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

BUILDING TECHNOLOGIES PROGRAM

Reaching for Peak Performance in Existing Homes – A Cold Climate Study With Synergy Construction

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December 2011

Building America
U.S. Department of Energy

This report received minimal editorial review at NREL

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Prepared for:

Building America

Building Technologies Program

Office of Energy Efficiency and Renewable Energy

U.S. Department of Energy

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Subcontract Number: KNDJ-0-40337-00

December 2011

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Contents

List of Figures

Unless otherwise noted, all figures were created by Building Science Corporation.

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List of Tables

Unless otherwise noted, all tables were created by Building Science Corporation.

Definitions

ABS	Air barrier system
ACH	Air changes per hour
ACH 50	Air changes per hour at 50 Pascal test pressure
BA	Building America Program
BSC	Building Science Corporation
ccSPF	Closed-cell spray polyurethane foam
CFL	Compact fluorescent lamp
CFM	Cubic feet per minute
CFM 50	Cubic feet per minute at 50 Pascal test pressure
DER	Deep energy retrofit. In the context of this Test Plan, this refers specifically to the National Grid DER Pilot program.
DOE	U.S. Department of Energy
DHW	Domestic hot water
XPS	Extruded polystyrene
HRV	Heat recovery ventilator
HVAC	Heat, ventilation, and air-conditioning
NREL	National Renewable Energy Laboratory
ocSPF	Open-cell spray polyurethane foam
TMY3	Typical Meteorological Year, version 3

Executive Summary

Building Science Corporation (BSC) seeks to further the energy efficiency market for New England area retrofit projects by supporting projects that are based on solid building science fundamentals and verified implementation. BSC has been working with Synergy Companies Construction, LLC on new and retrofit projects under the Building America (BA) Program. Two test homes, one in Millbury and one in Somerville, Massachusetts, are examined with the goal of providing case studies that could be applied to other similar New England homes.

The retrofit processes for the enclosure and mechanical systems are examined in detail and the decision-making process is discussed. The Millbury Cape retrofit, under the guidelines of the National Grid Deep Energy Retrofit (DER) Pilot Program, achieved very highly insulated enclosure values on all six sides and included triple-pane windows. An old oil-fired boiler and window air-conditioning units were replaced with a high efficiency electric heat pump. The Somerville Triple Decker, previously lacking wall insulation, also underwent significant thermal enclosure improvements, though the owner opted not to insulate the basement floor. Old gas-fired forced air systems were replaced with high efficiency gas-fired hydronic systems. No upgrade was made to the cooling system, which consisted of occasionally used window units. Both homes remained occupied throughout the retrofit process.

A variety of testing and analysis was performed for the two test homes. Blower door testing was performed for both the Millbury Cape and the Somerville Triple Decker to gauge the success of air sealing efforts. Utility bills from before and after the retrofits were collected from home occupants to compare measured fuel usage, showing clear reductions in post-retrofit energy use. These utility bill summations are compared to the results of BEopt energy modeling, to show incremental energy reduction from each retrofit measure. Finally, reported occupant satisfaction and other non-numerical observations are discussed.

Both projects successfully implemented many of the enclosure and mechanical retrofit measures promoted by Synergy Companies Construction, LLC and BSC, leading to positive results. Blower door testing showed significant air leakage reduction following completion of enclosure renovation and air sealing. Several iterative tests indicated the need for improvements in airtightness. After these were made, the Millbury Cape achieved a final value of 1.4 ACH 50 and the Somerville Triple Decker achieved 3.48 ACH 50.

Although the Somerville Triple Decker used gas for all heating both before and after the retrofit, the Millbury Cape used a mix of fuels. Wood pellets and oil were used before the retrofit; these were replaced with propane for domestic hot water (DHW) and electric heat pump heating, but still occasionally used pellets. Components of this pre- and post-retrofit fuel mix were converted to source energy to calculate project energy savings. The Millbury Cape and the Somerville Triple Decker showed source energy use reductions of 37% and 48%, respectively, compared to data from the previous year, even though there were approximately 8% more heating degree days during the post-retrofit period examined.

These energy results are graphed by month and compared to usage predicted by energy models created using BEopt. Although there were limitations to using BEopt to model certain elements

present in the pre- and post-retrofit homes, parametric analysis results give an idea of the incremental energy savings to be attributed to each upgrade from the pre-retrofit state.

Homeowner feedback supported the positive energy efficiency results; significantly improved comfort and satisfaction were reported. Feedback was received in the form of comfort-related survey responses as well as anecdotal comments about improvements such as the lack of ice dams and even interior temperatures.

Current results for both test homes are based on approximately half a year (heating season) of post-retrofit data and do not necessarily indicate average performance for future years. Additional observation is needed to fully gauge long-term energy performance, durability, and occupant comfort. Recommended future work includes continued monitoring of utility bills to verify long-term energy savings and point to ways in which usage could be reduced further. Environmental data monitoring could also be used to evaluate any reported thermal comfort or heating, ventilation, and air-conditioning (HVAC) distribution issues that may arise.

1 Introduction

BSC seeks to further the energy efficiency market for New England area retrofit projects by supporting projects that are based on solid building science fundamentals and verified implementation. BSC has been working with Synergy Companies Construction, LLC, a partner on our BA team, on new and retrofit projects under BA. Synergy Companies Construction, LLC is a local construction firm that has worked with BSC on a number of housing projects, both new and existing, which have attained superinsulated and very airtight enclosures.

With the high exposure of energy efficiency and retrofit terminology in the general media at this time, it is important to have evidence that measures being proposed will in fact benefit the homeowner through a combination of energy savings, improved durability, and occupant comfort. Concrete data from specific projects can close the gap between hype and reality.

This report explores the retrofit efforts and results of two Synergy Construction test homes. These test homes contribute to several basic areas of research. These include a combination of measures that is feasible, affordable, and acceptable to homeowners, as well as expectations versus results.

One of the two test homes, the Millbury Cape, was a participant in the National Grid DER Pilot Program (National Grid 2009). The program's goal is to achieve at least 50% better energy performance than a code-built or Federal Energy Yardstick home; the program provides financial incentives and technical support to participants. BSC has partnered with National Grid, providing technical guidance and support for the program.

1.1 Context and Relevance to Other Homes

Test Home 8.1a ("Millbury Cape") is a small, sturdily built Cape Cod-style house built in the 1950s in a neighborhood of many similar houses. There are many such neighborhoods in the New England area as well as in other parts of the United States. The occupants of these houses are often young families, or older couples whose children have left home ("empty nesters"). Particularly in the latter case, these families do not want to leave the neighborhood, but are concerned about being able to afford the increasing costs of energy.

Figure 1. Pre-retrofit Millbury Cape located in Millbury, Massachusetts

Figure 2. Post-retrofit Millbury Cape

The 8.1b Test Home ("Somerville Triple Decker") is a triple decker multifamily wood-framed building typical of New England, circa 1920. Thousands of these homes were built to house new immigrants and other workers in the early 1900s, efficiently sharing the cost of land, roofing, and foundation among the occupants (Irving 2011). These homes are frequently owned by one occupant and rented to others, sometimes to extended family. These aging original New England triple deckers will continue to need renovations for which this Somerville test home may serve as an example.

Working with Synergy Construction and BSC, architectural designer Laura Catanzaro of Holistic Design and Space Planning acted as a consultant and project manager for the efforts.

Figure 3. Pre- (left) and post- (right) retrofit Triple Decker located in Somerville, Massachusetts

2 Retrofit Measures

Although many of the energy efficiency measures for a retrofit are the same as for new construction, the underlying constraints are different. For new construction, the owner has a clean slate for implementing the most important energy-efficient aspects—detailing the air barrier; providing ventilation and ductwork for heating and cooling; selecting, installing, and air sealing windows; and providing large amounts of insulation. As such, these can be implemented following standard, proven details. On the other hand, for a retrofit, the reality of existing conditions results in "special case" details for nearly all portions of the building. The selection of a retrofit implies that there is something about the existing building that needs to be preserved—it may be all or parts of the exterior, it may be all or parts of the interior, it may be just the structural framing, or it may be a combination of the above. This complicates everything—from installing an effective air barrier to providing ventilation in the newly airtightened house.

For the two test homes in this report, the interiors were to be preserved–in fact, the homes were to be occupied throughout the retrofit project. As a result, most of the retrofit measures for the enclosure were constrained to be those that could be implemented without major disruption to the interior finishes or operation of the homes.

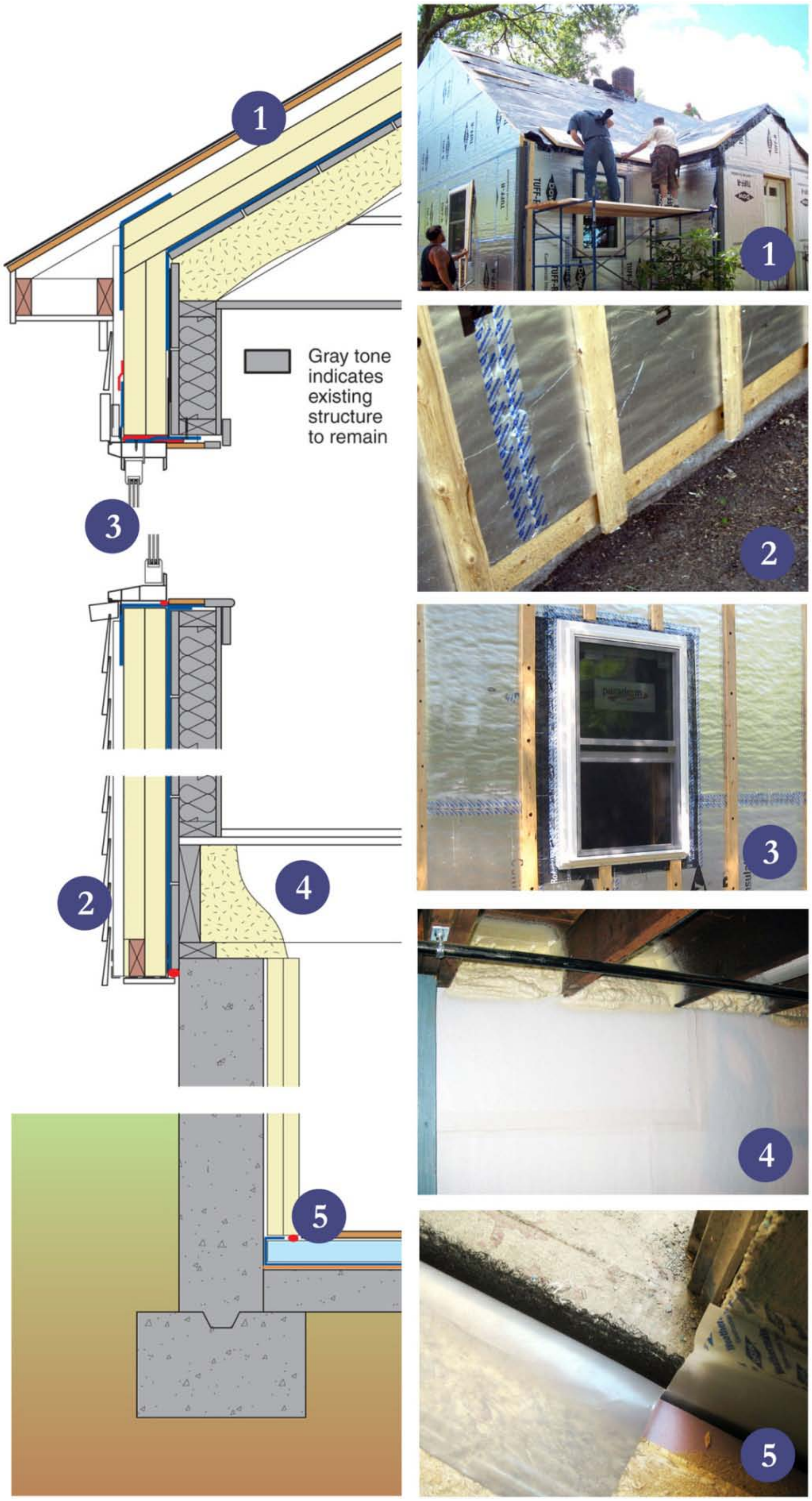
The measures are broken into two groups—building enclosure measures and mechanical system measures. Enclosure measures address energy efficiency by using air barrier systems (ABSs) and thermal layers to reduce heat loss or gain. Durability is also improved by appropriate water and vapor management methods. Mechanical measures address energy efficiency primarily by upgrading the efficiency of equipment.

In addition, the enclosure measures add new requirements to the mechanical systems: because of increased airtightness, ventilation must be provided and combustion safety must be addressed. And finally, the mechanical systems can and should be downsized to meet the new load conditions; smaller systems can be a benefit due to investment in the enclosure.

With both test homes located in Massachusetts, the retrofit measures that are described in this document are discussed in the context of cold climate (DOE Zone 5A) conditions.

2.1 Enclosure Measures

For a retrofit, the enclosure retrofit measures can be divided into the following general categories: above-grade wall assembly, roof or attic assembly, foundation assembly, window specifications, and air infiltration or ABS. As can be seen by comparing the profiles in Figure 4 and Figure 5, the retrofit projects for the Millbury Cape and the Somerville Triple Decker adopted similar strategies for each of these assemblies with the exception of the foundation assembly. Therefore, the strategies for enclosure measures are described in common for the two retrofit projects with additional notes highlighting any differences between them.



Enclosure Design

1 Roof Assembly: Unvented attic assembly with existing rafters filled with spray foam and two 2" layers foil-faced polyiscyanurate exterior insulating sheathing, joints staggered; ventilation under outer layer of roof sheathing created by 2X4's on the flat.

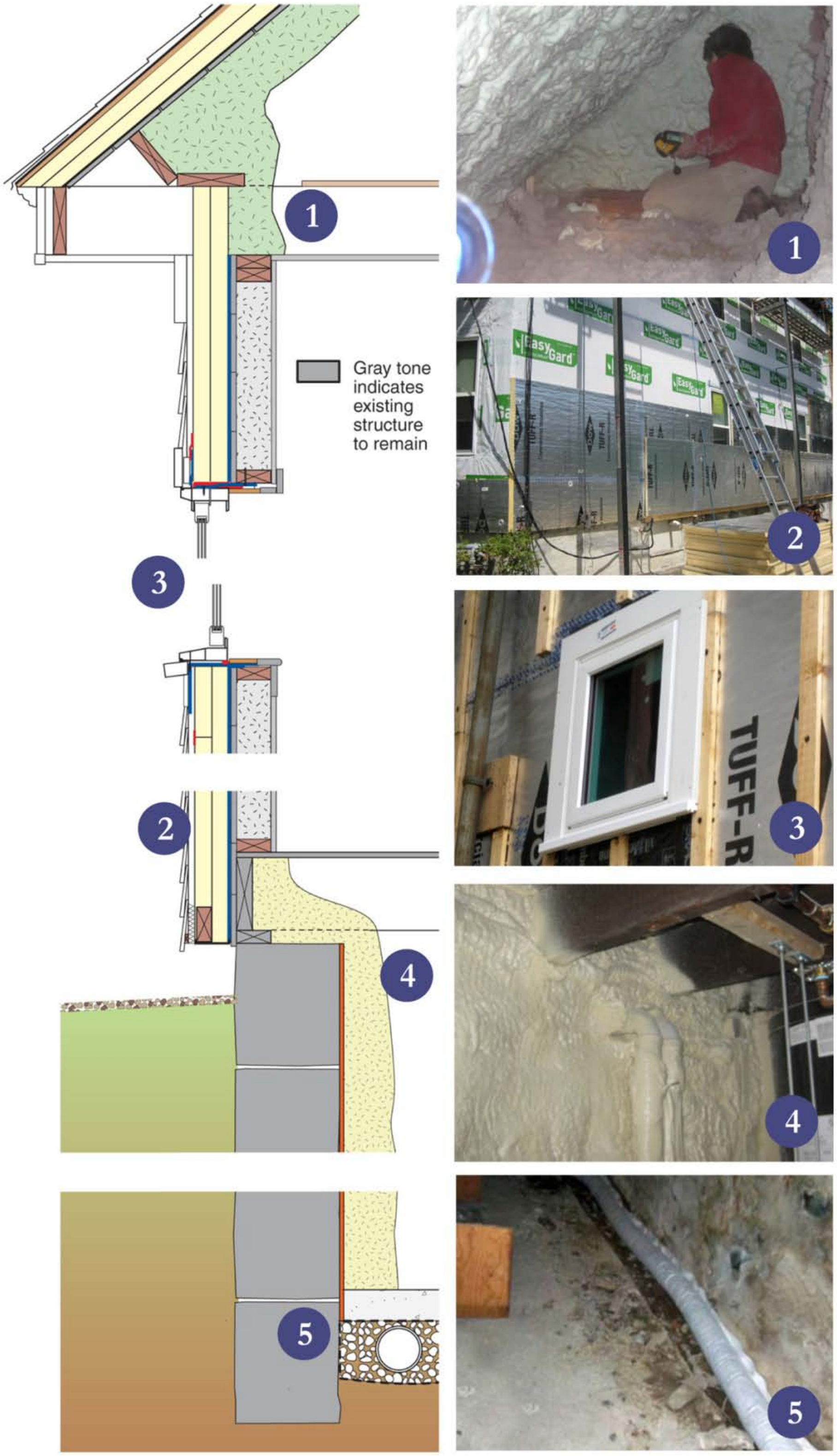
2 Wall Assembly: Existing batt insulation in wall cavities; two 2" layers foil-faced polyisocyanurate exterior insulating sheathing, seams staggered and taped; vertical strapping over insulating sheathing creates ventilation and drainage gap.

3 Window Specifications: New Paradigm triple glazed, argon-filled, low E double hung vinyl windows; U=0.25, SHGC=0.25.

4 Air Infiltration: Taped roofing membrane over existing sheathing for roof; taped housewrap over above grade walls; taped interior insulation board for foundation wall and basement slab; transition from roof to wall by overlapping roof membrane onto wall housewrap; from wall to foundation through mudsill by applying spray foam insulation on inside; from foundation wall to basement floor by sealant.

5 Foundation Assembly: 3" polyisocyanurate insulation applied to concrete foundation walls; drainage mat applied over existing slab, covered by polyethylene, taped rigid insulation, and then floating subfloor.

Figure 4. Enclosure profile for the Millbury Cape



Enclosure Design

❶ Roof Assembly: Unvented compact roof assembly with existing rafters filled with spray foam and two 2” layers foil-faced polyisocyanurate exterior insulating sheathing, joints staggered.

❷ Wall Assembly: Blown-in cellulose in wall cavities; two 2” layers foil-faced polyisocyanurate exterior insulating sheathing, seams staggered and taped; vertical strapping over insulating sheathing creates ventilation and drainage gap.

❸ Window Specifications: New Serious Materials fiberglass insulated glass units with suspended film; U=0.19, SHGC=0.24.

❹ Air Infiltration: Taped roofing membrane over existing sheathing for roof; taped housewrap over existing sheathing for above grade walls; closed cell spray foam on interior side of foundation wall; existing concrete slab for basement; transition from roof to wall by filling the intersection with spray foam on the inside; from wall to foundation wall through mudsill by applying spray foam insulation on inside; spray foam on foundation wall seals to existing slab floor.

❺ Foundation Assembly: Closed-cell spray foam with ignition barrier coating applied to rubble wall with drainage mat behind; spray foam extends up over the mud sill; perimeter sub-slab drainage and passive soil gas system added; no treatment of existing slab.

Figure 5. Enclosure profile for the Somerville Triple Decker

The Millbury Cape was a participant in the National Grid DER Pilot Program. This program specifies desired project characteristics for qualification, including fenestration, airtightness, and opaque enclosure guidelines. For reference, their targets for opaque R value, fenestration, and airtightness are summarized as follows (National Grid 2009):

> *Insulation - targets for effective R-value: roof-R60, above grade wall -R40, below grade wall - R20, basement floor - R10. Thermal bridging needs to be considered fully in estimation of thermal performance and minimized to the extent possible.*
>
> *Air Sealing Target – Ideal whole house sealed to achieve 0.1 (zero point 1) CFM 50 /sq. ft. of thermal enclosure surface area (6 sides) with high durability materials.*
>
> *Windows and Doors - target R5 (U ≤ 0.2) whole-unit thermal performance, infiltration resistance performance of ≤ 0.15 CFM/sq ft. of air leakage, per AAMA11 standard infiltration test.*

These components and their target performance values form a baseline from which the two projects' enclosure measures are described below: above-grade walls, roof or attic, foundation walls, basement floor, windows and doors, and ABS. The DER program also emphasizes durability, so a water management system is also an enclosure measure described.

In this section, the term *nominal R-value* is used to mean the sum of the nominal R-values of the insulation products used in the assembly being described.

Above-Grade Walls:

To provide at least nominal R-40 walls, insulating sheathing was applied over the exterior wood sheathing and wall cavity insulation was upgraded as needed (BSC 2007). In both test homes, two layers of 2-in. foil faced polyisocyanurate exterior insulating sheathing were applied. At the Millbury Cape, the wall cavities had existing fiberglass batt insulation; this was replaced only in sections where the interior wall was opened for other reasons. For the Somerville Triple Decker, there was no wall cavity insulation so cellulose was retrofitted from the exterior.

The full construction of the wall treatment for both homes was as follows:

- Existing siding and tar paper underlayment were removed.
- House wrap was applied over the existing board sheathing with seams taped to form an air barrier.
- 4 in. of insulating sheathing was applied over the house wrap; the seams of the insulating sheathing were staggered, both vertically and horizontally, and the outer layer seams were taped (Figure 6).

- Vertical wood strapping was applied over the insulating sheathing and attached to the wall studs using long screws (Figure 6).
- Fiber cement lap siding was attached to the wood strapping.
- Wall cavity insulation was added as needed.

Figure 6. Insulating sheathing on the Millbury Cape

Roof or Attic:

For both test homes, there were portions of the upper floors with living space located directly below the roof: this limited the amount of insulation that could be applied in the attic space. Therefore, the approach to both homes was to create unvented attics and to apply most of the insulation to the exterior side of the roof deck.

With a targeted nominal R-value of 60 for the roof, the approach used for both houses was to apply two layers of foil-faced polyisocyanurate insulating sheathing over the existing roof sheathing and to apply open cell spray foam in the rafter bays from underneath the roof deck, accessed from knee wall and unfinished attic spaces (Figure 7**).**

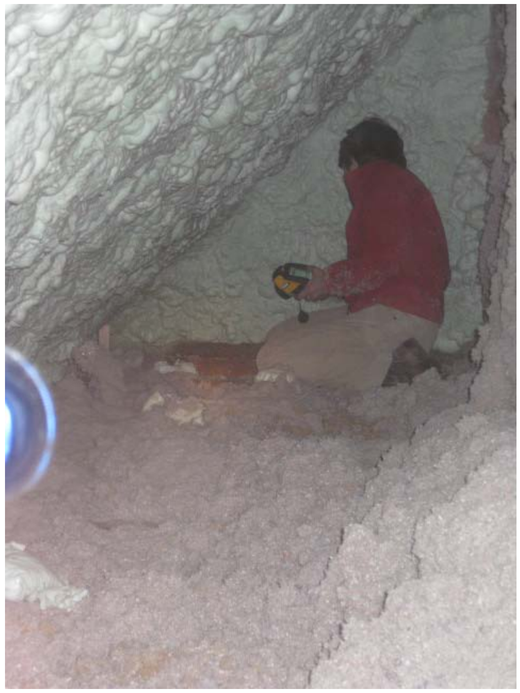


Figure 7. Attic insulation for the Somerville Triple Decker

The full construction of the roof treatment for both houses was as follows:

- Existing roofing shingles and tar paper were removed.
- Roofing membrane was applied over the existing board sheathing, with seams taped, to form an air barrier.
- The insulating sheathing was installed over the roofing membrane with seams staggered to minimize air channels.
- A new layer of plywood sheathing was installed, attached through the insulation to the existing rafters using long screws.
- The plywood was covered with ice and water shield for the entire roof.
- New asphalt shingles were installed.
- Spray foam insulation was applied to the rafter cavities (Figure 7).

For the Millbury Cape, 2 × 4s on the flat were inserted between the insulating sheathing and the new outer layer of plywood creating a vented roof capped by a ridge vent. In this case, the 2 × 4s were attached to the existing roof rafters and the plywood sheathing was attached to the 2 × 4s.

Foundation Walls:

Both test homes have full basements that are used for storage and mechanical equipment only. The targeted nominal R-value for basement walls is R-20 and for the test homes, the only feasible option was to insulate from the inside (BSC 2009e).

The Millbury Cape has cast concrete foundation walls. The foundation wall treatment was as follows:

- 3 in. of polyisocyanurate insulation board was applied to the interior side of the foundation wall.
- Closed cell spray foam was applied along the top of the foundation wall covering the rim joist.
- For the Millbury Cape, the spray foam was used to establish the continuity of the thermal layer and of the air barrier between the above-grade walls and the foundation walls (BSC 2009e).
- The Somerville Triple Decker has a parged rubble stone foundation wall with brick at the top. The foundation wall treatment was as follows (from exterior to interior):
- A drainage mesh was applied over the interior side of the foundation wall;
- 3 in. of closed cell spray foam was applied over this and extended up to the bottom of the subfloor above (Figure 8);
- An ignition barrier paint was applied over the spray foam.

Details for foundation wall treatment for rubble stone are covered by Lstiburek (2010a, 2010b).

The drainage mesh applied to the foundation wall for the Somerville Triple Decker is part of the water management system. Its purpose is to direct any water that passes through the foundation wall down below the floor. Because water does not pass through the closed cell spray foam, it would have sufficed to apply the drainage mesh just at the bottom of the wall. If the drainage mesh is extended up the wall, as in this case, it should not cover any wood framing.

Figure 8. Somerville Triple Decker basement wall insulation before application of ignition barrier

Basement Floor:

It is recommended that basement floors be insulated to at least nominal R-10. For a retrofit, this particular measure can be problematic because adding 2 in. of insulation to the floor raises the floor elevation, typically resulting in a ceiling height problem. It also can seem unnecessary to the homeowner, since the ground temperature at that level is moderate, and therefore the energy loss through the floor is relatively low. However, an untreated basement floor can be a source of moisture from condensation and possible capillary wicking from below (BSC 2009e).

For the Millbury Cape, the basement floor assembly was as follows (from bottom to top):

- Existing concrete slab
- Drainage mesh
- 2-in. layer of extruded polystyrene (XPS) with seams taped to create an air barrier
- Vapor barrier of polyethylene
- Floating oriented strand board subfloor.
- The drainage mesh in this assembly for the Millbury Cape provides some storage capacity for any water that does get through the foundation walls (Figure 9).

Figure 9. Millbury Cape basement floor construction

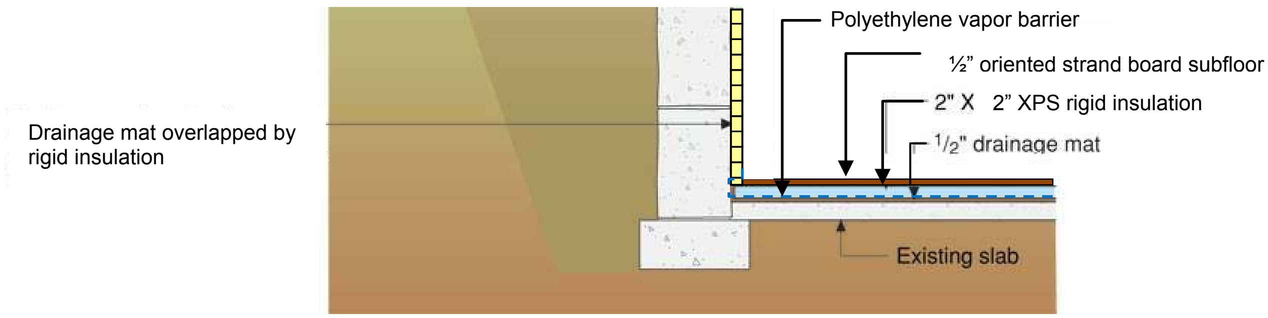


Figure 10. Millbury Cape floor assembly diagram

For the Somerville Triple Decker, the owner decided not to insulate the basement floor. However, a sub-slab perimeter drainage system and passive soil gas ventilation system were implemented (BSC 2009f).

Windows and Doors:

Window characteristics for both houses were the same.

The targeted window assembly R-value for doors and windows for the retrofits was R-5 or more (or U-value of 0.2 or less). For both test homes the window characteristics were as follows:

- New “triple-glazed” windows
- Window U-value of 0.2 or less
- Windows installed as “outie” windows.

An “outie” window is installed within the outside insulation layer of the wall and attached back to the rough opening using metal straps. With the window in this position, it is necessary to extend the existing interior jamb, head, and sill window trim to reach the position of the new windows (Figure 9).

New insulated R-5 exterior doors were installed at the Millbury Cape. The exterior doors of the Somerville Triple Decker were not replaced.

Figure 11. Millbury Cape “outie” windows

Water Management System:

The water management system needs to be coordinated with all components of the enclosure (BSC 2009a)—roof, walls (and windows/doors), and basement.

For the roof assemblies of both houses, the ice and water shield underlayment over the plywood sheathing provides water management and the eave overhangs extend the system beyond the roof/wall intersection. The Millbury Cape did not originally have sufficient overhangs to protect the walls, and existing water damage was discovered during the construction. As part of the retrofit, new overhangs and rakes were attached to the house after the exterior insulation layers had been applied to the roof and walls (Figure 12). For the Somerville Triple Decker, the existing overhangs were generally deep enough to cover the thicker walls, though a rafter extension was applied in certain portions of the eaves where more depth was desired.

Figure 12. The Millbury Cape eave and rake overhang

The drainage plane for the walls of both houses is the outer layer of insulating sheathing. To provide this function, all seams of the insulating sheathing were taped to prevent water from passing through the seams. The window flashing and sill pan were integrated with the surface of the insulating sheathing. The gap between the insulating sheathing and the lap siding formed by the vertical strapping provides space for drainage as well as ventilation to promote drying.

In the basement, the primary water management concern is to handle bulk and capillary water that penetrate through the foundation walls. In both test homes, the foundation wall is insulated with impermeable and moisture-insensitive materials. Any water that does pass through the wall will not damage the insulation and will be drained down the wall behind the insulation layer. At the bottom of the foundation wall, the water management system for both houses directs the water below the floor, away from the interior space. In the Millbury Cape, a strip of drainage mat behind the insulation at the bottom of the foundation connects with the drainage mat under the new floor providing a channel and storage buffer. In the Somerville Triple Decker, drainage mesh was applied to the wall behind the insulation and down into the interior perimeter drain trench so that any water that passes through the wall will be directed to the sub-slab drainage system.

Air Barrier System:

The ABS is the system that separates indoor (conditioned) air from outdoor (unconditioned) air. To be effective, it must be continuous over all six sides of the building. The retrofit plan needs to identify the air barrier for each component of the enclosure and how it is to be continuously transitioned to the air barrier of adjacent components (Lstiburek 2005).

For the Millbury Cape, the ABS consists of the following components:

- Self-adhered roofing membrane lapped and taped over the existing roof sheathing (roof)
- House wrap lapped and taped over the existing wall sheathing (walls)
- Insulation board with seams taped over the inside of the foundation walls and over the basement slab (foundation wall and floor).

The transition between the roof and exterior wall was sealed by extending the roofing membrane down and sealing it onto the wall house wrap—this was possible as there were no overhangs or eaves. The transition between the above-grade wall house wrap and the interior insulation on the foundation wall was accomplished by applying closed cell spray foam on the interior of the rim joist and sill plate and by sealing the bottom of the wall sheathing to the outside of the foundation wall. An application of sealant in the seam between the foundation wall and the basement floor transitions the air barrier between the foundation wall and basement floor. Sealant applied around the outer frame of the windows and doors established a connection between the doors and windows and the wall air barrier.

Figure 13. Somerville Triple Decker exterior wall air barrier

Synergy Construction also provided a "secondary" ABS for the Millbury Cape at the outer layer of the insulating sheathing of the roof and walls by taping all seams, taping the corners and the intersection between the roof and wall insulating sheathing, and sealing the layers together at edges and to the existing sheathing at the bottom and establishing a continuous sealed connection with the window frames.

For the Somerville Triple Decker, the ABS consists of the following components:

- Self-adhered roofing membrane lapped and taped over the existing roof sheathing (roof)
- House wrap lapped and taped over the existing wall sheathing (walls, Figure 13)

- Closed cell spray foam over the inside of the foundation walls and onto the basement slab (foundation wall)
- Existing concrete slab (basement floor).

Although the ABS for the Somerville Triple Decker was similar to that for the Millbury Cape for the above-grade walls and roof, the transition between the roof and walls was different because the roof deck and framing extended beyond the wall framing so there could not be a direct connection of the roofing membrane and house wrap. Because of this, the transition between the roof and wall air barriers was through the application of spray foam insulation in the roof/wall intersection on the interior.

For the Somerville Triple Decker, the transition between the above-grade wall house wrap and the spray foam insulation on the foundation wall is made through the mudsill and rim joist. The transition between the spray foam on the foundation wall and the existing basement slab is provided by having the basement wall spray foam extend down onto the slab floor.

Other Enclosure Measures:

Both homes had brick chimneys that were used (pre-renovation) as an exhaust flue for existing combustion equipment located in the basement. Because all atmospheric combustion equipment was eliminated in the retrofits, the chimneys were removed at the roof. In the Somerville Triple Decker, the chimney space was converted to a chase for ductwork.

Both homes had concrete stairs and landings at entrances. Without modification, these act as thermal bridges between the exterior and the wall framing at the doors. Therefore, at the Millbury Cape, the concrete was cut back and the insulating sheathing was extended down between the house and the concrete landing. At the Somerville Triple Decker the concrete was deteriorating, so it was replaced with a wood stair and landing with space for insulation between the landing and the wall.

Table 1 and Table 2 summarize the enclosure measures that were applied to the test homes.

2.1.1 Enclosure Parameters Before and After Retrofit

For both test homes, the owners have been living in these homes for a number of years. In both cases, the siding and the roofing had reached their end of service life, and therefore required replacement. However, the owners were concerned about future energy costs and their implications for the future life of the homes.

Although the pre-retrofit conditions seem energy inefficient, they are fairly typical for homes of the same vintage. The Millbury Cape had insulated exterior walls, an insulated attic floor, and double glazed windows, but the home was described by the occupants as drafty, and the cost of heating it in the winter was rising. The Somerville Triple Decker did not have any insulation, which is not unusual for a house built in the 1920s, and the owner was becoming concerned about the comfort and quality of life for herself and her tenants.

Table 1 and Table 2 summarize the pre-retrofit conditions of the enclosure for the test homes.

2.1.2 Enclosure Retrofit Costs

There is a significant difference between the cost of the needed exterior maintenance (replacing the siding or replacing the roof) and the cost for the energy retrofit. However, the siding or roofing project provides the perfect opportunity to execute energy efficiency improvements, and failure to do so basically eliminates the opportunity to do so for an extended period—the service life of the new siding or new roof. Fortunately, both of these projects were made possible because of the availability of rebates, grants, and other financial incentives, and the owners' persistence in tracking these down. Also contributing to the affordability was their collaboration with a contractor with experience in and enthusiasm about energy efficient construction.

The costs provided in the following tables are the actual construction costs to the owners for the enclosure measures prior to rebates or other incentives.

Table 1 summarizes the pre-retrofit condition, retrofit measure implemented, and the construction cost for the enclosure measures for the Millbury Cape.

Table 1. The Millbury Cape Enclosure Measures and Costs

Parameter	Existing Condition	Enclosure Measures	Construction Cost (number of units)
Roof or attic	Vented attic; fiberglass batts on attic floor	R-46 (nominal) at roof: 4-in. polyisocyanurate exterior insulating sheathing with 5½-in. ocSPF filling rafter cavities; asphalt shingles. In addition, R-13 fiberglass batts in attic floor	\$13,740 (approx. 1250 ft^2 roof deck area)
Above-grade walls	Fiberglass batts in 2 × 4 wall cavity	R-37 (nominal): 4-in. polyisocyanurate exterior insulating sheathing with existing fiberglass batt insulation in wall cavities; fiber cement lap siding over vertical strapping	\$26,430 (approx. 1400 ft^2)
Foundation wall	Concrete wall, uninsulated	R-19 (nominal): 3-in. polyisocyanurate insulating sheathing applied to inside of foundation wall and rim joist	\$5,089 (approx. 968 ft^2)
Basement floor	Concrete floor, uninsulated	R-10 (nominal): 2 in. XPS over existing concrete slab; drainage mat and 6 mil polyethylene sheet below rigid insulation	\$3,835 (approx. 660 ft^2)
Windows and doors	Wood, double glazed	U-value 0.25, SHGC 0.25 vinyl, argon triple glazed windows; new insulated doors	\$10,050 (15 windows, 3 doors, 2 basement windows)
Water management system	Roofing felt under asphalt shingles; tar paper under wood lap siding under vinyl siding; gutters directly on exterior wall (no overhang)	Self-adhered membrane under shingles; taped insulating sheathing behind lap siding; drainage mat below basement floor	Combined with other costs
ABS/ airtightness	None/ 2,860 CFM 50 or 10.4 ACH 50	Roofing membrane taped (roof), house wrap taped (walls), taped rigid insulation (foundation walls and basement floor), with taped or spray foam transitions/ 402 CFM 50 or 1.5 ACH 50	Combined with other costs
Other enclosure measures		Removed chimney roof penetration; stair landing cut back to allow continuous exterior wall insulation behind	\$1,900

Table 2 summarizes the pre-retrofit condition, retrofit measure implemented, and the construction cost for the enclosure measures for the Somerville Triple Decker.

Table 2. Somerville Triple Decker Enclosure Measures and Costs

Parameter	Existing Condition	Enclosure Measures	Construction Cost (number of units)
Roof or attic	Vented attic; cellulose behind kneewalls and in attic floor joists?	R-55 (nominal): 4-in. polyisocyanurate exterior insulating sheathing over roof deck with 8-in. ocSPF filling rafter cavities; asphalt shingles	\$25,000 (approx. 1470 ft^2 roof deck area.)
Above-grade walls	Balloon framed, uninsulated	R-40 (nominal): 4-in. polyisocyanurate exterior insulating sheathing with blown-in cellulose in wall cavities; fiber cement lap siding over vertical strapping	\$90,000 (approx. 2700 ft^2)
Foundation wall	Parged fieldstone wall, uninsulated	R-21 (nominal): 3 1/2-in. ccSPF applied to inside of wall over drainage mesh	\$10,000 (approx. 1056 ft^2)
Basement floor	Concrete floor, uninsulated	Uninsulated; perimeter sub-slab drainage and passive soil gas system added	Included in foundation wall cost (approx. 1040 ft^2)
Windows	Vinyl replacement windows and older wood windows	U-value 0.19; SHGC 0.24, fiberglass, insulated glass unit with suspended film	\$18,000 (32 windows)
Water management system`	Roofing felt under asphalt shingles; tar paper under wood lap siding; overhangs and gutters	Ice and water shield under shingles; taped insulating sheathing behind lap siding; drain wrap behind ccSPF on foundation wall; sub-slab perimeter drain system	Combined with other costs
ABS/ airtightness	None/ 16.5 ACH @ 50Pa	Roofing membrane taped (roof), house wrap taped (walls), spray foam (foundation walls), 3.5 ACH 50	Combined with other costs
Other measures		Structural, electric, plumbing, some new interior/exterior finishes, new doors, new roof, new siding, chimney removal, new chase, fire-blocking, and make-up air for gas stoves. Consulting costs as well.	\$30,000

2.2 Mechanical System Measures

A major source of energy savings for a retrofit is replacement of outdated, inefficient mechanical equipment. With improved R-values and airtightness of the house after the retrofit, smaller and more energy efficient systems can be installed (Ueno 2008). Because of the improved airtightness, it is important for occupant safety and indoor air quality that the installed mechanical systems have controlled outside-supplied combustion air and exhaust venting.

In addition, the improved airtightness introduces the need for mechanical ventilation.

The mechanical systems retrofit measures include upgrades to heating, cooling, ventilation, and DHW. These generally work together as an interdependent system, and the systems for the two test homes are quite different. Therefore these will be discussed separately. However, one common measure applied to both was to locate all mechanical equipment and ductwork within the thermal enclosure of the building.

2.2.1 Mechanical System Measures for the Millbury Cape

The following describes the existing mechanical systems and the retrofit mechanical systems installed for the Millbury Cape. It should be noted that natural gas is not available at the site.

Mechanical System—Existing Conditions

The existing conditions for the Millbury Cape were as follows:

- Heating was provided by hydronic baseboard/convector distribution with a 1950s-era oil-fired boiler as the heat source. Supplemental heat in the living room was provided by a wood pellet stove.
- For cooling, there were three window air-conditioning units—two on the first floor and one on the second floor.
- Hot water was provided by a two- to three-year-old indirect-fired hot water storage tank, with the oil boiler as the heat source (via a heat exchanger).
- The only mechanical ventilation provided was through spot exhaust fans in the bathrooms.

Mechanical System—Retrofit Measures

The decision process for upgrading mechanical equipment is another area that often evolves during the course of the project. During the planning phase for each test home, Ken Neuhauser of BSC prepared an analysis for the test home, identifying and comparing the possible configurations for heating, cooling, ventilation, and DHW systems. The analysis for the Millbury Cape is attached as Appendix A.

For the Millbury Cape, the initial assumption made by the owners was that the existing oil boiler would be replaced with a new energy efficient, sealed combustion boiler; that the existing indirect hot water would be integrated with the new boiler; that ventilation would be provided by two ducted heat recovery ventilators (HRVs) (one for each floor); and that a new split system heat pump with two air handler units would provide cooling. This approach would allow use of existing heating fuel type, existing heating distribution system, and existing hot water system—which was expected to have a lower initial cost.

After studying BSC's analysis and talking through the options with their mechanical contractor, the owners decided to take a completely different approach and use the system that the analysis indicated would have the lowest operational costs—air source heat pump heating and cooling with two ducted air handler units, central fan integrated supply for ventilation (BSC 2009g), and propane instantaneous water heater. This eliminated the use of oil as a fuel and removed the existing hydronic heating distribution system. On the expectation that natural gas would be available in the future, any requirement for combustion fuel was to be provided by propane.

Approximately 30% of the cost of the new equipment was covered by rebates and the National Grid DER Pilot program incentive.

The new system combines a mini-split heating and cooling air source heat pump system with a supply-only ventilation system. The mini-split consists of two small ducted air handlers (a 12,000 Btu/h unit in the basement and a 9,000 Btu/h unit in the second floor kneewall space), and a single outdoor unit. The air handler in the basement supplies heating and cooling to the first floor through floor registers. The air handler in the kneewall attic space on the second floor supplies heating and cooling to the second floor through wall and ceiling registers. All ductwork is sealed and insulated.

Ventilation is integrated with each air handler using a 6-in. outdoor air supply duct connected to the return side of the air handler with a motorized damper, connected to a fan cycling control (Figure 14). The fan cycling control ensures that the fan runs a programmed minimum amount of time to provide sufficient supply ventilation air, which is in turn distributed to the indoor spaces using the air handler's duct system. The motorized damper in the outdoor air supply duct is controlled by the fan cycling control to prevent over ventilation during times of significant space conditioning demands (BSC 2009g).

Figure 14. Millbury Cape ventilation system in kneewall

The existing pellet stove was sealed and modified to have direct outdoor air supply. It is used as a backup heating system when the air source heat pump is unable to keep up with the heating load. During the heating season following the completion of the retrofit, the owners discovered that the heat pump was unable to keep up with the heating load during some extremely cold weather in January and February. Thus, the wood pellet stove is serving as a backup heating system as well.

DHW is provided by a propane, sealed combustion, instantaneous water heater. This can be converted to natural gas when it becomes available.

Table 3 summarizes the existing and retrofit mechanical system measures, and gives the approximate cost to the owner for the upgrades.

Table 3. Millbury Cape Mechanical System Measures and Cost

Parameter	Existing Conditions	Retrofit	Approximate Retrofit Cost
Heating system	Oil boiler in basement with hydronic baseboard heat; pellet stove as backup	Air source heat pump split unit with two air handlers—one in basement and one in attic space; pellet stove (converted to direct vent) as backup	$17,375 (1 outdoor, 2 indoor units)
Cooling system	Window air conditioners (2 on first floor; 1 on second floor)	See above	See above
Ventilation	Spot exhaust only	Supply air with controller integrated with each air handler	$1500 (2 units)
DHW	Indirect (integrated with oil boiler)	Propane, instantaneous	$2800

2.2.2 Mechanical System Measures for the Somerville Triple Decker

During his June 2010 visit to the Somerville Triple Decker, Ken Neuhauser of BSC observed existing mechanical systems and made recommendations for upgrades. Additional details and photographs can be found in his report, included in Appendix B.

Space heating was provided separately for each of the three units (one on each floor). The first and second floor heating systems were natural gas furnaces located in the basement, with rated efficiencies of 90%+ and under 80%, respectively. The ductwork for both floors was unsealed and showed visible rusting for the second floor. The third floor heating system consisted of a gas-fired boiler, estimated to be about 30 years old, with hydronic baseboard distribution. DHW is provided by three gas-fired water heaters. All gas-fired appliances except one of the furnaces were vented through an unlined brick chimney. All units draw combustion air from the interior (basement).

The project team expressed initial interest in consolidating mechanical equipment to reduce costs and create common utility expenses to be shared among all building residents. Neuhauser's site visit report (Appendix B) outlined the potential advantages and drawbacks of separate versus consolidated space conditioning and DHW systems. Additionally, consideration factors for different system types were explored, as outlined in Appendix B Tables 1 and 2. Neuhauser pointed out that better overall efficiency with less distribution loss may be possible when multiple independent high performance furnaces and on-demand water heaters are used. He also highlighted the fact that if a consolidated system were to fail, service disruption would result while repairs took place. However, in addition to potential cost savings and billing consolidation, venting and fuel connections would be less complicated with a consolidated system.

For the final design, the project team elected to consolidate the space and DHW by replacing the furnaces, boiler, and water heaters with a single 80 gallon Phoenix Versa Hydro unit (Figure 15). The Versa Hydro is a modulating and condensing system that can also be integrated with solar DHW (a future project planned by the homeowner). From the experience of BSC, it may be difficult to achieve high efficiencies (as advertised) due to flue gas condensation limits. The temperature of water in the storage tank needs to be low enough for exhaust gas condensation to occur, which means that lower DHW and heating loop temperatures are required. BSC is interested in observing the long-term performance of the system in this home.

Figure 15. Somerville Triple Decker Phoenix Versa Hydro installation. Photo used with permission from homeowner.

Mechanical ventilation is provided by a Fantech VH704 HRV for each apartment (Figure 16). Each is capable of supplying 67 CFM and has a rated recovery efficiency of 53%. In addition to the outside air supplied by the HRV, makeup air is supplied over the gas stove hoods in each apartment. Both the stove exhaust and the makeup air supply ducts are run through the new chase, made from the shaft formerly occupied by the chimney.

Figure 16. Somerville Triple Decker Fantech HRV. Photo used with permission from homeowner.

The pre- and post-retrofit cooling system consists of older window air conditioner units for some bedrooms with estimated SEER ratings of 8 or 9. These units are reported to be used infrequently. Occupants also report opening windows during favorable outdoor conditions for cooling and ventilation.

Table 4 outlines the Somerville Triple Decker mechanical system upgrade costs to the owner.

Table 4. Somerville Triple Decker Mechanical System Measures and Costs

Parameter	Existing	Post-Retrofit	Approximate Cost
Heating system	Two floors gas-fired furnace forced air heating, one floor hydronic heating	Gas-fired Phoenix Versa Hydro used for hydronic heating and DHW	$26,000
DHW	Gas-fired hot water heaters	Same as above	Included in above
Ventilation	No mechanical ventilation provided	Fantech VH704 HRVs for each apartment, 80% effectiveness	$6,000
Internal load reduction: compact fluorescent lamps (CFLs)	Approximately 90% CFL lighting	100% CFL lighting	Cost not provided

2.3 Deciding Which Measures To Include in the Retrofit

As in nearly all construction projects, the final decision about the measures to include comes down to cost—initial cost, operational cost, or some combination. It can also be observed that the items eliminated due to cost are probably an indicator of the value perceived by the homeowner.

Given the targeted R-values for these retrofits, wall and roof insulation measures are "givens" for any complete energy retrofit. Airtightness is becoming better understood as a requirement for energy efficiency, though committing to a continuous ABS versus "using a blower door test to find the leaks" is still an obstacle. However, Synergy's experience with DERs has made it an advocate of the continuous air barrier.

Water management systems and durability issues are generally understood to be essential in retrofits, because the reason for undertaking the retrofit is to extend the life of an older building. However, it is not always understood that the changed conditions of heat loss and air infiltration will introduce new conditions that must be addressed. For example, for these test homes, the insulating sheathing applied over the existing framed walls will restrict the ability of the walls to dry to the outside (Ueno 2010). This is a new condition applied to the existing structure, which needs to be addressed by minimizing bulk water penetration from the outside as well as condensation risk from interior moisture loads.

Window and door replacement is a very expensive item but has major implications in the success of the air barrier and water management systems, as well as heat loss. At a minimum, the existing windows and doors need to be re-installed in order to be integrated into the air barrier and water management systems. For both of these test homes, new triple-glazed window units were factored into the budget from the beginning. For the Millbury Cape, insulated doors, including the basement door, were also included. During the planning of the retrofit of the Millbury Cape, there was some discussion of replacing the existing double-hung windows with casement windows because they typically have lower air infiltration rates, but the final decision was to retain the aesthetics of double-hung windows.

Insulating the basement is the retrofit measure most often left out of retrofit projects. The decision process for basement measures for these test homes is discussed in Section 2.3.1.

The decision-making process for specific mechanical system upgrades is best served by including an mechanical contractor or consultant who is experienced in DER projects on the project team. The mechanical equipment is perhaps the most expensive items in the construction cost, and expected savings are dependent on factors beyond the control of the owners. BSC assisted in the early decision process for these test homes by preparing an analysis of the options (see Appendices A and B), but ultimately this decision is most influenced by the mechanical contractor.

Table 5. Retrofit Measures Included

Parameter	Millbury Cape	Somerville Triple Decker
Roof or attic	Included	Included
Above-grade walls	Included	Included
Foundation wall	Included	Included (not in initial plan)
Basement floor	Included (not in initial plan)	Water management only
Windows and Doors	Included	Windows included
Airtightness	Included	Included
Heating	Included	Included
Cooling	Included	Not included
Mechanical ventilation	Supply only	Balanced
DHW	Included	Integrated with heating

2.3.1 Basement Decisions

For both test homes, insulation of the basement was initially left out of the plans. For the Millbury Cape, insulation of the basement walls was included but the basement floor was to be left uninsulated. For the Somerville Triple Decker, the initial decision was to leave the basement uninsulated and instead to provide insulation and air sealing in the first floor framing.

Basement heat loss can be a significant portion of a house's total heating load, especially in superinsulated buildings. Basement insulation can, of course, significantly reduce that load. In addition, correct application of basement wall and slab insulation can reduce moisture loads; this is of particular interest in retrofit situations where moisture control measures were not originally included in construction (Lstiburek 2005). The alternative approach of providing the insulation and air sealing in the first floor framing has been observed to be less effective (Ueno 2010).

For the Millbury Cape, the ultimate decision to include insulation of the floor of the basement was a combination of feasibility (there was sufficient head room to apply the insulation over the existing slab) and economics (the incentive from the National Grid DER Pilot program for implementing this measure covered a significant part of the cost offered by the contractor).

For the Somerville Triple Decker, the ultimate decision was to insulate the basement walls (including the basement in the conditioned space) rather than the basement ceiling (excluding the basement). Given the plumbing and ductwork that that penetrates the basement ceiling, it was recognized that creating an airtight seal at the ceiling would be very difficult. In addition, because they were retaining existing plumbing pipes, there was concern that fixing any of these pipes in the future would be require cutting out of the ceiling insulation. However, the basement floor was not insulated, although water management and soil gas venting measures were added.

3 Testing and Analysis

A variety of testing and analysis was performed for both test homes. Blower door testing was performed for both the Millbury Cape and the Somerville Triple Decker to gauge the success of air sealing efforts. Utility bills from before and after the retrofits were collected from home occupants to compare measured fuel usage, showing clear reductions in post-retrofit energy use. These utility bill summations are compared to the results of BEopt energy modeling, to show incremental energy reduction from each retrofit measure. Finally, reported occupant satisfaction and other non-numerical observations are discussed.

3.1 Measurements

Blower door tests were performed before and after the retrofits of the Millbury Cape and the Somerville Triple Decker. In the case of the Millbury Cape, BSC performed several iterations of testing, as described in this section. Blower door testing for the Somerville Triple Decker was performed by Nick Abreu of Conservation Services Group; a final testing number of 3.48 ACH 50 was reported and used for the energy modeling calculations. Appendix D contains the Conservation Services Group report.

For the Millbury Cape, BSC conducted blower door testing before the retrofit project started in April 2010, at substantial completion in November 2010, and again in May 2011 (as a final test after completion of air sealing corrections). The expected information from this testing included air leakage rates at the different points in the project and an assessment of how effective the blower door testing could be as a tool to improve airtightness at the end of the project. Appendix C contains all blower door test reports.

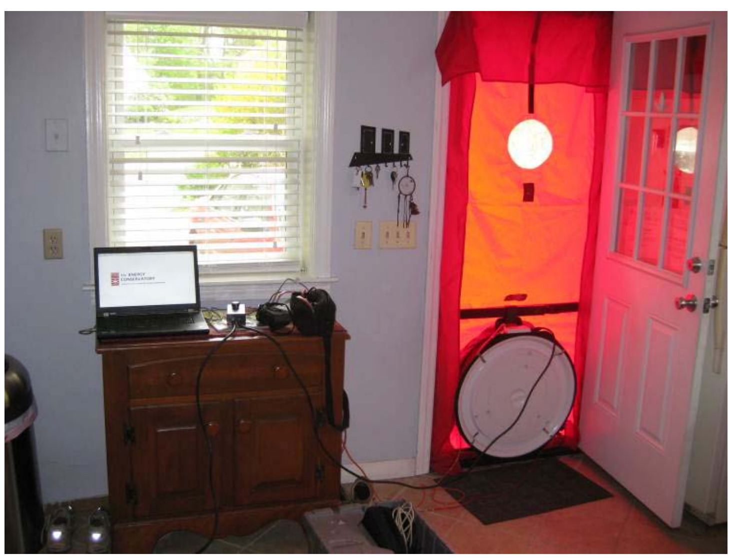


Figure 17. Blower door testing for the Millbury Cape

The following input information used to interpret the blower door test results was provided by the owner: 4,278 ft^2 total enclosure (six sides), 16,500 ft^3 volume. With the small addition made during the retrofit, the total enclosure would not change significantly but the volume would increase by about 500 ft^3.

Pre-retrofit blower door testing was performed in April 2010 using a single blower door on the main floor. Doors to all living spaces were put in an open position as well as the interior door to the basement. Closet doors and attic access were left closed. Additional setup included closing all windows and exterior doors, turning off all heating/cooling equipment, taping ducts that were not known to have dampers, and ensuring that there was water in the plumbing traps. For this first test, the flow measured at 50 Pa pressure difference was 2,860 CFM (10.4 ACH50).

The second blower door test was performed at substantial completion of construction in November 2010. This was prior to testing and commissioning of the ventilation system. Testing was performed with setup similar to that used in April. Initial test results were 576 CFM 50 (2.0 ACH 50). This was higher than the National Grid DER Pilot program target of 0.1 CFM/ft^2 of enclosure (428 CFM 50). With the house depressurized, the enclosure and mechanicals were inspected for air infiltration. Using this technique, it was discovered that the second floor outdoor air intake was not connected to the inlet termination on the exterior, thus creating a direct opening between the attic kneewall space and the exterior. This connection was corrected and sealed, and another blower door test was run. The test result for this second blower door test improved to 458 CFM 50 Pa (1.6 ACH 50).

During later site visits, the contractor found two holes in the exterior wall in second floor closets that had not been seen earlier, because they had been covered by items that were stored there during construction. These were openings in the framed wall (gypsum board and structural sheathing) where windows had been removed, each approximately 6–7 ft^2 This represented a 12–14 ft^2 hole in the primary air barrier; however, the holes did not extend through the exterior insulating sheathing, so there was no direct connection to the exterior. Furthermore, the insulating sheathing had been sealed to provide a secondary ABS for the walls. The contractor filled and sealed the holes in the framed wall. They also observed from visual inspection that the spray foam along the rim joist and top of the foundation wall did not fill around some of the piping, so additional spray foam was applied at these locations.

In May 2011, after corrections had been made for these conditions, BSC performed a final blower door test to determine how these corrections impacted the air infiltration. The test used the same setup as the previous tests. This time the test results were 402 CFM 50 Pa (1.4 ACH 50). A search for leakage locations with the house depressurized did not reveal any specific areas where air infiltration could be felt, except at the front door lockset (which had not been securely fastened following removal for painting).

An interesting discovery was made in regards to mechanical system air leakage during this final testing. During the setup, the upstairs air handler ventilation system controller was disconnected, and it was assumed that this would close the motorized damper for the outdoor air supply. The blower door test result of 466 CFM 50 was approximately the same as the November 2010 results. After checking the house for openings, it was discovered that the motorized damper actually remained open. Based on the measured air flow and comparison with earlier testing, the air loss through the 6-in. diameter hole through the exterior wall (~0.2 ft^2) was approximately equal to the air loss through the 12–14 ft^2 opening in the primary air barrier (gypsum and structural sheathing). If the contractors had not implemented a secondary air barrier at the outside layer of the insulating sheathing, the air leakage through the window openings would have been considerably higher.

In general, the air infiltration results were good, but not as good as had been hoped. However, attempting to locate leaks during blower door testing did not prove to be an effective tool for this test home. The ABS provides the main line of defense against air infiltration and it is not something that can be addressed at the end of the job. At best, using blower door testing as a tool in air sealing can be used to locate holes due to oversight or small leaks, especially if used with a smoke pencil. With a carefully planned and implemented continuous air barrier, the small leaks discovered are unlikely to make a significant difference, and the holes due to oversight are likely to be found through operational problems.

A summary of the blower door testing results for the Millbury Cape is shown in Table 6.

Table 6. Blower Door Testing for the Millbury Cape

Test Date	Test Results	Normalized	Changes Made Since Previous Test
April 2010	2860 CFM 50	10.4 ACH 50	
November 2010 Test 1	576 CFM 50	2.0 ACH 50	All retrofit measures implemented; air supply duct had not been connected to the inlet terminal leaving 6-in. hole to exterior
November 2010 Test 2	458 CFM 50	1.6 ACH 50	6-in. hole found in the previous test was covered and sealed for testing purposes
May 2010 Test 1	466 CFM 50	1.7 ACH 50	Air supply duct on second floor properly connected to inlet terminal; discovered and closed two 6–7 ft^2 openings in framed wall (but covered on the outside by insulating sheathing); sealed around pipes at top of foundation wall; accidentally left second floor air supply duct open to exterior
May 2010 Test 2	402 CFM 50	1.4 ACH 50	Closed air supply duct

3.2 Utility Bills

Utility bills from before and after the test home retrofits were collected and compared. Because the retrofits for both test homes were essentially completed in October of 2010, the comparable available utility data ranges were October 2010 to March 2011 and October 2009 to March 2010. The month of April was also available for the Somerville Triple Decker. These months constitute most of the heating season in New England; post-retrofit cooling season data were not available.

In order to have additional perspective on the results of the utility bill comparisons, heating degree days from the 2010–2011 and 2009–2011 cold weather periods were compared; local degree day information was obtained from DegreeDays.net (BizEE 2011).

Nearby weather stations were selected for both of the test homes. A Worcester, Massachusetts, weather station was selected for the Millbury Cape (located in Millbury, Massachusetts) and a Cambridge, Massachusetts, weather station was selected for the Somerville Triple Decker (located in Somerville, Massachusetts). Table 7 shows degree days for October–April 2010–2011 and October–April 2009–2010. As shown, the October–April period in 2010–2011 was significantly colder than that of 2009–2010 for both the Cambridge and Worcester weather stations.

Table 7. October to April Degree Days for Both Test Homes

	October–April 2010–2011 Degree Days	October–April 2009–2010 Degree Days	Difference
Millbury Cape (Worcester)	6,301	5,727	9%
Somerville Triple-Decker (Cambridge)	5,415	4,981	8%

Utility bills were collected from both test homes. In the case of the Millbury Cape, a mixture of fuels was used, including electricity, propane, wood pellets, and fuel oil. The use of fuel oil was discontinued after the retrofit while propane was incorporated. In the Somerville Triple Decker, both electricity and natural gas were used before and after the retrofit, even though HVAC system changes occurred. Energy usage during the cold months of 2009–2010 and 2010–2011 are recorded in Table 8. The Somerville Triple Decker includes April; this month was not available for the Millbury Cape. All fuel types were converted to MMBtu to obtain total site energy. Source energy was calculated using the conversion factors found in Figure 18. As shown in Table 8, the Millbury Cape achieved a source energy saving of 37% for the two periods compared; the Somerville Triple Decker achieved 48%. Due to the higher number of degree days in the 2010–2011 period versus that of 2009–2010, it is likely that higher source energy savings would have been achieved for both homes if weather conditions had been identical. However, it is important to recognize that one cold weather period of data from before and after the retrofit is insufficient to make conclusions about long-term average yearly energy savings.

Table 8. Energy Use by Fuel Type*

Test Home	Winter	Electricity	Gas	Propane	Pellets	Oil	Total Site	Total Source	Source Energy Savings
A	2010-2011	21.4		3.4	15.5		40.3	90.4	37%
	2009-2010	12.2			46.5	56.3	114.9	144.0	
B	2010-2011	9.8	44.9				54.7	79.9	48%
	2009-2010	18.1	88.0				106.1	152.6	

* All values reported in MMBtu.

Table 1 Source-Site Ratios for all Portfolio Manager Fuels	
Fuel Type	**Source-Site Ratio**
Electricity (Grid Purchase)	3.34
Electricity (on-Site Solar or Wind Installation)	1.0
Natural Gas	1.047
Fuel Oil (1,2,4,5,6,Diesel, Kerosene)	1.01
Propane & Liquid Propane	1.01
Steam	1.21
Hot Water	1.28
Chilled Water	1.05
Wood	1.0
Coal/Coke	1.0
Other	1.0

Figure 18. Source-site energy ratios taken from ENERGY STAR (2011)

3.2.1 Utility Bills for the Millbury Cape

Table 9 compares monthly electricity use for the heating seasons of 2009–2010 and 2010–2011. This shows a significant increase after the retrofit because the primary heating now uses electricity (air source heat pumps) whereas previously the energy use for heating was primarily recorded in the oil use. The owners used a wood pellet stove for a significant part of January and February 2011, which explains why the electricity use dropped after December 2010.

Table 9. Millbury Cape Electricity Use

Type	Oct	Nov	Dec	Jan	Feb	Mar	Totals
Existing 2009–2010	526 kWh	586 kWh	816 kWh	585 kWh	535 kWh	535 kWh	3583 kWh
Retrofit 2010–1011	658 kWh	1360 kWh	1486 kWh	1049 kWh	870 kWh	870 kWh	6293 kWh

Table 10 compares the nonelectricity fuel use for the heating seasons of 2009–2010 and 2010–2011. There was a significant drop in the use of the wood pellet stove after the retrofit. During 2009–2010, the wood pellet stove was used when supplemental heat was needed. During 2010–2011, it was used primarily during the periods in which the heat pump was unable to meet the heating load.

Table 10. Millbury Cape Other Fuel Use: October Through March

Type	Oil	Propane	Wood Pellets
Existing: 2009–2010	375 gal		150 40-lb bags
Retrofit 2010-1011		37.5 gal	50 40-lb bags

Table 11 shows the fuel costs for the heating season of 2009–2010 and for 2010–2011. The total savings in fuel costs for the initial six month period following the retrofit is $710.79 or a 33% reduction.

Table 11. Millbury Cape Fuel Costs: October through March

Type	Electricity	Propane	Oil	Wood Pellets	Total Cost
Existing: 2009–2010	$520.47		$858.00	$750.00	$2128.47
Retrofit 2010–1011	$951.37	$191.31		$275.00	$1417.68

Utility Bills for the Somerville Triple Decker

Monthly utility bill data were available for the Somerville Triple Decker, allowing energy usage from before and after the retrofit to be graphed by month. As the Somerville Triple Decker is a three-family home, bills were collected from each of the three apartments and combined to plot monthly energy usage for the whole building. Heating degree days were added to the graphs to show the relationship to energy use during the two cold weather periods.

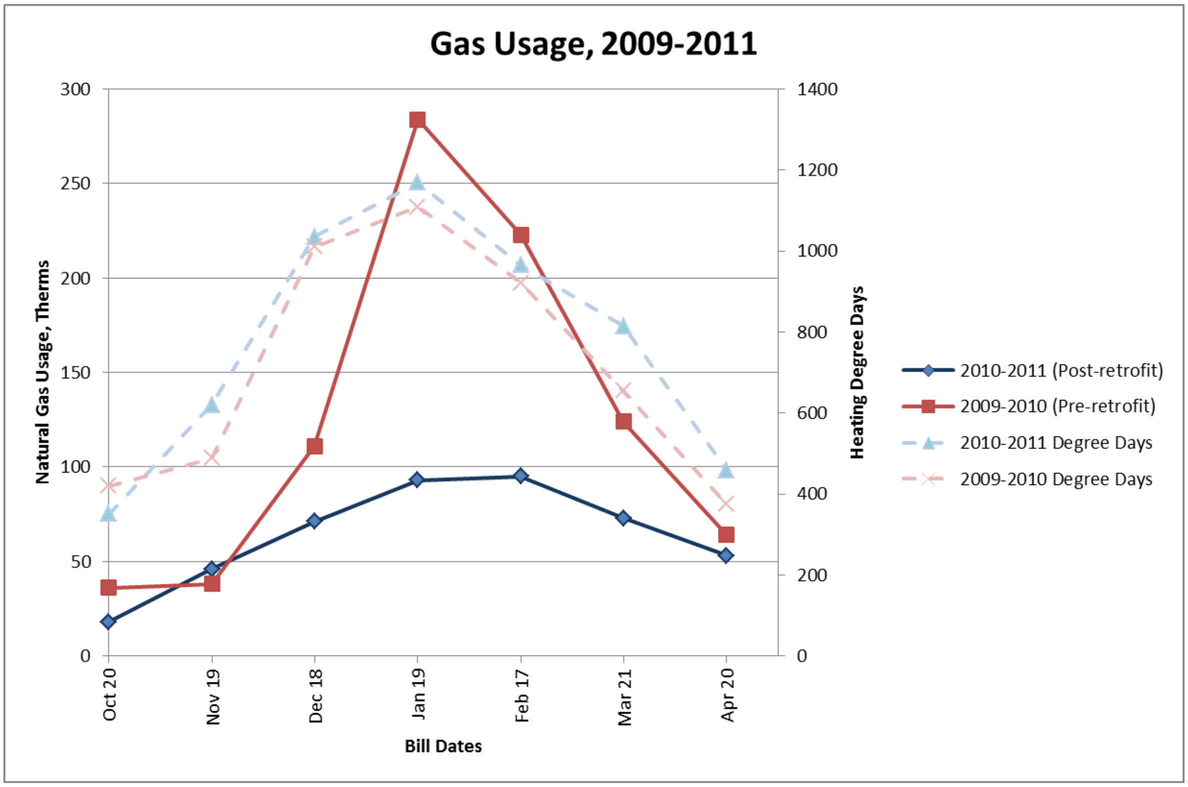


Figure 19. Somerville Triple Decker from October to April before and after the retrofit

Gas usage during the two periods shows a significant decrease after the retrofit, especially considering the fact that the post-retrofit winter was colder than pre-retrofit. It is interesting to note that the different between pre- and post-retrofit gas usage is much more extreme during colder than warmer or shoulder months.

Heating usage is related to indoor set point temperatures. Although indoor set point temperatures before and after the retrofit are not known, the homeowner noted that she always tried to use as little heat as possible pre-retrofit. It is possible that warmer wintertime set points were used in the highly insulated post-retrofit home, because less fuel was being used (i.e., takeback effects). However, pre-retrofit occupant comfort was likely lower due to mean radiant temperature effects (radiant heat loss to cold surfaces such as uninsulated walls. The upgrade to R-40 walls would increase surface temperatures, reduce radiant heat loss, and improve occupant comfort. As discussed in Section 3.4, all occupants reported increased winter comfort after the retrofit.

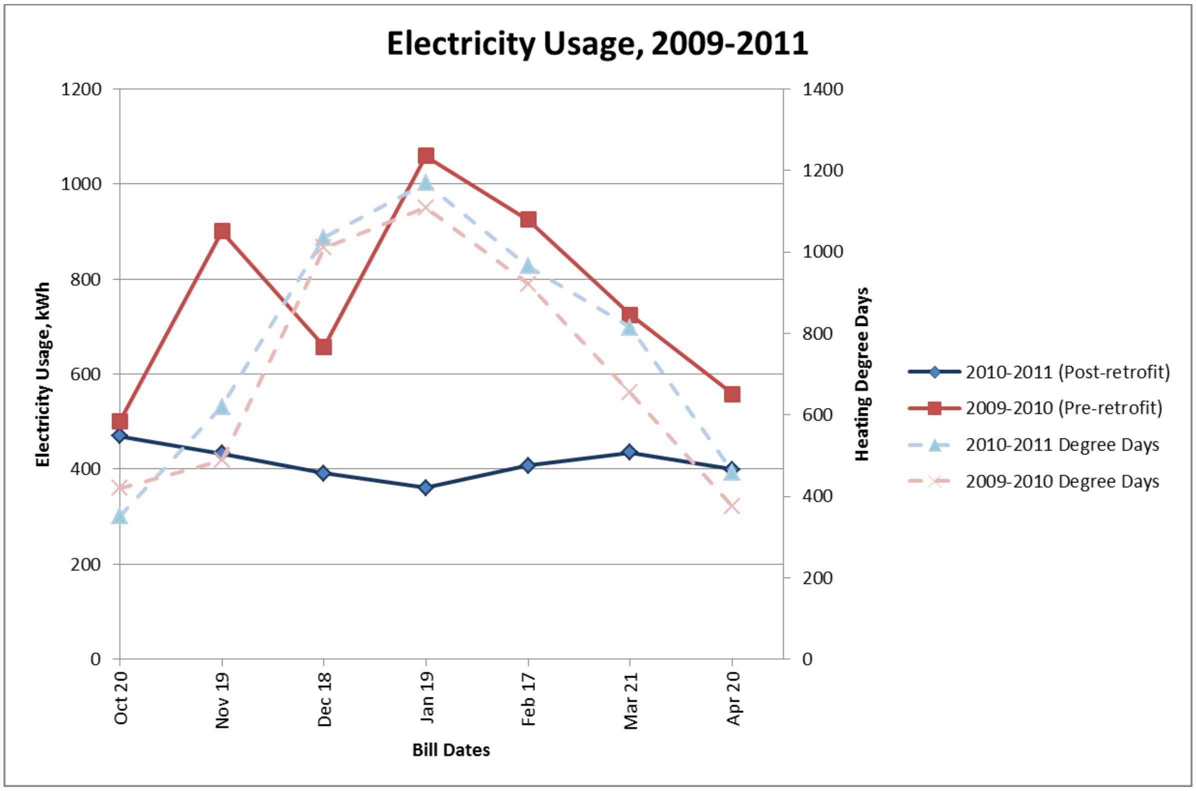


Figure 20. Somerville Triple Decker electricity usage from October to April before and after the retrofit

Electricity in the Somerville Triple Decker has more end uses than gas, making it more difficult to make conclusions about space conditioning savings from the retrofit. End uses such as lighting, appliances, and mechanical ventilation tend to make up a significant portion of electricity usage. When a year of post-retrofit data becomes available, the electricity usage during swing seasons (when little heating or cooling is needed) will allow base load to be determined. The base load can then be subtracted during heating and cooling seasons to determine space conditioning electricity usage. However, it should be noted that the fan energy formerly associated with the ducted hot air heating systems switched to pump energy for the post-retrofit hydronic system. In addition to the reduction of heating energy required due to the improved enclosure, this switch from fan to pump energy is a likely contributor to savings.

3.3 Modeling

The energy savings measures planned for these test homes were a combination of measures that have been successfully used in earlier retrofits as well as in new construction (Pettit 2009, BSC 2010a, 2010b). Whole house energy consumption simulations were not used in the planning phase for these test homes, in part because no simple to use and inexpensive tool was available during planning that explicitly supported retrofits.

New releases of BEopt, the house energy simulation program and primary analysis tool for BA, became available during the last quarter of 2010. This software contains newly provided support for the retrofit projects. This tool was used to simulate the expected energy use for these test homes based on the measures that were implemented. By comparing these results to the actual energy use available following completion of the retrofit project, a better understanding of the relative accuracy of energy use simulation in retrofit projects can be developed.

Designed to be easy to use with a limited number of allowed variations, some elements of the test homes were not possible to model precisely in BEopt. As discussed for each home in the following sections, approximations were used when necessary. These factors contribute to differences between utility bill numbers and modeling results.

In addition to some difficulties with modeling certain options, weather conditions are another point of difference between the models and utility bills. BEopt uses weather data from TMY3 (Typical Meteorological Year, version 3) files to calculate the hourly building loads. TMY3 files contain a year of hourly weather data meant to represent typical conditions at a particular geographic location over a long period of time (Wilcox and Marion 2011). The best available TMY3 file for the Millbury Cape was for Worcester, Massachusetts; the Boston, Massachusetts TMY3 file was selected for the Somerville Triple Decker. Table 12 shows heating degree days during the October–April period for both of these TMY3 files compared to heating degree days for the same months in 2009–2010 and 2010–2011, also shown earlier in Table 7. In the case of the Millbury Cape location, the TMY3 file has more heating degree days than the same period in either 2009–2010 or 2010–2011, while in the case of the Somerville Triple Decker location the TMY3 heating degree days are intermediate between those of the 2009–2010 and 2010–2011 periods.

Table 12. TMY3 File October–April Degree Days, Compared to Actual Weather

	October–April TMY3 Heating Degree Days	October–April 2010–2011 Degree Days	October–April 2009–2010 Degree Days
Millbury Cape (Worcester)	6,560	6,301	5,727
Somerville Triple Decker (Boston/Cambridge)	5,392	5,415	4,981

3.3.1 Energy Modeling for the Millbury Cape

As noted earlier, energy simulation was not used during project planning for the Millbury Cape. However, as the project neared completion, BEopt was introduced as an analysis tool for understanding the expected and observed energy use during the initial six months following completion of the retrofit.

There were three specific aspects about the Millbury Cape that could not be included in the model:

- The Millbury Cape is a Cape style 1½-story house with a shed dormer on a portion of the rear at the second floor. BEopt modeling does not currently support this specific house configuration, so the house was modeled without a second floor dormer.

- During construction, the shed dormer at the back of the house was extended to provide an additional 80 ft^2 of living space on the second floor. BEopt modeling does not support an addition (i.e., change of building geometry) occurring within a case, so the additional living space was not modeled.

- The owner used a wood pellet stove as a backup for the heat pump during the winter in January and February 2011. Prior to the retrofit, the owners used the wood pellet stove for supplemental heat during the winter. BEopt does not support modeling of a backup or a supplemental heat source, so the wood pellet stove was not included in the BEopt model.

Figure 21, shows a graph of the average yearly source energy use. It was generated for the BEopt model for the Millbury Cape showing incremental inclusion of the retrofit measures. This model projects an average yearly 45% reduction in source energy use following the retrofit.

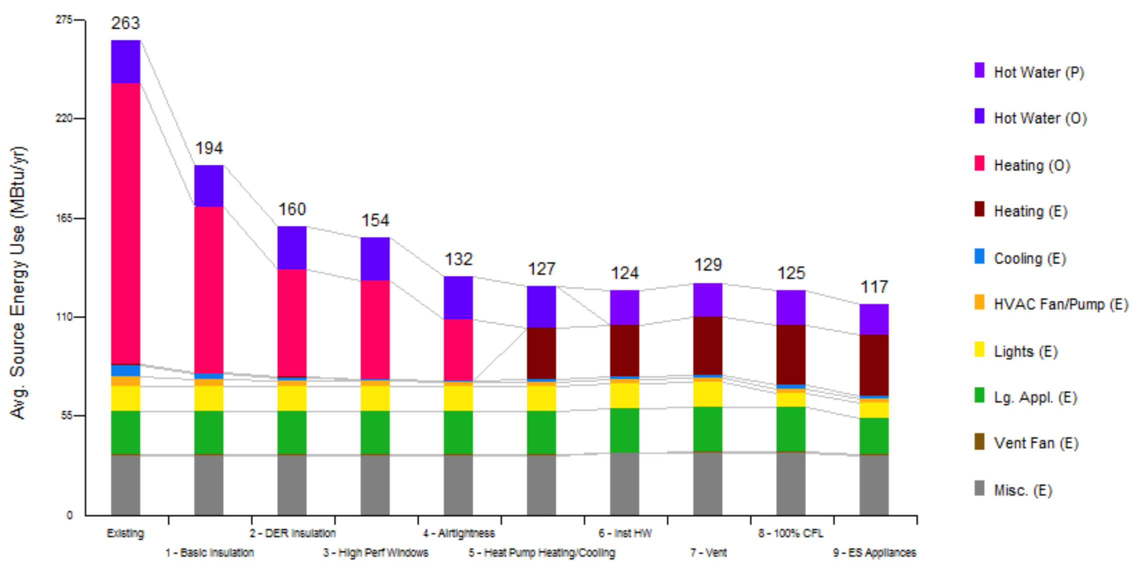


Figure 21. BEopt incremental modeling results for the Millbury Cape

As part of the energy modeling analysis, BEopt's hourly results were used to project site energy use for the existing and post-retrofit model for October through March. These were then compared to the actual site energy use for the existing conditions (October 2009 through March 2009) and to the actual site energy use for the retrofit (October 2010 through March 2011).

As can be seen in Table 13, Table 14, and Figure 22, the BEopt results for site energy use for the existing (pre-retrofit) model were higher than the actual use (after converting to MMBtu), whereas the BEopt results for the retrofit projected a significantly lower site energy use than was actually observed. The actual total source energy use for the period declined by 37%, whereas the BEopt model projects a 60% decline in total source energy use. Factors that could contribute to this discrepancy include 1) the specific items not included in the model as noted above, 2) the fact that there were a different number of heating degree days this winter than in the TMY3 file, 3) commissioning and adjustments are still being made during this initial operational period.

The energy conversion factor used for wood pellets in the following tables is 7,750 Btu/lb (Mass DOER 2007). The source-site ratios for the fuels used are given in Figure 18.

Table 13. Millbury Cape—Existing: Actual Energy Use Compared to BEopt Energy Use

Type	Actual October 2009 through March 2010	BEopt October 2009 through March 2010
Electricity	3740 kWh	3583 kWh
Oil in gallons	375 gal	879 gal
Pellets	150 40-lb bags	
Total site energy	114.9 MMBtu	144.7 MMBtu
Total source energy	144.0 MMBtu	175.8 MMBtu

Table 14. Millbury Cape—Retrofit: Actual Energy Compared to BEopt Energy Use

Type	Actual October 2010 through March 2011	BEopt October 2010 through March 2010
Electricity	6293 kWh	5663 kWh
Propane	37.5 gal	83.9 gal
Pellets	50 40-lb bags	
Total site energy	40.3 MMBtu	26.9 MMBtu
Total source energy	90.4 MMBtu	72.0 MMBtu

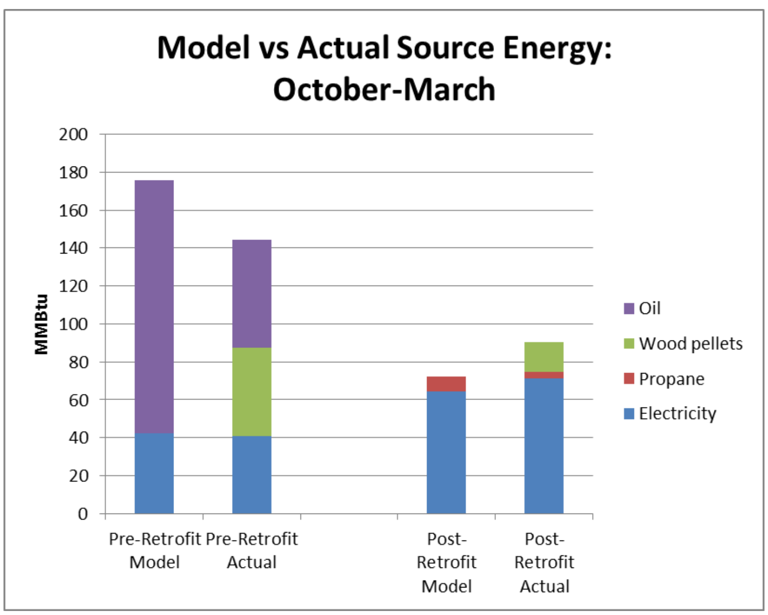


Figure 22. Millbury Cape source energy use pre- and post-retrofit

3.3.2 Energy Modeling for the Somerville Triple Decker

The Somerville Triple Decker was modeled in BEopt as well, even though the current version of the software is not designed to be used for multifamily homes. Since single-family assumptions are used, a model may underestimate the energy usage for a multifamily building due to the multiple kitchens, bathrooms, and assumptions about occupancy based on the number of bedrooms. Factors such as differences in set point temperatures for different apartments could not be fully captured. In addition to these issues, the following elements either could not be explicitly modeled using BEopt or were based on approximations because precise homeowner behavior was not known:

- **Skylights located on the northwest roof.** These were instead added to the windows on the northwest wall.

- **Different R-values for different walls.** Due to a miscommunication, cellulose was only blown into three out of the four walls. Total wall R-value was decreased proportionally to account for this difference.

- **The pre-retrofit heating system.** As described in Table 4, the pre-retrofit home was served by a different heating system on each floor: two relatively new gas-fired furnace ducted air systems, and one older gas-fired boiler hydronic system. In the model, this was represented by an annual fuel utilization efficiency 84% furnace for the entire building.

- **The post-retrofit combined heating and DHW "Versa Hydro" hydronic system.** Assuming optimal setup and operation, this was approximated with a gas-fired 90% annual fuel utilization efficiency hydronic heater and a gas fired DHW 0.80 energy factor heater.

- **The amount of air-conditioning actually used before and after the retrofit.** It was reported that cooling is used very sparingly, but since precise indoor temperature set points did not exist, a heating set point of 68 and a cooling set point of 75 were used based on occupant survey responses. No unoccupied setback was modeled.

- **The frequency with which the HRV is actually used after the retrofit.** The new ventilation systems can supply 70 CFM to each apartment, which is close to the ASHRAE 62.2 requirement for the whole building, considering four occupants and approximately 4160 square feet (ASHRAE 2010]. It was reported that the HRVs are turned o only n when necessary for bathroom and kitchen exhaust, or to provide additional fresh air during parties. Otherwise, they are left off. This nonstandard use of an HRV was approximated by using the "50% of A-62.2" (ASHRAE 62.2) option in BEopt with an 80% effective HRV.

- **The yearly miscellaneous electrical loads (MELs).** This modeling input can be responsible for vast discrepancies in energy use between identical homes. Based on occupant survey results indicating a relatively small amount of electricity end use, MELs were assumed to be 50% of the BA Benchmark, or 2055 kWh/year (170 kWh/month).

Taking into account these limitations, the BEopt model was created using the parameters outlined in Table 2 and Table 4. Additionally, occupant survey results were used to inform values for internal loads and temperature set points. Step 7 (Heating System) includes the approximated DHW upgrade (where the combined Versa Hydro system was added). It should also be noted that on Step 8 (Ventilation), the addition of the HRV increased energy use;

however, the resultant improvement in indoor air quality is an important benefit to the homeowner. Incremental source energy reductions with each retrofit step are shown in Figure 23.

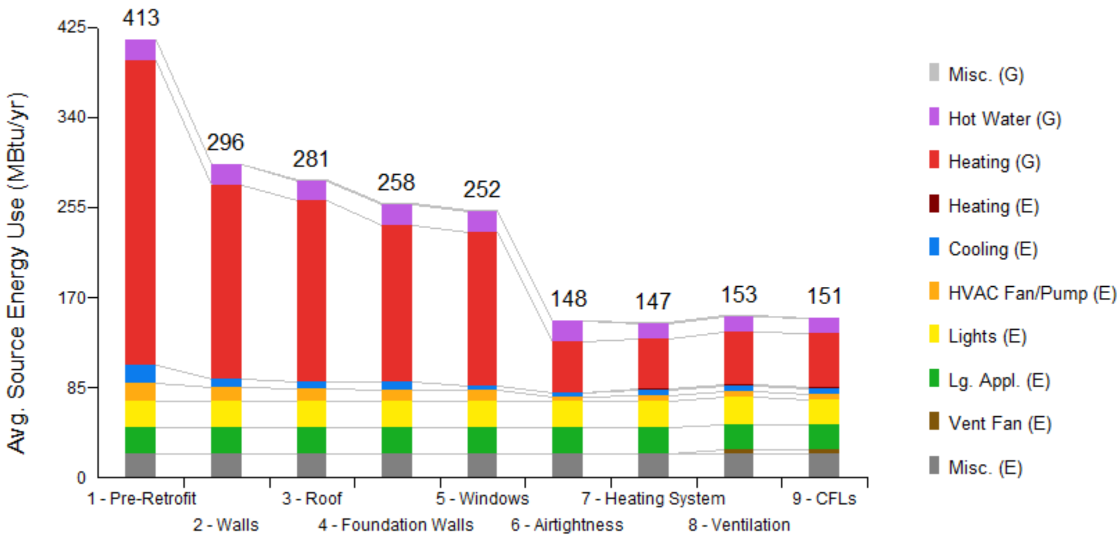


Figure 23. BEopt incremental modeling results for the Somerville Triple Decker

BEopt modeling results predict a yearly source energy reduction of 63% due to the retrofit. These results are compared to yearly energy use reported by utility bills in Section 3.2. For the Somerville Triple Decker, a decision was made to compare complete years of data since a year of pre-retrofit bills was available. Additionally, the seven months of available post-retrofit bills cover the heating season in which the most effect from retrofit upgrades should be observed. This is due to the lack of an air-conditioning system upgrade and the fact that occupants report using air conditioning and the HRV extremely sparingly. The pre-retrofit utility bill summation spans the period from May 2009 to April 2010 while the post-retrofit utility bill summation spans the period from May 2010 to April 2011. During this second period of time, the retrofit measures were in place from October 2010 to April 2011. The source energy reduction reported by utility bills during these two full years is calculated at 37%.

The comparison between modeling results and utility bills was broken into site electricity kWh, gas therms, and total source energy in MMBtu/year.

Table 15. Somerville Triple Decker BEopt Versus Utility Bill Yearly Energy Use

Type	Pre-Retrofit: BEopt Model	Pre-Retrofit: May 2009 to April 2010 Utility Bills	Post-Retrofit: BEopt Model	Post-Retrofit: May 2010 to April 2011 Utility Bills
Site electricity	9242 kWh	8129 kWh	7459 kWh	5919 kWh
Site gas	2815 therms	995 therms	599 therms	548 therms
Total source energy	413 MMBtu	202 MMBtu	151 MMBtu	128 MMBtu

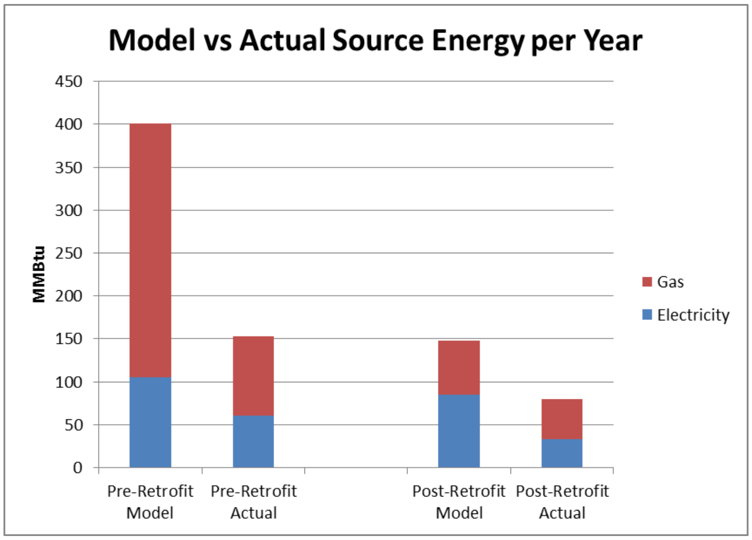


Figure 24. Somerville Triple Decker pre- and post-retrofit source energy breakdown

As observed in Table 15 and Figure 24, the model in all cases overpredicts energy usage compared to the values reported in occupant utility bills. In the post-retrofit case, the model overpredicts electricity usage by 20%, gas usage by 9%, and total source energy by 15%. In the pre-retrofit case, the model overpredicts electricity usage by 12%, gas usage by 65%, and total source energy by 51%. BSC and other practitioners have frequently observed such drastic modeling overpredictions of gas usage in pre-retrofit homes. The possible reasons for this observed discrepancy are an area of ongoing interest for BSC. In this case, heating was reported to have been used very sparingly before the retrofit, so average heating set point temperatures may have been significantly lower than modeled.

3.4 Occupant Feedback

Feedback was collected from the occupants of both the Millbury Cape and the Somerville Triple Decker. Comments from occupants who actually live in the homes studied can provide valuable insights that may be indecipherable from sources such as utility bills and models.

3.4.1 Occupant Feedback for the Millbury Cape

For the Millbury Cape, the owners provided the following feedback about the retrofit results during their first year of post-retrofit occupancy:

- "Every single one of my neighbors had huge ice dams—I had only snow on the roof and no ice" (Figure 25).
- The owners reported that the house stayed at an even temperature this winter regardless of the temperature outside.
- The owners found that it was better to keep the house at a constant heat (71°–72°F) rather than turning the heat down because it takes a while to reheat the house once the heat has been turned down.

- In January and February 2011, during periods when the heat pump could not provide sufficient heat, the owners shut off the heat pump and used the wood pellet stove to heat the entire house. Prior to the retrofit, the wood pellet stove could only heat the living room while the rest of the house remained cold.

- In March and April 2011, the owners were using the heat pump on fan mode for ventilation only. They report that this operating mode keeps the air “fresh” and (on warm days) it keeps the rooms cool.

- In July 2011, homeowner email communication contained the statement, “We are very happy with our retro house!”

Figure 25. Left: Post-retrofit Millbury Cape; Right: Neighbor’s home with ice dams

An occupant survey (see Table 16) was designed for and distributed to the occupants of the Millbury Cape. This survey is a modified version of the sample included in Norton et al. (2008). A blank copy of the survey is included in Appendix E.

Table 16. Millbury Cape Survey Responses

Question	Strongly Disagree	Disagree	Neutral/ Unsure	Agree	Strongly Agree
My home was comfortable in winter before the retrofit.		x “drafty”			
My home was comfortable this past winter (after the retrofit).					x
My home was comfortable on warm/hot days before the retrofit.		x			
My home is comfortable on warm/hot days (after the retrofit).					x
My home sometimes feels “stuffy.”				x “in winter”	
All the rooms in my house are equally comfortable.					x
I am satisfied with the overall comfort of my home.					x
My home has low utility bills for its size.				x	
The HVAC control systems in my home are easy to operate.				x	
I am satisfied with my home overall.					x
The low energy features of my home are important to me.					x

The first part of the survey is meant to pinpoint any unusually high internal loads. One television, one cable control box, one microwave oven, and one desktop computer were reported; no particularly high or unusual internal loads were described. The occupants did report the use of four ceiling fans.

Homeowners separately noted that the four ceiling fans mentioned in the survey were used to mitigate the stuffy feeling reported. Follow-up investigation of the ventilation system settings is needed to determine possible solutions to the reported stuffiness. However, the overall survey results and other homeowner comments indicate overall high satisfaction with the retrofit efforts.

3.4.2 Occupant Feedback for the Somerville Triple Decker

The same occupant survey was used for all three residents of the Somerville Triple Decker. In addition to helping gauge occupant perceptions and satisfaction, responses were used to inform the modeling inputs for both the pre- and post-retrofit conditions. Three completed surveys were received; one from each of the second and third floor single-occupant apartments and one from the first floor two-occupant apartment.

No particularly unusual internal loads were reported. Adding up internal loads for the whole apartment building, four computers, four televisions, four window air conditioners, and three microwaves were noted. One occupant reported the occasional use of a dehumidifier. All three survey respondents reported opening the windows during advantageous outdoor conditions to provide cooling and ventilation.

In the course of the occupant survey, it was discovered that the newly installed hydronic system does not have thermostats; instead, each of several radiators per apartment has a dial control (thermostatic radiator valve) numbered 0 to 5. While occupants estimated winter temperature set points of 68°–70°F, the lack of thermostats makes it difficult to know exact operating temperatures.

The homeowner also reported some control problems with the system, noting that occupants might leave windows open while the heat is on. This is an area that requires further investigation. If the windows were left open to provide ventilation and not because occupants were unable to turn down the heat as much as desired, it would be much more advantageous to run the HRVs. However, other comments by the owner indicate a reluctance to use the HRV except when absolutely necessary for exhaust and occasional high-occupant scenarios, as mentioned in the discussion of energy modeling assumptions.

The last page of the survey was meant to gauge occupant satisfaction with the retrofit. Occupants were asked to respond to questions on a scale of 1 to 5, marked as "Strongly Disagree," "Disagree," "Neutral/Unsure," "Agree," and "Strongly Agree," respectively.

Table 17 shows responses regarding occupant comfort and satisfaction. The letters A, B, and C are meant to represent the occupants of the first, second, and third floor respectively. The second floor occupant (B) is the homeowner.

Table 17. Somerville Triple Decker Survey Responses

Question	Strongly Disagree	Disagree	Neutral/ Unsure	Agree	Strongly Agree
My home was comfortable in winter before the retrofit.		A	B,C		
My home was comfortable this past winter (after the retrofit).					A,B,C
My home was comfortable on warm/hot days before the retrofit.		B,C		A	
My home is comfortable on warm/hot days (after the retrofit).					A,B,C
My home sometimes feels "stuffy."		B,C	A		
All the rooms in my house are equally comfortable.					A,B,C
I am satisfied with the overall comfort of my home.					A,B,C
My home has low utility bills for its size.					A,B,C
The HVAC control systems in my home are easy to operate.			A	B,C	
I am satisfied with my home overall.					A,B,C
The low energy features of my home are important to me.			C		A,B

Results indicate high overall satisfaction among all building occupants who completed the survey. Although the experiences of all occupants provide important data, the opinions of the homeowner are most central as they indicate satisfaction with the retrofit as a long-term personal investment. For example, although all occupants report increased comfort, the response to the last question indicates that the third floor occupant, C, may be uninterested in low energy buildings as an environmental effort or point of personal pride. If the homeowner, B, had felt the same way, there may not have been sufficient motivation to invest in the time and expense of the retrofit.

Regarding the question of home comfort on warm days, it should be noted that at the time of the survey, very few post-retrofit warm days had yet occurred. This question should be readdressed after a minimum of one complete summer in the post-retrofit house has been experienced. It is also interesting to note that the first floor occupant, A, felt that the home was comfortable on hot days before the retrofit while the others did not; the first floor is likely to stay coolest due to thermal buoyancy effects, as well as possible coupling to the basement/ground thermal mass.

In addition to interior comfort observations, the owner shared photos of the roof in winter following the retrofit and reported that few or no ice dams formed. The snow also took longer to melt than on neighboring roofs (Figure 26).

Figure 26. Post-retrofit Somerville Triple Decker, slow snow melting and no ice dams

In addition to positive feedback from human occupants, the homeowner made a strong assertion that the resident dogs and cat prefer the post-retrofit home. However, insufficient evidence was provided to corroborate the claim with a high degree of certainty.

3.5 Retrofit measure success and lessons learned

The following results indicate that the complete package of retrofit measures for the Millbury Cape was effective:

- During the six months following completion of the retrofit, source energy use was cut by 37% from the previous winter. Better results can be expected in the following years since finishing up tasks such as changing lighting from incandescent bulbs to CFLs, discovering operational problems, and commissioning were all taking place during those six months.
- Blower door testing shows that air infiltration for the home was dramatically reduced.
- The occupants report that the comfort level of the house was improved—less drafty, more even heating levels, air seems fresh.
- The following results indicate that the complete package of retrofit measures for the Somerville Triple Decker was effective:
- During the seven months following retrofit completion, source energy usage was reduced by 48% compared to the previous year.
- Blower door testing results show a significant reduction in air infiltration, likely contributing significantly to the observed energy use reduction.

- The roof was observed to be without ice dams, and accumulated snow took longer to melt.

- Three of the four occupants of the home responded to the survey, reporting increased overall comfort and satisfaction.

- Occupants prefer the hydronic heating/DHW system to the “very drying” hot air systems previously in place. However, the long-term controllability of the Versa Hydro system should be monitored, and the installation of thermostats with setback options considered.

- Current results for both test homes are based on approximately half a year of post-retrofit data and do not necessarily indicate average performance for future years. Additional observation, especially in warm weather, is needed to fully gauge the success of the efforts.

- Both of these homes successfully remained occupied during the retrofit process. However, their experiences underline the importance of good cooperation and communication between the contractor and client, especially with high performance retrofits. One lesson learned from the Millbury Cape project was the importance of coordinating all subcontractors from the start of the project. For this project, the HVAC contractor was not a subcontractor to the builders but instead was contracted by the owner. This arrangement complicated the coordination effort and caused the construction phase to last longer than originally anticipated. This highlights one of the difficulties that can be experienced, especially with HVAC work, in DER projects. To attain significant energy use reduction, new design and non-standard approaches are required for the HVAC component of the project. It is best for the HVAC system designer to be an integral part of the project team from the start.

- In the case of the Somerville Triple Decker, one lesson learned was that during the retrofit process there is a high likelihood of discovering work needed in more areas than originally planned. This increases time, costs, and inconvenience to occupants. For this project, it turned out that a variety of unexpected structural, electric, plumbing, and water management upgrades were needed in the interest of safety and durability. Good communication and teamwork are needed to successfully integrate these unanticipated upgrades.

3.6 Recommendations for Future Work

These test homes serve as examples of successful retrofits to typical New England homes. However, additional observation is needed to better understand long-term energy performance and durability. While utility data from this past winter (2010–2011) were available for both houses, it would be useful to continue to monitor the data to observe whether results are consistent for several years. If it can be obtained, the addition of utility bill data from other pre-retrofit years would help to create more accurate “baselines” of yearly energy use before the retrofits occurred. During the pre-and post-retrofit months available for comparison, the Millbury Cape showed a source energy reduction of 37% while the Somerville Triple Decker showed a source energy reduction of 48% from utility bills provided by the homeowners.

Environmental monitoring with data loggers is also a useful tool to evaluate home performance or troubleshoot problems. For the Somerville Triple Decker, one interesting area to examine would be the difference between indoor and outdoor temperatures during the cooling season. This is possible because air conditioners are used only in certain rooms of the house, while the temperature in other areas is allowed to float. If outdoor and non-air-conditioned indoor temperatures were logged simultaneously, the lag time between outdoor and indoor temperature changes could be recorded. This would show the effect of thermal mass and high insulation values. A future project might log and compare a different home’s temperature stability before and after a similar retrofit.

4 Conclusions

The two projects discussed in this report can serve as examples of successful retrofits to typical New England style homes. While limited post-retrofit data are available due to the recent completion of the projects, clear improvements in energy usage and occupant comfort are observed from the strategies advocated by Synergy Construction and BSC. Occupant preferences and costs also played a strong role in the decision-making process for both retrofit endeavors.

There are many challenges in the field of retrofit strategy and cost benefit research. While best practice strategies for new construction in different climates are relatively straightforward, every retrofit is a unique case. Existing buildings come from a variety of different eras and use a very wide variety of construction techniques. Aging or poorly constructed new buildings can have any number of failures that must be addressed. These failures can include structural issues, moisture problems, or occupant discomfort.

All of these issues contribute to the difficulty in arriving at cost benefit data for retrofits that can be applied to other retrofit projects. Construction costs for each element of a retrofit depend on many factors including geographic location, material availability and labor costs. It is common for initial cost estimates by a contractor to change midway through a project because additional issues are discovered during the process.

In addition to construction costs, utility bill savings from retrofit measures are also difficult to estimate before the project begins. As discussed, energy usage calculated by BEopt models representing both the pre- and post-retrofit conditions did not show a strong correlation with actual usage reported in utility bills. BSC will continue to research the use of BEopt to inform the retrofit design process and more accurately predict energy savings.

Appendices

Appendix A

National Grid Deep Energy Retrofit Pilot

From:	Ken Neuhauser, Building Science Corporation	Date:	November 30, 2007
To:	[redacted]	Re:	Mechanical System Options for [redacted] Residence
Cc:	David Legg – National Grid Betsy Pettit, Kohta Ueno – Building Science Corporation		

The following report represents an evaluation of a number of mechanical system options for your proposed deep energy retrofit project. Our analysis was motivated by the fact that natural gas was not available at this site and by the assessment that cost effective mechanical system solutions would be needed for this project to succeed as a deep energy retrofit (DER). The evaluation considered mechanical systems needed to efficiency and effectively provide:

- Heating,
- Water heating,
- Ventilation,
- Air mixing, and
- Cooling.

We compared the estimated installed cost, operational cost and complexity of various configurations. The re-use of existing heating distribution and water heating equipment was considered as an option.

We find that configurations which use an oil boiler and either the existing distribution system or a new distribution system to be reasonable options. We find that heating provided by a propane on-demand water heater (in combination with an air-source heat pump) or by a propane furnace could be considered if the per-gallon cost of propane is close to that of fuel oil.

Since two of the mechanical system functions (ventilation and air mixing) are not currently present in the home; the evaluation considers equipment and systems that would be added to serve these functions. Given that the cooling function is deemed to be met inefficiently in the existing configurations, different means of providing cooling are considered in the evaluation. Systems to provide cooling represent a significant portion of the estimated cost in each configuration evaluated.

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

Thank you,

Ken Neuhauser

Background

In retrofit projects it is common to encounter a situation where natural gas service is not available. Available fuels for heating and water heating in these situations would be oil, propane and electricity. Each of these fuels has advantages and disadvantages in terms of installed cost of equipment, operational cost, and performance. The choice of fuel for heating or water heating will dictate the viable options for meeting other mechanical system needs. For a high-performance retrofit, the choice of fuels, then, should be considered in light of the entire mechanical system that would be configured around the choice of fuel.

Since every retrofit situation is unique, appropriate system configurations must also consider building loads, usage patterns, existing equipment, the condition of existing equipment, and the feasibility of accommodating new equipment and services.

An evaluation of various mechanical system configurations was conducted to weigh the whole-system advantages and disadvantages for a specific Deep Energy Retrofit (DER) Pilot candidate project. The whole-system configuration is taken to be the mechanical equipment needed to meet the following needs:

- Heating,
- Water heating,
- Ventilation,
- Air mixing, and
- Cooling.

The whole-system configurations studied represent each of the available fuels as a primary heating fuel. The system configurations are projected to meet certain basic performance criteria in order to support the objectives of a high-performance retrofit.

Summary of Findings

Propane-fueled heating and water heating configurations do not appear to offer a significant cost advantage when oil-fueled heating or water heating equipment of the same type is available. The only configuration where propane-fueled heating and water heating appears to offer a significant installed cost advantage is in the configurations (Scenarios 4A and 4B) that use a propane on-demand water heater for both the water heating and back-up (to air-source heat pump) heating.[1] Even with the apparent installed cost advantage, the propane on-demand water heating and supplemental heating configurations would only be recommended if the cost per gallon of propane was expected to be close to- or less than the cost per gallon of heating oil for the foreseeable future. If the propane storage tank is owned by the homeowners rather than the propane supply company, it is possible that the cost of propane could be "shopped" more aggressively to maintain a per-gallon price that is closer to that of fuel oil.[2]

Based on fuel prices stated below, switching to propane for either water heating or primary heating will be more costly to operate than the currently installed equipment. Even best-in-class

[1] We are aware of the Toyotomi OM oil-fired on-demand water heaters but regard these as better suited for use in a boiler configuration. We would encourage, with conditions, the solicitation of bids for oil-boiler replacement that include the Toyotomi OM water heater as an option.

[2] If the homeowners are inclined to pursue propane heating options, they may wish to investigate the cost and feasibility of installing a propane storage tank.

efficiency for a propane on-demand water heater still represents a higher operational cost than any of the oil options. The operational cost disadvantage of propane heating is somewhat mitigated to the extent that a larger portion of the heating load would be met by an **air-source-heat pump (**ASHP) or a tertiary heat source (e.g. direct vent pellet stove). Electric-based heating, through the use of an ASHP, has noticeable operational cost advantages in the simple analysis. However, throughout the heating season, the efficiency and capacity of an ASHP declines with temperature to the extent that it is recommended to complement ASHP with other heating systems in a cold climate.

Based upon the installation cost and operational cost analysis, we would recommend that the homeowners solicit bids for any of the following complete system configurations:

- Oil hydronic heating using a new boiler and reusing the existing baseboard and hot water tank, air-source heat pump (ASHP) cooling and supplemental heat, 2 compact air handling units (AHU) with compact ductwork, **central-fan-integrated supply** (CFIS) ventilation (Scenario 1B in this evaluation)
- Oil hydronic heating using a new boiler and reusing the existing baseboard and hot water tank, ASHP cooling and supplemental heat, 1 central AHU, CFIS ventilation (Scenario 1C)
- Oil hydro-air heating with ASHP cooling and supplemental heat, boiler supplies existing DHW tank and hot water coils in 2 compact AHUs with compact ductwork, CFIS Ventilation (Scenario 2A)
- Oil hydro-air heating with ASHP cooling and supplemental heat, boiler supplies existing DHW tank and hot water coil in 1 central AHU, CFIS Ventilation (Scenario 2B)

If, as described above, propane costs approached oil costs (on a per gallon basis), the homeowners may also consider:

- ASHP heating and cooling, high efficiency ($EF \geq 0.90$) propane on-demand water heating and back-up heat through hot water coils in 2 AHUs with compact ductwork, CFIS Ventilation (Scenario 4A)
- ASHP heating and cooling, high efficiency ($EF \geq 0.90$) propane on-demand water heating and back-up heat through hot water coil in 1 central AHU, CFIS Ventilation (Scenario 4B)
- Propane furnace, ASHP cooling and supplemental heat, high efficiency ($EF \geq 0.90$) propane on-demand water heating, CFIS Ventilation (Scenario 6A)

In evaluating contractors' proposals, the homeowners are encouraged to consider secondary factors not reflected in this analysis. For example, hydro-air options will represent a cost premium relative to re-use of the existing baseboard, but this premium should be weighed against the value to the homeowners (if any) of better use of floor area enabled through removal of baseboard radiators.

It should be noted that this evaluation was not an exhaustive study of the performance of specific products: instead, it projects reasonable generalizations about certain classes of equipment. Pricing is also a general estimate (except for the examples provided by the [redacted] of actual proposed installation prices). The estimated system costs are meant to provide a first-cut evaluation of general system types and their relative costs. Note that some relative differences in estimated installed cost could be overwhelmed in actual contractor bids by installation variables and other factors.

Existing Conditions and Assumptions

Heating

It is understood that the current heating system in the home uses baseboard convector/radiators distribution with hot water supplied by an oil-fired boiler. The homeowners report that the boiler is original to the home. It is atmospherically vented and exhausts through a lined chimney. Although the DER Pilot application for this home reported an efficiency of 79% for the boiler, this is assumed to represent combustion efficiency. For the sake of analysis, the thermal efficiency of the system is estimated at approximately 70%.

The [redacted] also use a fireplace-insert pellet stove to provide a significant portion of their heating. It is not known whether this pellet stove is direct vented, power vented, or atmospherically vented.

Water Heating

The [redacted] have purchased a new indirect-fired hot water storage tank within the last 2-3 years. The boiler supplies hot water to the heat exchanger in this storage tank. From photos submitted, the tank appears to be a glass-lined model.

Ventilation

It is assumed that the current ventilation system consists of exhaust fans in the bathrooms. It is unknown whether the range hood exhausts to the outside or is recirculating. It is assumed that the home does not have provision for whole-house dilution ventilation.

Cooling

Cooling is currently provided by 3 or 4 window AC units. The efficiency of these units are probably in the range of 8 to 11 SEER. Window AC units typically do not offer the range of efficiency available with split systems (separate outside compressor/condenser and indoor evaporator coil). The most significant penalty to energy performance of window AC units is that they severely compromise building air tightness. The presence of window AC units is indicative of the occupants' desire for cooling, so it is expected that the post-retrofit condition will include a need for mechanical cooling.

Fuel Cost Assumptions

This analysis assumed the following fuel costs and availability:

- Oil at $2.50/gallon
- Propane at $2.40/gallon
- Electricity at $0.16/kWh
- Natural gas not available at site

The impact of these costs is examined in more detail in the section Operational Costs.

Basic System Parameters

Any configurations of mechanical equipment employed in the deep energy retrofit (DER) plan should meet the basic system requirements outlined below.

Sealed Combustion

Sealed combustion is a minimum standard that Building Science Corporation (BSC) recommends for residential construction. The reasons for this are 1) for combustion safety, and 2) to maintain the integrity of the building air barrier system. If no practical possibilities for sealed-combustion are available for a given application, direct-vent combustion may be acceptable per the DER pilot guidelines. Direct vent combustion provides mechanically induced intake of combustion air and mechanically induced exhaust of combustion products but pressure relief dampers or other air leakage connections to the venting and intake system may exist.

The scenarios put forth in this analysis presume that the pellet stove remaining in service either is direct vented in its current state, would be made to be direct vented, or would be replaced with a direct vented model.

Ventilation

The requirements of the National Grid (NGrid) Deep Energy Retrofit Pilot program and BSC recommendations are that homes be capable of meeting the ventilation requirements described in ASHRAE Standard 62.2. This standard establishes standards relating to two forms of ventilation:

1. Source control ventilation – e.g. bath and kitchen exhaust, and
2. Whole-building dilution ventilation

Source control ventilation can be satisfied by intermittently operated fan systems vented to the outdoors and capable of exhausting air at a rate of 100 cfm for kitchen range hoods, and 50 cfm for bath fans. Source control ventilation is needed to control contaminants (odors, excess humidity, cooking fumes, etc.) at their source.

Whole-building dilution ventilation is needed to dilute distributed contaminants within the home and to provide fresh air to occupants. The ventilation flow rate for whole building ventilation indicated in ASHRAE 62.2 is determined by the number of occupants and the floor area of the home:

7.5 cfm X number of occupants (generally assumed to be number of bedrooms +1)
+ 0.01cfm X floor area (in sq.ft.)

This required ventilation flow rate is further adjusted by effectiveness factors ranging from 1 to 1.5. These adjustment factors account for the configuration of the system, and whether the home provides a minimum amount of air mixing during each hour. A balanced system or fully ducted ventilation system with minimum air mixing requires no adjustment to the ventilation flow rate. A system that is not fully ducted (e.g. bath exhaust fan on a timer) will need a 25% higher flow rate in a home with mixing, or 50% higher flow rate in a home without periodic mixing.

Efficiency

The pursuit of low energy buildings should push the use of the best equipment efficiencies practical for a given situation. However, when loads are significantly reduced or a system is called on to meet only a part of the load, there is less of a reason (both in terms of financial payback, or energy reductions achieved) to specify the highest efficiencies. Therefore, it may be reasonable consider more modest equipment efficiencies in those cases.

For the purpose of establishing a floor for acceptable equipment efficiency, the following levels of performance should be attainable in new equipment with little or no cost premium:

- Gas boiler or furnace – 95+ AFUE
- Oil boiler – 86+ AFUE
- On-demand water heater – 0.83 EF
- Air conditioning unit – 14 SEER
- Air-source heat pump – 8.5 HSPF (9.0 or higher recommended)

One aspect of overall energy performance that is significantly affected by equipment decisions is that of infiltration. As mentioned already above, non-sealed combustion equipment presents a compromise to the air tightness of the building. Window air conditioners also present a breach in the air barrier system of a building and are not considered appropriate equipment for high performance projects.

Mechanical System Configurations

Each configuration considered in this evaluation represents a unique combination of:

1. Heating distribution type
2. Primary heating fuel
3. Primary heating appliance type
4. Water heating system type
5. Cooling equipment type and distribution

Table 1 below summarizes the various system configurations. Each configuration is discussed in more detail in the section Description of System Scenarios below.

Table 1: System Configurations Evaluated

Scenario	System Configuration	Primary Heating Appliance	Secondary Heating Appliance	Tertiary Heating Appliance	Water Heating System	Whole-House Ventilation (Dilution)	Cooling Equipment
0	Current Configuration	Oil Boiler	pellet stove		indirect-fired tank	none	Window AC
Options Using Existing Heating Fuel, Existing Heating Distribution, and Existing DHW System							
1A	oil hydronic w/ HRV ventilation, minisplit cooling	new Oil Boiler	pellet stove		indirect-fired tank	HRV	2 head minisplit
1B	oil hydronic w/ HP supplement, 2 AHU	new Oil Boiler	heat pump	pellet stove	indirect-fired tank	CFIS	HP w/ pancake AHU w/ HW coil, 1 up, 1 down
1C	oil hydronic w/ HP supplement, central AHU	new Oil Boiler	heat pump	pellet stove	indirect-fired tank	CFIS	central AHU split w/ HW coil
Options Using Existing Heating Fuel, Existing DHW System, and Ducted Heating Distribution							
2A	oil hydro-air w/ HP supplement, 2 AHU	new Oil Boiler	heat pump	pellet stove	indirect-fired tank	CFIS	pancake split w/ HW coil, 1 up, 1 down
2B	oil hydro-air w/ HP supplement, central AHU	new Oil Boiler	heat pump	pellet stove	indirect-fired tank	CFIS	central AHU split w/ HW coil

Scenario	System Configuration	Primary Heating Appliance	Secondary Heating Appliance	Tertiary Heating Appliance	Water Heating System	Whole-House Ventilation (Dilution)	Cooling Equipment
Options Using Propane Heating Fuel, Existing Heating Distribution and Existing DHW System							
3A	propane hydronic w/ HRV ventilation, minisplit cooling	new Propane Boiler	pellet stove		indirect-fired tank	HRV	2 head minisplit
3B	propane hydronic w/ HP supplement, 2 AHU	new Propane Boiler	heat pump	pellet stove	indirect-fired tank	CFIS	pancake split w/ HW coil, 1 up, 1 down
3C	propane hydronic w/ HP supplement, central AHU	new Propane Boiler	heat pump	pellet stove	indirect-fired tank	CFIS	central AHU split w/ HW coil
Options Using Electric Air-Source Heat Pump (ducted distribution) for Primary Heating with Propane Water Heating and Heat Back-Up							
4A	HP w/ propane on-demand water heater back-up, 2 AHU	heat pump	on-demand water heater	pellet stove	on-demand	CFIS	pancake split w/ HW coil, 1 up, 1 down
4B	HP w/ propane on-demand water heater back-up, central AHU	heat pump	on-demand water heater	pellet stove	on-demand	CFIS	central AHU split w/ HW coil
Options Using Propane Heating Fuel and Ducted Heating Distribution							
5A	propane hydro-air w/ HP supplement, 2 AHU	new Propane Boiler	heat pump	pellet stove	indirect-fired tank	CFIS	pancake split w/ HW coil, 1 up, 1 down
5B	propane hydro-air w/ HP supplement, central AHU	new Propane Boiler	heat pump	pellet stove	indirect-fired tank	CFIS	central AHU split w/ HW coil
6A	propane furnace w/ HP supplement	propane furnace	heat pump	pellet stove	on-demand	CFIS	central Furnace/ split AC

Relative System Costs

Cost of systems was estimated based upon available system cost information and component cost information. Because of the uncertainty of these costs, a "low" and "high" installed cost is presented for each system configuration. Since it is known that the existing system configuration would require a boiler replacement in the near future, the system configurations considered for a deep energy retrofit should be evaluated based upon the incremental cost relative to the cost of a basic boiler replacement.

Fortunately, the [redacted] were able to convey good information on the cost of a boiler replacement since they had recently received a quote for replacement of the existing boiler (reported to be original to the house) with a Buderus oil boiler. The reported cost for the boiler replacement is $5,800. Table 2 below represents estimates of the incremental cost of the configurations relative to the basic oil-boiler replacement. All of the retrofit configurations using an oil boiler assume the new boiler will be a high-performance direct vent or sealed combustion boiler with an installed cost that is $1,200 to $1,700 more than the basic boiler. The right three columns display, respectively, the low incremental cost estimate, the high incremental cost estimate and the average of these two. The highest six values are highlighted in each of these columns.

It should be noted that for scenarios involving propane heating and water heating fuel, the incremental cost estimates do not include the cost of removing an oil tank (estimated at $400-450) nor do they included the costs of a propane storage tank and its installation.

Table 2: Estimated System Cost Increment Relative to Cost of Maintaining Existing Configuration

		Best Guess Incremental Cost Estimate for Configuration		
Scenario	System Configuration	low	high	Average
0	Current Configuration	reference case	reference case	
1A	oil hydronic w/ HRV ventilation, minisplit cooling	$ 8,700	$ 11,700	$ 10,200
1B	oil hydronic w/ HP supplement, 2 AHU	$ 7,800	$ 10,700	$ 9,250
1C	oil hydronic w/ HP supplement, central AHU	$ 6,500	$ 10,100	$ 8,300
2A	oil hydro-air w/ HP supplement, 2 AHU	$ 9,000	$ 12,700	$ 10,850
2B	oil hydro-air w/ HP supplement, central AHU	$ 7,100	$ 11,100	$ 9,100
3A	propane hydronic w/ HRV ventilation, minisplit cooling	$ 9,200	$ 12,700	$ 10,950
3B	propane hydronic w/ HP supplement, 2 AHU	$ 8,300	$ 11,700	$ 10,000
3C	propane hydronic w/ HP supplement, central AHU	$ 7,000	$ 11,100	$ 9,050
4A	HP w/ propane on-demand water heater back-up, 2 AHU	$ 5,400	$ 9,400	$ 7,400
4B	HP w/ propane on-demand water heater back-up, central AHU	$ 3,500	$ 7,800	$ 5,650
5A	propane hydro-air w/ HP supplement, 2 AHU	$ 9,500	$ 13,700	$ 11,600
5B	propane hydro-air w/ HP supplement, central AHU	$ 7,600	$ 12,100	$ 9,850
6A	propane furnace w/ HP supplement	$ 4,500	$ 9,600	$ 7,050

While the incremental cost estimates are extremely rough, some positive conclusions may be drawn from examining the relative costs:

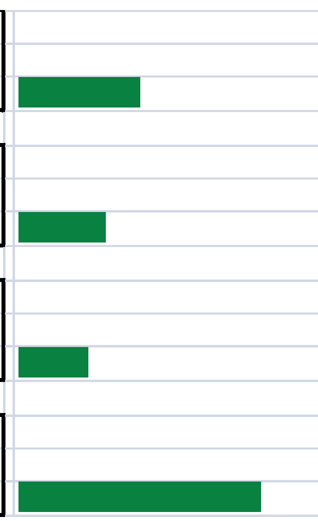
- Configurations that employ ducted cooling tend to be at a cost advantage relative to otherwise similar configurations using ductless minisplit cooling. This is because the ductless system would need to be paired with some other ducted system (e.g. ducted HRV) in order to provide adequate ventilation and mixing.
- Configurations that employ a central air handler appear to be at a cost advantage relative to otherwise similar configurations that employ two air handlers. The difference is more noticeable with configurations that involve hydro-air heating. Installation and contractor variables may overwhelm the differences indicated in this evaluation.
- Fuel oil-based heating and water heating systems do appear to offer a slight installed cost advantage when compared to otherwise similar propane-based options (e.g. compare 1A-C to 3A-C or 2A-B to 5A-B). However, this cost advantage is small enough that it could be overwhelmed by contractor variation.
- An on-demand water heater appears to be the lowest cost heating and water heating appliance option despite the existence of an indirect fired tank.
- A propane furnace with on-demand water heater option appears to be at a slight cost advantage relative to a propane boiler with air handler option even though the boiler is able to use the existing hot water storage tank. The furnace represents a relatively small cost increase over an air handler with a hot water coil plumbed to a water heating source. The on-demand water represents a significantly lower installed cost than a boiler.

Operational Costs

Fuel costs have a strong effect on operational cost effectiveness of systems. Table 3 below shows typical costs for fuels, the energy content of the fuel, and the resulting cost per unit of energy for each fuel. Bars to the right of the table provide a graphical representation of the relative cost per unit of energy for each of the fuel types.

Table 3: Fuel Cost and Energy Content

$2.40	Propane per gallon
91,000	Btu/gallon (NREL paper, HHV)
$0.026	dollars per thousand Btu
$2.50	Fuel oil per gallon
138,700	Btu/gallon (NREL paper, HHV)
$0.018	dollars per thousand Btu
$1.50	Natural gas per therm
101,000	Btu/CCF (NREL paper, HHV)
$0.015	dollars per thousand Btu
$0.16	Electricity per kWh COP=1
3,412	Btu/kWh
$0.047	dollars per thousand Btu



From this table it is evident that electricity is the most expensive fuel source in terms of energy content. Electricity used with a coefficient of performance (COP) of 3.0 would have a cost per thousand Btu that is similar to that of oil. Propane is also relatively expensive. When cost of fuel is combined with typical efficiency for various equipment types, it is possible to estimate the relative operational cost of the different scenarios. The table below represents these relative costs for heating and water heating for unique combinations represented in the scenarios. The two right-most columns indicate, respectively, (a) the calculated cost for a million Btu of heating and for (b) heating one gallon of hot water. It is appropriate to normalize the operational costs this way since the actual heating and DHW loads—although currently unknown—will be the same for each configuration. This allows for a straightforward operational cost comparison between the mechanical system configurations.

Interestingly, the table shows that even with a very efficient on-demand propane water heater (associated with Scenario 4A in the table), using propane to heat domestic hot water (DHW) is not more cost effective than the currently existing condition. With less than best-in-class efficiency, the cost effectiveness of propane water heating would be worse than the level of the currently existing equipment.

While Scenarios 1B -2b and 3B-6A would all use a blend of electric (ASHP) and fossil-fuel, the energy cost for heating presented in this analysis is not blended. For illustration purposes, ASHP heating is represented, unblended, for Scenarios 4A and 4B. This suggests that, in this abstraction, heating by ASHP is significantly more cost effective than either the oil-based or propane-based heating systems evaluated. However, in reality the efficiency and capacity of ASHP systems diminishes significantly at temperatures approaching winter design conditions.[3] Therefore, some amount of fossil-fuel supplement would be needed, resulting in an overall heating cost effectiveness that is somewhere between the unblended ASHP heating cost effectiveness and that of the complimentary fossil-fuel based system.

Table 4: Operational Cost Comparison

Scenario	Configuration Description	Primary Heating Fuel	Primary Heating Efficiency	DHW Fuel	DHW Type	DHW Efficiency	$/MBtu Heating	$/gallon DHW
0	Current Configuration	oil	0.70	oil	indirect-fired tank	0.64	$ 25.75	$ 0.016
1A	oil hydronic w/ HRV ventilation, minisplit cooling	oil	0.85	oil	indirect-fired tank	0.78	$ 21.21	$ 0.013
1B	oil hydronic w/ HP supplement, 2 AHU	oil	0.85	oil	indirect-fired tank	0.78	$ 21.21	$ 0.013
2A	oil hydro-air w/ HP supplement, 2 AHU	oil	0.85	oil	indirect-fired tank	0.78	$ 21.21	$ 0.013
3A	propane hydronic w/ HRV ventilation, minisplit cooling	propane	0.95	propane	indirect-fired tank	0.87	$ 27.76	$ 0.018
4A	HP w/ propane on-demand water heater back-up, 2 AHU	electric	8.5-9.5 HSPF	propane	on-demand	**0.95**	$ 18.60	$ 0.016
4B	HP w/ propane on-demand water heater back-up, central AHU	electric	8.5-9.5 HSPF	propane	on-demand	0.85	$ 18.60	$ 0.018
5A	propane hydro-air w/ HP supplement, 2 AHU	propane	0.95	propane	indirect-fired tank	0.87	$ 27.76	$ 0.018
6A	propane furnace w/ HP supplement	propane	0.95	propane	on-demand	0.85	$ 27.76	$ 0.018

[3] We are aware of "cold climate" heat pumps such as the Hallowell Acadia; however, our experience to date has shown these to carry a significant price premium relative to other high efficiency heat pumps. The magnitude of this price increment is such that it is generally larger than the cost of a back-up heating system as would be recommended to complement a non-"cold climate" heat pump.

It should be noted that the analysis represented in Table 4 assumes a propane cost of $2.40/gallon. If the cost for propane is closer to the $5.00/gallon suggested by one supplier, then the cost effectiveness disadvantages of the propane systems would be even more pronounced.

Description of System Scenarios

Scenario 1A – Oil Hydronic Heating, HRV Ventilation, Minisplit Cooling

Heating – This scenario maintains the existing hydronic baseboard distribution system as the primary heating system. A new boiler would be recommended for this scenario as 1) this would allow for direct venting or sealed combustion, 2) efficiency of the primary heating and water heating system would be significantly improved, and 3) the existing boiler has already been in services long enough that a boiler change-out at this time would be a reasonable pre-emptive measure. Besides the new boiler, the heating system, and secondary heating system would remain as they are presently.

Water Heating – This scenario maintains the existing indirect-fired hot water storage tank. Since the tank is relatively new, we would not recommend replacing the tank at this time. However, we do recommend that when the tank is in need or replacement that it be replaced with a stainless steel tank rather than a glass-line tank for greater durability.

Cooling – This scenario includes two ductless air conditioner heads to provide cooling.

Ventilation and Mixing – Because this scenario does not involve a ducted distribution system for heating or cooling, a ducted heat recovery ventilation system is recommended to provide ventilation and periodic mixing within the space. The mixing function that is provided by a fully ducted HRV is unlikely to be as effective as a ducted conditioning system because of the lower volume of air that it moves.[4] Still, a ducted ventilation system is recommended to provide some amount of distribution for the cooling and dehumidification provided by the ductless air conditioning units.

Cost of System – Depending on the boiler selected, the cost of replacing the existing oil-fired boiler with a new direct-vent or seal combustion boiler would be expected to be in the range of $7,000 to $8,000. Note that this represents an increase of $1,200 to $2,200 over the cost of the boiler replacement already deemed necessary to maintain the currently existing configuration. The installed cost for two ductless minisplit AC units can be expected to be between $5,000 and $7,000. The [redacted] have received a quote for installation of an HRV unit of ~$2750. The approximate total system cost for the configuration described for scenario 1A should be in range of $14,500 to $17,500.

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[4] Note that ASHRAE Standard 62.2 defines a fully ducted system as:

> ***fully-ducted ventilation system***: a ventilation system that supplies ventilation air through a duct to each common area and bedroom, or a ventilation system that exhausts air through a duct to outdoors from all kitchens and bathrooms, or a ventilation system that exhausts air through a duct to outdoors from all bedrooms.

The"minimum turn over" or air mixing is also defined in 62.2:

> ***minimum turnover***: whole-building air mixing such that at least 50 % of the house air volume is moved through a forced air distribution system each hour.

Scenario 1B – Oil Hydronic Heating, Air-Source Heat Pump Supplement, 2 Compact AHUs, Central-Fan-Integrated Supply Ventilation

***Heating* –** Heating in this scenario also uses the existing hydronic heating distribution and compliments this with a heat pump system that provides heating during milder weather when a heat pump would be more efficient. The heat pump system delivers heat through two small duct systems each served by a compact air handler.

***Water Heating* –** Hot water is provided by the by the oil-fired boiler through the existing indirect-fired hot water tank.

***Cooling* –** The air-source heat pump (ASHP) system provides cooling and some dehumidification. Two small air handlers with associated duct work would serve, respectively the first and second floors of the home.

***Ventilation and Mixing* –** The ducted distribution systems associated with the ASHP provides a very economical opportunity for effective ventilation and mixing with the use of a fan cycling controller, an outdoor air duct, and a motorized damper. In this configuration known as central-fan-integrated supply (CFIS) ventilation, a commercially available fan control device operates the air handler fan as well as the motorized damper in the outdoor air duct to ensure a preset minimum of both air mixing and dilution ventilation. A CFIS system would be added to each air handler.

***Cost of System* –** For hydronic heating and water heating this configuration will have identical casts to scenario 1A. The installed cost of the ASHP cooling and supplemental heating system can be expected to be slightly higher than the two-head minisplit AC system because of 1) the installation of the compact ducted distribution, and 2) the additional cost of a heat pump as compared to the air conditioning-only compressors of scenario 1A above. We are aware of an example of a similar system that a builder installed in a recent project for a cost of approximately $8,000.

It should be noted that the cost increment of a heat pump (approximately $300-600) relative to the cost of a cooling-only compressor is deemed a compelling investment given the efficiency advantage of heat pump heating in mild weather.

For ventilation and mixing, the CFIS system will provide cost savings relative to the HRV system of scenario 1A. In order experience the installed cost of a CFIS system is approximately $400. Even with two CFIS systems the cost of the ventilation system can be expected to be approximately $2K less than a ducted HRV system.

The approximate total system cost for the configuration described for scenario 1B should be in range of $13,600 to $16,500.

Scenario 1C – Oil Hydronic Heating, Air-Source Heat Pump Supplement, Central AHU, CFIS Ventilation

This configuration is similar to Scenario 1B with the exception that the ASHP system in 1C includes one central air handler and one outdoor compressor unit instead of two air handlers and two outdoor units.

For a basic system in this configuration, the forced-air system would be a single-zone system. This likely to be adequate for smaller homes and where spaces are relatively open to one another. However, in larger homes and homes where spaces tend to be closed off from one another and have strong load diversity, more than one conditioning zone may be desired to maintain uniform comfort conditions. Using a two-zone system would add to the cost and complexity of the system. The need for multiple zoning is reduced with the periodic mixing provided in all of the configurations evaluated

Cost of System – The variables that will drive the cost of this configuration include the difficulty in routing ductwork and the size of the heat-pump selected for the home. Assuming that the cost of routing duct work is ~50% for this scenario than for the compact ducted distribution and that a 2 ton heat pump is selected, then it is conceivable that the additional cost of the duct work is balanced by reduced equipment cost making the total system cost for this scenario roughly the same as for a two-air handler system such as represented in scenario 1B. Given the reduction in equipment compared to a two-air handler scenario, it is also reasonable to expect that the total cost for this scenario would be less than for the two-air handler scenario when premium efficiency air handling equipment is used.

Scenario 2A - Oil Hydro-Air, Air-Source Heat Pump supplement, 2 AHU, CFIS Ventilation

Heating – This scenario abandons the existing hydronic distribution system. Hot water is provided by an oil-fired boiler to hot water coils in air handlers that then distribute warm air through compact ducted distribution. Heat pumps complement the boiler-source heating by providing heating during milder weather when a heat pump would be more efficient.

The baseboard system may be abandoned in place or, removed to allow better use of the floor area. The scrap/recycling value of metal in the distribution may help to offset a portion of the removal cost.

Water Heating – Hot water is provided by the by the oil-fired boiler through the existing indirect-fired hot water tank.

Cooling – The air-source heat pump (ASHP) system provides cooling and some dehumidification. Two small air handlers with associated duct work would serve, respectively the first and second floors of the home.

Ventilation and Mixing – CFIS, one per air handler.

Cost of System – the cost of this configuration would the same as 1B plus 1) the cost for plumbing to hot water coils (estimated at $1,200-2,000) and any additional net cost associated with removal of the baseboard heating distribution.

Scenario 2B - Oil Hydro-Air, Air-Source Heat Pump supplement, Central AHU, CFIS Ventilation

This configuration is similar to Scenario 2A with the exception that the ASHP system in 2B includes one central air handler and one outdoor compressor unit instead of two air handlers and two outdoor units.

Cost of System – The total system cost for this scenario should be somewhat less than a two-air handler system such as represented in scenario 2A.

Scenario 3A through 3C – Propane Hydronic Scenarios

These scenarios are similar to scenarios 1A through 1C with the difference being that the oil-fired boiler is replaced with a propane-fired boiler in 3A-3C. This allows for a modest increase in efficiency relative to the oil-fired hydronic heating options.

Cost of Systems – These installed cost of equipment in these scenarios should be similar to scenarios 1A-1C. Installed cost of high efficiency propane boilers with appropriate controls would be in the same range as high efficiency sealed combustion or direct vent oil boilers with controls. There would, however, be an added cost of providing a gas line from the propane tank to the boiler. As with all scenarios that discontinue use of fuel oil, there would also be a cost for removal of the oil tank if the homeowners chose to do that. Depending upon the arrangement with the propane provider, there may also be costs associated with a propane storage tank and its installation.

Scenario 4A – ASHP, Propane On-Demand Water Heater Back-Up, 2 AHU, CFIS Ventilation

Heating – This scenario employs the ASHP with compact ducted distribution described for 1B, 2A and 3B above as the primary heating system. A propane-fired on-demand water heater provides hot water to a hot water coil in the air handlers to provide heating in conditions where the ASHP system would not have adequate capacity to meet the heating load.

Water Heating - A propane-fired on-demand water heater provides hot water. A small buffer tank and a pump to circulate from the buffer tank through the water heater is recommended if not included within the water heater. The existing hot water storage tank would be abandoned.

Cooling – The air-source heat pump (ASHP) system provides cooling and some dehumidification. Two small air handlers with associated duct work would serve, respectively the first and second floors of the home.

Ventilation and Mixing – CFIS, one per air handler.

Cost of System – The [redacted] have received a quote for an complete installation of an on-demand water heating system in the amount of $3,280. This quote included the cost of connection to existing gas piping but may not include the cost of running a gas line to the house from a storage tank. The cost of adding a small buffer tank and recirculating pump may be estimated to be approximately $500. With this additional cost, it may be more economical to install a premium efficiency water heater, such as a Navien CR A water heater, that includes a small buffer tank and internal circulation pump.

Based on the quote received by the [redacted] and the estimated add for buffer tank and pump, the installed system cost for an on-demand water heating system is approximately $3,200 to 3,800 less than the estimated installed cost of a high efficiency, sealed/direct vent oil-fired boiler. Therefore, the cost of scenario 4A would be expected to be in the range of $11,200 to $15,200.

Scenario 4B – ASHP, Propane On-Demand Water Heater Back-Up, Central AHU, CFIS Ventilation

This configuration is similar to Scenario 4A with the exception that the ASHP system in 4B includes one central air handler and one outdoor compressor unit instead of two air handlers and two outdoor units.

Cost of System – The total system cost for this scenario is expected to be somewhat less than a two-air handler system such as represented in scenario 4A.

Scenario 5A - Propane Hydro-Air, Air-Source Heat Pump supplement, 2 AHU, CFIS Ventilation

This configuration is similar to Scenario 2A - Oil Hydro-Air, Air-Source Heat Pump supplement, 2 AHU, CFIS Ventilation" except that it employs a propane-fired boiler instead of an oil-fired boiler.

Cost of Systems –These installed cost of equipment in this scenario should be similar to scenario 2A. There would, however, be an added cost of providing a gas line from the propane tank to the boiler. As with all scenarios that discontinue use of fuel oil, there would also be a cost for removal of the oil tank if the homeowners chose to do that. Depending upon the arrangement with the propane provider, there may also be costs associated with a propane storage tank and its installation.

Scenario 5B - Propane Hydro-Air, Air-Source Heat Pump supplement, Central AHU, CFIS Ventilation

This configuration is similar to Scenario 5A with the exception that the ASHP system in 5B includes one central air handler and one outdoor compressor unit instead of two air handlers and two outdoor units.

Cost of System – The total system cost for this scenario is expected to be somewhat less than a two-air handler system such as represented in scenario 5A.

Scenario 6A – Propane Furnace, On-Demand Water Heater, Air-Source Heat Pump supplement, Central AHU, CFIS Ventilation

Heating – A high efficiency, sealed combustion gas (propane) furnace paired with an air source heat pump for mild weather heating provides the most efficient heating system in terms of source (primary) energy use. Given the added complication and cost, albeit modest, of a furnace relative to an air handler, the propane furnace option is evaluated only in a central furnace/air handler configuration. An oil-fired furnace was not evaluated because we are not aware of direct-vent or sealed combustion oil-fired furnaces.

Water Heating – This configuration requires a separate combustion appliance to meet the water heating needs. This may be considered an advantage whereas the heating and water heating are not both dependent upon the same combustion appliance.

Cooling – The air-source heat pump (ASHP) provides cooling and some dehumidification.

Ventilation and Mixing – CFIS.

Cost of System – The cost of this system can be readily compared to that of scenarios 4B and 5B.

Relative to scenario 4B which uses an on-demand water heater to provide both water heating and hydro-air heating with a central air handler, scenario 6A represents an added cost for a furnace as compared to an air handler (~$500) and a cost savings in avoiding the plumbing and pumps associated with a hydro-air system (~$1,200). Therefore, a two-combustion appliance configuration using a propane furnace and on-demand water heater can be expected to be somewhat less costly than a one combustion appliance configuration using an air handler and on-demand water heater.

Relative to scenario 5B which uses a propane boiler to provide hot water to both an air handler and a domestic hot water storage tank, scenario 6A represents an added cost for a furnace as compared to an air handler (~$500) and a cost savings for the propane-fired on-demand water heating system relative to a a high efficiency, sealed combustion propane boiler (approximately $3,200 to 3,800).

Appendix B

Building Science Corporation

2010.06.18

Laura Catanzaro
Holistic Design
238 Columbia Street
Cambridge, MA 02139

617 218-7018

Re: [redacted]
Basement and Mechanical System Strategies

CC: **Betsy Pettit, FAIA – Building Science Corporation**
Andrew Proulx, PE – EnerSpective

Dear [redacted]:

It was a pleasure to have the opportunity to visit [redacted] home at [redacted] with you. This is an exciting retrofit project with great potential for energy savings. The great potential for energy savings appears to be matched by enthusiasm of the project team.

The purpose of my visit to the project was to assess the existing systems and proposed conditions in order to provide outline recommendations for treatment of the basement and for design of mechanical systems. Observations on the use of the basement lead to a recommendation to insulate and condition the basement space. Particulars of the basement observations and recommendations are discussed below. The mechanical system configuration that appears to be most appropriate for the 3 family home consists of forced-air conditioning and ventilation systems for the first and second floor apartments and a hydronic radiant system with separate ventilation distribution for the third floor. In the recommended system configuration, on-demand water heaters provide domestic hot water for each apartment as well as heating for the top floor apartment.

The evaluation of mechanical system strategies considers the ability of the mechanical system to efficiency and effectively provide:

- Heating,
- Water heating,
- Ventilation,
- Air mixing, and
- Cooling.

My evaluation also takes into consideration that the mechanical systems should allow for – but not necessarily require – separate metering of utilities.

The following pages present discussion and recommendations relative to strategies for the basement and mechanical system.

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

Thank you,

Ken Neuhauser

1. Observations

Basement

The foundation walls appear to be of thickly parged rubble stone and brick construction. The floor of the basement is concrete with some areas of exposed earth. Considerable efflorescence was observed on the parge coat.

Clearance between the first floor framing and basement floor varies somewhat and is generally less than 6'-6". There is a considerable amount of piping and ductwork below the floor framing. Stair access to the basement from the first floor is along an exterior wall and in a corner of the structure. The stairs are not wide.

Evidence of water as well as damp surfaces were observed on both of two visits to the building.

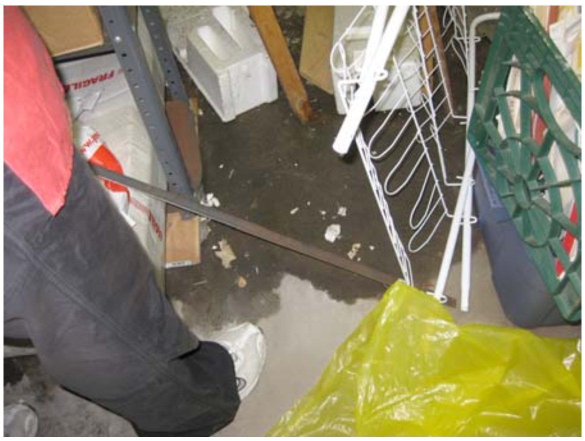

Figure 1: Damp floor in basement storage area

Figure 2: Damp floor and wall in basement

The basement is used for a large variety of household storage including clothing, books and papers. An area of the basement is set up as a workshop. Plans indicate that laundry for the three apartments will be moved to the basement.

Heating and Water Heating Equipment

Two furnaces, a boiler and three storage water heaters are located in the basement.

First Floor Heating System

A gas-fired furnace serving the first floor is a relatively recent vintage American Standard Freedom 90. This is a condensing furnace with an AFUE rating of 92. It is configured as a forced-draft unit but appears to be convertible to sealed combustion or direct vent. The furnace is vented with PVC pipe.

Supply duct work for this system is of galvanized sheet metal. The branch ducts appearsto be of larger-than-typical dimensions with relatively straight runs to elbows connecting to register boots. There is no evidence of duct sealing. There is a single return for this system with a plenum of approximately 12" round duct connected to a rectangular section at the air handler. There is an uncovered filer slot accommodating a 1" thick filter.

Second Floor Heating System

The gas-fired furnace serving the second floor apartment appears to be slightly older than the furnace serving the first floor. It is a Lennox G12 model. It is not a condensing furnace therefore will likely have efficiency below 80%. It is vented through 4" galvanized vent pipe to an unlined chimney flue.

The return for this system is a panned return located at the first floor landing of the back stairs. Some of the ductwork is rusty.

Figure 3: Panned return for 2nd floor heating system

Figure 4: Supply ductwork serving 2nd floor

Third Floor Heating System

The third floor heating system consists of a gas-fired boiler and hydronic baseboard distribution. The boiler appears to be at least 30 years old and is reported to have had operating problems in the past heating season. The baseboard heating loop is assumed to be a series loop with no convector bypass. The heating pipes serving the third floor heating loop are not consistently insulated between the boiler and the third floor.

Water Heaters

Each of the apartments is served by an atmospherically vented, storage-type, gas-fired water heater. These appear to be less than 5 years old. There are no heat traps on the hot water supply piping connected to these water heaters. A small amount of pipe insulation was noted on the hot water supply piping for one of the water heaters.

Chimney

The boiler, one of the furnaces and all three of the water heaters are vented through an unlined brick chimney. Each flue in this chimney is approximately 8” square.

Figure 5: East chimney flue

Figure 6: West chimney flue

Apartments

First Floor Apartment

The first floor apartment has a ceiling height of approximately 8’9”. Supply and return registers are generally unobstructed. The first floor apartment has a closet toward the front on the West side that is approximately 8’ deep and 3’ wide. The chimney passes through the apartment in an enclosure that is approximately 2’ deep by 6’ wide.

Second Floor Apartment

The first floor apartment has a ceiling height of approximately 9'. The ceiling in the kitchen, hallway, bedroom and room adjacent to the kitchen is covered in an adhered 12x12 tile. The owner indicated that the ceiling finish does not positively contribute to the appearance of the apartment. Some supply and return registers are obstructed. A supply register in the bathroom floor was noted. The kitchen has a recirculating range hood. The second floor apartment has a closet toward the front on the West side that is approximately 8' deep and 3' wide. The chimney passes through the apartment in an enclosure that is approximately 2' deep by 6' wide.

Third Floor Apartment

The third floor apartment occupies the space directly under the roof framing. The front access stair to the apartment is open from the stairs up to the ceiling on the underside of the roof rafters thus creating a space that is very high above the first run of stairs up to the intermediate landing. Adjacent to this high interior volume is an enclosed space overhanging the second floor porch that does not presently have access. The apartment does not have the large closet as noted for the first and second floor apartments. The apartment appears to have limited closet space. Kneewalls in this apartment are approximately 4'6" high and the flat ceiling section is approximately 8' wide. Operable panels or hatches providing access to the space behind the kneewalls were not visible. The rear access door to the apartment was blocked with a large piece of furniture. The apartment has a dormered section in the middle of the South/East facing roof.

The kitchen of the third floor apartment did not have a range hood.

2. Discussion

Basement

Comment on Uninsulated Basement Approaches

The project team has asked BSC to comment on the approaches being considered by the project team. These include 1) air sealing and insulating the floor over the basement with a spray foam and cellulose application, and 2) insulating just the perimeter sill with SPF and then air sealing the separation between the basement and living space with targeted application of spray foam. The project team conveyed the impression that bringing the basement within the thermal enclosure would be prohibitively expensive.

Both of the proposed approaches of insulating the floor over the basement present performance concerns:

- Risk of elevated moisture and associated biological growth in the basement environment
- Inadequate separation between unconditioned, moisture-prone environment and living space
- Thermal losses from mechanical equipment.

The basement currently exhibits signs of bulk water intrusion. Open soil areas can be expected to contribute significant moisture through evaporation. Ground coupled assemblies will tend to have lower temperatures than surrounding air during summer conditions. This results in a tendency toward elevated relative humidity in spaces enclosed by ground-coupled assemblies. Insulating between the basement and living space and insulating the mechanical distribution in the basement will make the basement space generally colder than current conditions. This will tend to increase relative humidity in the space relative to current conditions.

Current conditions provide an undesirable environment for storage. It would be unacceptable to continue this use of the space with an increased moisture load.

It is our experience that framing cavity SPF application in a floor over a basement will not provide a robust air separation between the basement and the living space. A partial or spot application of foam sealant can be expected to be less effective than a full cavity SPF application. Use of the space will also contribute to air exchange between the basement and the living space and will also expose users to conditions of the basement environment.

Moisture and other contaminants would also be exchanged with the living space through leakage in forced air systems located in the basement and through use of a clothes dryer in the basement (filtering basement air through clothing in the dryer).

Even when the floor over the basement is thoroughly insulated against conductive losses to the basement, an uninsulated basement will contribute to thermal loads through exchange of air that takes place between the basement and the living space.

Comment on Insulated Basement Approaches

Bringing the basement into conditioned space provides for a better basement environment for storage, use and the inevitable air flow connection to living space. Providing a thermal enclosure for the basement space could also be done in such a way that it renders the basement a comfortable and useable space. The amenity value that this provides to the building and its users should not be overlooked.

Wall Insulation

Given the construction of the foundation wall, applying closed-cell spray foam would be the appropriate method of insulating the foundation walls and providing control of air flow through the foundation wall. Spray foam in the basement must be protected by a thermal barrier if the space is subject to uses other than access to utilities. ½ gypsum applied over 1-5/8" metal studs will provide an adequate thermal barrier. The metal stud support can be partially embedded in the SPF layer to provide additional rigidity to the gypsum but there should be at least 1" of SPF between the studs and the foundation wall.

Bulk water that passes through the foundation wall is managed by the closed-cell foam and then transitioned, at the bottom of the wall, to the floor drainage system. A screened drainage mat or rigid insulation board against the base of the wall can provide a gap through which water that leaks through the foundation wall can access the floor drainage system.

Insulation to the interior of foundation walls will create a challenge to adequate clearance at the access stairs. If closed cell SPF insulation cannot be applied to the interior of the foundation wall adjacent to the stair, then it would be important to re-point and re-parge this portion of wall to provide a measure of air flow control. Also, a ground roof should be installed to the exterior of the foundation wall in the vicinity of the stairs.

Basement Floor Insulation

Technically viable approaches for insulating the basement floor include:

1. Excavating the existing slab and some ground to install an insulated slab over gravel,
2. Insulating over the existing slab and providing drainage below the insulation and a floating floor above, and
3. Leaving the slab as is

The approach involving excavation of the existing slab will obviously incur the greatest cost of these three approaches. It will also provide for the most robust performance and provides the opportunity to increase the usability of the basement space by increasing the height of the space. Drainage and bulk water management is provided by the gravel layer, perimeter drain tile and a sump pump (in an air tight sump crock).

Insulating over the existing slab will require careful detailing of an air barrier above or at the insulation layer. The insulated floor system – consisting, for example, of a drainage mat, rigid insulation, and floating plywood subfloor – would be 2-3" in thickness. This reduction in head height would significantly compromise the usability of the space. In order for drainage across the top of the concrete slab to be effective, the concrete surface must be reasonably smooth and slope to a sump or to multiple sumps.

Leaving the slab as is would represent a compromise to the energy performance objectives. It will necessitate use of mechanical dehumidification in the basement. It will also preclude the placement or storage of moisture sensitive or cellulosic materials in contact with the floor. Bulk water management and drainage in this arrangement is provided by an interior perimeter drain (French drain) that is connected to a sump and air sealed (e.g. with concrete) from the basement space.

Mechanical Systems

The evaluation of mechanical system options considers the ability of the alternatives to efficiency and effectively provide:

- Heating,
- Water heating,
- Ventilation,
- Air mixing, and
- Cooling.

The project team had expressed an interest in consolidating mechanical equipment in order to reduce costs and allow for common utility expenses that could be cooperatively shared among the residents of the building. BSC considers multiple independent systems to offer advantages over a consolidated system approach. The decision between consolidated and multiple independent systems represents a major bifurcation of viable mechanical system approaches. The table below assembles some of the potential advantages and risks of each fundamental approach.

Table 1: Potential Advantages and Risks

	Consolidated System Approach		**Multiple Independent Systems**	
Criteria	Potential Advantage	Risk	Potential Advantage	Risk
Efficiency		DHW losses or recirculation energy	Higher efficiency equipment options, less distribution losses	
Cost	Possibly less costly depending upon ventilation strategy and contractor bids	Boiler installation can overwhelm cost of multiple equipment installation		Installation of combustion equipment in each apartment may increase total system costs
Feasibility	Simpler venting and fuel connections, primary systems located in basement	Hydronic Heating distribution to middle apartment may require spot demolition of walls and ceilings	Standard packaged components and standard installation	More vent penetrations, need to provide gas service to mechanical closet on 2nd and 3rd
Service/Repair Disruption		Heating and DHW both unavailable if boiler is down, lack of redundancy	Limited service disruption if equipment needs repair	More equipment to maintain
Flexibility in Billing Arrangements		Separate metering/billing complicated	Easily accommodates separate or consolidated billing	

Efficiency – Because of the inherent avoidance of distribution losses, and the ready availability of premium efficiency equipment, the multiple independent system approach would appear to offer advantages in efficiency. On the other hand, the consolidated system approach might afford the installation of a premium efficiency boiler that would rival the efficiency of distributed furnaces and water heating appliances.

Cost – Each fundamental approach offers a variety of options. It is not possible to generalize on the relative installation cost advantages of different configurations.

Feasibility – It would appear that the consolidated system approach involves few vent penetrations and avoids the need to run gas lines to 2nd and 3rd floor mechanical closets. It is also possible that the consolidated approach could represent greater implementation challenges if new hydronic heating distribution and separate ventilation distribution is installed.

Service and Repair Disruption – The consolidate system approach ties the heating and water heating functions of all apartments to a single combustion appliance[1]. While good quality boilers and pumps should operate reliably for many years, the consequence of a system failure could be significant. In the multiple independent systems approach, the equipment in one apartment can be taken off line without affecting the other apartments. Effects on the overall building conditions would be very minor is a system for a single apartment were to fail. The multiple independent systems approach, because it uses more heating and water heating appliances, will represent a greater amount of overall mechanical system maintenance. However, quality equipment properly installed would be expected to require relatively infrequent maintenance or repair.

Flexibility in Billing Arrangements - It is understood that the households within the building operate in a cooperative spirit and would prefer to share a single utility bill among the residents. The multiple independent system configurations do not preclude the use of a single gas meter or consolidated billing. However, the multiple independent system configuration is also conducive to separate service and billing. It is possible that metering could be retrofit to the consolidated system approach to allow for allocation of utility expenses among apartments but this would encounter complication, cost and possible legal issues.

[1] One variation to the consolidated approach would be to use the existing furnace serving the first floor until such time as this equipment needs replacement.

Below is a matrix of the mechanical equipment configurations considered in this evaluation. Following the table of configurations are tables that summarize the potential advantages and risks of possible configurations serving each of the mechanical system functions.

Table 2: Mechanical System Configurations

Mechanical System Functions					
Heating Source	Heating Distribution	Compatible DHW System	Compatible Ventilation System[2]	Ventilation and Mixing	Accommodation of Cooling[3]
	Consolidated System Approach				
Boiler (common)	Hydronic	Common storage tank	HRV with separate distribution	Possibly provided by HRV	No
	AHU / ducted	“	HRV	AHU fan cycling for minimum mixing	Yes
		“	Central-fan-integrated supply ventilation	“	Yes
	Multiple Independent Systems Approach				
Furnace (per apartment)	AHU / ducted	On-demand water heater (per apartment)	HRV	AHU fan cycling for minimum mixing	Yes
		“	Central-fan-integrated supply ventilation	“	Yes
On-demand water heater (per apartment)	Hydronic	“	HRV with separate distribution	Some mixing provided by HRV	No
	AHU / ducted	“	HRV	AHU fan cycling for minimum mixing	Yes
		“	Central-fan-integrated supply ventilation	“	Yes

[2] Ventilation systems would be separate systems serving each apartment.

[3] This represents whether the cooling function could be added to the same distribution system as use by the heating function.

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Mechanical System Function – Heating

System Configuration:	Central Boiler with Hydronic Distribution		Central Boiler with Ducted (forced air) Distribution		Individual Furnace (per apartment)	
Criteria	Potential Advantage	Risk	Potential Advantage	Risk	Potential Advantage	Risk
Efficiency				AHU with ECM may not be available Challenge to simultaneous obtain: • Adequate supply temperature • Condensing return temperature • Low pressure drop across coil	Reliable high efficiency condensing performance with variable speed and output.	
Cost	Simpler venting and gas connection	Boiler installation can overwhelm cost of multiple equipment installation Entails added expense for ventilation distribution, and mixing Need to add distribution for 1st and 2nd floor	Ducted distribution accommodates lower cost ventilation options Simpler venting and gas connection	Boiler installation can overwhelm cost of multiple equipment installation	Condensing, variable speed furnaces available at modest cost Ducted distribution accommodates lower cost ventilation options	Additional gas lines to mechanical closets
Feasibility	Simpler venting and fuel connections, primary systems located in basement	Hydronic Heating distribution to middle apartment may require spot demolition of walls and ceilings	Duct for first floor accommodated in basement	Duct work would need to be added to serve 2nd and 3rd floors	Duct for first floor accommodated in basement	Duct work would need to be added to serve 2nd and 3rd floors
Service/Repair Disruption		Heating and DHW both unavailable if boiler is down, lack of redundancy		Heating and DHW both unavailable if boiler is down, lack of redundancy	Limited service disruption if equipment needs repair	More equipment to maintain
Flexibility in Billing Arrangements		Separate metering/billing complicated		Separate metering/billing complicated	Easily accommodates choice of separate or consolidated billing	

Mechanical System Function – Heating (continued)

System Configuration:	Individual On-Demand Water Heater per apartment with Hydronic Distribution		Individual On-Demand Water Heater per apartment with Ducted (forced air) Distribution	
Criteria	Potential Advantage	Risk	Potential Advantage	Risk
Efficiency				AHU with ECM may not be available Challenge to simultaneous obtain: • Adequate supply temperature • Condensing return temperature • Low pressure drop across coil
Cost	Cost of large storage tank avoided	Entails added expense for ventilation distribution, and mixing Additional gas lines to mechanical closets Need to add distribution for 1st and 2nd floor	Ducted distribution accommodates lower cost ventilation options Cost of large storage tank avoided	Additional plumbing for hydro-air connection could overwhelm cost of direct-fired furnace connection Additional gas lines to mechanical closets
Feasibility		Hydronic Heating distribution to middle apartment may require spot demolition of walls and ceilings	Duct for first floor accommodated in basement	Duct work would need to be added to serve 2nd and 3rd floors
Service/Repair Disruption	Limited service disruption if equipment needs repair	More equipment to maintain	Limited service disruption if equipment needs repair	More equipment to maintain
Flexibility in Billing Arrangements	Easily accommodates choice of separate or consolidated billing		Easily accommodates choice of separate or consolidated billing	

Mechanical System Function – Water Heating

System Configuration:	Central Boiler and Storage Tank		Individual On-Demand Water Heater per apartment	
Criteria	Potential Advantage	Risk	Potential Advantage	Risk
Efficiency		Boiler may not achieve condensing efficiency in water heating Potential distribution losses or recirculation energy	Condensing models offer reliable high efficiency	
Cost	Cost of large storage tank and pumps may be less than installation of three distributed water heaters			Installation of three separate combustion appliances likely to cost more than installation of storage tank Connection to be made to apartment hot water supply line.
Feasibility	Hot water supply lines not altered. Hot water lines to readily accessible in basement	May want to add recirculation		Connections to apartment hot water supply may require opening wall or ceiling of 1st and 2nd floor apartments
Service/Repair Disruption	DHW unavailable in building if boiler is down		DHW available in other apartments if equipment needs repair	More equipment to maintain
Flexibility in Billing Arrangements		Separate metering/billing complicated	Easily accommodates choice of separate or consolidated billing	
Accommodation of Solar Water Heating	Solar storage tank as preheat tank to hot water storage tank. Circulator with thermostatic control between solar storage and hot water tank		Solar storage tank can be connected to existing hot water supply lines to provide hot water or pre-heating.	

Mechanical System Functions – Ventilation, Ventilation Distribution, and Mixing

System Configuration:	**HRV with Dedicated Distribution**		**HRV connected to Forced-Air Heating Distribution**		**Central-Fan-Integrated Supply Ventilation**	
Criteria	Potential Advantage	Risk	Potential Advantage	Risk	Potential Advantage	Risk
Efficiency	Thermal recovery	Additional fan energy	Thermal recovery	Additional fan energy	Makes use of heating (and cooling) fan use	Additional fan energy if distribution not used to provide cooling
Effectiveness		may not provide adequate air mixing	Good distribution and mixing if forced-air system operated with minimum cycling control		Effective distribution and mixing	
Cost		Dedicated distribution represents additional cost. HRV unit cost		HRV unit cost	Equipment and materials <$200/system	
Feasibility	Duct for first floor accommodated in basement	Duct work would need to be added to serve 2nd and 3rd floors Need to locate intake and exhaust	Uses heating distribution ductwork	Need to locate intake and exhaust	Uses heating distribution ductwork Only requires intake	

Note that exhaust-only ventilation is not recommended for this project due to the lack of control over ventilation air source and connection between apartments.

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3. Recommendations

Basement

The recommended approach for the basement is to insulate and condition this space. The walls are best insulated with 2" of a closed-cell spray foam protected behind ½" paperless gypsum board. Additional fiberglass or mineral wool insulation should be added between studs behind the gypsum board.

If closed cell SPF insulation cannot be applied to the interior of the foundation wall adjacent to the stair, then it would be important to re-point and re-parge this portion of wall to provide a measure of air flow control. Also, a ground roof should be installed to the exterior of the foundation wall in the vicinity of the stairs.

We appreciate that there are concerns about the global warming potential of blowing agents used in most closed-cell spray foam and encourage you to research closed-cell spray foams using non-HFC blowing agents.

The project should solicit pricing for the following basement slab approaches:

1. Excavation of the current slab and installation of a new insulated slab over gravel. This configuration is to include sub-slab drainage connected to a sump. The sump is to have an air tight lid. The sub slab drainage should be connected to a passive soil vent pipe extending through the building and out through the roof. Wall drainage must be connected to the sub-slab drainage system.
2. Excavation of a perimeter French drain connected to a sump. The sump is to have an air tight lid and the perimeter drain must have a robust air flow control layer such as concrete. The sub slab drainage should be connected to a passive soil vent pipe extending through the building and out through the roof. Wall system drainage must be connected to the perimeter drainage system.

The first option is the preferred performance option.

Note that the second option will require use of a dehumidifier in the basement. It will also preclude the placement or storage of moisture sensitive or cellulosic materials in contact with the floor.

Mechanical Systems

The recommended general approach to the mechanical systems is to provide independent systems to each apartment. Recommendations for providing the mechanical system functions to each apartment are as follows:

First Floor Apartment

Heating – Re-use the existing condensing furnace. The furnace can be replaced with a higher efficiency variable speed model when the current furnace ceases to function. The existing furnace should be supplied with a combustion air intake. Installing the intake at this time, with proper integration with the enclosure retrofit, will facilitate future installation of a high performance sealed-combustion furnace.

The duct system should be carefully evaluated for components that need replacement. If the return plenum is found to be inadequate, it should be reconstructed with a larger and air tight filter compartment. A canvas vibration isolation sleeve should also be added. The duct system should be cleaned and air sealed.

Water Heating – Gas-fired, sealed combustion, on-demand (tankless) water heater. If the water heater does not incorporate a buffer tank (as does Navien water heaters, for example), the design of the system should include a small buffer tank with a circulator pump controlled by the tank thermostat.

Ventilation, Ventilation Distribution, and Mixing – A central-fan-integrated supply (CFIS) ventilation system added to the heating distribution system would be the most cost effective ventilation approach for the first floor. See www.fancycler.com for a listing of equipment and suppliers.

An HRV with supply connected to the furnace return and exhaust drawing from either the bathroom and kitchen or bedroom would also provide acceptable performance, but at an increase equipment and installation cost.

Second Floor Apartment

Heating – Install a new gas-fired, sealed combustion condensing furnace in a mechanical closet constructed at the back of the large central closet. Routing the intake and exhaust through the roof is preferable if reasonably feasible. It appears that venting and intake may also be routed through the exterior wall of the closet toward the front as there are no windows at the front portion of this side wall.

Supply duct work can be accommodated in a dropped ceiling at the hallway and kitchen. This will provide an opportunity to improve the appearance of the ceiling in these areas. Supply registers should be placed high on walls. The return may be located above the door to the large central closet. A return air grille should be installed to provide a return air path from the bedroom.

Water Heating – Gas-fired, sealed combustion, on-demand (tankless) water heater. The owner may consider a condensing water heater for the owners unit. A condensing water heater will be more expensive but will offer efficiencies in the range of 0.93-0.95 EF. If the water heater does not incorporate a buffer tank, the design of the system should include a small buffer tank with a circulator tank controlled by the tank thermostat. Routing the intake and exhaust through the roof is preferable if reasonably feasible. It appears that venting and intake may also be routed through the exterior wall of the closet toward the front as there are no windows at the front portion of this side wall.

Ventilation, Ventilation Distribution, and Mixing – A CFIS ventilation system added to the heating distribution system would be the most cost effective ventilation approach for the second floor.

An HRV with supply connected to the furnace return and exhaust drawing from either the bathroom and kitchen or bedroom would also provide acceptable performance, but at an increase equipment and installation cost.

Third Floor Apartment

Heating – Re-use the existing hydronic distribution system. Hot water to be provided by an on-demand water heater through a heat exchanger. The on-demand water heater may be located in an enclosure over the second floor porch that is to be made useable in the renovation. This location is also near the location of the heating supply riser from the basement. The intake and exhaust should be routed through the roof if reasonably feasible.

The supply temperature should be set to at least 105F during the heating season to allow for proper functioning of the baseboard convectors. If the water heater is a condensing model, the supply temperature should also be low enough such that it will provide a high probability of return temperatures below 120F.

The addition of thermostatic radiator valves and radiator bypass piping will allow for more even heating of the apartment (or uneven when desired) and compensate for foibles in the sizing of the radiators relative to room loads.

Water Heating – Gas-fired, sealed combustion, on-demand (tankless) water heater also used for heating. A condensing water heater will be more expensive but will offer efficiencies in the range of 0.93-0.95 EF. The design of the system should include a small buffer tank for DHW with a circulator tank controlled by the tank thermostat. Routing the intake and exhaust through the roof is preferable if reasonably feasible.

Ventilation, Ventilation Distribution, and Mixing – Because the heating system makes use of the existing hydronic distribution, a separate ventilation distribution system is needed. A ducted HRV will provide ventilation, ventilation distribution and a small amount of mixing. The HRV may be located in the newly acquired space over the second floor porch or, possibly, in the bathroom. It appears that the space above the flat ceiling provides the most direct access for ventilation duct work to reach spaces throughout the apartment.

Appendix C

BUILDING LEAKAGE TEST

Date of Test: 2010_04_15	Technician: KN
Test File: 2010-04-15 Millbury_bsmt open CG	
Customer:	Building Address: 4 Shirley Ln Milbury, MA 01527

Test Results

1. Airflow at 50 Pascals: 2860 CFM (+/- 0.5 %)
   (50 Pa = 0.2 w.c.) 10.40 ACH

2. Leakage Areas: 326.3 in2 (+/- 2.5 %) Canadian EqLA @ 10 Pa
   183.6 in2 (+/- 3.9 %) LBL ELA @ 4 Pa

3. Minneapolis Leakage Ratio: 0.67 CFM50 per ft2 surface area

4. Building Leakage Curve: Flow Coefficient (C) = 286.7 (+/- 6.0 %)
   Exponent (n) = 0.588 (+/- 0.015)
   Correlation Coefficient = 0.99800

5. Test Settings: Test Standard: = CGSB
   Test Mode: = Depressurization
   Equipment = Model 3 Minneapolis Blower Door, S/N 4

Infiltration Estimates

1. Estimated Average Annual Infiltration Rate:

2. Estimated Design Infiltration Rate: Winter: 397.9 CFM
   1.45 ACH

   Summer: 167.1 CFM
   0.61 ACH

Cost Estimates

1. Estimated Cost of Air Leakage for Heating:

2. Estimated Cost of Air Leakage for Cooling:

BUILDING LEAKAGE TEST Page 2

Date of Test: 2010_04_15 Test File: 2010-04-15 Millbury_bsmt open CG

Building Conditions

Inside Temperature:	67 deg F	Heating Fuel:	Gas
Outside Temperature:	54 deg F	Heating Fuel Cost:	
# of Stories	2.0	Heating Efficiency:	
		Heating Degree Days:	5641
Wind Shield:	M	Cooling Fuel Cost:	
# of Occupants	2.0	Cooling SEER:	
		Cooling Degree Days:	275
# of Bedrooms:	2.0		
Volume:	16500 ft3	Ventilation Weather Factor:	1.07
Surface Area:	4278 ft2	Energy Climate Factor:	18.0
Floor Area:			
Design Winter Wind Speed:	18.0 mph	Design Winter Temp Diff:	61 deg F
Design Summer Wind Speed:	7.0 mph	Design Summer Temp Diff:	13 deg F

Comments

BUILDING LEAKAGE TEST   Page 3

Date of Test: 2010_04_15 Test File: 2010-04-15 Millbury_bsmt open CG

Data Points: Data Entered Manually

Nominal Building Pressure (Pa)	Fan Pressure (Pa)	Nominal Flow	Temperature Adjusted Flow	% Error	Fan Configuration	Baseline Std Dev (Pa)
-1.7	n/a					+/- 0.00
-45.0	224.3	2662	2629	-0.0	Ring A	
-61.1	41.9	3134	3095	-2.3	Open	
-75.1	57.5	3660	3615	0.8	Open	
-55.4	38.9	3025	2987	0.1	Open	
-49.2	33.2	2800	2765	-0.4	Open	
-44.8	31.2	2715	2681	2.2	Open	
-25.2	106.3	1850	1827	-0.5	Ring A	
-20.8	83.5	1644	1624	-0.2	Ring A	
-1.6	n/a					+/- 0.00

BUILDING LEAKAGE TEST

Date of Test: 2010_11_24	Technician: KN
Test File: 2010-11-24 Millbury_bsmt open	
Customer:	Building Address: 4 Shirley Ln Millbury, MA 01527

Test Results

1. Airflow at 50 Pascals: (50 Pa = 0.2 w.c.) — 576 CFM (+/- 4.0 %)
   2.03 ACH
2. Leakage Areas: — 76.8 in2 (+/- 15.6 %) Canadian EqLA @ 10 Pa
   47.2 in2 (+/- 26.2 %) LBL ELA @ 4 Pa
3. Minneapolis Leakage Ratio: — 0.13 CFM50 per ft2 surface area
4. Building Leakage Curve: — Flow Coefficient (C) = 84.3 (+/- 42.3 %)
   Exponent (n) = 0.491 (+/- 0.116)
   Correlation Coefficient = 0.92510
5. Test Settings: — Test Standard: = CGSB
   Test Mode: = Depressurization
   Equipment = Model 3 Minneapolis Blower Door, S/N 4

Infiltration Estimates

1. Estimated Average Annual Infiltration Rate:
2. Estimated Design Infiltration Rate:
   Winter: 102.3 CFM
   0.36 ACH
   Summer: 43.0 CFM
   0.15 ACH

Cost Estimates

1. Estimated Cost of Air Leakage for Heating:
2. Estimated Cost of Air Leakage for Cooling:

Date of Test: 2010_11_24 Test File: 2010-11-24 Millbury_bsmt open

Building Conditions

Inside Temperature:	67 deg F	Heating Fuel:	Gas
Outside Temperature:	54 deg F	Heating Fuel Cost:	
# of Stories	2.0	Heating Efficiency:	
		Heating Degree Days:	5641
Wind Shield:	M	Cooling Fuel Cost:	
# of Occupants	2.0	Cooling SEER:	
		Cooling Degree Days:	275
# of Bedrooms:	2.0		
Volume:	17000 ft3	Ventilation Weather Factor:	1.07
Surface Area:	4278 ft2	Energy Climate Factor:	18.0
Floor Area:			
Design Winter Wind Speed:	18.0 mph	Design Winter Temp Diff:	61 deg F
Design Summer Wind Speed:	7.0 mph	Design Summer Temp Diff:	13 deg F

Comments

Date of Test: 2010_11_24 Test File: 2010-11-24 Millbury_bsmt open

Data Points:

Nominal Building Pressure (Pa)	Fan Pressure (Pa)	Nominal Flow	Temperature Adjusted Flow	% Error	Fan Configuration	Baseline Std Dev (Pa)
1.0	n/a					+/- 0.46
-48.4	89.6	563	556	-0.2	Ring B	
-45.1	81.7	538	531	-1.2	Ring B	
-38.3	72.9	508	502	1.6	Ring B	
-31.3	64.6	478	472	6.0	Ring B	
-29.7	46.0	404	399	-7.8	Ring B	
-4.3	n/a					+/- 0.96

BUILDING LEAKAGE TEST

Date of Test: 2010_11_24 Technician: KN
Test File: 2010-11-24 Millbury_bsmt open duct sealed

Customer: Building Address: 4 Shirley Ln
Millbury, MA 01527

Test Results

1. Airflow at 50 Pascals: 458 CFM (+/- 0.9 %)
   (50 Pa = 0.2 w.c.) 1.62 ACH

2. Leakage Areas: 45.4 in2 (+/- 4.0 %) Canadian EqLA @ 10 Pa
   23.6 in2 (+/- 6.6 %) LBL ELA @ 4 Pa

3. Minneapolis Leakage Ratio: 0.11 CFM50 per ft2 surface area

4. Building Leakage Curve: Flow Coefficient (C) = 32.7 (+/- 10.5 %)
   Exponent (n) = 0.675 (+/- 0.029)
   Correlation Coefficient = 0.99732

5. Test Settings: Test Standard: = CGSB
   Test Mode: = Depressurization
   Equipment = Model 3 Minneapolis Blower Door, S/N 4

Infiltration Estimates

1. Estimated Average Annual Infiltration Rate:

2. Estimated Design Infiltration Rate: Winter: 51.1 CFM
   0.18 ACH

   Summer: 21.5 CFM
   0.08 ACH

Cost Estimates

1. Estimated Cost of Air Leakage for Heating:

2. Estimated Cost of Air Leakage for Cooling:

BUILDING LEAKAGE TEST Page 2

Date of Test: 2010_11_24 Test File: 2010-11-24 Millbury_bsmt open duct sealed

Building Conditions

Inside Temperature:	69 deg F	Heating Fuel:	Gas
Outside Temperature:	37 deg F	Heating Fuel Cost:	
# of Stories	2.0	Heating Efficiency:	
		Heating Degree Days:	5641
Wind Shield:	M	Cooling Fuel Cost:	
# of Occupants	2.0	Cooling SEER:	
		Cooling Degree Days:	275
# of Bedrooms:	2.0		
Volume:	17000 ft3	Ventilation Weather Factor:	1.07
Surface Area:	4278 ft2	Energy Climate Factor:	18.0
Floor Area:			
Design Winter Wind Speed:	18.0 mph	Design Winter Temp Diff:	61 deg F
Design Summer Wind Speed:	7.0 mph	Design Summer Temp Diff:	13 deg F

Comments

BUILDING LEAKAGE TEST Page 3

Date of Test: 2010_11_24 Test File: 2010-11-24 Millbury_bsmt open duct sealed

Data Points:

Nominal Building Pressure (Pa)	Fan Pressure (Pa)	Nominal Flow	Temperature Adjusted Flow	% Error	Fan Configuration	Baseline Std Dev (Pa)
1.2	n/a					+/- 0.07
-48.3	60.1	462	447	-0.2	Ring B	
-42.8	51.5	428	414	0.3	Ring B	
-38.2	43.1	392	380	-0.8	Ring B	
-33.6	38.2	369	357	1.7	Ring B	
-27.5	27.5	313	304	-1.1	Ring B	
-0.9	n/a					+/- 0.39

BUILDING LEAKAGE TEST

Date of Test: 05/12/2011 Test File: 2011-05-12 Millbury Test 2	Technician: Phil Kerrigan Cathy
Customer:	Building Address: 4 Shirley Avenue Millbury, MA

Test Results

1. Airflow at 50 Pascals: (50 Pa = 0.2 w.c.)	466 CFM (+/- 0.3 %) 1.65 ACH
2. Leakage Areas:	53.7 in2 (+/- 1.2 %) Canadian EqLA @ 10 Pa 30.4 in2 (+/- 1.9 %) LBL ELA @ 4 Pa
3. Minneapolis Leakage Ratio:	0.11 CFM50 per ft2 surface area
4. Building Leakage Curve:	Flow Coefficient (C) = 47.8 (+/- 3.1 %) Exponent (n) = 0.582 (+/- 0.008) Correlation Coefficient = 0.99958
5. Test Settings:	Test Standard: = CGSB Test Mode: = Depressurization Equipment = Model 3 Minneapolis Blower Door, S/N 4

Infiltration Estimates

1. Estimated Average Annual Infiltration Rate:

2. Estimated Design Infiltration Rate:	Winter:	65.8 CFM 0.23 ACH
	Summer:	27.6 CFM 0.10 ACH

Cost Estimates

1. Estimated Cost of Air Leakage for Heating:
2. Estimated Cost of Air Leakage for Cooling:

Date of Test: 05/12/2011 Test File: 2011-05-12 Millbury Test 2

Building Conditions

Inside Temperature:	69 deg F	Heating Fuel:	Heat Pump
Outside Temperature:	57 deg F	Heating Fuel Cost:	
# of Stories	2.0	HSPF:	
		Heating Degree Days:	5641
Wind Shield:	M	Cooling Fuel Cost:	
# of Occupants	2.0	Cooling SEER:	
		Cooling Degree Days:	275
# of Bedrooms:	3.0		
Volume:	17000 ft3	Ventilation Weather Factor:	1.07
Surface Area:	4278 ft2	Energy Climate Factor:	18.0
Floor Area:			
Design Winter Wind Speed:	18.0 mph	Design Winter Temp Diff:	61 deg F
Design Summer Wind Speed:	7.0 mph	Design Summer Temp Diff:	13 deg F

Comments

Test started at 1:40 PM. Minor winds
Basement door open, upstairs kneewall doors closed
NOTE: UPSTAIRS OUTSIDE AIR DUCT DAMPER WAS OPEN DURING THIS TEST

Date of Test: 05/12/2011 Test File: 2011-05-12 Millbury Test 2

Data Points:

Nominal Building Pressure (Pa)	Fan Pressure (Pa)	Nominal Flow	Temperature Adjusted Flow	% Error	Fan Configuration	Baseline Std Dev (Pa)
-0.5	n/a					+/- 0.08
-50.9	63.2	473	468	0.1	Ring B	
-45.9	56.1	446	441	0.3	Ring B	
-41.0	47.9	413	408	-0.8	Ring B	
-36.8	42.8	390	386	0.0	Ring B	
-30.4	34.0	348	344	0.1	Ring B	
-26.6	29.1	322	318	0.2	Ring B	
-1.0	n/a					+/- 0.43

BUILDING LEAKAGE TEST

Date of Test: 05/12/2011 Technician: Phil Kerrigan Cathy

Test File: 2011-05-12 Millbury Test 2a

Customer: Building Address: 4 Shirley Avenue
Millbury, MA

Test Results

1. Airflow at 50 Pascals: 402 CFM (+/- 0.8 %)
   (50 Pa = 0.2 w.c.) 1.42 ACH

2. Leakage Areas: 42.5 in2 (+/- 5.8 %) Canadian EqLA @ 10 Pa
   22.9 in2 (+/- 9.4 %) LBL ELA @ 4 Pa

3. Minneapolis Leakage Ratio: 0.09 CFM50 per ft2 surface area

4. Building Leakage Curve: Flow Coefficient (C) = 33.4 (+/- 14.9 %)
   Exponent (n) = 0.636 (+/- 0.040)
   Correlation Coefficient = 0.99612

5. Test Settings: Test Standard: = CGSB
   Test Mode: = Depressurization
   Equipment = Model 3 Minneapolis Blower Door, S/N 4

Infiltration Estimates

1. Estimated Average Annual Infiltration Rate:

2. Estimated Design Infiltration Rate: Winter: 49.6 CFM
   0.18 ACH

   Summer: 20.8 CFM
   0.07 ACH

Cost Estimates

1. Estimated Cost of Air Leakage for Heating:

2. Estimated Cost of Air Leakage for Cooling:

BUILDING LEAKAGE TEST   Page 2

Date of Test: 05/12/2011 Test File: 2011-05-12 Millbury Test 2a

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Building Conditions

Inside Temperature:	69 deg F	Heating Fuel:	Heat Pump
Outside Temperature:	57 deg F	Heating Fuel Cost:	
# of Stories	2.0	HSPF:	
		Heating Degree Days:	5641
Wind Shield:	M	Cooling Fuel Cost:	
# of Occupants	2.0	Cooling SEER:	
		Cooling Degree Days:	275
# of Bedrooms:	3.0		
Volume:	17000 ft3	Ventilation Weather Factor:	1.07
Surface Area:	4278 ft2	Energy Climate Factor:	18.0
Floor Area:			
Design Winter Wind Speed:	18.0 mph	Design Winter Temp Diff:	61 deg F
Design Summer Wind Speed:	7.0 mph	Design Summer Temp Diff:	13 deg F

Comments

Test started at 1:40 PM. Minor winds
Basement door open, upstairs kneewall doors closed

Date of Test: 05/12/2011 Test File: 2011-05-12 Millbury Test 2a

Data Points:

Nominal Building Pressure (Pa)	Fan Pressure (Pa)	Nominal Flow	Temperature Adjusted Flow	% Error	Fan Configuration	Baseline Std Dev (Pa)
0.3	n/a					+/- 0.11
-49.4	45.8	404	399	-0.4	Ring B	
-44.5	41.3	383	379	1.1	Ring B	
-39.6	34.3	350	346	-0.9	Ring B	
-34.4	29.2	323	319	0.2	Ring B	
0.2	n/a					+/- 0.19

Appendix D

ENERGY STAR VERSION 2 HOME VERIFICATION SUMMARY

Date:	March 22, 2011	Rating No.:	
Building Name:	25 Ellington Road	Rating Org.:	Conservation Services Group
Owner's Name:		Phone No.:	508.326.7506
Property:	25 Ellington Road	Rater's Name:	Nicholas Abreu
Address:	Somerville, MA	Rater's No.:	041
Builder's Name:			
Weather Site:	Boston, MA	Rating Type:	Projected Rating
File Name:	25 Ellington Road POST.blg	Rating Date:	3/30/10

Building Information

Conditioned Area (sq ft):	2743	Housing Type:	Multi-family, whole building
Conditioned Volume (cubic ft):	23487	Foundation Type:	Conditioned basement
Insulated Shell Area (sq ft):	6987	HERS Index:	53 *****+
Number of Bedrooms:	1		

Building Shell

Ceiling w/Attic:	None	Window/Wall Ratio:	0.09
Vaulted Ceiling:	R20 LDF+39,C U=0.017	Window Type:	U:0.19, SHGC:0.22
Above Grade Walls:	R14,FG3,4-16,+26A U=0.025	Window U-Value:	0.190
Found. Walls (Cond):	R20I R=20.0	Window SHGC:	0.220
Found. Walls (Uncond):	None	Infiltration:	Htg: 3.48 Clg: 3.48 ACH50
Frame Floors:	None	Measured Duct Leakage:	0.00 CFM25
Slab Floors:	Uninsulated slab U=0.365	Leakage to Outside:	0.00 CFM

Mechanical Systems

Heating:	Fuel-fired hydronic distribution, 105.0 kBtuh, 95.0 % EFF.
Water Heating:	Integrated, Gas, 0.86 EF.
Programmable Thermostat:	Heat=No; Cool=No

Note: Where feature level varies in home, the dominant value is shown.

This home MEETS OR EXCEEDS the EPA's requirements for an ENERGY STAR Home.

REM/Rate - Residential Energy Analysis and Rating Software v12.9

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ENERGY STAR HOME VERIFICATION SUMMARY

Date:	March 31, 2010	Rating No.:	
Building Name:	25 Ellington Road	Rating Org.:	Conservation Services Group
Owner's Name:		Phone No.:	508.326.7506
Property:	25 Ellington Road	Rater's Name:	Nicholas Abreu
Address:	Somerville, MA	Rater's No.:	041
Builder's Name:			
Weather Site:	Boston, MA	Rating Type:	Projected Rating
File Name:	25 Ellington Road.blg	Rating Date:	3/30/10

Building Information

Conditioned Area (sq ft):	2743	Housing Type:	Multi-family, whole building
Conditioned Volume (cubic ft):	23487	Foundation Type:	Unconditioned basement
Insulated Shell Area (sq ft):	6180	HERS Index:	130 ***+
Number of Bedrooms:	1		

Building Shell

Ceiling w/Attic:	R19,FG3,X-16 U=0.086	Window/Wall Ratio:	0.09
Vaulted Ceiling:	R19,FG3,6-16,C U=0.074	Window Type:	Double - Wood
Above Grade Walls:	R11,FG3,4-16 U=0.104	Window U-Value:	0.490
Found. Walls (Cond):	None	Window SHGC:	0.580
Found. Walls (Uncond):	Uninsulated	Infiltration:	Htg: 16.51 Clg: 16.51 ACH50
Frame Floors:	R0,X-16 U=0.299	Measured Duct Leakage:	RESNET/HERS default
Slab Floors:	None	Leakage to Outside:	RESNET/HERS default

Mechanical Systems

Heating:	Fuel-fired air distribution, 82.0 kBtuh, 80.0 AFUE.
Heating:	Fuel-fired air distribution, 60.0 kBtuh, 92.0 AFUE.
Heating:	Fuel-fired hydronic distribution, 100.0 kBtuh, 83.0 % EFF.
Water Heating:	Conventional, Gas, 0.60 EF.
Water Heating:	Conventional, Gas, 0.60 EF.
Water Heating:	Conventional, Gas, 0.63 EF.
Programmable Thermostat:	Heat=No; Cool=No

Note: Where feature level varies in home, the dominant value is shown.

This home DOES NOT MEET the EPA's requirements for an ENERGY STAR Home.

REM/Rate - Residential Energy Analysis and Rating Software v12.71

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Appendix E

Questionnaire on the Energy Us and Comfort of Your Home

PLEASE COMPLETE AND RETURN THIS QUESTIONNAIRE WITHIN 4 DAYS w

This short questionnaire is designed to help us understand the energy use within your home as part of a home energy study sponsored by the U.S. Department of Energy. It will be used in conjunction with an analysis of your utility bills. Your name will be kept confidential and will not appear in publications of the results of this study.

How many people are currently living in your apartment? ***[Please type an "x" for one response.] w***

1
2
3
4
5
6
More than 6 - Please enter the number of people living in your apartment: ______

How many television sets do you have? ***[Please type an "x" for one response.] w***

1 ***w***
2
3
4
5
6
More than 6 - Please enter the number of television sets: ______

How many desktop computers do you have? ***[Please type an "x" for one response.] w***

1
2
3
4
5
6
More than 6 - Please enter the number of desktop computers in your home: ______

Is there generally someone at home all day on the weekdays? ***[Please type an "x" for one response.] w***

Yes
No

At what temperature do you set your thermostat during the day ***in the winter***?
[Please type an "x" for one response.] w

68oF
69oF
70oF
71oF
72oF
73oF
74oF
Other – Please enter your thermostat setting: _____oF

At what temperature do you set your thermostat during the day ***in the su er***?
[Please type an "x" for one response.] 73$_o$F

- 74$_o$F
- 75$_o$F
- 76$_o$F
- 77$_o$F
- 78$_o$F
- 79$_o$F
- Other – Please enter your thermostat setting: _____$_o$F

Do you change your thermostat settings at night?

- Yes
- No

Do you use natural ventilation (opening windows at night) to avoid air conditioner and ventilation system use?

- Yes
- No

Please indicate if you have any of the following items in your home or yard:

Second refrigerator

If you know the approximate model year, please enter it here ___

Independent freezer (not part of a refrigerator)

Plasma TV

Microwave oven

Cable or satellite TV control box

Dehumidifier

Whole house fan (attic fan)

Heated waterbed

Window air conditioner

If checked, please indicate how many window air conditioners there are in your home: ___

Portable electric heaters

If checked, please indicate how many portable electric heaters you use in your home: ___

Aquarium

If you know the number of gallons, please enter it here: ___

Ceiling fans

If checked, please indicate how many ceiling fans are in your home: ___

Hot water circulation pump

PLEASE USE THE SPACE BELOW TO TELL US OF ANY POTENTIALLY HIGH ENERGY USES IN YOUR HOME. Examples include a welding or woodworking shop, a large number of grow lights for houseplants, an electric car, and a hobby that requires electricity or natural gas.

Please indicate the extent to which you agree or disagree with the following statements.
[For each statement, p ease put parenthesis ( ) around one response.]

	Stron ly Stron ly D sa ree	D sa ree i	Neutral/ Unsure	A ree	i Agree
1. My home was comfortable in winter before the retrofit.	1	2	3	4	5
2. My home was comfortable this past winter (after the retrofit).	1	2	3	4	5
3. My home was comfortable on warm/hot days before the retrofit	1	2	3	4	5
4. My home is comfortable on warm/hot days (after the retrofit).	1	2	3	4	5
5. My home sometimes feels "stuffy."	1	2	3	4	5
If you answered "strongly agree" or "agree," during what season does this occur? __________					
6. All rooms in my home are equally comfortable.	1	2	3	4	5
7. I am satisfied with the overall comfort of my home.	1	2	3	4	5
8. My home has low utility bills for its size.	1	2	3	4	5
9. The HVAC control systems in my home are easy to operate.	1	2	3	4	5
10. I am satisfied with my home overall.	1	2	3	4	5
11. The low energy features of my home are important to me.	1	2	3	4	5

PLEASE USE THE SPACE BELOW FOR ANY FURTHER COMMENTS YOU HAVE ABOUT

YOUR HOME.

THA YOU FOR PARTICIPATING IN THIS STUDY!

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DOE/GO-102011-3457 ▪ December 2011

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