Residential Exterior Wall Superinsulation Retrofit Details and Analysis

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ABSTRACT

The issues of climate change, energy security, and economics are all strong drivers for improving energy efficiency levels in a variety of sectors. In residential construction, although some inroads have been made in new houses, the stock of existing housing represents a huge opportunity for energy retrofits. The vanguard of these efforts has been pushing toward retrofitting very high insulation levels (i.e., "superinsulation," or "deep energy retrofits").

Several cold-climate residential retrofit projects have been completed using an exterior insulation approach on light-frame above-grade walls. This type of retrofit is a reasonable step if a recladding of the building is already being done for aesthetic or ongoing maintenance reasons. The methods demonstrated here result in walls with insulation levels in the R-35 to R-40 range.

This paper presents many of the lessons learned from these experiences, including overall enclosure strategies, such as air barriers, drainage planes, and moisture control. Several case-specific solutions to particular problems are described, including exterior air barrier approaches, wall sill replacement, and several approaches dealing with window penetrations. In addition, detailing recommendations and economic analysis of these measures are presented. Hygrothermal simulations were run to evaluate the changes in sensitivity to moisture intrusion due to these retrofit measures.

INTRODUCTION

The issues of climate change, energy security, and economics are all strong drivers for improving energy efficiency levels in a variety of sectors. The residential and commercial building sectors consumed roughly 40% of the primary energy used in the United States in 2008; this can be further subdivided into the residential (21%) and commercial (18%) sectors (DOE/EIA 2009). In residential construction, although some inroads have been made in new houses, the stock of existing housing represents a huge opportunity for energy retrofits. For instance, Gitt (2009) notes that of the existing stock of 120 million housing units, 70% of them were built before any energy codes were enacted. Although the effectiveness or ineffectiveness of various energy codes can be debated, it is reasonable to assume a general trend of increasing energy efficiency with the presence of (and/or more stringent) energy codes.

The nationwide distribution of housing stock by geographic census region and age is shown in Figure 1, based on US Energy Information Administration (EIA 2005) data. It demonstrates trends noted by others (Lutz 2004): for instance, much of the oldest housing stock is concentrated in the Northeast, and since the 1970s, the majority of new construction was concentrated in the South and West regions.

Given the body of older, less-efficient housing stock, it appears that there is substantial "low-hanging fruit" for energy efficiency retrofits in existing housing. The current political climate is conducive to the implementation of home energy efficiency improvements, both on state and federal levels. However, energy retrofits have historically proven to be difficult to implement in quantity, due to "regulatory constraints, high costs, and the complexities of reaching a fragmented market" (Gitt 2009). Existing homes are a particular challenge because of the variety of building types, characteristics, site-

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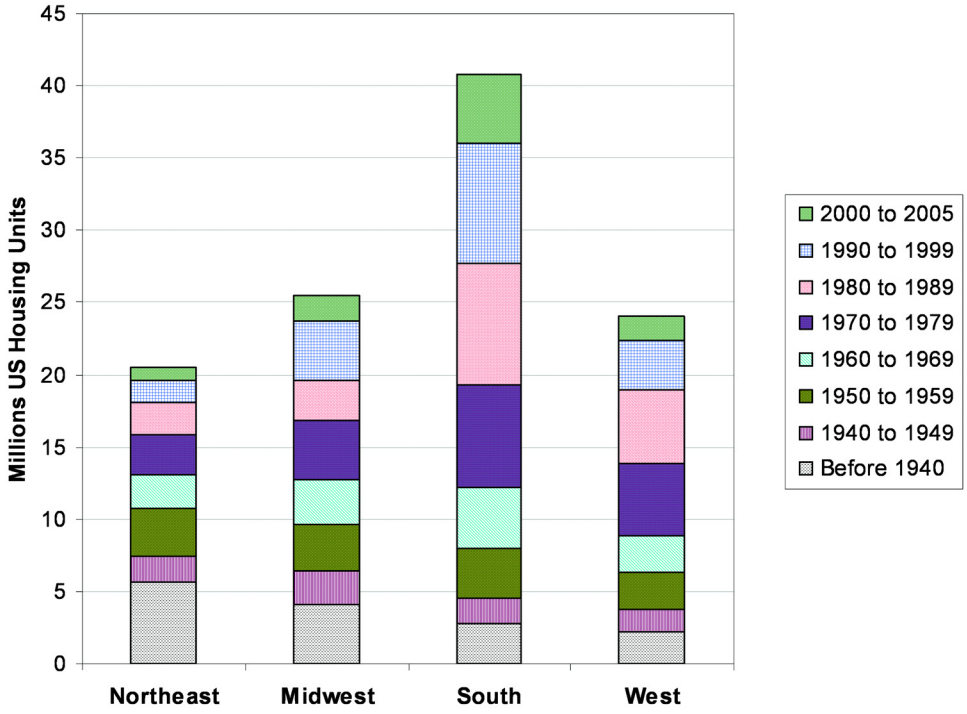

Figure 1 *Vintage of US housing units, subdivided by US census region (EIA 2005).*

specific assemblies, enclosure details, and mechanical systems associated with each of them. Most importantly, upgrades must not compromise the durability, health, or life safety of the houses.

This research addresses one specific segment of energy efficiency retrofits: the exterior retrofit of substantial amounts of insulation on wood frame above-grade walls, done during exterior recladding for other (aesthetic or maintenance) reasons. This retrofit substantially increases the R-value of existing walls, and can be detailed to substantially improve overall building airtightness. Three case study houses using this technique are examined in this paper.

Of course, these retrofits only address space conditioning (heating and cooling) loads. Based on the information above, the Northeast and Midwest are the most relevant regions, due to their heating-dominated loads, which show the greatest benefit from opaque R-value and airtightness improvements. In addition, these regions have the largest concentration of older housing stock: older houses often have high air leakage levels, and low levels of—or nonexistent—insulation. These houses may also have cladding that is near the end of its service life, lending them to recladding.

BACKGROUND

Exterior Insulation Retrofits

Typical insulation retrofits of wood frame walls involve the addition of insulation in the stud bay, either by filling through holes drilled from either the interior or exterior (i.e., "blown in"), or in the course of a retrofit that removes the interior finishes. However, the insulation level is typically limited by the dimensions of the wall framing to nominal R-13 to R-19 (RSI 2.3 to 3.3) levels, unless materials such as closed-cell urethane spray foams are used. In addition, thermal bridging through the wood framing further reduces the R-value below nominal levels.

In an effort to achieve wall insulation levels higher than these limitations, several "superinsulation" projects were built using rigid board insulation retrofitted to the exterior of the existing frame wall. The projects used 4 in. of polyisocyanurate foam rigid insulation (R-26/RSI 4.6); it is similar to an assembly used in new construction described by Lstiburek (2008). This assembly not only allows higher levels of insulation, but also eliminates most of the wall's thermal bridging. Specifically, the addition of 4 in. of polyisocyanurate foam is a nominal change from roughly R-13 to R-39 (RSI 2.3 to RSI 6.9; factor of 3 increase), but if a 23% framing factor is assumed, the true insulation values change from R-9 to R-35 (RSI 1.6 to RSI 6.2; factor of 3.9 increase).

A comparison of high R-value wall assemblies is beyond the scope of this paper; however, a study comparing the thermal resistance, durability, buildability, material use, and cost can be found online (Straube and Smegal 2009). Several wall assemblies described in that report (double stud wall, Larsen truss) can be built as an exterior retrofit; both of them use fibrous fill insulation. However, these fibrous fill insulation

walls are sensitive to wintertime outward moisture movement from interior sources, either by vapor flow or airflow, with the latter being of greater importance. As a result, to ensure durability, these walls depend upon the workmanship of the air barrier and (to a lesser extent) the vapor barrier. The cold temperature of the exterior wall sheathing (due to the insulation levels/reduction in heat flux) results in substantial periods when there is wintertime condensation risk at that surface. In contrast, the retrofit described here places roughly 2/3 of the thermal resistance outboard of the condensing surface (interior face of the existing sheathing boards). This raises the wintertime condensing surface temperature, and substantially reduces the risk of interstitial condensation. Therefore, the assembly described here has some notable durability advantages. In addition, this assembly addresses thermal bridging at the rim joist, which is often a weakness in double stud walls.

In terms of airflow control, it is recommended that the primary air barrier in a cold climate be located on the interior, to avoid exfiltration of moisture-laden air and resulting interstitial condensation (Lstiburek 2006). In an exterior retrofit, however, the air barrier is typically retrofitted outboard of the existing structure, which raises some durability questions. In this case, though, the air barrier is located 1/3 of the way through the thickness of the assembly (from the interior): again, the high insulation value outboard of the air barrier greatly reduces the condensation risks of this assembly.

One final question revolves around the choice of an exterior retrofit, as opposed to an interior ("gut") retrofit. Insulating wall assemblies beyond cavity fill levels requires the disruption of either the interior or exterior fabric; the choice is a value judgment that must be made on a case-by-case basis. One of these surfaces may have greater or less aesthetic or historical significance. However, there are some arguments to be made for an exterior retrofit. For one, the interior is still habitable during this retrofit; in fact, two of the following case studies were conducted on occupied houses. Increasing the thickness of the wall at the interior results in a loss of habitable square footage. In exterior retrofits where the existing cladding is first removed, it provides an opportunity to inspect the condition of the building, including finding and repairing previously undetected leakage or moisture damage. More limited insulation techniques might not find these issues, resulting in long-term moisture damage consequences, which would be exacerbated by the reduction in heat flow (and thus drying potential) due to insulation retrofits. The exterior insulation technique described here places non-moisture-sensitive insulation outboard of the existing structure, thus providing a layer of protection

Finally, applying insulation on the exterior can successfully handle details such as stairwells on exterior walls and intersecting tee walls, which have limited options when insulating from the interior.

Previous Work

The authors do not mean to imply that the use of substantial amounts of thermal insulation outboard of the structure is an innovative technique by any means; this method has a long history in the building science community. The basic concepts were spelled out by Hutcheon (1964); this method involves the use of a vapor-, air-, and water-control layer exterior to the structure (e.g., bituminous adhered membrane), with insulation outboard of this layer, and the finish cladding exterior to the insulation. These concepts were also described by Lstiburek (2007); some implementations have included the pressure-equalized rain screen insulated structure technique (PERSIST) construction method (Baker and Makepeace 2001), residential exterior membrane outside insulation technique (REMOTE) by the Cold Climate Housing Research Center (Benesh 2009), and the Building America/Hydaburg Tribe house (Lstiburek 2009). The challenges associated with exterior insulation, such as cladding attachment through thick nonstructural insulation, and the attachment of nonconditioned portions of the outer shell (e.g., decks and porch roofs) were also encountered in the projects described here. However, it should be noted that the techniques used in these projects are not completely analogous to this previous work.

The exterior insulation concept is not limited to new construction; some similar techniques were applied in a retrofit situation by Orr and Dumont (1987), in their so-called "chainsaw retrofit." This project was the exterior insulation retrofit of a circa 1970 stucco-clad bungalow; one key point was that the entire exterior enclosure was wrapped with a 6 mil (0.15 mm) polyethylene vapor and air barrier. In order to avoid wrapping the overhanging roof eave, the entire detail was cut off flush (thus the "chainsaw retrofit" name), rendering the shape of the house a relatively simple solid with planar faces. An exterior wood frame was constructed outboard of the walls and roof, fiberglass insulation was applied in the cavity formed by the frame, and exterior sheathing and cladding were applied. High levels of exterior insulation were installed: R-39 (RSI 6.8) roof, and R-40 (RSI 7.0) walls. The researchers measured a substantial increase in airtightness, going from 2.95 ACH 50 (air changes per hour at 50 Pa test pressure) to 0.29 ACH 50. Measured results indicated a substantial reduction in heating load (factor of 2.4 reduction).

Researchers at Oak Ridge National Laboratory (Stovall et al. 2007) examined some exterior wall insulation and airtightness retrofit options. They first took laboratory thermal performance ("hot box") measurements of heat flow reductions in test walls (both opaque wall only, and with an installed window). The wall upgrades included options commonly used in retrofit residing, including 3/8 in. (9.5 mm) and 1/2 in. (12 mm) extruded polystyrene (XPS) foam, 1 in. (25 mm) of foil-faced polyisocyanurate, and expanded polystyrene (EPS) contoured to fit the profile of hollow vinyl siding. The researchers also performed laboratory measurements of the air leakage characteristics of several window-to-wall air sealing methods. They combined this information with whole-house

Figure 2 *Front views of case study houses (left to right): Concord Four Square, Arlington Duplex, and Bedford Farmhouse.*

Table 1. Summary of Case Study Characteristics

#	Location and Label	Square Footage	Housing Type	Construction Era	Renovation Completed	Basement
1	Concord, MA Four Square	2800 sf + 800 sf basement	Single Family	c. 1915	2007	Conditioned
2	Arlington, MA Duplex	1280+1800 sf + 1280 sf basement	Duplex (over/under)	c. 1930	2009	Unconditioned
3	Bedford, MA Farmhouse	1500 sf + 1060 sf basement	Single Family	c. 1850	2009	Conditioned

energy simulations, to estimate energy savings associated with these retrofits for three house models in ten climate zones. The predicted heating and cooling energy cost savings showed expected patterns of greater savings with increasing R-value; for reference, the 1 in. (25 mm) foil-faced polyisocyanurate showed typical savings in the 10–15% range when applied over an existing insulated frame wall. It is interesting to note that these levels of savings were even seen in cities typically associated with greater cooling loads, such as Phoenix, AZ, Atlanta, GA, and Bakersfield, CA. The one exception was Miami, FL, which only showed 5% savings with the described assembly. Of course, it must be remember that although many cities showed the same percentage (10–15%) savings, the absolute magnitude of savings (and thus associated energy paybacks) will vary with local heating and cooling loads.

CASE STUDIES

Three residential renovation projects were completed using exterior foam insulating sheathing installed during recladding; the projects and their results are described in the following case studies. All of these projects include the retrofit of high levels of exterior wall insulation (~R-26, or RSI 4.6), which results in total nominal insulation levels in the R-35 to R-40 (RSI 6.2–7.0) range. The projects had programmatic goals of achieving high overall insulation levels (i.e., "super-insulation" or "deep energy retrofits"). The wall retrofit was only one of many measures undertaken in these energy retrofits: other upgrades included roof insulation, foundation insulation, window replacement, and mechanical equipment replacement.

All three of the case study houses are located in the Boston area of Massachusetts (DOE Climate Zone 5A, 5600-6400 HDD 65°F or 3110-3560 HDD 18°C in locations listed below). They are all wood frame houses that are older than 1940s vintage. All are built on basement foundations, with rubble stone walls below grade, and concrete block or stone above grade. All of the houses are two to three stories, and include the area enclosed by the sloped roof area within the conditioned space, using an unvented ("compact") roof design. Figure 2 shows each house's facade, and Table 1 summarizes each case's characteristics.

Case Study 1: Concord Four Square

This case study was a circa 1915 Sears, Roebuck & Co kit home; the floor plan is the ubiquitous American Four Square, which was how this project is commonly referred to. The project was described in detail by Pettit (2008, 2009), including aspects of construction, building enclosure details, descriptions of mechanical systems replacements, plus modeled and actual energy performance. The renovation included stripping of the exterior wall and roof finishes, insulation of these assemblies (both exterior to the structure and in the framed cavity), recladding of exterior walls (with wood lap siding), insulation of basement walls and slab, replacement of all

windows, and complete replacement of the mechanical system.

It should be noted that the roof design did not lend itself to a chainsaw-style retrofit (removing the overhanging eaves to simplify air sealing details): the bearing point of the roof rafters is cantilevered outboard of exterior stud frame wall, attached to the horizontal ceiling joist. This would have required substantial structural work to remove the eaves, in order to simplify the air sealing detail.

Since this project was completed from the exterior, all of the interior finishes were left intact; there were many features worth preserving, including maple floors, interior wood trim, and interior lath and plaster in good condition. Some preservationists consider deep energy retrofits to be a threat to historic houses, claiming that these measures are "stripping away much of the charm, character, and historical value that attract people to these modest older houses in the first place" (Zimmerman 2009). However, this house can be considered an exemplary case of an architecturally sensitive energy retrofit that preserves and celebrates the original character of the house, replicating or mimicking the original exterior details.

Case Study 2: Arlington Duplex

This case study was a circa 1930 duplex; the two units are arranged in an over/under manner, with the first floor comprising one unit, and the second and third (attic) floors comprising the second unit. The project was prompted by a unit owner who had an interest in deep energy retrofits, and obtained funding and material contributions from a variety of sources. The project was partly funded by the Massachusetts Department of Energy Resources. The specifics of the construction of this project are covered by Joyce (2009), which includes section drawings, construction sequence, and detailed photographs.

The renovation included stripping the exterior wall and roof finishes, insulation of these assemblies (both exterior to the structure and in the framed cavity), recladding exterior walls with cellular PVC lap siding, and replacement of all windows. The choice of measures was a matter of energy and economic analysis, as well as discussions with the homeowner, who wanted to limit the budget and associated scope of work.

For instance, the heating plants (single-pipe steam boilers; natural draft combustion) were retained, as single-pipe steam does not lend itself to a simple replacement with hydronic heating; it should be noted that steam systems have intrinsic efficiency limitations. The author's recommendation to the client was to include the basement within the conditioned enclosure (by insulating and air-sealing the basement walls), in order to recapture distribution losses from the boiler systems, simplify air barrier detailing, and include greater usable volume within the conditioned space. However, this would require the addition of combustion safety measures to the existing equipment (i.e., makeup air kits), since the units are being brought within the conditioned space. The homeowner instead chose to isolate the basement from the first floor, removing the basement ceiling finish and using low-density spray foam to insulate and air-seal the joist bay cavities from below.

Case Study 3: Bedford Farmhouse

The final case study was a circa 1850 single-family farmhouse, which was being renovated by Habitat for Humanity of Greater Lowell for use as energy-efficient affordable housing. Technical guidance for the project was funded by the Department of Energy's Building America Program. This property was unconditioned and empty prior to this renovation.

The renovation included demolition of poorly constructed additions, stripping the exterior wall and roof finishes, insulation of these assemblies (both exterior to the structure and in the framed cavity), recladding exterior walls with vinyl siding, insulation of basement walls and slab, replacement of all windows, and complete replacement of the mechanical system. Although interior finishes were originally left intact, during construction, a decision was made to perform a gut demolition, to remove the need for lead paint removal/encapsulation of the existing interior trim. Construction was completed by Habitat for Humanity volunteers and students from a local technical high school.

WALL ASSEMBLY CONSTRUCTION SPECIFICS

Wall Assembly Overview

The retrofit wall assembly used in these case studies was largely the same, albeit with slight variations. The wall was composed of the following layers (Figure 3):

- Existing structure: the existing cladding and water control layer (building paper, rosin paper) were stripped from the building, revealing the board sheathing; all projects here had horizontal board sheathing. The sheathing was examined for any signs of long-term moisture damage; any problems could be repaired, and noted for closer attention when assembling new drainage plane details.
- If the wall cavities were uninsulated, they were retrofitted with insulation; dense-pack cellulose was used at the Concord Four Square, and fiberglass batt at the Bedford Farmhouse. The Arlington Duplex already had been retrofitted with blown-in insulation.
- A layer of spun-bonded polyolefin housewrap was then applied as an exterior air barrier and a secondary drainage plane. In addition, it serves as a temporary weather barrier during construction. Alternatively, it can be detailed to function only as an exterior air barrier, which simplifies window detailing in some cases. This layer is located between the board sheathing and the polyisocyanurate foam, and there is some risk of retaining moisture in this space, due to "sandwiching" of flat surfaces and the resulting capillarity. Therefore, a housewrap

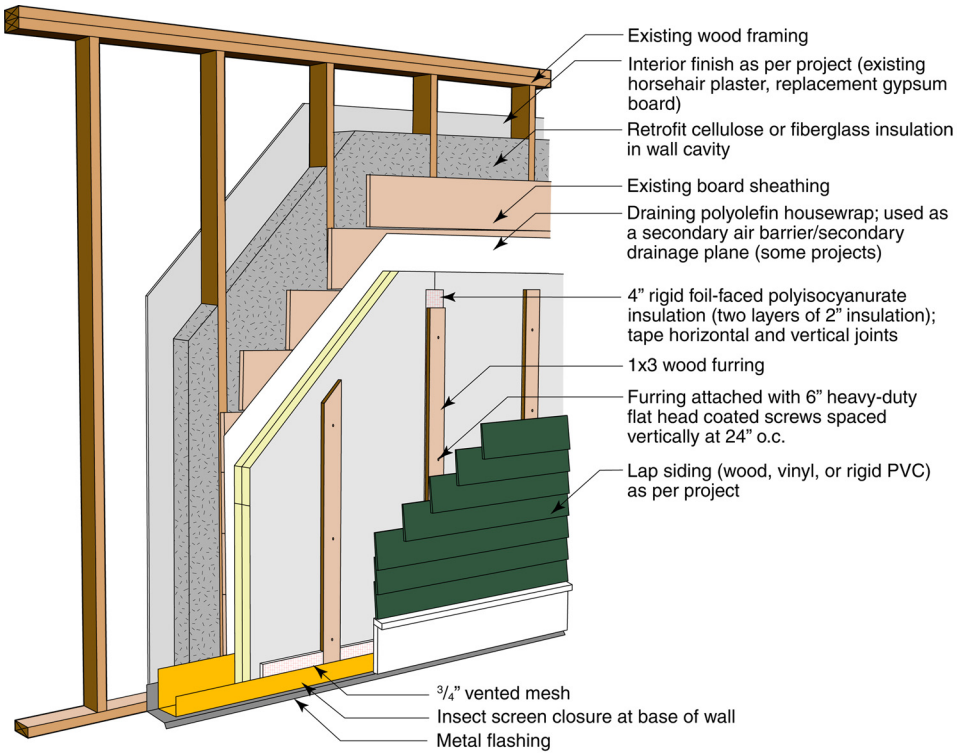

Figure 3 *Isometric view of wall retrofit assembly, showing assembly components.*

with corrugations to provide drainage was chosen. In order for this layer to be effective as an air barrier, connection details were required: for instance, at the foundation to above-grade wall connection, the housewrap was caulked to the lowest piece of board sheathing.

- At the Bedford Farmhouse, after the housewrap was applied, the design team noted during a site visit that the installation was not conducive to use as an air barrier. Problems included tenting at inside corners, incomplete coverage, and a piecemeal application; it would have basically required a reapplication of this layer to have a functional air barrier. As a result, the team decided to no longer use the housewrap layer, instead providing details to use the outer layer of polyisocyanurate at the air barrier, connecting it in a continuous manner. The results of this alternate approach are covered in the Case Study Lessons Learned section.
- Two layers of 2 in. (51 mm) foil-faced polyisocyanurate were applied, with staggered seams between layers, to avoid a "straight-through" path for air or water penetration. The seams of the outer layer of foam were taped with adhesive tape, to provide the primary drainage plane/water control layer, as well as a secondary layer of airflow resistance. Foil-faced polyisocyanurate was chosen because of its high per-inch insulating value, as well as the ability to tape the foil surface (as opposed to expanded polystyrene or fiberglass-faced polyisocyanurate; however, taped seams are common with extruded polystyrene). Typically, the layers of foam were temporarily held in place with oversized (~3 in. diameter) metal washers, commonly used in commercial roofing.
- Vertical wood 1 × 3 strapping (0.75 in. × 2.5 in. or 19 mm × 64 mm) was applied outboard of the foam at the stud locations, using self-drilling heavy-duty flat-head screw fasteners with sufficient length to provide attachment to the stud. This strapping serves several purposes. First, it acts as an oversized washer, holding the foam to the surface of the house. Second, it acts as a substrate for cladding attachment. Third, and most importantly, the ¾ in. (19 mm) space created by the strapping results in a drainage and ventilation cavity. Drained wall systems are widely recommended as the best strategy for controlling rain penetration. (Ritchie 1961; CMHC 1999; Lstiburek 2006); wall ventilation has been demonstrated to add significant drying capacity to cladding assemblies (Straube et al. 2004; Straube and Burnett 2005). Both of these increase the durability of the assembly, and greatly limit the amount of rain penetration to the secondary drainage plane (housewrap).

Wall Assembly Details

Two aspects of this assembly are worth covering in more detail: the strapping attachment over rigid foam sheathing, and the window plane location.

Figure 4 *Laboratory mock up testing of deflection with load; 2 in. (51 mm) XPS foam and 1 × 3 strapping, 24 in. (610 mm) o.c.*

Strapping Attachment. A question commonly asked in the field concerns the strength and durability of strapping attached through rigid plastic foam insulation, and the possibility of sagging of the cladding or crushing of the foam. These concerns, while understandable, have little validity; this is borne out by a long history (20+ years) of large numbers of similar assemblies in the field with no evidence of systematic problems.

The problem can be broken down into several components. Two are the loads perpendicular to the wall: the pull-out and compression loads, which are associated with wind loads. The pull-out strength can be calculated from the fastener strength, penetration depth, and placement schedule as required for a particular loading. Allowable compressive loads can be calculated based on the compressive strength of the rigid foam sheathing layer. Representative published compressive strengths are 10–15 psi (69–103 kPa) for expanded polystyrene (EPS), 15–30 psi (103–207 kPa) for extruded polystyrene (XPS), and 25 psi (172 kPa) for polyisocyanurate (at 10% deformation or yield). With 1 × 3 (2.5 in., or 64 mm) strapping at 24 in. (610 mm) on center (o.c.), the loads that could be transferred through the foam are 225 and 375 pounds per square foot (psf) (10.7 and 18.0 kPa), respectively, for XPS (lower value) and polyisocyanurate. For reference, the design wind pressures mentioned in the codes are in the range of 20 to 30 psf (ICC 2009), an order of magnitude lower than the allowable compressive loads.

The remaining load is the vertical load, due to the dead weight of the cladding. This load does not act on the screw as a cantilever beam extending horizontally from the backup wall, which might be considered a reasonable first approximation. Instead, in reality, the strapping, foam, and screws act together as a simple truss: the screw acts in tension, and a compression strut forms through the strapping and the foam. This calculation is not performed here; however, laboratory mock up tests were conducted (Figure 4), demonstrating a very high safety factor.

The test wall was a 4 ft × 8 ft (1220 mm × 2440 mm) panel, with 2 in. (51 mm) XPS on a 24 in. (610 mm) o.c. wood stud frame, rigidly attached to the block wall. The foam sheathing was held in place with 1 × 3 strapping, fastened using 4 in. (102 mm) No. 10 screws spaced at 12 in. (305 mm). A steel 1 in. × 1 in. (25 mm × 25 mm) channel was fastened across the two strapping pieces, and a cable was attached to the channel at the centerline of the panel. A dial indicator was set up so that it would measure the deflection of the channel near the strapping (so as to minimize the effect of any deflection of the channel). At a 20 lb (9.1 kg) loading, which is equivalent to a cladding weight of 0.6 psf (30.0 Pa), deflection was under measurement limits (<0.001 in., or 0.03 mm). At a loading of roughly 250 lb (113 kg), the displacement was under 0.003 in. (0.08 mm); this is equivalent to a cladding load of 7.8 psf (370 Pa). For reference, typical cladding loads are 0.5 psf (24 Pa) for vinyl siding, 1–2 psf (48–96 Pa) for wood lap siding, 2–3 psf (96–144 Pa) for fiber cement lap siding, and 8–10 psf (380–480 Pa) for cement stucco.

Lastly, it should be noted that extruded polystyrene and polyisocyanurate are viscoelastic materials, and will experience creep over sustained loadings. One manufacturer recommends additional design safety factors to compensate for this property, with 3–1 for static loads, and 5–1 for dynamic loads (Dow 2007). Given the relationships between loadings and capacity shown above, these loads are well below levels where creep is a consideration.

Window Plane Location. Construction of walls with thick exterior rigid foam results in a thick wall; therefore,

doors and windows require details to account for the resulting deep wells. A window requires some type of sill extension to account for the wall thickness: the window plane location in the wall can be towards the exterior (colloquially known as an "outie" window), or towards the interior ("innie" window). An exterior window is detailed with an extension "box," to provide solid attachment for the window in the plane of the nonstructural foam. An interior window requires exterior jamb, sill, and head extensions, which need to be exterior-grade materials. Basic details of both of these options are shown in Figure 5; complete details with construction sequencing will be published in the future. Benesh (2009) and Holladay (2009) discuss of the pros and cons of the two options. It should be noted that the choice is also influenced by the location of the primary water control layer/drainage plane, as the connection between the window drainage system and the wall's drainage plane is critical.

The advantages of an exterior window installation include the following:

- If the drainage plane is located at the exterior face of the foam (either taped foam sheathing or housewrap), an exterior window greatly simplifies flashing details to an in-plane installation. An interior window installation combined with an outer drainage plane would require three-dimensional corner flashing details to transfer drainage (such as the subsill pan flashing) through the layers of foam, to the exterior drainage plane.
- In an interior installation, since the window opening penetrates through the 3/4 in. drainage and ventilation cavity, the trim extension details must allow drainage at the window head. In an exterior installation, the window installation is similar to conventional construction.
- An exterior installation can use trim extension details built from interior trim materials, including drywall returns; in contrast, an interior installation requires trim extension details for exterior use. This results in the interior installation being slightly less economical.
- An exterior installation provides a similar exterior appearance to conventional construction.
- If an interior installation used a flanged window were used, it would require more significant demolition or deconstruction to replace the window, relative to an exterior installation.

Advantages of an interior window installation include the following:

- If the drainage plane is the housewrap layer (interior to the foam), the window flashing connections are very simple with the interior window installation. In contrast, an exterior window installation would require wrapping the drainage plane around the extension box, in a three-dimensional manner.
- The window is structurally supported by the building's frame, as opposed to an extension box; some strongly advocate the interior window for this reason (Holladay 2009).
- By virtue of being inset into the wall, the window's face has greater protection from wind-driven rainfall, reducing the rain loading seen by the window. Similarly, the window is more shielded from nonperpendicular wind exposure.
- An exterior window is in a well or "tunnel" separating it from the interior. Due to conductive and radiative effects, the exterior window surface may remain colder and more vulnerable to condensation or frosting (Benesh 2009). However, the frosting observation was drawn from anecdotal experience in an Alaska climate; these problems have not been experienced by the author and his colleagues in exterior window installations in a Zone 5A climate. There was window condensation noted in the Arlington case study project, which uses interior windows. The problem was later diagnosed as being caused by underventilation, resulting in excess wintertime relative humidity levels, combined with the insulating effect of operable window shades.
- Some have argued that the interior window installation provides a significant benefit in overall thermal performance (Holladay 2009), due to placement of the window further within the insulated enclosure. The magnitude of this effect should be quantified by means of thermal simulations.
- In a retrofit situation, the interior window detail can be used with the existing interior window trim, if there is a goal to preserve that trim (as was the case in the Concord and Arlington projects). An exterior window detail would require crafting of extensions that match the interior wood trim, which would likely be costly and/or not aesthetically pleasing.

The interior window has greater shading/reduced solar gain due to its geometry; this may be a benefit or a penalty, depending on climate location and orientation of the fenestration. A simulation run on a test house using a Massachusetts climate file indicated that there was a slight penalty associated with this shading.

In the Concord and Arlington projects, interior windows were chosen, because of the location of the water control layer (housewrap behind foam), and the historic nature of the interior trim. At the Bedford project, an exterior window was used, since the exterior plane of the foam was being used as the drainage plane, and because the interior was gutted during construction.

CASE STUDY LESSONS LEARNED

Upon completion, all projects were tested several times for air infiltration (i.e., blower door), using infrared imaging to visualize air leakage paths. This provided some feedback to the effectiveness (or lack thereof) of various measures and

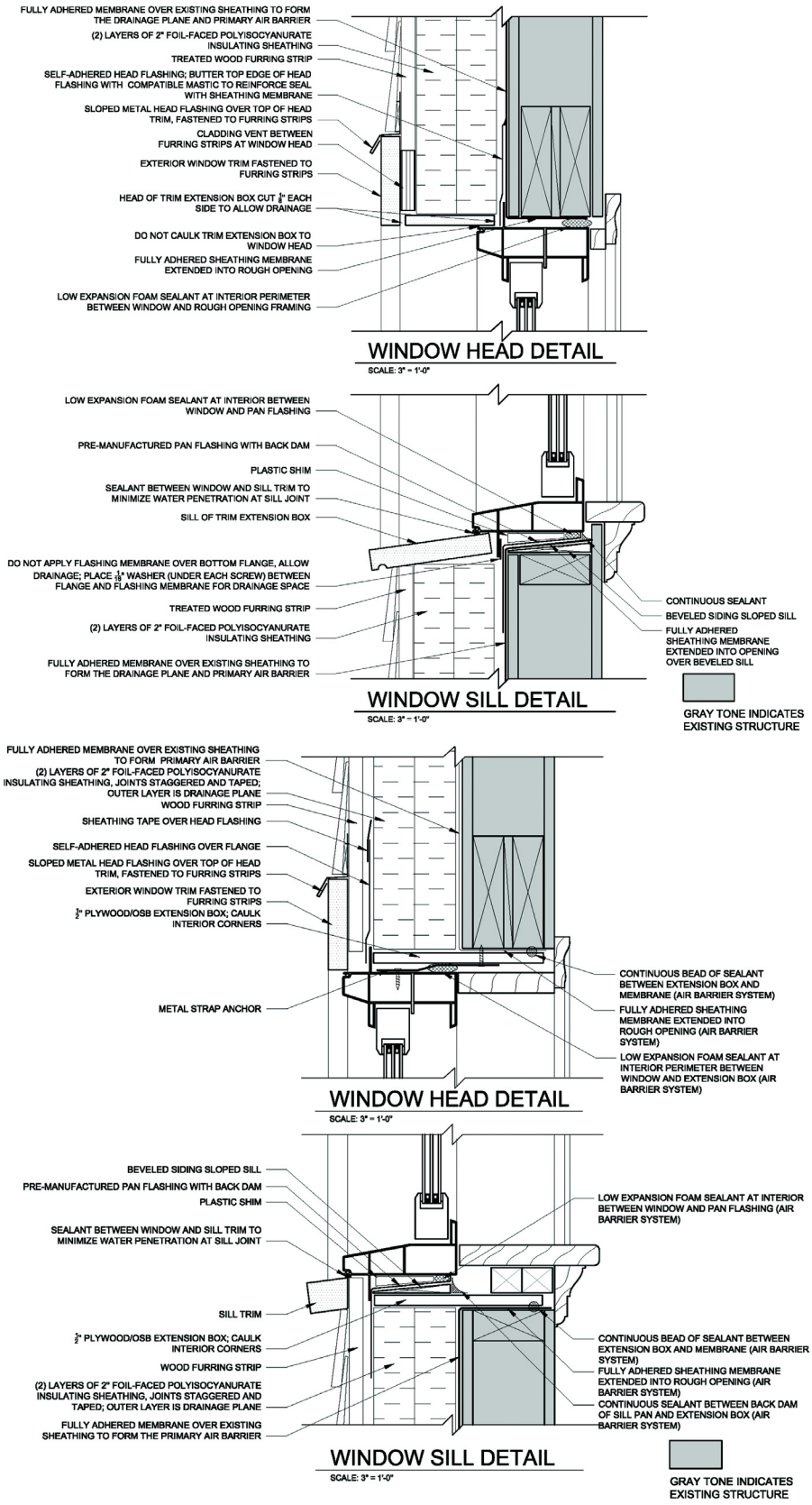

Figure 5 *Details of interior ("innie") window installation (top) and exterior ("outie") window installation (bottom), showing head and sill details (jamb detail omitted for clarity)*

Table 2. Summary of Infiltration Testing Results

#	Location and Label	Conditioned Surface Area, ft^2	CFM 50	ACH 50	EqLA, in^2	EqLA/100 ft^2 enclosure area
1	Concord, MA Four Square	5954	1511	3.1	156	2.5
2	Arlington, MA Duplex	6075	2129	5.0	220	3.4
3	Bedford, MA Farmhouse	5335	2260	6.2	233	4.2

details. The overall results from the Bedford project are covered in specific detail.

Air Barrier Performance

The air infiltration test results shown here represent the overall leakage for the house; therefore, it is difficult to consider these figures to be a perfect representation of the effectiveness of any given technique or detail, especially given the small sample size. Instead, the results show the combined effect of the materials, details, workmanship, and house-specific conditions in a given case study. Direct measurement of details under laboratory conditions would be better suited for testing specific techniques and details.

During the planning of these projects, it was hoped that the layering present in the assembly (housewrap, and multiple layers of rigid foam) would result in excellent air barrier performance. For instance, Straube and Burnett (2005) point out that if secondary layers are airtight, they can contribute greatly to overall airtightness, instead of relying on a single nominal air barrier layer.

The resulting performance is shown in Table 2. Table headings include conditioned enclosure surface area (in square feet, including below-grade surface area), the infiltration test result (in CFM 50, or cubic feet per minute at 50 Pa test pressure), ACH 50 (air changes per hour at 50 Pa), EqLA (equivalent leakage area, in square inches) (Canadian General Standards Board [CGSB] 1986), calculated at a 10 Pa pressure differential), and EqLA per 100 ft^2 of enclosure area. A test prior to renovation was performed on one of these three projects (the Arlington Duplex); that test result was 15.6 ACH 50. The other houses were not tested before renovation, but given their vintage, leakage in the 10–15 ACH 50 range is plausible. It should be noted that since the Arlington project was a duplex, both pre- and post-renovation tests were done using two blower doors, in a "nulling" test (neutral pressure between units), to eliminate inter-unit leakage and only measure leakage to the exterior.

Overall, the results were good for the Concord Four Square, reasonable for the Arlington Duplex (and a vast improvement from 15.6 ACH 50), and somewhat disappointing for the Bedford Farmhouse. Several facts should be recalled: the Arlington Duplex does not include the basement within the conditioned space, with the air barrier (spray foam) instead used at the basement ceiling. The Bedford Farmhouse did not have the housewrap layer as an air barrier: instead, the exterior foam layer was detailed as an air barrier.

During infiltration testing (house held at negative pressure; typically 20–25 Pa), an infrared camera was used to find discrete air leakage points. As a general observation, the field of wall typically showed little sign of air leakage, with some exceptions. Some penetrations through the interior walls (electrical receptacles, sill plate, window trim apron) showed signs of air leakage; however, this method only shows the interior exit point of the air leakage, without revealing the complete pathway. However, in other cases, specific air leakage points could be pinpointed, and some of them were quite significant.

- **Windows and doors:** The air seal at the replacement windows was somewhat disappointing: all showed signs of air infiltration, and some units showed substantial leakage (i.e., visible with infrared as warm leakage plume from exterior, Concord Four Square). Problems were expected, given that all windows were sliding double hung windows, which face intrinsic problems due to their sliding air seal, and the change in the plane of the weatherstripping (meeting rail). In addition, some doors had demonstrably poor air seals (including particularly leaky basement doors), which is a relatively common problem and not unique to energy retrofits.
- **Window/wall connection:** In general, the window/wall connection appeared to be well sealed, with minimal signs of significant leakage. One exception was a skylight at the Arlington Duplex, which showed signs of significant leakage behind the interior drywall finish. In addition, jets of leakage appeared from the window interior apron trim. Although this could have been addressed during window replacement by removing the trim, it was a balance between air sealing and disruption of interior finishes/increases in scope of work.
- **Mechanical:** Several mechanical exhaust fans proved to be significant leakage locations, including the kitchen range hood at the Concord Four Square and the bathroom exhausts at the Arlington Duplex, as shown in Figure 6. In addition, leakage bypassing the backdraft damper is visible. It is not clear whether the leakage occurs at the exterior penetration, or via leakage of the exhaust duct within the joist cavity.

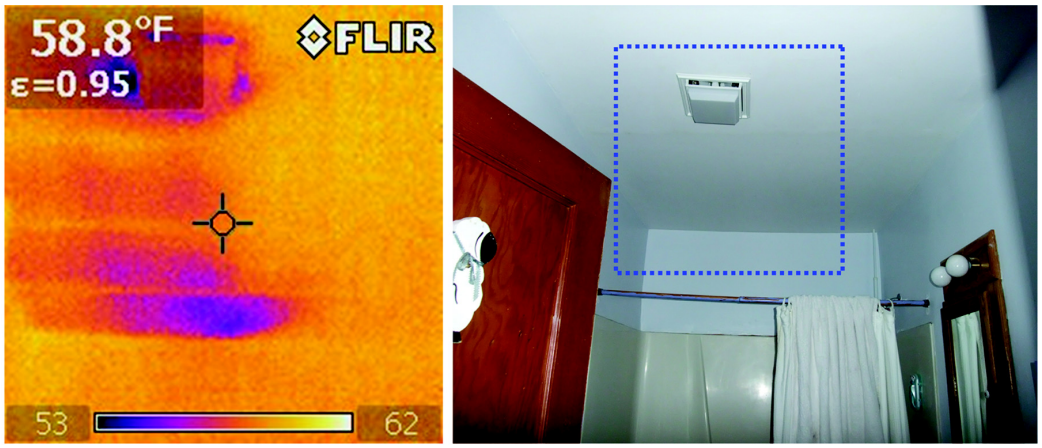

Figure 6 *Air infiltration visible at bathroom exhaust fan; exterior wall beyond shower. Infrared image shows strapping/furring at ceiling, perpendicular to joists, supporting lath and plaster.*

- **Foundation:** At the Concord and Bedford projects, the interior of the basement wall was insulated and air-sealed with high-density urethane spray foam, extending up into the rim joist cavities. The resulting foundation air seal was good (including the rim joist), except where there were application problems due to a lack of access or attention to detail. At the Arlington project, there was still significant leakage through the spray-foam-sealed basement ceiling (1000+ CFM 50, measured with a nulling test), despite a visually complete job. Interzonal pressures also indicated that the basement was still significantly connected to the above-grade space (–20 Pa when house at –50 Pa).
- **Slab retrofit detail:** One unexpected leak occurred at the Concord Four Square: the existing slab was retrofitted with a drainage spacer mat, rigid insulation, and a new slab. The drainage mat was terminated at the surface of the slab at the chimney penetration; during infiltration testing, significant air leakage occurred at the open drainage mat. This is evidence that the below-grade portion of the building enclosure has a non-negligible contribution to air leakage. Details of this leakage are covered in Pettit (2009).
- **Roof/wall connections:** In the Concord and Arlington projects, spray foam was used to connect the unvented roof air barrier to the wall air barrier, as shown by details in Joyce (2009) and Pettit (2009). Air barrier failures were found here only at incidental (nonsystematic) locations. However, the Bedford Farmhouse had different results, discussed below.
- **Overhanging bays:** The Arlington house had a relatively complicated geometry, with cantilevered bays extending from the foundation walls; during pre-renovation testing, these locations were shown to be tremendous air leakage sites. During the retrofit, the joist bays were sprayed with low-density urethane foam insulation. However, final testing revealed that there was still some diffuse leakage (i.e., could not localized to any specific source point) associated with these areas, observed as leakage at the interior. It is likely that although the spray foam provided an excellent air barrier in the bays, there were still elements that were not connected, resulting in exterior air barrier discontinuities.
- **Geometry:** In general, it appears that more complicated building geometries result in a lower chance of successfully retrofitting an exterior air barrier. For instance, the Concord Four Square has a simple geometry, with a square floor plan and a pyramidal hip roof with dormers. In contrast, the Arlington and Bedford projects involve more complicated floor plans (many corners) and intersecting roofs and walls. These air barrier details require more situation-specific detailing, and can be more difficult to execute correctly.

Bedford Project-Specific Issues

The overall air leakage at the Bedford project was noticeably worse than the other two projects. Some of these issues were gross air barrier defects, such as 2 ft^2 holes connecting the foundation space to the exterior, leaking bulkhead doors, or incorrectly built attic isolation walls. Others were ascribed to a general failure of the air barrier system installation: exterior visual inspection during cladding installation revealed several locations where the exterior insulation was not correctly detailed as an air barrier, with visible gaps and untaped seams.

In addition, leaks were found using blower door testing. At the roof/wall eave connection, spray foam was not used due to budget constraints; instead, workers installed blocks of rigid foam cut to fit the opening, and sealed the perimeter with one-component urethane foam. However, substantial leaks were found, which is understandable given the limited access at that

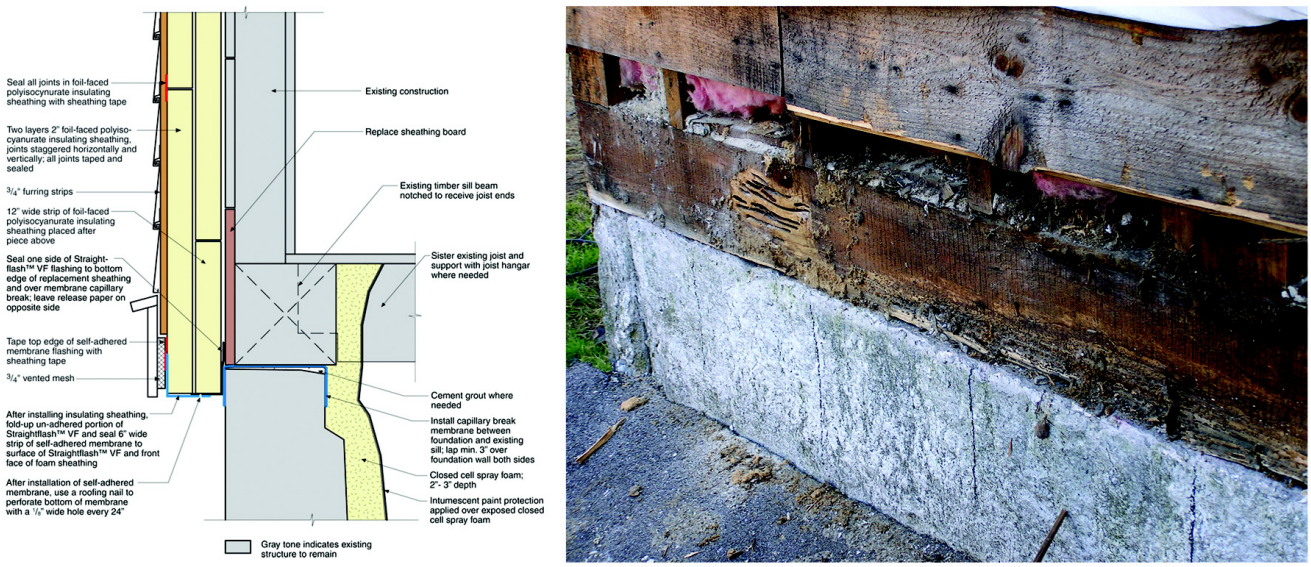

Figure 7 *Sill detail, including air barrier transition wrapped to front of foam, and capillary break over foundation (left); existing sill beam, showing long-term moisture damage (right).*

location. The roof gable ends were part of the conditioned space enclosure (unvented roof); however, noticeable leakage was found coming in at the gaps between the board sheathing, indicating an air barrier failure exterior to that layer. It was retrofitted with spray foam from the interior. In addition, the connection detail between the foundation wall and the above-grade wall was difficult to achieve; a detail was drawn that provides air barrier continuity without introducing bulk water to the interior (Figure 7). However, this detail did not provide acceptable air barrier performance when executed in the field. In addition, it should be noted that the sill beam showed significant rot on several sides of the house, perhaps due to splash-back, capillarity, or bulk drainage issues, thus requiring sill replacement. A thorough inspection of the existing structure, although intrusive, is strongly recommended to avoid investing an energy retrofit on an unsound frame.

The overall conclusion from this project was that detailing the retrofitted exterior rigid foam as the primary air barrier is a difficult proposition, and that success is further hampered by complicated geometries (including roof/wall connections). This assembly appears to be extremely sensitive to workmanship and builder comprehension of the vital connection between air barrier elements. In addition, the presence of two layers of insulation (with staggered seams) appears to do little to ensure air barrier effectiveness: its continuity between building components is of far greater importance, which is consistent with the Straube and Burnett's (2005) recommendations.

ANALYSIS

Additional topics that received further analysis included a hygrothermal analysis of the sensitivity of this retrofit assembly to bulk water intrusion, some analysis of the economics of this retrofit, and aspects of this retrofit affected by the building codes.

Hygrothermal Analysis: Sensitivity to Water Intrusion

One concern with this exterior insulation technique was whether or not it might increase the risk of moisture damage in the wall assembly. For the most part, the retrofit assembly tends to improve durability of the wall, due to the drained and ventilated cavity, the redundant drainage planes (multiple layers of foam, housewrap), and the reduction in interstitial condensation risk by elevating the condensing surface temperature with exterior insulation.

On the other hand, the one concern is that the foil-faced foam is impermeable to water vapor (<0.03 perm, or 2 ng/Pa·s·m^2). In the current assembly, incidental moisture (rain leakage, etc.) that enters the vulnerable portions of the wall can dry to the exterior (through the sheathing, building paper, and cladding). However, the retrofit largely eliminates this drying to the exterior. In addition, the increase in airtightness may or may not decrease drying due to air movement through the wall. Therefore, a window might currently leak water into the wall, but might be able to dry (to interior and exterior) sufficiently to avoid damage. However, by removing the drying to the exterior by adding the foil-faced polyisocyanurate, the same leak might accumulate sufficient moisture to cause damage.

To gain some intuition to the level of detail required, one-dimensional hygrothermal simulations were run on the wall before and after the retrofit in WUFI 4.2 (IBP 2008), using a Massachusetts climate. Models were run for three years of

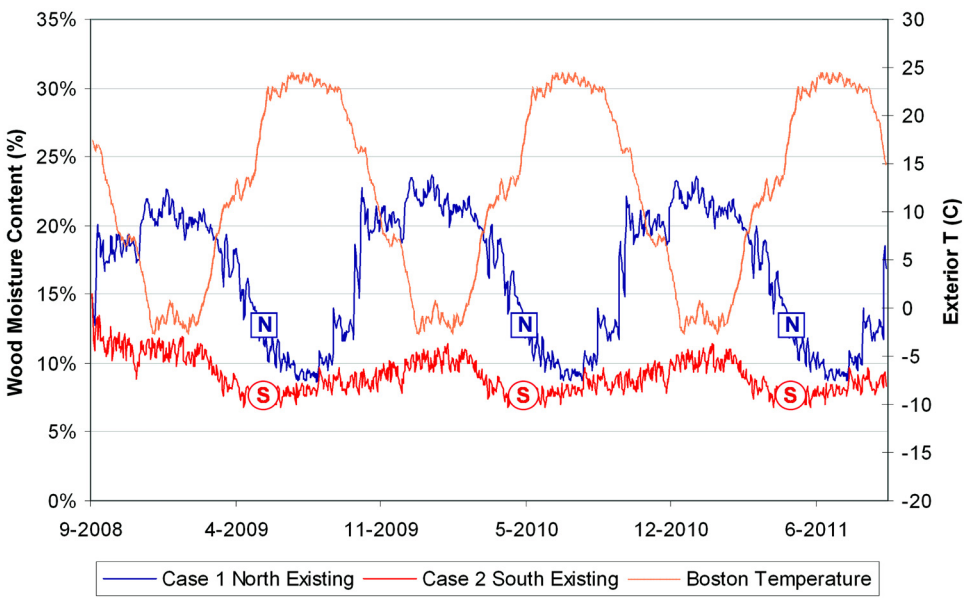

Figure 8 *Existing wall with 0.5% of incident rain penetration, north and south exposures, with exterior temperature for reference (seasonal patterns).*

simulated time, to determine increasing or decreasing moisture content patterns. Water was introduced at the board-sheathing-to-insulation interface, and selected as a fraction of incident driving rainfall on the wall surface.

The first step was to estimate the level of a "survivable" leak in the existing wall. Simulations were run examining the moisture content of the innermost 1/4 in. (6 mm) of the board sheathing. Initial simulations using 1% incident rain penetration showed the north exposure wall reaching wintertime moisture contents of over 40%, which would likely result in severe damage. Interestingly, though, on the south side, moisture contents peaked below 15%.

When the rain penetration was reduced to 0.5% of rainfall, the results are shown in Figure 8 (with the exterior temperature to show seasonal patterns): moisture contents peak in wintertime to 23%, and dry to below 10% in summertime, with a seasonally stable pattern.

However, when these same rain penetration levels are applied to the retrofitted wall (Figure 9), the north side shows a seasonally increasing moisture content, exceeding 30% by the third winter. This indicates a greater sensitivity to rain penetration. If the rain penetration is reduced by half (to 0.25%), the moisture content of the north-side sheathing stays at safe levels, with lower peak moisture contents relative to the original wall (peaks at roughly 17%).

A final set of simulations was run to determine the effect of exterior insulation material properties on rain leakage vulnerability. In addition to foil-faced polyisocyanurate, XPS and EPS were also compared, at the same thickness. Although XPS allows greater drying than foil-faced insulation, at the thickness used in this simulation (4 in., or 102 mm), the permeability is sufficiently low (0.25 perm, or 14 ng/Pa·s·m^2) that the wall shows a similar increased vulnerability to moisture accumulations. However, the EPS wall appears to have stable moisture cycling behavior, and is even drier than the original wall during the wintertime peaks. Although these simulations might point to EPS as a promising option for exterior insulation retrofits, there are some drawbacks to this material, including lower R-value per inch, lower compressive strength, poorer workability (edge cutting), and difficulty in detailing the material as a water control layer/drainage plane.

These results demonstrate that if an exterior foam retrofit is done, it is vital to ensure that windows and other penetrations are flashed properly. In fact, this potential damage is a strong reason to consider window replacement, in order to provide subsill window pan flashings at all window openings. This information was used to persuade the homeowner of the Arlington project to take this course of action. Alternately, pan flashing might be retrofitted to existing window installations, although it would likely requite removal and reinstallation of the windows.

Economic Analysis

Deep energy retrofits often face the criticism of not being economically justified, due to diminishing returns (of space-conditioning energy savings) associated with additional layers of insulation. The retrofit technique presented here is not intended (nor likely) to be a widely deployed measure; however, there is a self-selected market of customers who are interested in retrofits of this nature, who might not use economic payback as their sole value metric.

This analysis is not intended as a complete rigorous economic analysis by any means; it is a component of the

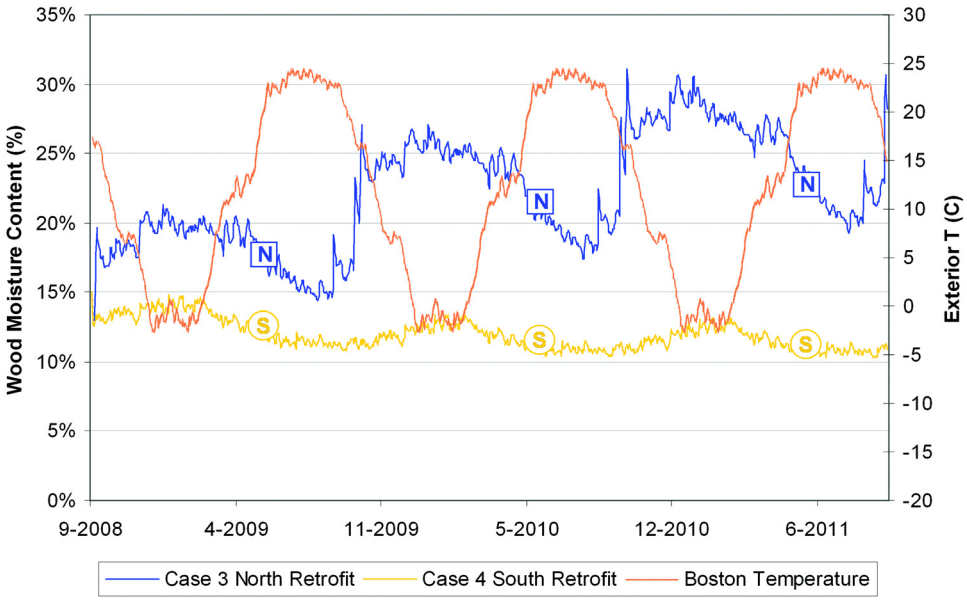

Figure 9 *Retrofitted wall with 0.5% of incident rain penetration, north and south exposures, with exterior temperature for reference (seasonal patterns).*

Arlington project case study. The information presented here is not meant to provide a cost-benefit justification for situations beyond this case study, although it is valuable for providing inputs and boundary conditions for future energy modeling.

A DOE-2 based simulation of the Arlington house was created, using house dimensions and characteristics (including air leakage); the model was then tuned to the historic energy use data. The proposed retrofit measures were then incrementally added to the simulation to estimate their effect. A Boston weather location was used; the heating oil cost at the time (late 2008; US $4.00/gal) was used in these simulations; current EIA data project heating oil costs in the $2.50–$3.00 range through 2011 (EIA 2010).

Most importantly, in these simulations, the effect of the exterior insulation retrofit included both the decrease in U-factor as well as the component's contribution to improved house airtightness. Improvements in airtightness have a tremendous effect on overall heating energy use, and it seems reasonable to apportion the total airtightness benefit by component (walls, roof, windows, or foundation). Our estimates were that 20% of the total improvement could be apportioned to the housewrap and first layer of polyisocyanurate, and 5% of the improvement to the second layer of polyisocyanurate. The incremental cost of the exterior retrofit was $4/ft^2 of wall area (incremental above the base recladding cost); this was based on written estimates by the contractor, and is in line with 50% material costs/50% labor costs. Using these assumptions, the simple payback periods for the wall retrofit measures were

- First 2 in. (50 mm) of polyisocyanurate: $8200 estimated installation cost; $816 annual savings, 10 year simple payback (15 years without airtightness increment). Payback periods increase to 16 and 25 years, respectively, at a fuel price of $2.50/gallon.
- Second 2 in. (50 mm) of polyisocyanurate: $4100 estimated installation cost; $188 annual savings, 22 year simple payback (37 years without airtightness increment). Payback periods increase to 35 and 59 years, respectively, at a fuel price of $2.50/gallon.

It appears that in this case, the first 2 in. (50 mm) layer of insulation is justified, especially given the replacement cycle time of walls. Of course, several circumstances make these a relatively optimistic set of calculations, including the high existing air leakage rate and the low efficiency of the heating plant. In addition, these calculations are based on the assumption that a cladding replacement is being done for aesthetic or maintenance purposes, and the only incremental cost is the addition of the foam and strapping assembly.

The second 2 in. (50 mm) layer is more difficult to justify, especially if lower fuel costs are used. However, one line of reasoning supporting the installation of the second layer looks at the longer-term future of the building. This recladding is a rare opportunity to insulate the opaque walls; it would be extremely difficult to provide this incremental upgrade at a later date, since it is clad with an expensive and durable finish, with window, door, and roof connection details. In addition, the replacement cycle for the cladding is quite likely to be beyond the simple payback figures stated above; these calculations do not take fuel cost escalation into account.

The energy performance of all of the retrofit projects is currently being recorded, and may be presented at a later date. However, the Arlington project is the sole case study where the original mechanical system was retained, thus allowing the disaggregation of enclosure vs. mechanical savings. The energy savings associated with the Concord Four Square are presented in Pettit (2009).

Building Codes

In buildings that fall under the International Building Code (IBC), as opposed to the International Residential Code (IRC), it should be noted that there is a requirement for fireblocking of exterior concealed wall cavities (ICC 2009, section 717.2.6, Architectural trim). This fireblocking must be placed at a maximum interval of 20 ft (6096 mm); and limit open space to 100 ft^2 (9.3 m^2). This can be addressed, for instance, by providing fireblocking every two stories, with openings for cladding drainage and ventilation above and below the fireblocking.

CONCLUSION AND FURTHER WORK

There is a substantial opportunity for energy retrofits of existing housing stock; however, these upgrades must be undertaken without compromising the durability or health and life safety of the houses. An exterior retrofit method using rigid foam sheathing was used on three Boston-area case study houses; the assembly and its components are described in detail. There are several advantages to this method, including thermal performance and durability.

The air barrier performance of these case study houses was measured; results varied from good to somewhat disappointing, although all were a substantial improvement over original performance. Air barrier issues included some locations common to all construction, including windows, doors, and mechanical penetrations. However, it was noted that complex house geometries appeared to be associated with greater difficulty in obtaining airtightness. Furthermore, the air barrier retrofit technique used at the Bedford Farmhouse was not highly successful; detailing the retrofitted exterior rigid foam as the primary air barrier is a difficult proposition.

Although this assembly improves durability in other respects, hygrothermal analysis shows that the assembly reduces the ability of the wall to safely dry incidental bulk water leakage, perhaps by a factor of two. This is a strong motivation to provide scrupulous water management details when performing this retrofit, particularly in the installation of window subsill pan flashings. The vapor permeance of the insulation material has a noticeable effect on the drying of these systems, with more permeable materials (such as EPS) providing more forgiveness.

Overall, it appears that this technique can improve airtightness, but there are limitations to its ultimate performance. Moving to greater airtightness levels may require the use of different techniques, including simplification of the geometry followed by a fully adhered air barrier membrane (i.e., "chainsaw retrofit"). A retrofit project is currently planned in Freeport, ME, evaluating this technique. In addition, the use of exterior spray foam as a retrofit air barrier/thermal barrier/water control layer is a likely candidate to produce excellent airtightness; this method is discussed by Coldham (2009) and Straube and Smegal (2009).

ACKNOWLEDGMENTS

The author would like to thank the US Department of Energy's Building America Program for funding most of the research underlying this paper, as well as the Massachusetts Department of Energy Resources (DOER), which funded the analysis and testing of the Arlington project.

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