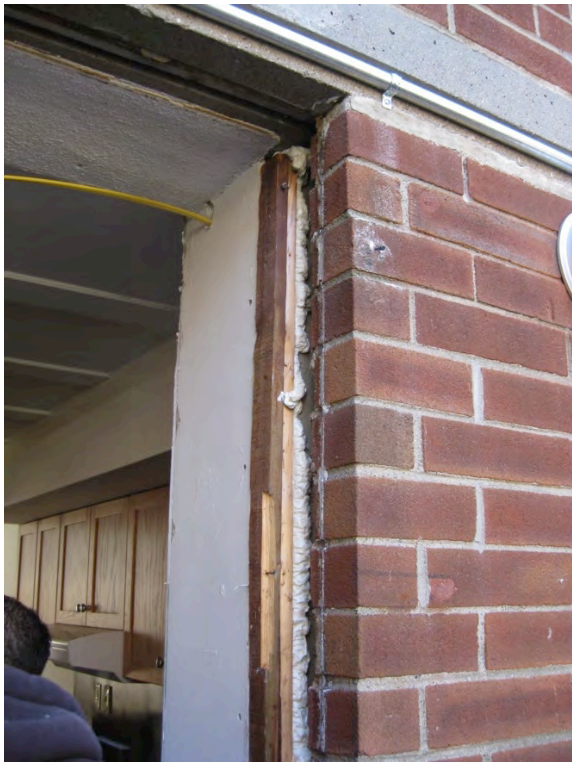

**Figure 15. Left: Visual access enables verification of seal between buck and masonry opening; Right: Foam sealant in gap between wood buck and CMU backup wall.**

When the wood buck was cut away approximately flush with the face of the CMU backup wall, it left a significant gap between the buck and the brick. The window unit covers this gap, but a jamb flashing is needed at the jamb of the opening. Therefore, a substrate for the jamb flashing was needed to allow this flashing to bridge the cavity between the CMU backup wall and the brick. A piece of metal coil stock was used in the first mock-up unit window installation. Subsequently, the window installation subcontractor demonstrated that the off-cut of the wood buck could be reattached as a substrate for the jamb flashing membrane provided that the application of foam sealant at the jamb buck was not excessive.

**Figure 16. Left: Metal coil stock support for jamb flashing between wood buck and brick return; Right: Wood buck off-cut reattached as jamb flashing support.**

# 5 Implementation Assessment

## 5.1 Air Sealing

### *5.1.1 Construction Observations*

After the air sealing scope was developed and before the renovation work was fully ramped up, the property owners designated an additional vacant apartment unit as a mock-up unit for the general contractor to use to implement the renovation scope. This enabled the project team to identify implementation challenges. It also provided the opportunity to discover additional areas requiring air sealing.

BSC observed the mock-up apartment after the contractor had performed initial demolition work. These observations confirmed many of the air sealing needs identified in previous investigations. The observations also highlighted the need for air sealing work to be resistant to rodents as on going rodent activity was evident in this apartment (see Figure 17). BSC conveyed a report (see Appendix E) to the architect conveying suggestions relative to the air sealing scope drawings excerpted in Figure 10.

**Figure 17. Left: Copious evidence of rodent activity on floor of second floor closet; Right: Rodent hole behind kitchen cabinet location and apparent pre-existing attempt at sealing base of wall to floor with joint compound.**

BSC observed a condition in this apartment unit where the duct soffit (which, in turn was opened to the demising wall) is open to the apartment. This opening was found to contribute significantly to the total enclosure air leakage of the apartment. BSC worked with the general contractor and architect to devise a suitable remedy for this situation that was added to the air sealing scope of work. The remedy had to accommodate considerable variability found for the particular condition.


**Figure 18. Opening into soffit at second floor of low-rise mock-up apartment.**

**Figure 19. Left: Opening into duct soffit along side vertical riser. View into soffit and demising wall cavity (with dirty batt insulation) beyond; Right: drywall closure for duct soffit.**

On multiple occasions, BSC conducted site visits to the mockup apartment unit to assess the general contractor's implementation of the project scope relating to air flow control. BSC conducted air leakage testing in the mock-up apartment unit to assess whether the air sealing performance target was attained and whether it appeared attainable within the limits of the project work scope.

**Figure 20. Left: Early attempt at sealing exhaust duct. Note annular seal between sleeve and duct but not between duct sections or sleeve and wall; Right: Backlit image of early attempt at sealing exhaust duct illustrates where air seal is needed.**

During the mock-up phase of work, the full renovation scope of work could not be implemented. The mechanical system work, because it would involve four adjacent apartments rather than being isolated to one apartment, could not be performed at this stage. The final air leakage measurement attained in the mock-up apartment was 1.65 ELA / 100. It was expected that the mechanical system work would result in additional air leakage reduction (see Appendix F). Although it seemed possible that the scope of air sealing work *could* achieve the target, the work in the mock-up unit fell short of a proof-of-concept.

The results of the mock-up and other pre-retrofit airtightness testing are presented and discussed in Section 5.1.2.

The project team expended considerable effort in resolving details and processes in the mock-up apartment units. When the construction work began in earnest, it was to proceed at a very fast pace. The main focus of the work within each apartment was the kitchen replacement. Most of the air sealing scope was implemented in conjunction with the kitchen replacement work. The kitchen replacement scope was implemented during daytime hours over the course of two to three days. At the end of each day, the apartment was to be left in a functioning condition. At the end of the first day, the new kitchen cabinets and counter were in place and the kitchen sink was operational. This rapid implementation schedule requires a high level of coordination between various trades. The result is something of a production line retrofit where trades move rapidly from one apartment to another. The difference between a production line and this construction process is that rather than the work subject moving through a line of workers and tradespersons, the contractors move through apartments in stationary lines of buildings.

The drywall subcontractor and the general contractor identified an opportunity afforded by the sequence of the renovation work. Because one side of the demising wall at the kitchen is opened shortly after the wall on the other side of the wall is refinished, there is an opportunity to thoroughly seal the demising wall from the open side of the wall. This enabled better visual confirmation of the sealing work. The sealing sequence also made it possible for the contractor to seal the demising wall to the exterior wall without cutting the drywall of the exterior wall, as had been indicated in the architectural air sealing drawings.

**Figure 21. Demising wall at kitchen air sealed from open side of wall.**

**Figure 22. Airflow control connection between drywall and exterior wall achieved through open side of wall.**

Observation of the rapid sequence air sealing work also revealed instances where clarification of the intent of the scope is needed. In observing progress in two apartments, BSC noted that a new bathroom exhaust duct passing through the exterior wall assembly had been sealed at different locations in each apartment. In the first apartment, the wallboard of the furred out exterior wall had been cut away to allow the duct to be sealed at the penetration through the CMU of the exterior wall. In the other apartment, the drywall was cut neatly around the exhaust duct that appeared to have been sealed to the drywall.

**Figure 23. Large opening in drywall around exhaust duct allows access to exhaust duct penetration through CMU backup wall – the primary airflow layer for the exterior wall.**

This variation observed in the field points to a need for project documents (drawings, specifications, and supplemental instructions) to clearly identify the layer of the assembly intended to be the airflow control layer. It is not practical for a drawing set to anticipate all the possible conditions that might be encountered in the field. Even at this development, where the nature of the apartments appears to be extremely repetitive, significant variations were encountered. Therefore, documents that direct air sealing work only specifically – e.g. by calling out where to apply sealant (see Figure 10) – may fall short of achieving performance objectives. If the documents also convey intent and explain which components, layers, or surfaces in the assemblies perform required functions, contractors would be better positioned to identify effective solutions to unanticipated conditions.

For the exterior wall assembly of the Castle Square low-rise apartments, the primary airflow control layer is the CMU wall and concrete frame. The interior face of these elements is coated with an asphaltic damp proofing material that is presumed to render the CMU a reasonable air barrier. If it is clearly communicated to the air sealing contractor that the back of the CMU wall is the primary airflow control layer, the contractor is more likely to understand that the proper method of sealing the exhaust duct penetration is to cut away the exterior wall drywall to allow access to the duct penetration through the CMU layer.

**Figure 24. Inside of CMU layer in exterior wall. Note dampproof coating and through-wall flashing**

### *5.1.2 Air Leakage Testing*

#### *5.1.2.1 Initial Implementation Evaluation Testing*

During the initial implementation of the renovation scope in the first renovated apartments, BSC provided performance testing of the air sealing scope to inform the general contractor and the project design team about the success achieved relative to performance goals. The testing was highly dependent on alignment of construction schedules, on the ability to provide sufficient advance notice to residents, and on BSC availability. Once beyond the mock-up implementation, there was a very slim chance for the confluence of the necessary conditions.

At the early stages of the project, BSC was able to secure opportunities to test a group of four apartment units at three discrete points:

- Before renovation work commenced
- After the kitchen replacement, air sealing, and HVAC work were implemented, but before windows were installed
- After the renovation scope was completed.

Although the intention of the intermediate air leakage testing was to isolate the effect of the air sealing scope and air sealing associated with the HVAC scope, it was not possible to test the apartments in a state that isolated these measures. In conjunction with the interior scope of work that included the air sealing and kitchen replacement, subcontractors also removed trim and finishes around windows. Sheet plastic had been taped around the rough sill and returns of the window opening, but this could not replicate the conditions before interior finishes were removed. The reality evident in this effort is that the kind of choreographed production required for this scale of project and for occupied rehab is not compatible with precisely sequential research testing.

**Figure 25. Left: Plastic sheeting at sill of window opening billowing inward during depressurization testing; Right: Plastic sheeting at window jamb return billowing inward during depressurization testing.**

Table 1 is a compilation of airtightness results from the 11 units that were tested before retrofit work began. These units are located in Buildings 8, 12, and 16. Unguarded test results in four airtightness metrics are shown for each. This sample represents several unit types with different surface areas and volumes. These differences are accounted for in the geometry-normalized results shown in the last three columns.

**Table 1. Pre-Retrofit Results From Buildings 8, 12, and 16**

| Building, Unit Number and Unit Type (end or middle unit) | Unguarded CFM50 | ELA/100 $ft^2$ Enclosure | ACH50 | CFM50/$ft^2$ Enclosure |
|---|---|---|---|---|
| Building 8, Unit 31A, middle unit | 1796 | 4.01 | 11.8 | 0.63 |
| Building 8, Unit 31B, end unit | 1303 | 2.94 | 8.1 | 0.44 |
| Building 8, Unit 31C, middle unit | 1802 | 5.03 | 11.9 | 0.64 |
| Building 8, Unit 31D, end unit | 1472 | 3.53 | 9.1 | 0.50 |
| Building 8, Unit 35B, middle unit | 1786 | 5.31 | 11.7 | 0.63 |
| Building 8, Unit 35D, middle unit | 1651 | 4.36 | 10.8 | 0.58 |
| Building 12, Unit 9B, middle unit | 1692 | 4.92 | 13.0 | 0.67 |
| Building 16, Unit 18A, middle unit | 1185 | 4.05 | 9.1 | 0.47 |
| Building 16, Unit 18B, end unit | 830 | 1.89 | 6.0 | 0.31 |
| Building 16, Unit 18C, end unit | 1495 | 6.10 | 10.8 | 1.00 |
| Building 16, Unit 18D, end unit | 1151 | 3.12 | 8.3 | 0.43 |

Table 2 shows all post-retrofit testing data. Units tested after the renovation work are located in Buildings 7, 8, 16, and 17.

**Table 2. Post-Retrofit Results From Buildings 7, 16, and 17**

| Building, Unit Number and Unit Type (end or middle unit) | Unguarded CFM50 | ELA/100 $ft^2$ Enclosure | ACH50 | CFM50/$ft^2$ Enclosure |
|---|---|---|---|---|
| Building 7, Unit 41A, end unit | 563 | 0.74 | 3.5 | 0.19 |
| Building 7, Unit 41B, middle unit | 837 | 1.54 | 5.5 | 0.30 |
| Building 7, Unit 45A, middle unit | 1147 | 1.99 | 7.5 | 0.41 |
| Building 7, Unit 45B, middle unit | 1066 | 1.37 | 7.0 | 0.38 |
| Building 7, Unit 47A, middle unit | 1258 | 2.90 | 8.2 | 0.44 |
| Building 7, Unit 47B, middle unit | 1036 | 2.41 | 6.8 | 0.37 |
| Building 7, Unit 49A, middle unit | 782 | 1.66 | 5.1 | 0.28 |
| Building 7, Unit 49B, end unit | 605 | 1.22 | 3.7 | 0.21 |
| Building 8, Unit 31A, middle unit | 842 | 2.18 | 5.5 | 0.30 |
| Building 8, Unit 31B, end unit | 636 | 1.27 | 3.9 | 0.22 |
| Building 8, Unit 35A, middle unit | 870 | 1.52 | 5.7 | 0.31 |
| Building 8, Unit 35B, middle unit | 918 | 2.09 | 6.0 | 0.32 |
| Building 8, Unit 37A, end unit | 964 | 1.75 | 4.6 | 0.25 |
| Building 8, Unit 37B, middle unit | 910 | 2.25 | 6.0 | 0.32 |
| Building 8, Unit 39A, end unit | 601 | 1.21 | 3.7 | 0.21 |
| Building 8, Unit 39B, end unit | 958 | 1.24 | 4.6 | 0.25 |
| Building 16, Unit 10A, end unit | 992 | 2.26 | 6.5 | 0.35 |
| Building 16, Unit 10B, middle unit | 1092 | 2.54 | 6.8 | 0.37 |

| Building, Unit Number and Unit Type (end or middle unit) | Unguarded CFM50 | ELA/100 $ft^2$ Enclosure | ACH50 | CFM50/$ft^2$ Enclosure |
|---|---|---|---|---|
| Building 16, Unit 12A, middle unit | 1374 | 2.76 | 9.0 | 0.49 |
| Building 16, Unit 12B, middle unit | 926 | 2.13 | 6.0 | 0.33 |
| Building 16, Unit 14A, middle unit | 889 | 1.84 | 5.9 | 0.31 |
| Building 16, Unit 14B, middle unit | 1037 | 2.54 | 6.8 | 0.37 |
| Building 16, Unit 16A, middle unit | 1081 | 2.98 | 8.3 | 0.42 |
| Building 16, Unit 16B, middle unit | 1011 | 2.14 | 7.8 | 0.40 |
| Building 16, Unit 18A, middle unit | 919 | 1.7 | 7.1 | 0.36 |
| Building 16, Unit 18B, end unit | 904 | 1.91 | 6.5 | 0.34 |
| Building 17, Unit 2A, end unit | 562 | 1.09 | 3.5 | 0.19 |
| Building 17, Unit 2B, middle unit | 900 | 2.10 | 5.9 | 0.32 |
| Building 17, Unit 4A, middle unit | 971 | 1.94 | 6.3 | 0.34 |
| Building 17, Unit 4B, middle unit | 1254 | 2.93 | 8.2 | 0.44 |
| Building 17, Unit 6A, middle unit | 878 | 2.02 | 5.8 | 0.31 |
| Building 17, Unit 6B, end unit | 636 | 1.19 | 3.9 | 0.22 |

Unfortunately, it was not possible to test all of the same units that were tested in the pre-retrofit case (Table 1). The only units for which both pre- and post-retrofit data were collected are Building 8, Units 31A, 31B, and 35B, and Building 16, Units 18A and 18B. Again, these units represent a variety of unit types of varying sizes. The change in air leakage measurement for these five units is shown in Table 3.

**Table 3. Direct Comparison of Pre-Retrofit and Post-Retrofit Air Leakage Test Results**

| Building and Unit Number, and Unit Type | Unguarded CFM50 (% change) | ELA/100 $ft^2$ enclosure (% change) | ACH50 (% change) | CFM50/$ft^2$ Enclosure (% change) |
|---|---|---|---|---|
| Building 8, Unit 31A, middle unit | –53% | –46% | –53% | –52% |
| Building 8, Unit 31B, end unit | –51% | –57% | –52% | –50% |
| Building 8, Unit 35B, middle unit | –49% | –61% | –49% | –49% |
| Building 16, Unit 18A, middel unit | –22% | –58% | –22% | –23% |
| Building 16, Unit 18B, end unit | 9% | 1% | 8% | 10% |

Of these five units, three show a strong reduction in air leakage measurement, one apartment exhibits a modest reduction, and one actually shows a slight increase. This small sample of pre-retrofit and post-retrofit air leakage data highlights the variations that are encountered in a project of this scale, even where, at first glance, the construction appears to be incredibly uniform and the scope of work repetitive.

Unit 18B in Building 16 had the lowest pre-retrofit air leakage measurement of the apartments tested. In fact, the normalized pre-retrofit air leakage measurements for this particular apartment are very close to the average post-retrofit air leakage measurements. Given that this apartment unit started with a relatively low air leakage measurement, there are factors that could explain why the post-retrofit air leakage measurement was actually higher for this unit:

- Unit 18B in Building 16 is among a set of units tested early in the construction and wherein it was discovered that some of the backdraft dampers were not functioning properly.
- There is natural variability in the effectiveness of the air sealing given the variability of building conditions and differences among crews performing the work.

During post-renovation scope air leakage testing of the first group of apartments, BSC found a noticeable amount of airflow through the grille for the new exhaust added to the bathroom and through the range hood for the exhaust added to the kitchen. The implementation of mechanical exhaust systems for the kitchen and bath included backdraft dampers in the exhaust ductwork (supplemental to the backdraft flappers on the bath fan and range hood). However, the functioning of these added backdraft dampers could be impeded, for example, by ductwork that is out of round or by debris in the backdraft damper sleeve. After BSC brought these problems to the attention of the project team, the general contractor accessed the dampers and repaired the installations where necessary. The general contractor also committed to verifying proper functioning of each subsequent backdraft damper installed. BSC did not observe apparent failures of the backdraft damper in testing conducted after the initial group of apartments.[6]

Even with perfect sealing of the exhaust duct penetrations and supplemental backdraft dampers in the exhaust duct, it would be reasonable to expect a small amount of leakage around a closed backdraft damper. Therefore, some amount of net increase in air leakage measurement can be expected to result from adding two mechanical exhaust systems.

The opening observed at the intersection of the duct riser and duct soffit (see Figure 18 and Figure 19) provides an example of how variations in the building construction would impact the construction crews' ability to implement effective air sealing. Figure 19 shows a wide berth between the duct riser and the sidewall of the closet. This provided room for the drywall subcontractor to install a drywall patch to close the face of the duct soffit. In other apartments, it was observed that the space between the duct riser and sidewall was approximately 1 in., thus making the drywall patch remediation impossible. In unit 18B of Building 16, which is an end-unit apartment, this connection between the duct riser and duct soffit occurs at the back of a narrow closet rather than at the side of a wide and easily accessible closet. As shown in Figure 26, access to this connection is constrained by the geometry of the closet and by tenant belongings.

[6] Because of the need to limit additional disturbance of residents, and because of practical limits of research resources, it was not possible for BSC to return to retest the first group of post-renovation apartments tested.


**Figure 26. Duct riser to duct soffit connection at the back of a narrow closet in end-unit apartments.**

Other more widespread factors would result in air leakage reduction variations. During air leakage testing, BSC observed that some of the new window units are extremely difficult or impossible to latch closed. Although the casement units can be cranked closed, air leakage through the window unit would be less when the latch cams pull the sash against the frame gasketing. During observation of window installations, BSC noted that the seal between the new window units and the window opening appeared to vary between window installation crews (see discussion in Section 5.2.7). From this it might reasonably be inferred that different crews achieved varying levels of effectiveness in sealing the gap between wood bucks of the window opening and the masonry opening.

These factors might explain the slight net increase in air leakage measured at unit 18B of Building 16, but the convergence and magnitude of these factors in this observed case are unusual.

To gauge the overall impact of the renovation on air leakage performance in the midst of the observed variability, statistical methods were used to calculate a 90% confidence interval for the difference between the mean pre- and post-retrofit airtightness results for all Castle Square units. Using results from the 11 sample pre-retrofit units and 32 sample post-retrofit units, the range of pre- to post-retrofit improvement achieved for the entire project was estimated. Confidence intervals are useful for the analysis of sample data meant to represent a larger set. For this type of project, it would be very unlikely for the project budget to allow pre- and post-retrofit airtightness testing of every unit.

Ninety percent confidence intervals were calculated for all three of the geometry-normalized airtightness results included in Table 1 and Table 2: ELA/100 $ft^2$ enclosure, ACH50, and CFM50/$ft^2$ enclosure. CFM50, the “raw data” value calculated by blower door testing, was omitted because differences in volume and surface area among the apartment units would distort the comparison.

In Table 4, the "sample mean difference" in the third column is computed by taking the mean of the pre-retrofit data shown in the first column and subtracting the mean of the post-retrofit data in the second column. The 90% confidence interval in the last column is computed from the sample sizes, means, and standard deviations using standard statistical methods. Due to sample sizes lower than 30, the T-table rather than the Z-table was used. This 90% confidence interval indicates 90% confidence that the mean difference between pre- and post-retrofit airtightness test results for all units at Castle Square falls within the intervals specified. The values in these intervals show significant improvement from pre-retrofit sample means. The ranges do not contain any negative numbers, which would have meant that that air sealing efforts made the units more air leaky. For example, the results for ACH50 show 2.90 to 5.21 as the 90% confidence interval. This means that we are 90% confident that for all units at Castle Square, the air-sealing efforts reduced ACH50 values by an average of somewhere between 2.90 and 5.21 ACH50 or between 29% and 52%.

**Table 4. Statistical Comparison of Pre-Retrofit and Post-Retrofit Air Leakage Test Results**

| Airtightness Metric | Pre-Retrofit Sample Mean (based on 11 units) | Post-Retrofit Sample Mean (based on 24 units) | Sample Mean Difference (pre-retrofit minus post-retrofit) | 90% Confidence Interval for Leakage Reduction From Air Sealing |
|---|---|---|---|---|
| ELA/100 $ft^2$ enclosure | 4.1 | 1.92 | 2.20 | 1.56 to 2.83 |
| ACH50 | 10.1 | 5.99 | 4.06 | 2.90 to 5.21 |
| CFM50/$ft^2$ enclosure | 0.6 | 0.32 | 0.25 | 0.16 to 0.35 |

Although an overall improvement in air leakage is shown, the goal of 1.25 ELA/100 $ft^2$ of enclosure was achieved for only six of the post-retrofit apartments shown in Table 2. Given the very limited nature of the retrofit scope relative to the potential air leakage pathways, it is not surprising that few of the apartments achieved the ambitious air leakage target. Furthermore, initial testing on sample "mock-up" apartments did not give definitive proof that the specification was achievable.

As described in Section 4.1, the project scope included the sealing of all penetrations made accessible with the kitchen renovation. However, most demising wall and exterior wall area was outside the scope of work. To properly seal these areas it would have been necessary to remove drywall extensively in the apartment. This extensive and disruptive interior work could not be accommodated within the project budget and the fundamental project constraint that the units needed to remain occupied during the renovation.

Supplemental diagnostic testing was conducted on selected apartments post-retrofit. A comparison of the fully unguarded (adjacent apartments open to exterior) and guarded blower door air leakage measurements are shown in Table 5. Measurements suggest that interunit leakage remains a significant component of overall air leakage measurements.

**Table 5. Post-Retrofit Diagnostic Testing for Select Apartments in Buildings 16 and 17**

| Building and Unit Number | Unguarded CFM50 | Left Side Guarded CFM50 | Right Side Guarded CFM50 | Inferred Guarded CFM50 | Difference Unguarded to Inferred Guarded |
|---|---|---|---|---|---|
| Building 16, Unit 10A (end unit) | 1092 | NA | 1039 | 1039 | 5% |
| Building 16, Unit 10B (middle unit) | 992 | 955 | 782 | 745 | 25% |
| Building 16, Unit 12A (middle unit) | 926 | 748 | 786 | 609 | 34% |
| Building 16, Unit 14B (middle unit) | 1037 | 933 | 826 | 722 | 30% |
| Building 16, Unit 16A (middle unit) | 1081 | 654 | 1017 | 590 | 45% |
| Building 16, Unit 16B (middle unit)* | 1011 | 812 | no data | 507[i] | 50% |
| Building 16, Unit 18A (middle unit)* | 919 | 614 | no data | 427[i] | 54% |
| Building 16, Unit 18B (end unit) | 904 | 716 | NA | 716 | 21% |
| Building 17, Unit 2A (end unit) | 562 | NA | 437 | 437 | 22% |
| Building 17, Unit 4A (middle unit) | 971 | 676 | 735 | 440 | 55% |
| Building 17, Unit 4B | 1254 | 844 | 1048 | 638 | 49% |
| Building 17, Unit 6A (middle unit) | 878 | 601 | 671 | 394 | 55% |

* Leakage reduction measured at neighboring unit applied as reduction for common demising wall.

Ideally the demising walls would provide a continuous airflow control surface from concrete floor to concrete ceiling and from the airflow control surface of the exterior wall at the front to the airflow control surface of the exterior wall at the rear of the apartment. Presently there are four major deficiencies to this continuity:

- Drywall of the demising wall does not reach the underside of concrete ceiling behind duct soffits.
- Drywall does not connect to the air barrier surface of the exterior wall (coated CMU or coated cast concrete) at rear of building. Note: demising wall drywall connected to exterior wall at front of building through kitchen renovation scope.
- Partitions connecting to the demising wall. In particular, the partition connecting to the demising wall adjacent to the flue chase appears to represent a significant vulnerability.
- Drywall does not connect to concrete floor slab because of rodent activity or dimensional gap. The vinyl base is either missing or does not adequately connect the demising wall to the floor.

The following issues were noted as possible air leakage pathways through or around the airflow control layer of the exterior wall:

- The wood buck is not properly sealed to the CMU opening. Interior finish would need to be removed at windows to remedy the problem.
- The bathroom exhaust duct may not be properly sealed to the inside surface of the CMU backup wall.
- At locations where the CMU backup wall meets the cast concrete, the frame may not be a solid mortared connection.

The observations during post-retrofit testing identified factors that, to a greater or lesser extent, contribute to the post-retrofit air leakage performance. These are unlikely to be significant or widespread enough to account for the observed difference between measured performance and the aggressive air leakage targets:

- Some of the backdraft dampers inserted into exhaust ducts (supplemental to the flappers incorporated in the exhaust fans) appeared not to provide robust backflow prevention, as airflow from exhaust grilles was noticeable during testing in a number of apartments.
- Air leakage was felt around installed through-the-wall air conditioners during testing, through the unit, particularly through the electrical cord opening.
- Some new sliding windows would not completely latch.
- Door gaskets do not seat completely. It was observed that either the solid wood doors that were retained or the steel door frames are not completely square. Gasketing and door sweeps sufficient to perform with the door in the closed position would have prevented operation of the door in many cases.
- At several locations on the second floor walls and soffits, the drywall surface appears to have settled downward, creating a gap between the drywall and the underside of the floor/ceiling assembly (Figure 27).

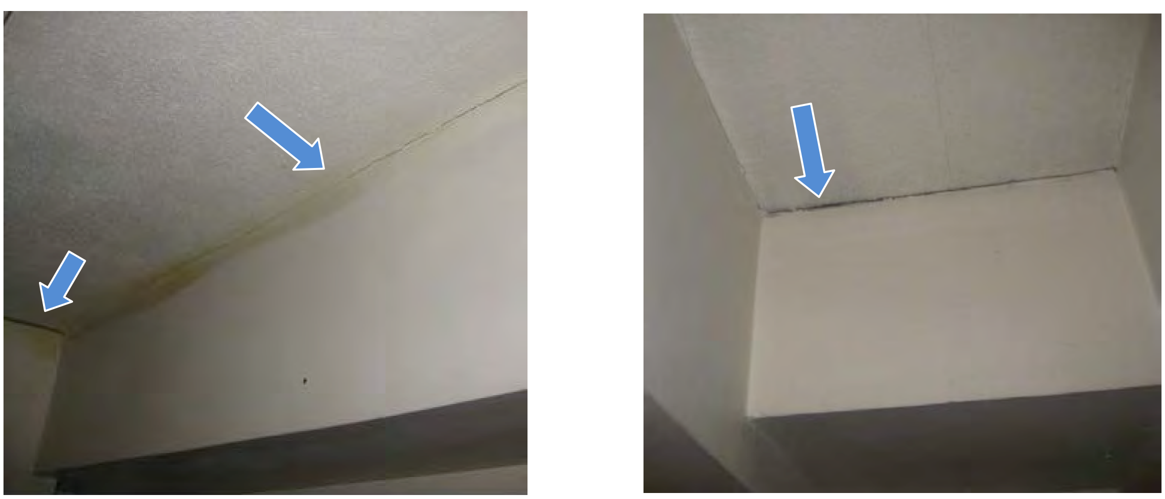

**Figure 27. Gaps between drywall and floor/ceiling assembly observed at second floor**

## 5.2 Window Replacement

When the regular post-mock-up installation of windows began, BSC was called to the site to review the initial window installations. Despite the care to resolve issues in the mock-up apartment, several important performance issues emerged.

### 5.2.1 Location of Airflow Control

In high performance construction and renovation, it is very important that workers implementing a measure understand the function of components affected by their work. The window installation foremen who worked on the mock-up and initial window installations understood the airflow control and water management function of the components they installed as well as components of the surrounding assembly.

In an attempt to simplify the window installation, the window installation foremen experimented at the first apartment window installation with using the expanding foam sealant for the flashing membrane substrate.

**Figure 28. Left: Expanding foam sealant installed to bridge the cavity between the brick and the CMU; Right: Expanding foam sealant trimmed to provide substrate for flashing membrane.**

The risks inherent in this approach are twofold. First, there is no opportunity to visually verify the air seal at the critical juncture, that is, between the CMU opening and the wood bucks. Second, where the foam sealant bridges the brick cavity, this could lead to the mistaken interpretation by subsequent installation crews that the brick is the airflow control layer. With the weep holes and generally porous nature of the brick, it is not an air barrier component.

After reviewing this alternative with BSC personnel, the subcontractor agreed that using the wood buck off-cut is preferable and would be the method employed on the remainder of the job.

### 5.2.2 Varying Size of Opening and Consequences for Sill Flashing

The general contractor had been aware that the window sizes varied subtly throughout the development. Before placing the first large window order – windows for nearly half the complex – the general contractor measured every window in the complex.

At the first apartment where windows were installed as part of the regular construction process, problems with the size of the window became apparent. Although the windows fit within the rough openings given by the existing wood bucks, the height of the stone sill at the exterior relative to the height of the sill buck varies. For the sill flashing to be above exterior sill trim and/or slope onto the exterior sill trim, the window openings require varying amounts (heights) of blocking at the sill. Because of the tight tolerances of the window size relative to the rough opening, the window installers were not always able to install sufficient blocking to raise the sill flashing above the exterior trim (see Figure 29 and Figure 30).

**Figure 29. Sill blocking even with height of exterior sill prior to installation of exterior sill trim piece.**

**Figure 30. Left: Exterior sill trim above height of sill blocking; Right: Back-sloped sill trim.**

This situation with the position of exterior elements relative to the window opening would have been difficult to recognize from the interior.[7] It is presumed that, when windows throughout the complex were measured, they were typically measured from the interior, as exterior access to most of the windows would have required a ladder or lift.

After the initial window order, the general contractor adjusted the height of windows in subsequent window orders for the project.

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[7] In a structure where the brick is supported independently of the concrete frame, creep may have been considered a factor in the elevation of the exterior sill above the sill in the masonry opening. In this structure, the brick wall is constructed as infill between concrete frame elements, including concrete slabs that interrupt the brick at each floor, so creep is not considered an important contributor to the problematic placement of the exterior sill relative to the window opening.

### *5.2.3 Room for Proper Seal at Window Head*

Another issue related to the window size tolerance is the implementation of the weather seal at the window head. The head of the window opening is the concrete slab forming the ceiling of the apartment and floor of the unit or space above. The window is set back from the edge of the slab. At most of the window openings, a reglet in the bottom of the slab provides a drip edge. Protection from driven rain or water that clings to the underside of the slab is provided by a sealant joint at the window head. Due to the constrained space of the window opening relative to the vertical dimension of the window and the need for blocking at the sill, the head of the window unit was typically very tight to the slab ceiling. In many observed cases, the only sealant joint possible at the window head was a fillet bead. A fillet bead is very reliant on adhesion to substrate to provide a good seal. Such adhesion may not be robust in situations where the substrate is not clean as would be expected in a retrofit situation (note limitations on cleaning of the substrate discussed in Section 5.2.5).

During a series of window leakage tests conducted on behalf of the window manufacturer, one of the windows tested was found to leak at the head of the window where a fillet bead seal had failed. BSC advised that the window head be shimmed down from the top of the window opening to allow for a design joint of backer rod and sealant but that this should only be done if the sill pan flashing can be maintained above the exterior sill trim (see Appendix G).

### *5.2.4 Corners of Sill Pan Flashing*

The flashing of the window opening was executed entirely of nonformable self-adhered bituminous membrane. In general, the installing subcontractor did well to push the membrane into corners to avoid tenting of the membrane. With the extremely tight sizing tolerance on many of the windows, there is a danger of tearing the sill pan corners when the window unit is pushed into the opening (see Figure 31).

Preformed corner pieces would be preferable to a membrane for the sill pan flashing as these would be less likely to be abraded, cut, or torn by the corners of the window during window installation.

**Figure 31. Corner of sill pan flashing in a very tight spot. Note that backing is left on the portion of the flashing membrane to the inside of the window to facilitate turning the membrane up at the sill to form a back dam.**

### *5.2.5 Adhesion of Flashing Membrane*

On some of the early window installations, the bituminous membrane used for the window flashing was not consistently adhered to the brick surface at window jambs (see Figure 32). The risk of this situation is that, should water get past the outer sealant joint between the window frame and the brick, it would be directed into the wall cavity or to the rough opening framing rather than into the sill pan flashing at the bottom of the window opening.

Some techniques that may be typically applicable in retrofitting flashing to brick masonry were not viable for this project. Regletting of the brick was not considered because this would have added a significant complication to the already involved installation procedure. Dust generated by cutting or grinding of the brick would have been a problem given that apartment units were occupied. With the presence of older asbestos-containing caulking around the window opening, it was necessary to minimize disruption of the brick returns at the window opening. Because the face of the window is inset from the face of the single-wythe brick, there is very limited surface area for a concealed or protected flashing to adhere.

It is possible that dust and debris on the brick surface prevented good adhesion of the membrane. In this project, it was not possible to scour the brick clean because of the presence of asbestos-containing caulk on the brick around the window opening. A liquid-applied primer may have helped with the adhesion of the membrane. It is also possible that a membrane better suited to adhering to irregular surface would provide a more robust jamb flashing for the window opening. BSC recommended that the installation incorporate the use of a liquid primer at the brick openings.

**Figure 32. Jamb flashing membrane poorly adhered to brick substrate as evident in gaps between the membrane and the brick.**

### 5.2.6 Location of Weeps for Window Opening

The window units have a means to drain water through weep holes formed into the window frame. The window openings must also be allowed to drain any liquid water that accumulates in the opening. BSC explained to the window installation subcontractor, general contractor, and owner's representative that the weather seal is to be made continuous at the exterior edge of the window frame on three sides (top and sides) to allow drainage by gravity at the bottom and that the air seal is to be made continuous at the interior edge of the window frame on all four sides.

The replacement window installations at Castle Square include a snap-in closure piece at the bottom of the window. The bottom edge of this closure piece is flexible to allow the closure piece to conform to irregularities of surface. The plastic closure piece fit like a squeegee over the aluminum sill trim at some installations. At other installations, there was a noticeable gap under the closure piece. Where the closure piece fit tight against the aluminum sill trim, it essentially acted as a weather seal that would prevent the window opening from being able to drain. The initial advice from BSC to provide for some drainage of the window opening was to stop the sealant joint at the jambs short of the sill trim (see Figure 33).

The weep opening at the corner also provided a potential path for rainwater entry at precisely the most vulnerable location of the window opening. BSC recommended to the project team to continue the sealant joint at the jamb down to the sill trim and provide weeps for the window opening by notching the closure piece with a "V" cut at roughly the ¼ points from to either side of the sill closure (see Appendix G). BSC also recommended that the sealant joint continue along the joint between the sill trim and the brick return at either side of the sill.

**Figure 33. Sealant joint stopped short to allow drainage also presents potential path of water entry.**

**Figure 34. Left: Sealant joint between sill aluminum sill trim and brick, and "V" cut weep notched into sill trim closure; Right: Weep holes at ¼ points of the sill closure trim.**

### *5.2.7 Air Sealing at Window Interior*

The window installation subcontractor had used a low-expansion foam sealant to air seal the interior window perimeter. It is noted that the foam sealant can create an obstruction to subsequent finish work and that the expansion of the foam sealant sometimes causes voids in the sealant joints. In other observed instances, the foam sealant fails to completely seal the window to the opening. From the variability in the air seal effectiveness evident to visual observation, it appears that effectiveness of "canned foam" air sealant is highly dependent on skill of application.

**Figure 35. Left: Expanding foam sealant at window jamb and fillet bead of sealant at head of early window installation; Right: Poor seal at window perimeter with gaps permitting view to outside.**

The series of window leakage tests conducted by the window manufacturer highlighted the importance of the perimeter air seal at the interior edge of the window frame in resisting pressures and air flow that has the potential to carry water through the opening. Where the gap between the window frame and the rough opening is sufficiently uniform, backer rod and sealant supplemented with sealant around window attachment brackets can be expected to provide a more robust air seal than foam sealant.

# 6 BEopt Modeling

## 6.1 Multifamily Modeling Abstractions

Energy modeling is used to analyze the predicted performance of a representative end-unit apartment and of a representative middle-unit apartment. The representative units are two-story walk-up apartments, as is the nearly universal condition within the low-rise portion of the Castle Square development.

The geometries of multifamily and attached housing present several challenges when modeling these homes in BEopt. There are also difficulties in modeling mechanical systems shared by multiple dwelling units.

Enclosure surfaces shared in common with another dwelling unit are assumed to be adiabatic; however, this condition cannot be directly represented in BEopt. The problem is actually twofold: it is not possible to specify an adiabatic surface, and all walls must have the same construction. The selected workaround is a fictitious garage with very high R-value walls. This permits specifying which walls are adiabatic, but only on the first floor.

The apartment units that are the subject of this project have occupied units adjacent on one or both sides, as well as above. The adiabatic ceiling is modeled as an R-100 assembly. Given that the walls are below R-5, this ceiling input is a reasonable approximation of relative enclosure conduction losses and gains.

To negotiate the limitations on adiabatic walls, the two-story apartment units are modeled as having only one story, keeping finished floor area constant. This results in the correct exposed wall area for the end unit. Having reduced the model to a single story, the fictitious garage can be used to simulate the second adiabatic demising wall of the middle unit.

Modeling the two-story apartment as a single story doubles the roof and floor areas. As no insulation can be added to the ceiling or floor in the actual project, the modeling abstraction is expected to have minimal effect on the determined optimal path. The increased area is, however, expected to increase the heat loss of the model relative to the actual building.

BEopt allows window areas to be specified per orientation, so the solar gains should be accurate despite the nonliteral geometry. However, a small error is introduced by the solar gains on opaque wall areas.

The mechanical systems are described in the simulation tool using system types available in the software and having efficiencies similar to those expected from the actual systems. A high-efficiency gas-fired boiler will provide both space heat and domestic water heating in these housing units. One boiler and one storage tank (heated by the boiler) will serve groupings of two or four apartment units. Each apartment has an air handler with a hot water coil connected to the boiler. BEopt does not directly model this system configuration. Gas combustion systems with similar efficiency were selected to represent both the heating system and the water heating system.

The space heating system is modeled as a furnace because duct leakage is significant. Prior to the retrofit, the ducts were very leaky, as measured by depressurization, and partly located in a vented mechanical room. The new boiler is sealed combustion, allowing the mechanical room to be closed off from the exterior (louver removed from door and door gasketed), and these ducts and air handling equipment effectively brought into interior, semiconditioned space. The boiler is expected to operate in condensing mode much of the time during space heating. The heating equipment is therefore represented in the model as a furnace with 92% energy factor (EF). During DHW production, condensing operation at the boiler is unlikely, so the water heating system is represented as a tankless water heater with efficiency close to 82%. Because one tank is shared among several apartments, storage losses are a small fraction of total DHW gas use.

The exhaust-only ventilation system was straightforward to model in BEopt, as were the lighting upgrades. The air conditioners are through-wall units permanently installed in a flashed and air-sealed sleeve. The performance of the pre-retrofit air conditioners is unknown. Some units lacked cooling, and many installed units were intended for windows. Through-wall installation of window air conditioners compromises airflow over the outdoor coil, so the actual performance is likely much worse than the rated or modeled SEER.

Aside from the walls shared with other dwelling units, the enclosure was relatively straightforward to model. The slab and uninsulated masonry walls were described using existing BEopt assembly library entries; windows were specified using National Fenestration Rating Council ratings.

## 6.2 Modeling Inputs

Inputs used to describe the building components for the existing conditions case, post-retrofit case, as well as for selected alternatives are presented with the cost information used in Table 6.

Table 6 presents inputs used to describe the building components for the existing conditions case, post-retrofit case, and for selected alternatives with the cost information. In most cases, the measure cost was calculated as the sum of several line items in the builder's requisition. In cases where necessary detail was not available, a best estimate is used based on the larger work scope in which the energy-saving measure was included.

**Table 6. Selected BEopt Modeling Inputs**

| Building Component | Pre-Retrofit Parameter | Post-Retrofit Parameter and Alternatives | Cost of Upgrade | Cost Source |
|---|---|---|---|---|
| **Walls** | Brick and block cavity wall with interior strapping and wall board. Input as 6-in. hollow CMU | No change. Input as: 6-in. hollow CMU; no upgrade | N/A | N/A |
| **Windows** | U = 0.45, SHGC = 0.55 | U = 0.2, SHGC = 0.17 | $150/ft$^2$ of window | Installed cost |
| | | Alternate: Double-glazed U = 032, SHGC = 0.30 | $146/ft$^2$ | Alternate product quote |
| **Infiltration** | 8.1ACH 50 | 5.9 ACH 50 | $4.80/ft$^2$ of conditioned floor area | Installed cost |
| **Heating System** | Gas furanace, 78% AFUE | Hydro-air system with shared condensing boiler and variable speed blower air handler per apartment. Input as: Gas furnace, 92.5% AFUE | $10,076 | Installed cost |
| **Duct Sealing** | 30% leakage to outside | 7% leakage to outside | $1,607 | Installed cost |
| **Cooling System** | Assorted PTACs Input as SEER 10 | SEER 13 | $1,006 | Installed cost |
| **Ventilation** | None | 100% of 62.2, CFIS | $700 | BSC estimate, with input from contractor data |
| **Lighting** | 60% fluorescent hardwired | 100% Fluorescent, hardwired | $656 | Installed cost |
| **DHW Heater** | Gas EF 0.59 | Indirect-fired storage tank supplied by high-efficiency gas boiler. Input as: Gas tankless, EF 0.82 | $1,193 | Installed cost |

## 6.3 Modeling Results

The simulation model predicts that the renovation scope will result in 16% source energy use reduction for the representative end-unit apartment.

In Figure 36 and Figure 37, the cost data for each measure are entered as the total cost for relevant scopes of work. The advantages are that these costs are specific to this project, and known to the owners. The cost for each measure is given in Table 6.

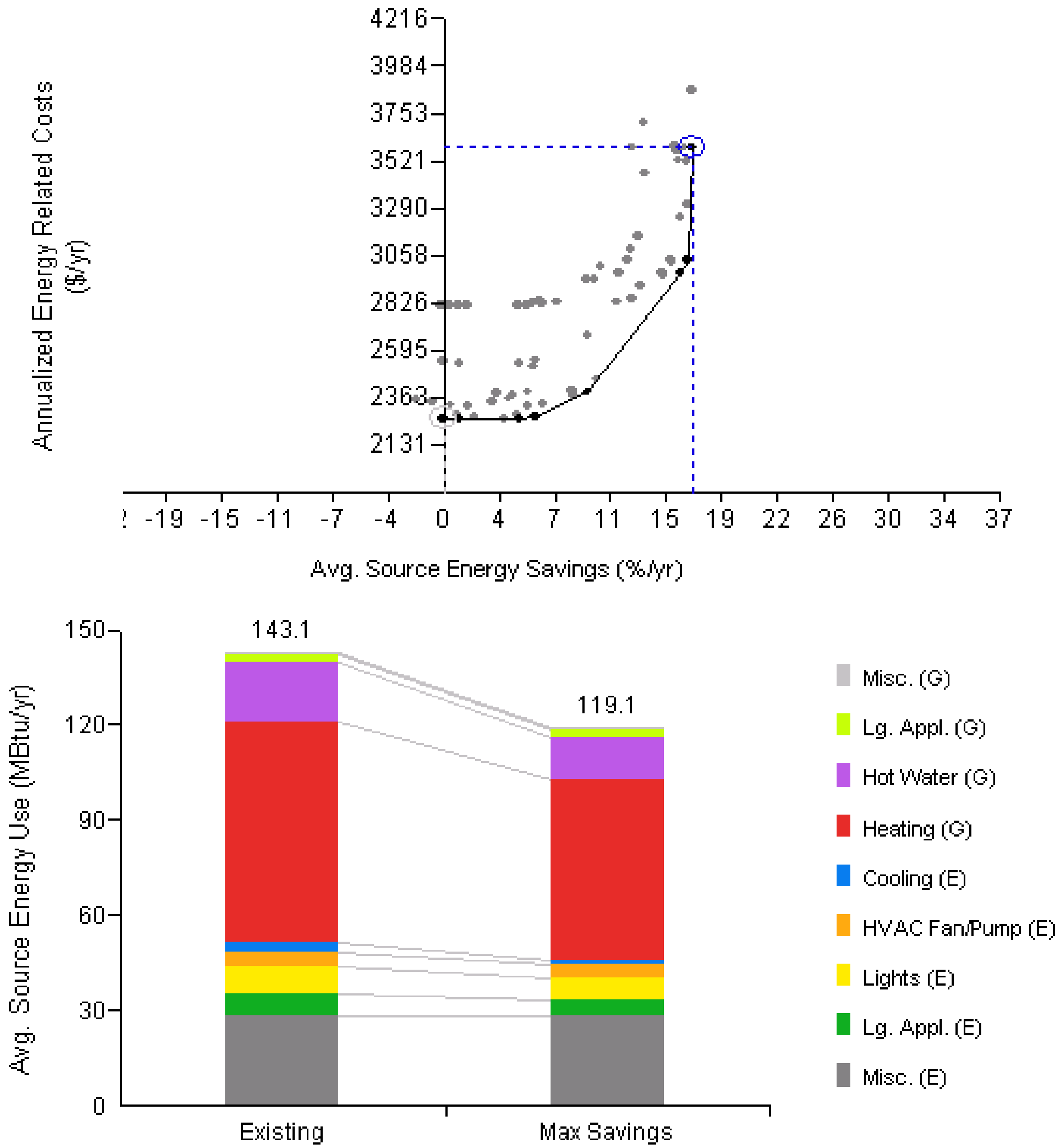



**Figure 36. Representative end-unit apartment BEopt results for as-designed condition and selected alternatives.**

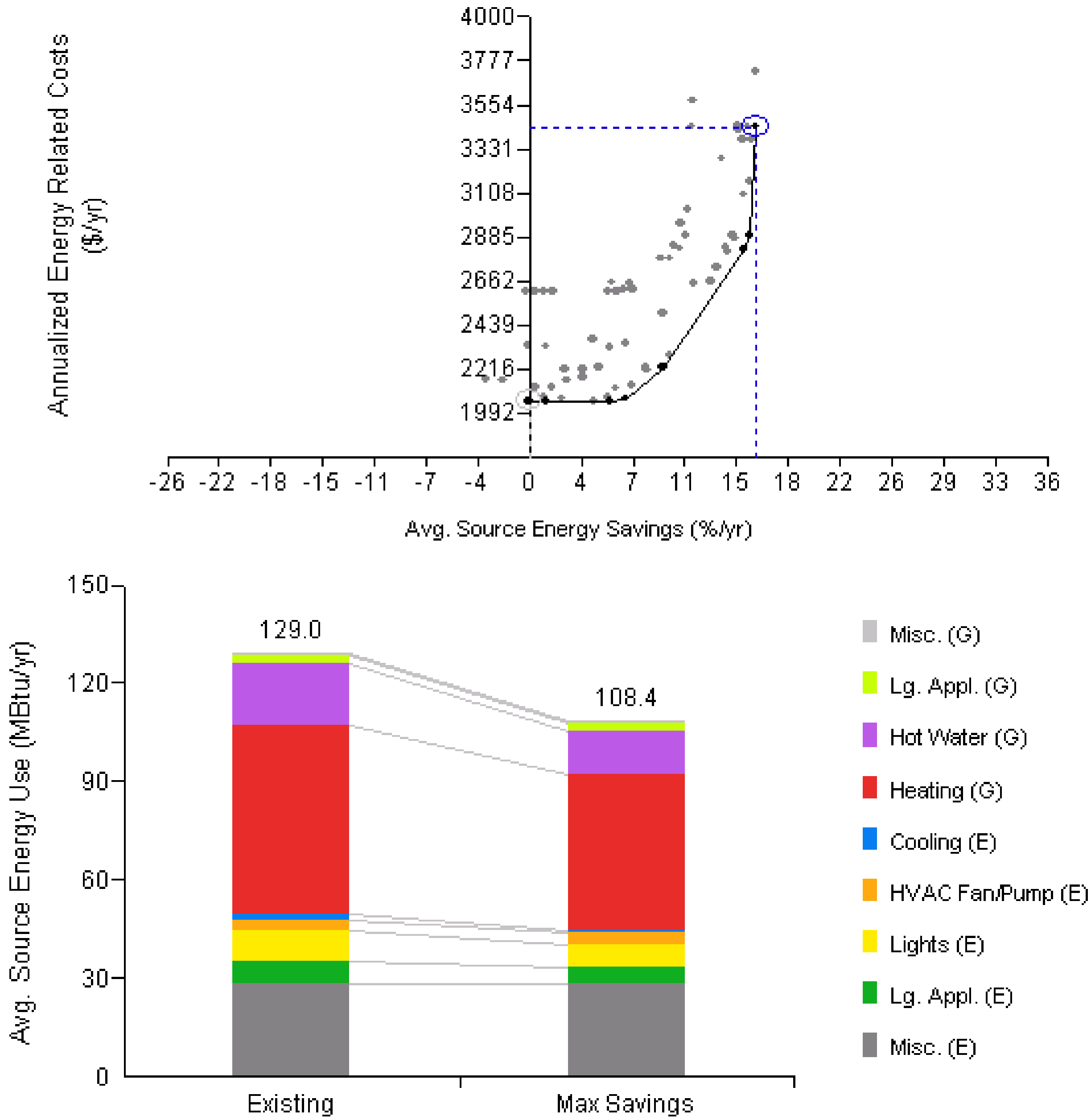



**Figure 37. Representative middle-unit apartment BEopt results for as-designed condition and selected alternatives.**

Ideally, an alternate cost would be available for each measure, corresponding to the work scope, which would have been performed at this time as part of regular periodic maintenance of the buildings, without special concern for energy performance. Regular maintenance of this sort, typically on a 15–20 year schedule, is a normal part of multifamily budgeting. Using scheduled maintenance as a baseline for the cost and energy savings of the retrofit would likely give answers more useful for decision making.

For example, the building owners (CSTO and Winn) had determined a need to replace the windows during this refinancing cycle for nonenergy reasons. The reported incremental cost of the R-5 windows relative to windows that would otherwise meet requirements is less than 2% of the total installed cost. Figure 38 compares the annualized energy-related costs using the all-in cost to those using the incremental cost. This graph essentially compares the annualized energy-related costs under two measure cost scenarios. In the first scenario, the total cost of the high performance measure is assigned as an energy-related cost. In the second scenario, only the cost increment for the high performance measure relative to "what the project would have done anyway" is assigned to the measure.

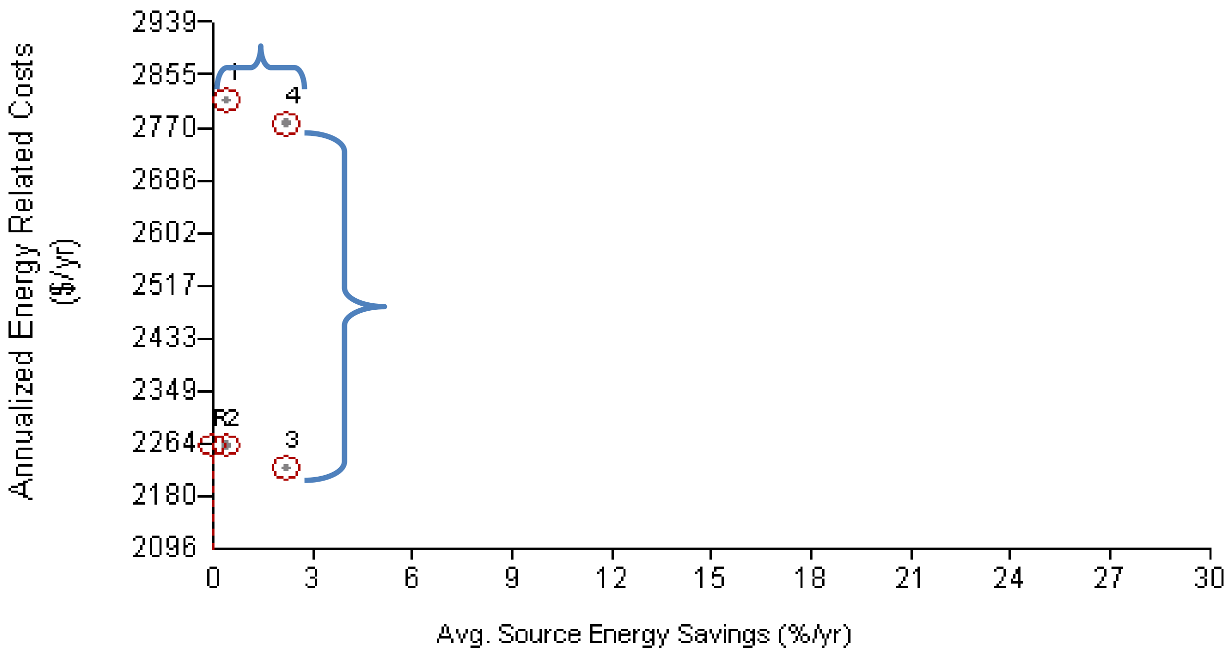



**Figure 38. Castle Square low-rise or "garden" apartments.**

Another factor important to this window measure is that, proper detailing and remediation contributed significantly to air leakage reduction. In scenarios 3 and 4 shown in the graph, a significant portion of the overall air leakage reduction benefit is assigned to the window measure.

As represented in this graph, a so-called energy savings cost effectiveness analysis using the energy-modeling tool produces radically different results, depending on what is determined to be the incremental energy-related cost of the measure and on which benefits are assigned to the measure. Furthermore, the large region of cost effectiveness representations for this single measure considers only the energy-related benefits. Clearly any cost analysis must be specific as to what incremental energy-related cost and benefits are used for each measure, and must acknowledge important value criteria that cannot be captured in the analysis.

# 7 Recommendations for Future Work

## 7.1 Indoor Air Quality Assessment

One of the objectives that the residents and owners sought to achieve with the renovation is improved IAQ. Prior to the retrofit, there was widespread discontent associated with cooking odors from neighboring apartments. Cooking odors may also be interpreted as a surrogate for airborne contaminants more generally.

Surveys of resident perception relative to IAQ and possibly monitoring and measurement, would help to substantiate the success of the renovation work in improving conditions. Comfort and IAQ are likely to be perceived as more strongly correlated to resident satisfaction than energy savings. As such, building users and owners may be more likely to pursue investments in measures seen to benefit comfort and IAQ.

As of this writing, the CSTO has initiated a survey of residents to gather perceptions about the project and about performance issues in terms of thermal comfort and IAQ. Preliminary feedback from residents indicates the problems with odor transmission between apartments are reduced but not eliminated.

Assessments or research that can help to establish the positive attainment of comfort and IAQ improvements will enable this stronger motivation to be harnessed for measures that also improve energy performance.

## 7.2 Thermal Comfort and Ventilation

During the first winter of operation (concurrent with this writing), CSTO and Winn management received complaints that the ventilation system causes apartments to become very cold at night. One particular complaint is that the toilet, which has a supply register adjacent to it, becomes very cold at night. Whether temperatures within the apartment decrease appreciably or whether the thermal comfort perceptions stem from air distribution patterns is unknown. It could also be that new digital thermostats are programmed with an aggressive setback that suppresses calls for heating during night hours and therefore reduces the opportunity for ventilation supply to operate in conjunction with heating.

It is also not known whether distributed mechanical ventilation might reduce the seasonal need for air conditioning in warmer months.

## 7.3 Generic Details

Details and implementation procedures were developed to respond to the specific conditions of this project. Given the widely recurring need for window replacement in this general building type, generic window replacement details would be of benefit to the goal of reducing energy use in this building type. In addition to generic versions of details for drained cavity wall assemblies such as are represented by this project, it would be important to develop guideline details for other common assemblies such as mass masonry construction. Details that address the phasing, or implementation of retrofit over the course of discrete projects would also be useful to this building type.

# 8 Conclusions

## 8.1 Visually Verifiable Details

Both the air sealing work and the window replacement highlighted the importance of details and sequence that allow for visual verification of work. This is important, not just for quality control purposes, but also to enable the person doing the work to be able to verify that the measure is properly implemented.

## 8.2 Identify Control Functions in Design Documentation

The construction documents for the project included many specific instructions relative to air sealing measures. The benefit of specific instructions can be built upon by instructions that clearly identify which layers or components of construction assemblies are intended to serve critical functions of water, airflow, vapor, and thermal control. This would enable contractors faced with unforeseen conditions in the field to more readily identify (or improvise) solutions that are consistent with design intensions.

## 8.3 Size Window To Accommodate Improved Water Management and Air Sealing

The challenges encountered relative to the size of replacement windows illustrate the need to consider necessary mitigation incorporated into the component replacement. The replacement of windows was taken by the project as an opportunity to provide necessary improvement to water management of window openings. Measures providing water management may not (as in this case) be evident in existing window installations. Therefore, the geometries that determine the proper size of the replacement window will not be the same as those that dictated the size of existing windows. In particular, the sizing of replacement window units must consider the space needed for appropriate flashing and drainage of the opening. The selection of window size must also consider the space needed for proper weather seals and air seals; i.e., the installation should accommodate a full design joint rather than provide clearance for a fillet joint only.

## 8.4 Large-Scale Occupied Renovation Projects Are Not Conducive To Isolating Measure Impact

The research project hoped to be able to isolate and quantify effectiveness of various air sealing measures. The air leakage testing that is required to isolate the effects of individual measures proved impractical. Multiple visits to occupied units were problematic, both in terms of imposing on residents and access to apartments given placement of belongings and active use. Sequencing of construction given the superseding needs of the project cannot be expected to provide precise isolation of measures for evaluation purposes.

## 8.5 Seize Opportunities Presented by Work Involving Removal of Wall Finishes

Interior walls, whether demising walls or partitions, can serve as important air leakage pathways connecting apartments to one another and connecting apartments to air leakage sites in the building enclosure. In an occupied renovation project such as that of Castle Square, it would be prohibitively costly and disruptive to comprehensively pursue compartmenting of apartments. Given that it is generally not possible to remediate and seal all of the wall surfaces within an occupied apartment unit, the maximum opportunity should be sought from any work that does open an existing wall assembly. In this project, significant attention was given to providing continuous airflow control at surfaces of the wall assemblies accessible through the scope of work. Because of airflow *through* the wall cavities (as a duct) and not just across the wall surface, it would be advisable to provide a closure across the wall cavity as part of the airflow control remediation at all wall assemblies that are opened.

# 9 Appendices

## 9.1 Appendix A: Tabulation of Results of Resident Input From Early Design Charrette

This appendix presents a tool used to identify stakeholder priorities. It was developed by the Hickory Consortium and is provided courtesy of Elton + Hampton Architects and used with permission from Elton + Hampton Architects as well as from the Castle Square Tenants Organization.

See attached.

# Castle Square Redevelopment

## Green Charette No. 1

| Category | Orig. | Issue | Personal | Castle Sq. | Global | Total |
|---|---|---|---|---|---|---|
| Indoor Comfort & Ventilation | | Ventilation in kitchen leaves apartment | 16 | 7 | 7 | 30 |
| Miscellaneous | 56 | Insect/Rodent Infestation (Mice Eating Through Walls, Cockroaches Everywhere) 昆蟲/老鼠 (很多昆蟲/老鼠在單位裡, 與在垃圾箱 | 7 | 7 | 4 | 18 |
| Indoor Comfort & Ventilation | 22 | Poor Indoor Air Quality due to Cigarette Smoke, Cooking Smells 因為抽煙味, 煮飯味, 造成室內空氣質量不佳 | 13 | 4 | 1 | 18 |
| Miscellaneous | 42 | Allow Installation of Individual Direct TV Dish Receivers to be Installed, or Install a Central Reviewers 准許居民安裝衛星盤 | 3 | 8 | 5 | 16 |
| Indoor Comfort & Ventilation | 10 | Bathroom Vents Require Installation and/or Repair 廁所氣孔需要裝施或維修 | 10 | 4 | 2 | 16 |
| Indoor Comfort & Ventilation | 23 | Poor Ventilation Throughout Units (Kitchens, Bathrooms, Bedrooms, etc.) 單位裡每個地方通風都不足夠(廚房, 廁所, 睡房, 等等) | 10 | 3 | 3 | 16 |
| Indoor Comfort & Ventilation | 18 | Inconsistent Heating/Air Conditioning 冷氣/暖氣不穩定 | 12 | | 1 | 13 |
| Indoor Comfort & Ventilation | 13 | Frequent Drafts from Windows, Doors, A/C Units in Windows 太多風從窗戶, 門口, 冷氣孔漏進單位 | 7 | 1 | 4 | 12 |
| Water | 74 | Low Flow Flush Toilets Do Not Work Properly- Numerous Flushes Required 馬桶沖水設備不佳- 需要沖多過一次 | | 11 | | 11 |
| Water | 71 | Inadequate Amount of Hot Water熱水不足 | 4 | 2 | 3 | 9 |
| Indoor Comfort & Ventilation | 19 | Individual Thermostats Needed in Units 每個單位都需要溫度調整器 | 5 | 1 | 3 | 9 |
| Miscellaneous | | New Kitchen Cabinets | 2 | 1 | 6 | 9 |
| Landscaping | 24 | Bad Smell from Woodchips/Mulching on Landscape 腐土和木片的臭味 | 2 | 2 | 3 | 7 |
| Miscellaneous | 43 | Closet and Drawers Require Maintenance 需要維護櫃子與抽屜 | | 3 | 4 | 7 |
| Indoor Comfort & Ventilation | 14 | High Level of Noise Penetration Between Units 隔音不佳, 大量的雜音由其他單位流出 | 4 | 2 | 1 | 7 |
| Energy & Electricity | 4 | Install Windows with Reflective Glass 安裝有反射性的玻璃窗 | 5 | | 2 | 7 |
| Energy & Electricity | 8 | Overall Improved Electric Wiring 改善整體的電力/電線系統 | 4 | 3 | | 7 |
| Energy & Electricity | 9 | Poor Lighting in Units (Bedrooms and Living Rooms Fixtures) 單位裡的燈光設備不足(睡房和客客廳的設備) | 5 | 1 | 1 | 7 |
| Miscellaneous | 68 | Windows Require Child Safety Locks窗戶需要安裝幼童的安全鎖 | 1 | 3 | 3 | 7 |
| Indoor Comfort & Ventilation | 11 | Bedroom Windows cannot Accommodate A/C Units 睡房窗戶不能夠裝上冷氣機 | 4 | | 2 | 6 |
| Landscaping | 38 | Redesign Children's Sprinkler System (Summer Outdoor Play Area) 重新設計幼童使用的噴水系統(夏季室外玩耍地區) | | 3 | 3 | 6 |
| Landscaping | | Basketball Court--too many puddle collect flies | | 3 | 2 | 5 |
| Miscellaneous | 45 | Consider Card Access to Buildings Instead of Key Entry 使用電卡進入大夏 - 取代鎖匙 | 1 | 3 | 1 | 5 |
| Energy & Electricity | 1 | Improve Amount of Insulation in Units 改善/增加單位裡的絕緣材料 (隔風材料) | 5 | | | 5 |
| Energy & Electricity | 5 | Kitchen Appliances Require Replacements; Do Not Operate Properly 廚房裡的電器需要更換; 操作的不正確 | | | 5 | 5 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Water | 75 | More Efficient and Effective Bathroom Fixtures 更有效率和更有效的廁所設備 | | 1 | 4 | 5 |
| Energy & Electricity | 6 | More Efficient Lighting/Appliances to Lower Utility Costs 效率更好的燈光設備/和電器來省電費 | 3 | 1 | 1 | 5 |
| Miscellaneous | 50 | Healthier/Safer Chemical Cleaning Products 更健康與安全的化學清潔用品 | 1 | | 3 | 4 |
| Indoor Comfort & Ventilation | | HR hot water--not enough | 4 | | | 4 |
| Indoor Comfort & Ventilation | 15 | HVAC Vents Require Repair and Cleaning 所有的通風口需要維修和清潔 | | | 4 | 4 |
| Landscaping | 31 | Increased Green Areas with Additional Flower Beds for Gardening 增加更多草地與地方另外加可以種植物的花園 | 1 | 1 | 2 | 4 |
| Miscellaneous | 58 | Laundry Facilities Installed on Each Floor在大夏裡的每一樓安裝洗衣設備 | | | 4 | 4 |
| Water | 69 | "Dual" Flush Toilets Suggested for Bathroom提議安裝"雙沖" 的馬桶 | 1 | | 2 | 3 |
| Energy & Electricity | | Better Air Conditioner-- size too small | 1 | 1 | 1 | 3 |
| Indoor Comfort & Ventilation | | Hallway ventilation/elevator | 1 | 1 | 1 | 3 |
| Landscaping | 26 | Improve Grade Changes in Landscape 改善風景區等級的改變 | 1 | 1 | 1 | 3 |
| Landscaping | 27 | Improve Outdoor Paths and Create Seating Areas 改善室外的路到和裝置更多可以坐的地方 | | 2 | 1 | 3 |
| Miscellaneous | 53 | Inadequate Amount of Laundry Facilities, Facilities Being Used Inappropriately 公共的洗衣設備不足, 和被不適當的使用 | 1 | | 2 | 3 |
| Landscaping | 28 | Inadequate Amount of Trees and Vegetation for Proper Shading and Indoor Temp. Control 樹量與植被不足造成不適當的陰影和室內溫度 | | 1 | 2 | 3 |
| Water | 73 | Leakage in Bathrooms and Kitchens廁所裡和廚房漏水 | | 3 | | 3 |
| Water | | Need safety grips in bathrooms | 2 | 1 | | 3 |
| Landscaping | | Need to fix lock to doors | 1 | | 2 | 3 |
| Landscaping | 34 | Outdoor Recreational Spaces (Basketball Court) Requires Repair 室外的籃球場需要維護 | 3 | | | 3 |
| Landscaping | 37 | Plant Additional Trees & Gardens 種更多樹與花園 | 1 | | 2 | 3 |
| Miscellaneous | 41 | ADA Accessibility Requires Improvements (Ramp Repair, Push-Button Entrances, etc.) 需要改善地區的設備使殘障人士行動方便 (維修舷梯, 按鈕進出入口, 等等.) | | 1 | 1 | 2 |
| Water | 70 | Bathroom Floor Drains廁所的地上安裝排水溝 | | 2 | | 2 |
| Indoor Comfort & Ventilation | | Black smoke in apartment | | 1 | 1 | 2 |
| Miscellaneous | 49 | Gym/Exercise Space Suggested for Buildings 有提出在大夏裡建運動的地方 | | | 2 | 2 |
| Indoor Comfort & Ventilation | 16 | Inadequate Amount of Natural Ventilation 不足自然空氣 | | 2 | | 2 |
| Miscellaneous | 54 | Increase Amount of Recycle Receptacles, Increase Awareness to Residents the Importance of Recycling 增加更多回收容器, 讓居民增加知識有關回收的重要 | | 1 | 1 | 2 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Water | | Install drain pans under water heaters | 1 | 1 | | 2 |
| Water | | Make water fixtures efficient and work better | 2 | | | 2 |
| Landscaping | 35 | Outdoor Spaces Inaccessible for Handicap Residents 殘障的居民不容易通用室外的地區 | 1 | | 1 | 2 |
| Miscellaneous | 62 | Replace Flooring換地板 | | 1 | 1 | 2 |
| Water | | Tankless water heater | | 1 | 1 | 2 |
| Indoor Comfort & Ventilation | | Want own ventilation for apartment | | 2 | | 2 |
| Energy & Electricity | | Better location for A/C because Bedrooms Hot | 1 | | | 1 |
| Miscellaneous | 57 | Installation of Low VOC Materials 安裝低量 VOC 的材料 | | | 1 | 1 |
| Water | 72 | Interested in Rain Water Collection對雨水收取有興趣 | | 1 | | 1 |
| Landscaping | 33 | Landscape Requires Maintenance 風景區需要維護 | | | 1 | 1 |
| Miscellaneous | 60 | More Storage Required in Units在單位裡需要更多的倉庫 | 1 | | | 1 |
| Indoor Comfort & Ventilation | 21 | Outdoor Shading Devices Required on Specific Units (Constant Exposure) 在某個單位裡需要室外窗簾設備 (太多陽光照射) | | | 1 | 1 |
| Energy & Electricity | 7 | Outside Insulation Installment Method Preferred 比較想要在室外安裝絕緣材料 (隔風材料) | | 1 | | 1 |
| Water | 76 | Requested Environmentally Friendly Shower Stalls that are Handicap Accessible 要求在殘障人士單位的廁所裡安裝環保的淋浴間 | | | 1 | 1 |
| Landscaping | 40 | Residents would like Therapeutic Stepping Stones Incorporated into New Gardens 居民希望新的花園可以安裝治療墊腳石 (石頭料 | 1 | | | 1 |
| Landscaping | | Shawmut Street Peace Garden | 1 | | | 1 |
| Miscellaneous | | Wall Painting | | 1 | | 1 |
| Water | 77 | Water Leakage from Windows and A/C Units in Windows有水從單位裡的窗戶和冷氣孔漏出來 | | 1 | | 1 |
| Miscellaneous | 44 | Concern for Displacement of Residents During Renovation 擔心當裝修時, 居民需不需要暫時搬走 | | | | 0 |
| Landscaping | 25 | Covered Outdoor Areas with Chess Tables (Pagoda Style) 在室外地區蓋可以下棋的桌子 (蓋在塔子裡面) | | | | 0 |
| Indoor Comfort & Ventilation | 12 | Designated A/C Unit Wall Penetration is too High- Inaccessible 冷氣孔太過高 (有困難使用) | | | | 0 |
| Miscellaneous | 46 | Designated Smoking Areas 固定的吸煙地區 | | | | 0 |
| Miscellaneous | 47 | East/West Entrances Suggested for Additional Access 提供西/北的入口讓出入更容易 | | | | 0 |
| Miscellaneous | 48 | Fire Safety Concerns Throughout Units and Common Areas 關心有關單位和其他地區的火警安全設備 | | | | 0 |
| Miscellaneous | | Fix intercoms | | | | 0 |
| Indoor Comfort & Ventilation | | Heating --cold (Highrise) colder higher | | | | 0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Miscellaneous | | HR better enclosure | | | | | 0 |
| Indoor Comfort & Ventilation | | HR ventilation | | | | | 0 |
| Miscellaneous | 51 | Improved ADA  Accessibility Indoors 需要改善室內設備使殘障人士行動方便 | | | | | 0 |
| Miscellaneous | 52 | Inaccessible Electrical Panel in Handicap Apartments 在殘障人士的單位裡沒辦法使用電路板 | | | | | 0 |
| Indoor Comfort & Ventilation | 17 | Inadequate Natural Light不足自然光 | | | | | 0 |
| Energy & Electricity | 2 | Inadequate Voltage in Units, Frequent Power Outages 單位裡電力不足, 時常停電 | | | | | 0 |
| Miscellaneous | 55 | Increase Amount of Trash Barrels 增加更多垃圾桶 | | | | | 0 |
| Landscaping | 29 | Increased Accessibility in Outdoor Spaces/Landscape 使室外空間/風景區更加容易通用 | | | | | 0 |
| Landscaping | 30 | Increased Courtyards 增加庭院 | | | | | 0 |
| Indoor Comfort & Ventilation | 20 | Inoperable Windows 不能夠使用的窗戶 | | | | | 0 |
| Landscaping | 32 | Install a Fenced in Area for Dogs 安裝一個有圍牆的設備讓小狗使用 | | | | | 0 |
| Energy & Electricity | 3 | Install Photovoltaic Panels to Power Common Areas 安裝光致電壓板 (太陽能源板) 在公用地區提供電力 | | | | | 0 |
| Landscaping | | Low Rise--ice forms on 2nd floor stairs | | | | | 0 |
| Miscellaneous | 59 | Lower Maintenance Costs降低維修的費用 | | | | | 0 |
| Energy & Electricity | | Need covers on A/C to protect from Water/Snow | | | | | 0 |
| Energy & Electricity | | Need more energy efficient A/C | | | | | 0 |
| Miscellaneous | 61 | No Enough Elevators 電梯不足 | | | | | 0 |
| Indoor Comfort & Ventilation | | Not enough windows | | | | | 0 |
| Landscaping | 36 | Outdoor Spaces Requested for Units on Upper Floors 要求蓋室外的地區在頂樓上的單位 | | | | | 0 |
| Landscaping | | Parking different from visitors to help disabled | | | | | 0 |
| Landscaping | 39 | Remove Stepping Stones in Outdoor Pathways 在室外的走道去除墊腳石 | | | | | 0 |
| Indoor Comfort & Ventilation | | Smell in hallway | | | | | 0 |
| Miscellaneous | 63 | Smoke Alarms Activated Frequently due to Cooking因為煮菜, 煙霧感應器時常響 | | | | | 0 |
| Miscellaneous | | stairways in HR wet: repair windows | | | | | 0 |
| Miscellaneous | 64 | Television/Music Suggested for Laundry Facilitates洗衣設備房裡安裝電視/音樂 | | | | | 0 |
| Miscellaneous | 65 | Trash Chute Door Does Not Operate Properly垃圾收集箱不能夠正確的使用 | | | | | 0 |
| Miscellaneous | 66 | Trash Collection Area Requires Daily Maintenance (Improve Cleanliness & Odor) 垃圾收集地區每天需要維護 (改善潔淨 與氣味) | | | | | 0 |
| Miscellaneous | 67 | Unpleasant Smells- Resident's Pets Urinate in Common Areas/Stairwells不雅的嘔味- 居民的寵物在樓梯/公共地方小便 | | | | | 0 |
| Indoor Comfort & Ventilation | | Want management to fix vents rather than complain about smells | | | | | 0 |
| | | | | | | | 0 |

## 9.2 Appendix B: Castle Square Renovation Project Specification Section 01575, Air Tightness and Testing Requirements

Courtesy of Elton + Hampton Architects. Used with permission

See attached.

SECTION 01575

AIR TIGHTNESS AND TESTING REQUIREMENTS

PART 1 - GENERAL

1.01 SUMMARY

A. Perform renovations of apartments, corridors, trash closets, elevator vestibules, and other rooms to achieve continuous enclosure air barriers that limit air leakage into (or out of) the space and verify air leakage control through testing. Assemblies modified or added as part of the renovation scope must be made to be air-, smoke-, and gas-tight. Apartments must achieve specific air leakage targets as indicated in this section.

The Owner's testing agency will be made available to provide technical assistance and testing for the first (6) garden apartments and the first (6) midrise apartments. Thereafter the Owner's testing agency will verify attainment of the air leakage target by sampling approximately 10% of apartments.

B. See Section 01564 for related integrated pest management

C. See Section 07210 for building insulation

D. See Section 07410 for exterior insulation panel system

E. See Section 07530 through 07720 for roofing and accessories.

F. See Section 07840 for firestopping

G. See Section 07900 for air sealers and joint sealers

1.02 DEFINITIONS

A. Air sealing: the use of sealants, gaskets or air barrier materials to establish or maintain the continuous of air flow control.

B. Air barrier materials: any durable materials having an air permeance not to exceeding 0.004 CFM/sq ft at 0.3 iwg [0.02 L/s.m2 @ 75 Pa] when tested in accordance with American Society for Testing and Materials (ASTM) E 2178.

1.03 SUBMITTALS

A. Product Data: Submit manufacturer's product data and installation instructions for each material and product used.

B. Shop Drawings: Submit shop drawings indicating material characteristics, details of construction, connections, and relationship with adjacent construction.

C. Samples: Submit two representative samples of each material specified indicating visual characteristics and finish. Include range samples if variation of finish is anticipated.

1.04 REFERENCES

A. ASTM E 2178 (2003) Standard Test Method for Air Permeance of Building Materials

B. ASTM E 779 (2003) Standard Test Method for Determining Air Leakage Rate by Fan Pressurization

C. ASTM E 1827 (1996; R 2007) Standard Test Methods for Determining Airtightness of Buildings Using an Orifice Blower Door

PART 2 – BUILDING AIR TIGHTNESS REQUIREMENTS

2.02 INTENT

A. Work performed under this renovation scope is to result in enclosures of apartments, corridors, trash closets, elevator vestibules, and other rooms that are air-, smoke-, and gas-tight. Principal benefits to obtained through robust air flow control include:

1. Energy Performance: reduced energy consumption through reduction in uncontrolled infiltration into- and exfiltration out of the building; reduced energy consumption through better containment of space conditioning within conditioned zones; reduced energy consumption through more efficient ventilation system function.

2. Indoor Environmental Quality: control transfer of smoke, odors, and other air-borne contaminants between apartments and other spaces within the building; improve ventilation effectiveness.

3. Pest Management: eliminate open pathways for pests to move into or through the apartments or other parts of the building.

B. The design professionals have made the effort to trace a continuous plane of air tightness for enclosures throughout the building and to indicate flexible seals at all moving joints. If the boundary of the air barrier is not clearly defined in the project drawings, the contractor must alert the Architect.

C. The air barrier material(s) and air sealing materials must have an air permeance not to exceed 0.004 CFM/sq ft at 0.3 iwg [0.02 L/s.m2 @ 75 Pa] when tested in accordance with American Society for Testing and Materials (ASTM) E 2178. Low density spray foam may be used in difficult to access areas such as pipe and duct chases within walls. The air barrier must be durable to last the anticipated service life of the assembly in which it is applied. Sealant and gaskets used to join adjacent air barrier materials must allow for the relative movement of assemblies and components.

D. Join and seal the air barrier material of each assembly modified or added as part of the renovation scope to the air barrier material of adjacent assemblies. The air barrier materials of adjacent assemblies must be joined and sealed in a flexible manner, allowing for the relative movement of these assemblies and components.

E. Seal all floor to floor penetrations including but not limited to electrical and mechanical chases, piping, control wiring and fire protection that are made accessible in the course of renovation work.

F. Avoid unnecessary penetrations through the air barrier material of enclosure assemblies. Any unavoidable penetrations of the air barrier by electrical boxes or conduit, plumbing, and other components or services must be made air-, smoke-, and gas-tight. Do not install lighting fixtures with ventilation holes through the air barrier.

G. Provide a motorized damper in the closed position and connected to the fire alarm system to open on call and fail in the open position for any fixed open louvers such as at elevator shafts. Damper and control to close all ventilation or make-up air intakes and exhausts, when leakage can occur during inactive periods.

H. Provide tight fitting gaskets or weatherstripping for elevator vestibule doors, stair access doors, trash closet doors, doors to trash rooms, and doors to mechanical rooms.

I. All apartment unit entry doors shall be re-fitted with tight fitting gaskets.

J. Spaces intentionally operated under negative pressure to prevent migration of contaminants or odors to other parts of the building must be thoroughly compartmentalized by air sealing the enclosure of the space. Such spaces include but are not limited to trash chutes, trash closets, trash rooms, elevator shafts, and electrical closets.

2.03 BUILDING AIR LEAKAGE TARGET AND TESTING

A. Apartment units shall be air sealed to achieve an effective leakage area (ELA) of 1.25 $in^2$ (square inches) or less per 100 $ft^2$ (square feet) of enclosure area. ELA shall be calculated according to calculation methodology indicated in ASTM E-779 and measured by blower door testing. The apartment enclosure area is the sum of all gross wall, ceiling and floor areas.

B. The architect has defined the bounds of the enclosure and will calculate its surface area to be used in the blower door testing results calculation. For each apartment, the walls, ceilings, and floors abutting adjacent apartments or common areas are to be considered part of the enclosure of the apartment.

C. The Owner's testing agency will be made available to provide technical assistance and testing for the first (6) garden apartments and the first (6) midrise apartments. . Thereafter the Owner's testing agency will verify attainment of the air leakage target by sampling approximately 10% of apartments. Completed apartments will be selected for testing by the Owner's testing agency.

D. If testing shows an apartment to have failed to meet the air leakage target, the Contractor shall make repairs to the air barrier of the apartment so that it meets the air leakage target or the Contractor shall demonstrate, to the Owner's satisfaction, that deficiencies in the air barrier enclosure of the apartment are outside of the scope of the project.

E. The Contractor shall coordinate with the Owner's testing agency and facilitate testing and assessment of air sealing work.

F. Contractor shall notify the Owner at least 10 working days prior to completion of air sealing work in apartments in order to provide the Owner the opportunity schedule testing, alert residents and arrange to witness the tests.

G. The Owner's testing agency shall inspect apartment units selected for testing prior to conducting the air leakage test. This inspection is to verifying that the continuous air barrier is in place and installed without failures in accordance with installation instructions. The Owner's testing agency may elect to refer a selected apartment for additional work and reschedule testing if inspection reveals air sealing work to be incomplete or inadequate.

H. The Owner's testing agency shall communicate results of inspection and testing within two days of inspection and/or testing so that repairs to the continuous air barrier, if needed to comply with the required air leakage target, can be done in a timely manner.

I. For buildings where doorways for each apartment lead directly to the outdoors (i.e., where there is not common interior corridor providing access to apartments), apartments to either side of an apartment being tested shall have multiple doors and/or windows to outside open during the testing. For buildings where apartments are accessed primarily through common interior corridors, apartments to either side, above, and below the apartment being tested shall have a door to the corridor as well as windows to the exterior open during the testing.

J. The air leakage test for selected apartments must be performed in accordance with ASTM E - 779 with the following additions and exceptions using either method one or method two.

1. Method one:

a. The test consists of measuring the flow rates required to establish at least 5 negative apartment pressures from at least 25 Pa to at least 50 Pa. Both before and after the apartment depressurization, at least 12 bias pressure readings must be taken across the envelope and averaged over at least 5 seconds. None of the bias pressure readings must exceed 30% of the minimum test pressure.

2. Method two:
   a. The test consists of measuring the flow rates required to establish at least 5 positive apartment pressures from at least 50 Pa to at least 75 Pa. Both before and after the apartment pressurization, at least 12 bias pressure readings must be taken across the envelope and averaged over at least 5 seconds . None of the bias pressure readings must exceed 20% of the minimum test pressure.

K. The Owner's testing agency shall provide calculations supporting testing results upon request of either the Owner or the Contractor so that the Owner and Contractor can verify that the results are within an acceptable margin of accuracy (i.e. +/- 8% leakage area with 95% confidence interval).

L. At the Owner's direction, the Owner's testing agency may perform additional measurements or assessments of the enclosure air flow control at the time of inspection/testing apartments. At the Owner's direction, the Owner's testing agency may also perform measurements or assessments of air flow control for enclosures outside of apartments. The Contractor shall coordinate with the Owner's testing agency and facilitate this testing and assessment of air enclosure air flow control.

END OF SECTION

## 9.3 Appendix C: Air Sealing Inspection Checklist

See attached.

Air Sealing Inspection Checklist - LOWRISE    Unit Number: ________    Inspector: ________________

| | KITCHEN | | BATHROOM | | LIVING ROOM | | BEDROOM(S) | | UPSTAIRS HALL CLOSET | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Inspection Guidelines** | Corrections Needed | Complete | Corrections Needed | Complete | Corrections Needed | Complete | Corrections Needed | Complete | Corrections Needed | Complete |
| | √ & date | √ & date | √ & date | √ & date | √ & date | √ & date | √ & date | √ & date | √ & date | √ & date |
| Air seal window including closed cell foam at sill and jamb | | | | | | | | | | |
| Caulk door frame to drywall; door gasket | | | | | | | | | | |
| Air seal electrical panel. | | | | | | | | | | |
| Seal gap around supply/return duct plenums connecting apt to mech. closet | | | | | | | | | | |
| Seal at soffit closure above vertical duct. | | | | | | | | | | |
| Seal top of duct riser and bottom of concrete | | | | | | | | | | |
| Seal at new bath and kitchen vent. | | | | | | | | | | |
| Flash over exhaust duct penetrations through brick; air seal penetrations through CMU. | | | | | | | | | | |
| Replace existing registers. Seal from inside of duct to face of drywall with tape. Trim tape at face of drywall so that tape will be concealed by register flanges. Add new sleeve at end of existing duct to eliminate gap. | | | | | | | | | | |
| If soffit is opened, seal all penetrations. Drywall behind soffit is continuous. Drywall extends and seals to ceiling. | | | | | | | | | | |
| Seal all plumbing, electrical and other penetrations through the sound board/drywall. | | | | | | | | | | |
| Connect and seal between the bottom of the wall and the floor. | | | | | | | | | | |
| Connect and seal between the top of the wall and the ceiling/floor assembly above. | | | | | | | | | | |
| Where the floor to exterior wall junction is exposed, clean & apply liquid-applied water proofing to seal wall to floor slab. | | | | | | | | | | |

| Inspection Guidelines | KITCHEN | | BATHROOM | | LIVING ROOM | | BEDROOM(S) | | UPSTAIRS HALL CLOSET | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Corrections Needed | Complete | Corrections Needed | Complete | Corrections Needed | Complete | Corrections Needed | Complete | Corrections Needed | Complete |
| | √ & date | √ & date | √ & date | √ & date | √ & date | √ & date | √ & date | √ & date | √ & date | √ & date |
| Connect & seal drywall/soundboard of demising wall to exterior wall. At side of kitchen adjacent to the exterior wall. Remove 2'-4" wide strip of drywall to allow drywall of the demising wall to be sealed to exterior wall. | | | | | | | | | | |
| Where duct stub penetrates surface of demising wall, cut back duct, cap and seal air, smoke, and gas tight. Install drywall behind duct to extend to floor/ceiling for continuous fire rating. | | | | | | | | | | |
| Provide air tight electrical boxes throughout or seal each electrical box. | | | | | | | | | | |
| Where CMU back-up wall of exterior wall is exposed, apply mastic over accessible cracks or minor holes in CMU back-up wall. Patch major holes (broken block) in CMU wall. | | | | | | | | | | |
| Where tub/tiles are replaced, use cross weaved polyethylene taped to studs. | | | | | | | | | | |
| Air Sealing Around A/C Sleeve | | | | | | | | | | |
| Air tight light fixtures. | | | | | | | | | | |

## 9.4 Appendix D: General Contractor Window Installation Recipe With BSC Edits

See attached.

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Low Rise Window installation recipe | | | | | | | | | |
| | | | | | | | | | |
| | | | CWC Notes from 2010-09 version | BSC Comments | | | | | |
| 1 | Remove 1st floor security grates by grinding screw heads off | | | | | | | | |
| 2 | Label grate for which unit and put it in a storage unit for others to reinstall | | | | | | | | |
| 3 | Remove the A/C and place on the floor of the unit (the tenant owns this unit) | | | | | | | | |
| 4 | Remove the A/C sleeve from the interior | | | | | | | | |
| 5 | Razor cut the existing caulking on the interior of the window (entire perimeter) | | | | | | | | |
| 6 | Razor cut the existing caulking on the exterior of the window (entire perimeter) | | | | | | | | |
| 7 | Remove the window in its entirety | | | | | | | | |
| 8 | Remove existing new caulking from the brick | | | | | | | | |
| 9 | Remove the existing sill flashing and existing caulking from bluestone sill | | | | | | | | |
| 10 | If the bluestone sill comes out, place it back in place in a bed of construction adhesive | RFI | is this acceptable? | hold off on reinstallation of bluestone sill until after sill buck is sealed to CMU | | | | | |
| 11 | Remove interior wood sills | | | | | | | | |
| 12 | ~~Drill holes in jamb bucks on an angle and foam the window buck to the CMU~~ | | | cut back jamb bucks and sill buck to nearly flush with face of CMU wall in order to allow access to gap between wood bucks and CMU on bottom and sides of window opening | | | | | |
| | | | | 13 Cut shims (if present) off jamb buck to edge of gypsum wallboard (to remain) | | | | | |
| | | | | 14 apply self-adhered membrane flashing over face of multiple bucks such as at meeting jamb of mulled unit. Membrane is to cover joint between the wood framing members. Roll membrane according to manufacturers instructions to ensure adhesion. | | | | | |
| 13 | ~~Foam under the sill buck to the CMU gap~~ | | | 15 seal wood bucks to CMU using expanding foam sealant | | | | | |
| | | | | 16 reinstall bluestone sill if removed | | | | | |
| 14 | ~~Install sill blocking/solid shim~~ | | | 17 Install shims (or solid shim such as beveled siding) and sill blocking on sill buck to provide bearing for window sloped to exterior. Sill blocking to extend to within ?/?" (+/-) [NOTE sill blocking to accommodate new metal sill cap. Leave gap between metal sill cap and sill blocking.] of bluestone sill but not contact sill or any mortar adhered to sill (i.e. leave a gap). Outside edge of sill blocking to be higher than bluestone sill. | | | | | |
| | | | | 18 install flat stock to bridge gap and support between buck and brick return and the gap between the sill blocking and bluestone sill | | | | | |
| | | | | 19 apply sealant to seal sill blocking to sill buck | | | | | |
| | | | | 20 apply sealant to seal between sill blocking/sill buck and jamb buck as well as between jamb buck and floor/ceiling slab at corners | | | | | |
| 15 | Install new metal sill on bluestone in a bed of sealant | | | 21 | < should metal sill cap be caulked to brick at sides? | | | | |
| 16 | ~~Install new prefabricated sill in a bed of sealant on blocking~~ | | | not used | | | | | |
| 17 | ~~Install peel and stick from sill pan to metal sill~~ | | | 22 Install self-adhered membrane sill pan. Extend and adhere to metal sill cap. Turn sides up jambs approximately 4-6" taking care to run membrane tightly into corner (avoid "tenting" the membrane!) Leave back edge of membrane folded up at back of sill blocking. | | | | | |
| 18 | ~~Install peel and stick from sill pan corner up 6 on the jamb in each corner "~~ | | | combined with above | | | | | |
| 19 | ~~Install peel and stick from face of drywall on the jambs out to the brick jambs~~ | | | 23 Install self-adhered membrane jamb flashing from jamb buck out to brick jamb returns. Lap bottom of jamb flashing min. 2" over up-turned legs of sill pan. Roll membrane according to manufacturers instructions to ensure adhesion to jamb buck and brick. | | | | | |
| 20 | Install 6 installation clips to window frame " | | | 24 | | | | | |
| 21 | Install window into the opening | RFI | Bead of sealant on the membrane on the sill before window install? No. | 25 | | | | | |
| 22 | ~~Backer rod and caulk head of window to concrete deck on the interior~~ | | | 26 form continuous line of sealant between window and window opening around all four sides of window. Use backer rod and sealant or low-expanding foam sealant (NOTE: different foam than used to fill gap between wood bucks and CMU). Seal to be toward inside edge of window frame. [air seal is at interior of window frame, 4 sides] | | | | | |
| 23 | ~~Air seal with caulking sill blocking to sill buck on interior~~ | | | done in step 19 above | | | | | |
| 24 | ~~Air seal with caulking window jambs to peel and stick membrane on interior~~ | | | done in step 26 above | | | | | |
| 25 | Install head installation snap clips and snap trim at head | | | move to end | | | | | |
| 26 | Install wood window sills and aprons | | | 27 …and trim sill pan membrane flush with top of interior sill | | | | | |
| 27 | Install interior wood casing on jambs (to cover clips) | | | 28 | | | | | |
| 28 | Paint wood sills and casing | | | 29 | | | | | |
| 29 | ~~Caulk exterior perimeter of window~~ | | | 30 caulk exterior of window at head and jambs. Stop caulk at jambs ~1/4" above metal sill cap [weather seal is at exterior edge of window, 3 sides.] | | | | | |
| | | | | 31 install plastic, clip-in sill trim | | | | | |

## 9.5 Appendix E: BSC Letter to Project Team Addressing Observations of Demolition in Mock-Up Apartment Unit

See attached.

2010.10.26

Bruce M. Hampton, AIA, LEED AP

Elton+Hampton Architects

Ph: 617.708.1071
Fx: 617.782.9525

bruce@eltonhamptonarchitects.com

**Re:** **Castle Square, Low-Rise Mock-Up Unit – Observation on Demolition**

**CC:** Heather Clark, Winn Development
Mike Marotta, Elton+Hampton Architects
Margaret Wood, Tom O'Neil; Pinck and Company
Betsy Pettit, FAIA, Peter Baker, P. Eng.; Building Science Corporation

Dear Mr. Hampton:

Yesterday I had the opportunity to visit Unit 7A of Building 11 both before and after demolition in preparation for the mock-up renovation scope implementation. In most cases, observations of the mock-up unit confirmed the need for strategies identified in the air sealing scope (Drawings A-5.15 and A-5.16). In some cases, conditions observed differ from observations in the previous low-rise mock-up unit. This communication is intended to address implications of these different conditions.

One condition observed – a gap between drywall and the floor ceiling assembly within the finished space – was not observed in the previous low-rise mock up unit and is not addressed in A-5.15. If sufficiently widespread within a unit, this condition may impact the air leakage measurement attainable within the current renovation scope.

If you have any questions regarding this report, please contact me as per the contact information below.

Thank you,

Ken Neuhauser



30 Forest Street | Somerville, MA 02143 | Phone 978.589.5100 | Fax 978.589.5103 | www.buildingscience.com

## 1. Observations Pertinent to Directives of A-5.15

### *General Air Sealing: Units to Meet ELA 1.25 sq. inchper 100 s.f. of Envelope*

Rodent activity was much evident in this unit. Durably sealing large gaps may require that metal mesh (e.g. Stuf-Fit) be imbedded in sealant. Covering gaps with drywall would also provide a durable closure of the opening but will require use of sealant to achieve air flow control. This applies to all sealing in the apartment unit.

The contractor demonstrated that the size of the new electric panel will be much larger than the existing panel. In the previous mock-up unit, the electric panel was found to be a significant source of air leakage into the unit. Obviously, holes in the electric service panel box within the wall cavity should not be sealed. The new panel cover presents the opportunity to caulked the panel cover to the drywall at installation.

The panel cover may accommodate gasket tape at the flange behind the panel cover door. Such supplemental air sealing could be delegated to follow-on maintenance or youth core implementation.

### *Air Sealing at Kitchen Remodel*

**Note 1 – Seal around all plumbing, electrical and other penetrations through the sound board/drywall with appropriate sealant. Pipe penetrations and any other holes will be sealed with fire caulking. If soffits are opened, all penetrations will be sealed. Ensure that new drywall extends to ceiling and seal drywall to ceiling.**

Because of the evident rodent activity, durability of seals over larger holes and gaps may require that metal mesh be imbedded in sealant.

The contractor indicated that the implementation plan includes keeping the bottom track of the soffit framing that is against the demising wall. While this will simplify refinishing of the soffit, it may complicate sealing penetrations in the demising wall surface in the soffit. It may also alter the strategy for providing a continuous surface sealed to the underside of the floor/ceiling assembly as it will not be practical to install a new layer of drywall against the demising wall in this area.

**Figure 1: Copious evidence of rodent activity in second floor closet**

**Figure 2: Soffit above kitchen**

**Note 2 – Connect and seal between the bottom of the wall and the floor.**

At the base of the wall, it appeared that drywall joint compound had been used in a previous attempt to seal the gap between the base of the wall and the floor (see **Figure 3**). This compound was cracked and appeared loose in a few locations. An elastomeric sealing compound should be used in this location to ensure the durability of the seal.

**Note 5 – Connect and seal the drywall/soundboard of the demising wall to the exterior wall**

A gap at this intersection was evident in the kitchen soffit (see **Figure 4**). A piece of wood strapping is fastened to the wall at this location. Sealing the demising to the exterior wall will require 1) sealing the demising wall to the strapping and 2) sealing the strapping to the demising wall.

**Figure 3: Apparent existing joint compound sealing at base of kitchen wall**

**Figure 4: Intersection of demising wall and exterior wall structure in kitchen soffit**

**Note 6 – Where the duct stub penetrates the surface of the demising wall, cut back duct, cap and seal air, smoke, and gas tight. Install drywall behind duct to extend to the floor/ceiling to ensure continuous fire rating.**

The duct soffit that runs perpendicular to the demising wall was not opened at the time of my visit. From the vantage point of the kitchen soffit, it was not apparent to me whether or not the duct stub penetrates the demising wall. Regardless of whether the duct penetrates the surface of the demising wall, it will be important to open this soffit to seal openings into the demising wall at this location.

**Figure 5: View from kitchen soffit (demolished) into perpendicular soffit containing supply duct**

### *Additional Notes*

**Note 11 – Seal at soffit closure above vertical duct**

This note refers to the opening into the duct soffit found adjacent to the connection with the vertical duct riser that is exposed in a second floor closet. In the previous mock-up unit, access to the approximately inch-wide gap was very constrained. The position of the vertical duct relative to the bathroom partition wall in the present mock up unit provides for a more easily feasible closure of this gap.


**Figure 6: Opening into soffit at second floor of previous low-rise mock-up apartment**

**Figure 7: Opening into soffit at second floor of present low-rise mock-up apartment. Note opening into demising wall.**

## 2. Observations of Air Sealing Needs not Addressed in A-5.15

At several locations on the second floor walls and soffits, the drywall surface appears to have settled downward creating a gap between the drywall and the underside of the floor/ceiling assembly (see **Figure 8** and **Figure 9**). Given that the renovations will be implemented under very tight schedules and while the apartments will be occupied by resident belongings, it may not be practical to address these gaps during the planned occupied rehabilitation of the apartments. The type of air sealing that would be suited to this situation would be best implemented in conjunction with painting of the units. Where widespread and significant, the gaps between drywall and floor/ceiling assembly may impact the air leakage measurement attainable within the scope of the planned rehabilitation work.

**Figure 8: Gap between drywall and floor/ceiling assembly at second floor**

**Figure 9: Gap between drywall and floor/ceiling assembly at second floor**

## 9.6 Appendix F: BSC Letter to Project Team Addressing Air Leakage Assessment of Low Rise Mock-Up Unit

See attached.

# Memo

**DATE:** December 10, 2010

**TO:** Bruce M. Hampton, AIA, Elton+Hampton Architects

**FROM:** Ken Neuhauser, Building Science Corporation

**RE:** First air leakage assessment of low rise mock-up unit

**CC:** Heather Clark, Dave Thunell; Winn Development
Mike Marotta, Elton+Hampton Architects
Margaret Wood, Tom O'Neil, Mary Jennings; Pinck and Company
Chuck Perry, Deanna Foster; CWC Builders, Inc.
Betsy Pettit, FAIA, Peter Baker, P. Eng.; Building Science Corporation

Air leakage testing performed in the mock up unit,7A in Low Rise Building 11 determined the effective leakage area (ELA) to be 1.65 sq.in. per 100 sq.ft. of total apartment enclosure. The apartment enclosure area is the sum of all gross wall, ceiling and floor areas. The testing result reflects performance of the unit in condition found with the exception that the bath fan grille was covered with masking tape.

The measures ELA/100 ratio is very close to the target of 1.25 ELA/100 indicated in Section 01575 of the Specifications. It should be noted that several factors or conditions would influence the measurement taken to be different than measurement that would be conducted for the purpose of assessing compliance with the performance target (hereafter "compliance testing conditions").

Given that some factors render the measurement taken on 12/08 optimistic while others render the measurement pessimistic, it is not possible to indicate with certainty whether the air leakage target will be achieved in this unit with completion of the scope and under compliance testing conditions. However, it appears likely, that the ultimate measured performance for this first mock-up unit will be close to the performance target.

Factors that tend to render the measurement of 12/08 optimistic relative to compliance testing conditions include the following (explained in more detail below):

– Neighboring apartment units were closed during the testing, and

– The bath fan grille was essentially sealed with tape during the testing.

Factors that tend to render the measurement of 12/08 pessimistic relative to compliance testing conditions include the following (explained in more detail below):

\+ Kitchen range hood back-draft damper was not installed at the time of testing,

\+ The interior side of the A/C sleeve was fitted with a non-gasketted metal cover, and

\+ The unit entry door sweep installed may not reflect the product or implementation to be followed on subsequent low-rise units.

### *Explanation of factors and conditions pertaining to air leakage measurement of 12/08*

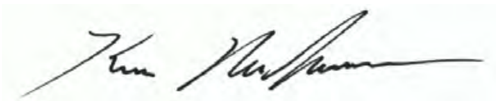
– With the doors and windows in the adjacent apartments closed, the pressure difference across the demising assemblies would likely have been less than the pressure difference across exterior wall assemblies. In the compliance testing conditions, adjacent units would be opened to the exterior in order to ensure that pressure differences across demising assemblies track those across exterior enclosure assemblies. I expect that opening the neighboring apartments to the exterior would have only modestly increased the measured leakage.

– An air leakage test conducted just prior to taping the bath fan grille measured a significantly higher effective leakage area. Since it is likely that some air will leak past a back-draft damper, the taping of the grille probably resulted in a greater reduction in effective leakage area than would result from installation of a back-draft damper in the bath exhaust.

- Significant air flow was felt at the range hood grille when the building was depressurized. Air flow through the range hood under building depressurization would be reduced by a backflow damper in the kitchen exhaust.
- Daylight was visible through the joint between the A/C sleeve and the temporary A/C sleeve cover. If the A/C unit is effectively gasketed in the A/C sleeve, it would be expected that leakage through the sleeve and A/C unit would be less than leakage drawn through the A/C sleeve during the air leakage testing.
- The bristle door sweep installed at the unit entry door did not appear to firmly contact the threshold. It was also noted that, due to the configuration of the metal threshold, the door sweep could not be lowered on the door without impeding operation of the door. While on site, I discussed with Chuck Perry the potential benefit of moving the door sweep to the inside of the door and of sealing between the metal threshold and the floor.

If you have any questions about the information presented above or the air leakage testing conducted, you can reach me as per the contact information below, or at ken@buildingscience.com.

Thank you,



Ken Neuhauser

## 9.7 Appendix G: BSC Letter to Project Team Addressing Water Management and Air Sealing Details for Low-Rise Window Installations

See attached.

Building Science Corporation

# Memo

**DATE:** June 14, 2011

**TO:** Bruce M. Hampton, AIA, Elton+Hampton Architects
Mary Jennings, Pinck and Company

**FROM:** Ken Neuhauser, Building Science Corporation

**RE:** Water management and air sealing details for low-rise window installations

**CC:** Heather Clark, Biome Studio
Mike Marotta, Elton+Hampton Architects
Margaret Wood, Tom O'Neil; Pinck and Company
Betsy Pettit, FAIA, Peter Baker, P. Eng.; Building Science Corporation

This morning, Peter Baker and I had an opportunity to review several window installations while on site to observe the window leakage testing. Based on these observations, we offer recommendations relative to 1) weeps for the window opening, 2) caulking at the window head, and 3) air sealing at the interior of the window.

### *Weeps for Window Opening*

**Recommendation:** The caulking at the exterior of the window should be continuous at the jamb and connect to a fillet bead along the joint between the aluminum sill trim and brick jamb return at either side of the aluminum sill trim. Weep holes should be provided by cutting small "V" notches in the applied plastic trim closure piece at approximately 6" from either side of this piece.

**Discussion:** The previously developed detail to provide weep holes for allowing water to drain from the window opening was to stop the caulking short of the aluminum sill trim cap to either side of the opening. The intention was to allow for water to drain to either side of the plastic trim closure piece that was noted to create a tight seal against the aluminum trim cap at early window installations.

On observation today, it was noted that the opening at the lower corner of the window opening not only allowed water to drain out of the opening, but also provided a hole at a location where there is the potential for water to enter into the window opening. Providing the weep holes in the plastic trim will provide adequate drainage for the window opening and will also allow the caulking at the jamb and sides of aluminum sill trim to provide protection to the otherwise vulnerable corner of the opening.

We acknowledge the caulking installer for valuable contributions to the discussion on site this morning.

### *Caulking at the window head*

**Recommendation:** If height of sill pan relative to exterior trim allows, the window should be installed with a ¼" gap between the window and concrete slab at the window head in order to allow for a design caulk joint.

**Discussion:** We noted that the window head was sealed at the exterior with a fillet bead of caulk. The windows are installed very tight to the concrete slab above. A gap between the window frame and concrete slab will allow for sealant (or backer rod and sealant) between these two components. This would provide a more robust seal against water penetration.

The placement of the window against the concrete may be a necessary consequence of raising the window sill blocking and drainage pan above the level of the exterior sill trim piece. In subsequent window installations, if the height of the window sill blocking and drainage pan can be maintained above the height of the exterior sill trim (first priority), the window head should be shimmed down ~1/4 from the concrete slab in order to allow for a better sealant joint.

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### *Air sealing at the interior of the window*

**Recommendation:** Use backer rod and sealant to seal the window frame to the rough opening at the interior perimeter of the window.

**Discussion:** In observing the results of window leakage testing at one of the window openings it was noted that the interior air seal between the window and the rough opening is a component important to resisting water penetration. Where the gap between the window frame and the rough opening is sufficiently uniform, backer rod and sealant supplemented with sealant around window attachment brackets can be expected to provide a more robust air seal than foam sealant.

If, after reviewing this information, you have further questions, please contact me as per the contact information below or at ken@buildingscience.com.

Thank you,

Ken Neuhauser
Building Science Corporation

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## About this Report

This report was prepared with the cooperation of the U.S. Department of Energy's, Building America Program.

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