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The Performance House—A Cold Climate Challenge Home

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Consortium for Advanced Residential Buildings

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Building America
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The Performance House—A Cold Climate Challenge Home

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Definitions

ACH50	Air changes per hour at 50 Pascal
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
BA	Building America
BEopt	Building Energy Optimization
Btu	British thermal unit
CARB	Consortium for Advanced Residential Buildings
ccSPF	Closed-cell spray polyurethane foam
CFL	Compact fluorescent lamp
cfm	Cubic feet per minute
DOE	U.S. Department of Energy
EDB	Entering dry-bulb (temperature)
EF	Energy factor
EPA	U.S. Environmental Protection Agency
ERV	Energy recovery ventilator
EWT	Entering water temperature
gpm	Gallons per minute
HVAC	Heating, ventilation, and air conditioning
IAP	Indoor air package
IECC	International Energy Conservation Code
kW	Kilowatt
LDB	Leaving dry-bulb (temperature)
LED	Light-emitting diode
LFL	Linear fluorescent lamp

LWT	Leaving water temperature
MERV	Minimum efficiency reporting value
PV	Photovoltaic
RESNET	Residential Energy Services Network
SEER	Seasonal energy efficiency ratio
SHGC	Solar heat gain coefficient
SIR	Savings to investment ratio
TC	Total capacity
TERC	Thermal Enclosure Rater Checklist
VOC	Volatile organic compound
XPS	Extruded polystyrene foam

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Executive Summary

Working with builder partners on test homes allows for vetting of whole-house building strategies to eliminate any potential unintended consequences prior to implementing these solution packages on a production scale. To support this research, the Consortium for Advanced Residential Buildings partnered with Preferred Builders Inc. on a high performance test home in Old Greenwich, Connecticut. The philosophy and science behind the 2,700 ft^2 "Performance House" were based on the premise that homes should be safe, healthy, comfortable, durable, efficient, and adapt with the homeowners. The technologies and strategies used in the "Performance House" were not cutting-edge, but simply "best practices practiced." The focus was on simplicity in construction, maintenance, and operation. When seeking a 30% source energy savings targets over a comparable 2009 International Energy Conservation Code-built home in the cold climate zone, nearly all components of a home must be optimized. Careful planning and design are critical.

To maintain the constructability of the home design, the following specifications were deemed ideal solutions for this project:

- Exterior insulation was limited to 1.5 in. extruded polystyrene so that finishing details around windows and doors didn't need to extensively change and cladding warranty issues were avoided.
- Rather than going to a more expensive flash-and-batt cavity insulation strategy to air seal the framing, a spot applied low-expanding spray foam system was used to air seal the wood joints prior to the wall cavities being filled with dense-packed blown insulation.
- Closed-cell spray polyurethane foam (ccSPF) was strategically used to air seal and provide a vapor barrier at the rim/band joists, foundation walls/slab, and roof deck. These are key transition points for maintaining continuous thermal, air, and moisture barriers across the entire building shell.
- To meet code requirements of a thermal or ignition barrier over the ccSPF exposed in the attic, exposure-rated foil-faced fiberglass batts were installed against the ccSPF and inset stapled to the rafters.
- The energy recovery ventilator was installed with its own dedicated distribution system to reduce the complexity of integrating with the central distribution system and minimize energy consumption associated with whole-house ventilation.
- As space cooling loads are not significant in this climate zone, single-stage seasonal energy efficiency ratio 16 air conditioners were selected. The controls for two-stage systems can be complicated and are often not properly installed or commissioned.
- For the heating equipment a modulating condensing boiler was selected to provide both space and water heating. This allowed for better matching of the building's heating loads. Specific attention does need to be allocated during the design and commissioning processes to ensure that hydro-coil return water temperatures to the boiler are below 130°F (low enough to promote condensation of combustion vapors), so that high system efficiencies are achieved.

To help builders and architects seeking to match the performance of this home, a step-by-step guide through the building shell components of the U.S. Department of Energy's Challenge Home (DOE 2012) are provided in a pictorial story book. The end result was a Challenge Home that achieved a Home Energy Rating System Index Score of 20 (43 without photovoltaics, the minimum target was 55 for compliance). This home was also awarded the 2012 HOBI for Best Green Energy Efficient Home from the Home Builders & Remodelers Association of Connecticut and one of three winners in the Connecticut Zero Energy Challenge (2012).

For this home, achieving 30% source energy savings while maintaining traditional systems and comforts expected by homeowners was past the point of diminishing returns on investment (based solely on the annualized energy related costs: the increase in mortgage related to incremental first costs for the efficiency measures and associated savings in future utility bills) at current market costs. Another cost metric that is used in assessing energy improvements is the savings-to-investment ratio (SIR). The SIR for the solution package without solar photovoltaics (over a 15-year savings period) was only 0.29, so from a purely energy efficiency perspective, this solution package is not cost-neutral (i.e. equal to one). If the solar electric system is included as part of the overall package, the SIR was 0.52. In this case, the solutions package with solar is still not cash positive. If state efficiency incentives are included in the cost analysis, the SIR increases to 0.34 without solar and 0.82 with solar.

The "Performance House" demonstrates how a home can be designed and constructed in the cold climate zone to be energy efficient, low maintenance, sustainable, and comfortable. Lower price premiums are still needed for solutions such as ccSPF and light-emitting diodes, but this is anticipated as their market demand increases. For a solution package of this level to become commercially viable, there is still a need to improve the home appraisal process to better value the multiple benefits of a solution package of this type over standard builder practices.

1 Introduction

The objectives of test home evaluations are to demonstrate and document the viability of market-ready systems at an initial prototype scale that improve the energy efficiency of new construction homes to levels that are 30% better (excluding on-site generation) than the Building America (BA) House Simulation Protocols Benchmark home. The BA Benchmark is "consistent with the 2009 International Energy Conservation Code (IECC), with additional definitions that allow the analyst to evaluate all residential end uses consistent with typical homes built in 2010" (Hendron and Engebrecht 2010). Through these demonstrations, important information is obtained on the costs to implement and gaps requiring additional research are often identified. In addition, these projects provide valuable data on the commercial viability of "best in class" residential energy efficiency solution packages. These homes typically incorporate a combination of recently released new technologies or new building techniques to allow for evaluation of market readiness and suitability.

Working with builder partners on test homes allows for vetting of whole-house building strategies to ensure that there are no unintended consequences prior to implementing these solution packages on a production scale. In addition, these test homes provide an opportunity to work with the builder and contractors on formalizing scopes of work, trade sequencing, guidance documentation, etc. This information is critical prior to moving to a production scale level as community build-outs can have multiple supervisors and contractors that need to have clearly defined roles and expectations of their tasks prior to construction.

To support this research, the Consortium for Advanced Residential Buildings (CARB) has partnered with Preferred Builders Inc. on a high performance test home located at 23 Brown House Road in Old Greenwich, Connecticut. The existing 1,100 ft^2 home on this property was in very poor condition and therefore removed. During this process, as many materials as practical were recycled. Once demolition was completed, work began on the 2,700 ft^2 "Performance House." The philosophy and science behind the "Performance House" were based on the premise that homes should be safe, healthy, comfortable, durable, efficient, and adapt with the homeowners.

Figure 1. This 1970s home was taken down to make way for the "Performance House"

(Preferred Builders Inc.)

Recent BA research on new construction homes in the cold climate region has focused on high-R wall assemblies and ductless heating, ventilation, and air conditioning (HVAC) systems (Aldrich 2012; Stecher and Allison 2012a; Stecher et al. 2012b). The whole-house building approach of this project focused on optimizing more typical builder practices to provide energy efficiency while simplifying the construction, maintenance, and operation of the home. Though these building specifications will still be pushing builders to the next level, it will not be a completely new way of doing things. By taking this approach, it is believed that greater and quicker market adoption can be achieved.

2 Research Goals

The primary questions addressed by this research were:

- What solution package can be readily implemented in a cold climate home to achieve 30% greater energy savings compared to the BA House Simulation Protocols for new construction?
- Is that solution package commercially viable? Where are opportunities to reduce costs in this solutions package?
- What are the major gaps to achieving this solution package at a production scale (cost, risk adversity, implementation complexity, etc.)?

In addition to these primary whole-house research questions, CARB performed a short-term evaluation of the hydro-coil heat system. Recent research by NorthernSTAR, another BA research team, has shown that to get higher air temperatures with low return water temperatures (to maximize condensing efficiency) for hydro-air space heating, standard configurations needed to be altered. It seems that standard manufacturer equipment configurations only result in return water temperatures equal to supply air temperatures. NorthernSTAR's design preference, based upon its research, is for hot water tanks providing both space and water heating (i.e. when compared to tankless water heaters and combi-boilers) (Schoenbauer et al. 2012). Still, combi-boilers are becoming the industry norm for these hydro-air installations, so further evaluation of this configuration is warranted. The goal of this testing was to answer the following research questions:

- How does the hydro-coil system used in this test home compare to manufacturer's rated performance (capacity and water/air temperatures)?
- Does the condensing boiler supplying the heat to the hydro-coil system achieve suitable return temperatures to actually condense?

3 Research Method

When approaching a 30% source energy savings targets, nearly all components of a home must be optimized. Therefore, a builder needs to take a holistic view to ensure that each component of a building works together properly for maximum performance. The technologies and strategies used in the "Performance House" are not cutting edge, but simply "best practices practiced." The focus was on simplicity in construction, maintenance, and operation. An overview of the design process for this home is presented below. In addition, Section 4 includes a step-by-step photo timeline of the construction process for others who are interested in achieving comparable performance levels to this test home.

> "Building science is a big part [of the design process], especially with new products that have come out. Everything needs to be compatible with each other," the builder explained. "It starts by design and planning well before construction begins when you are building a home that is so airtight and energy-efficient."
>
> – Peter Fusaro (Source: Shea 2012)

Careful planning and design are critical. The biggest successes happen when the design team works with the builder, HVAC contractor, third-party verifier, and owner to solve potential conflicts before they are built.

3.1 Design Specifications and Energy Modeling

The test home was modeled in an hourly energy simulation tool to investigate the effect of various energy saving measures to be recommended. CARB analyzed the building performance in BEopt™ (Building Energy Optimization version 1.3), a software produced by the National Renewable Energy Laboratory (Christensen et al. 2004) that provides capabilities to evaluate residential building designs and identify cost-optimal efficiency packages at various levels of whole-house energy savings along the path to net-zero energy capable homes. For the economic analysis, the economic values in Table 1 were used per the BA House Simulation Protocols requirements (Hendron and Engebrecht 2010). Economic analysis at a 4% loan interest rate is also discussed.

Table 1. Inputs of Economic Analysis

Economic Variables	Modeling Inputs
Project Analysis Period	30 years
Inflation Rate	3.0%
Discount Rate (Real)	3.0%
Loan Period	30 years
Loan Interest Rate	7.0%
Electricity Rate*	$0.1846/kWh + $8.00 monthly charge
Natural Gas Rate*	$1.347/therm + $8.00 monthly charge
Fuel Escalation Rate	0.0%

* State average for Connecticut

Though sophisticated technologies and strategies are available to achieve a high-efficiency home, the goal of this project was to optimize those systems that a builder could easily incorporate into current building practices. To that end, the following strategies were used when determining the design specifications.

- Exterior insulation was limited to 1.5 in. extruded polystyrene (XPS) so that finishing details around windows and doors didn't need to extensively change and cladding warranty issues were avoided (several major manufacturer installation guidelines limit thickness of exterior insulation under cladding to 1.5 in., unless furring strips are used).
- Rather than going to a more expensive flash-and-batt cavity insulation strategy to air seal the framing, Owens Corning's Energy Complete system was used to air seal the wood joints prior to the wall cavities being filled with dense-packed blown insulation.
- Closed-cell spray polyurethane foam (ccSPF) was strategically used to air seal and provide a vapor barrier at the rim/band joists, foundation walls/slab, and roof deck.
- To meet code requirements of a thermal or ignition barrier over the ccSPF exposed in the attic, exposure-rated foil-faced fiberglass batts were installed against the ccSPF and inset stapled to the rafters.
- The energy recovery ventilator (ERV) was installed with its own dedicated distribution system to reduce the complexity of integrating with the central distribution system and minimize energy consumption associated with whole-house ventilation.
- As space cooling loads are not significant in this climate zone, single-stage seasonal energy efficiency ratio (SEER) 16 air conditioners were selected. The controls for two-stage systems can be complicated and are often not properly installed or commissioned.
- For the heating equipment a modulating condensing boiler was selected to provide both space and water heating. This allowed for better matching of the building's heating loads.

Minimizing building loads (through improvements to the thermal envelope and reducing building infiltration) and improving the indoor environmental quality were key focuses in this project. Indoor environmental quality encompasses indoor air quality (airborne contaminants) and other health, safety, and comfort issues. In addition to energy efficiency, there was a desire to make a home that was sustainable and required as minimal maintenance as possible. CARB took a base specification based on these projects goals and then performed additional optimization analysis to evaluate modifications for the final building specifications. The following variations to the building specifications were investigated:

- Above-grade wall assembly
    - R-21 wall cavity insulation
    - R-21 wall cavity insulation + 1 in. of XPS foam on exterior
    - R-21 wall cavity insulation + 1.5 in. of XPS foam on exterior
    - R-21 wall cavity insulation + 2 in. of XPS foam on exterior

- Attic assembly
    - Vented attic with R-49 blown insulation at ceiling plane
    - Vented attic with R-60 blown insulation at ceiling plane
    - Unvented attic with R-38 ccSPF + 3.5 in. batts (R-13) at roof deck
- Foundation assembly
    - R-10 rigid interior
    - R-20 rigid interior
    - ¾ in rigid exterior (R-5) and 3 in. ccSPF interior (R-20)
- Building infiltration
    - 1.0–5.0 ACH50, in increments of 1
- Cooling system
    - SEER 14, 16, 18 (two-stage), and 21 (two-stage)
- Ductwork
    - 4%, 7.5%, and 15% leakage fraction
- Water heater/boiler
    - Gas premium (0.67 energy factor [EF])
    - Gas tankless (0.82 EF)
    - Gas condensing tankless (0.96 EF)
- Solar photovoltaics (PV)
    - None, 2.5–7.5 kW (in 1-kW increments).

The inclusion of an unvented attic strategy was due to zoning restrictions by the town of Greenwich. For the R-7 zone, the town has a floor area ratio allotment of 36% of the lot size. For this project, that equates to 2,705 ft^2. The garage counts in the square footage because people can convert it into living space, which would put it over the allowable square footage. The basement does not count because it is below grade. The floor area ratio of the design home was 2,693 ft^2 without the attic. Due to the height of the structure being just less than 35 feet, the town considers the attic as a possible third floor and was counting it as additional square footage, pushing the builder over the floor area ratio allotment. To remedy this problem with the town, it was decided to go with a roof system that was framed in a manner to prevent future conversion of the attic into living space. This was done through the use of varied vaulted ceilings for the second floor and several structural cross members to block potential clear paths in the attic.

Figure 2 shows the BEopt optimization iterations (and least-cost optimization curve), the selected CARB solution package, and the least-cost optimization point (referenced by the arrow) achieving similar source energy savings as the BA design. It should be noted that there are input limitations of the BEopt software that result in solution packages that are not realistic (due to it not having the ability to do “component based infiltration” improvements). Therefore, two optimizations were run and combined in post-processing. For the optimization analysis, all costs are those provided in BEopt or extrapolations from similar specifications within BEopt. The cost analysis provided in Section 6 is based on the builder's actual costs, but as we don't have revised costs for all the measures that were selected in the optimization analysis, the costs of the design specification was not revised from the library values within BEopt.

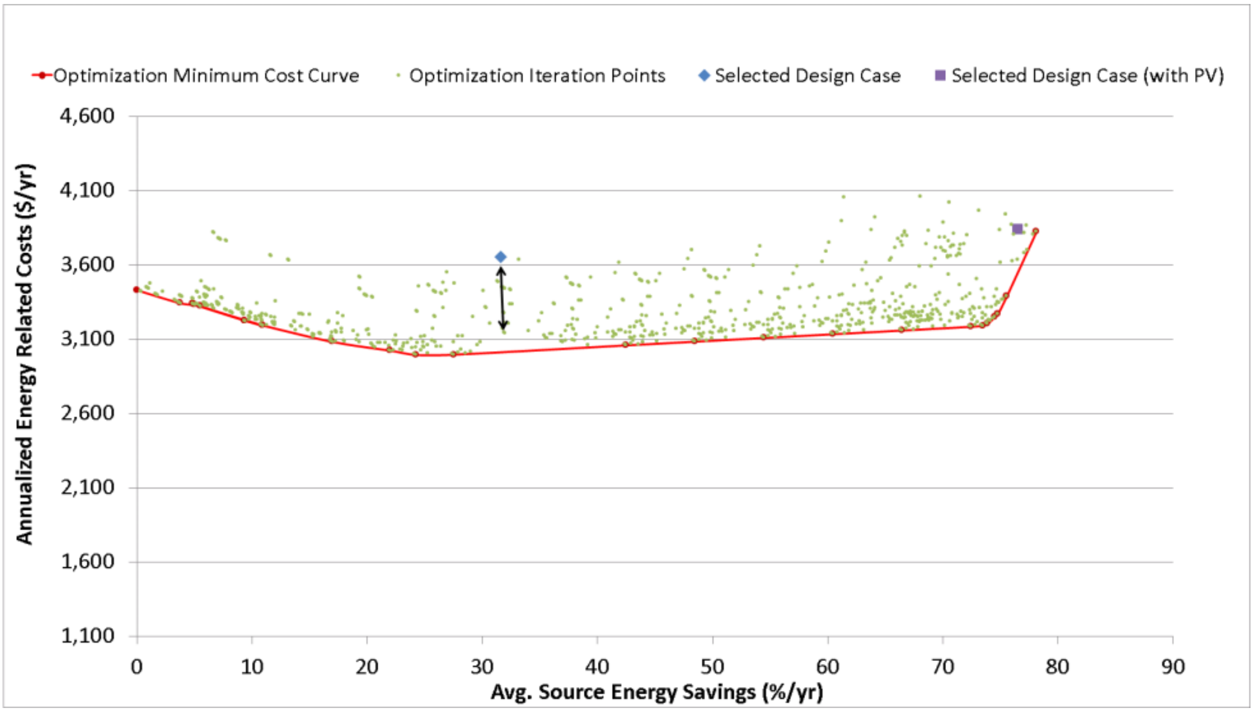

Figure 2. Optimization curve from BEopt[1]

The final CARB recommended specification that is projected to achieve 30.9% energy savings is provided in Table 2. Based solely on annualized energy-related costs (increased mortgage cost for the efficiency measures and reduced utility bill costs), the design case ($3,652/yr) would appear not to be cost beneficial compared to other alternatives (code: $3,422/yr; least-cost with equivalent energy savings: $3,145/yr). If a 4% loan interest rate is assumed, the design case annualized energy-related cost drops 8.7% to $3,334.

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[1] The selected design is located above the optimization iteration points because of the way that the BEopt optimization process functions. The optimization process works by iteratively and selectively searching for combinations of design alternatives which are the most cost effective option at a particular savings mark. These optimal combinations are then connected to form the least-cost optimization line. During this selection process, the algorithm also identifies "some near optimal alternative designs" (Christensen et al. 2004). However, the generated selection of near-optimal points does not serve as a comprehensive gathering of all possible permutations. This is done to minimize analysis run time. As a result, several options, including the design case, was not generated as a point in the optimization process.

Table 2. Final Building Specifications Summary

Component	BA Recommended Specification
Foundation Assembly	Poured concrete foundation with exterior ¾-in. drainage board (R-3) over waterproof barrier and ccSPF on the interior wall (R-20) and under the slab (R-13)
Above-Grade Wall Assembly	1.5 in. of XPS (R-7.5) over sheathing, spray foam air sealing of wall cavities, and blown cavity insulation (R-21)
Ceiling/Attic Assembly	Unvented attic with 5.5 in. ccSPF (R-36) plus 3.5 in. foil-faced fiberglass batt (R-13), cool roof shingles (SRI-29)
Window Glazing	Dual pane, low-e windows with vinyl frame (U-0.28/SHGC[a]-0.27)
Infiltration	1.0 ACH50
Ventilation	ERV with carbon dioxide override control
Cooling System	Two 1.5-ton split-system air conditioners (SEER 16)
Heating System	Two hydro-coils with variable-speed fan coils to each provide 24 kBtu/h capacity (heat supplied by boiler). Radiant floor in basement.
Ductwork	Ducts located in finished space; less than 2 cfm/100 ft^2 total leakage
Water Heating	Natural gas wall-mounted boiler (96% annual fuel utilization efficiency)
Lighting	CFL[b]-LED[c]-LFL[d] = 0% – 90% – 10%
Appliances	ENERGY STAR® refrigerator, dishwasher, clothes washer, and exhaust fans
Site Generation	7.44 kW roof-mounted PV system

[a] Solar heat gain coefficient
[b] Compact fluorescent lamp
[c] Light-emitting diode
[d] Linear fluorescent lamp

Comparing the BA-recommended solutions package to the least-cost optimization curve, there is no point on the curve that falls directly under the BA proposed package. There is a lower cost option with nearly the same percentage energy savings. The difference between the BA-recommended specifications and this point is provided in Table 3.

Table 3. BA Solution Package Comparison to Least-Cost Package with Similar Energy Savings

Component	BA Solution Package	Least-Cost Package With 30% Energy Savings
Cooling System	SEER 16, single stage	SEER 21, two stage
Lighting	CFL-LED-LFL = 0% – 90% – 10%	CFL-LED-LFL = 21% – 0% – 13%

This lower cost alternative was not selected for the following reasons:

- As mentioned earlier, the controls for two-stage systems can be complicated and are often not properly installed or commissioned. As space cooling loads are not significant in this climate zone, single-stage SEER 16 air conditioners were selected to minimize first cost and simplify the mechanical systems.
- Substituting LEDs for CFLs (cost in $\$/ft^2$) is a very high cost premium even though the savings aren't significant. The advantages of LEDs are their instant-on (versus a warmup

period for CFLs), higher lumens per Watt, longer life expectancy (~50,000 hours versus ~8,000 hours for a CFL), easy disposal (no mercury), and ability to be effectively dimmed. LEDs are still a fairly recent technology, so costs are still fairly high. With greater market adoption, it is anticipated that the cost of LED lighting will continue to reduce drastically (Rowlands-Rees 2011).

Figure 3 shows the cumulative percentage energy savings (line graph) resulting from adding each improvement measure and the impact on the whole-house source energy use (bar graph). The air sealing and increased thermal performance of the building shell associated with the ccSPF application realized the highest energy savings. As the source energy savings goals continue to increase, it becomes ever more difficult as lighting, appliances, and miscellaneous electric loads become a larger portion of the overall energy consumption. In this particular case, lighting, appliances, and miscellaneous electric loads increased from 36% to 45% of the overall total. With ENERGY STAR appliances and LEDs already specified, there is little that a builder can incorporate to minimize the loads with today's available products.

Comparison to Existing 1970s Home

Interestingly enough, when comparing the newly built home (without PV) to the original, smaller 1970s home, the new home is predicted to use 33.4% less source energy. This is primarily due to the 1970s home having electric baseboard heating. In addition, the site to source multiplier of 3.365 for electric energy consumption versus 1.092 for natural gas consumption makes the new construction home more favorable by this metric.

Looking at it from an operational cost perspective, the annual utility bills for the 1970s home are predicted to be $1,089 less than the newly built home (without PV). If PV is included in this analysis, the newly built home is predicted to have utility savings of $625 over the 1970s home.

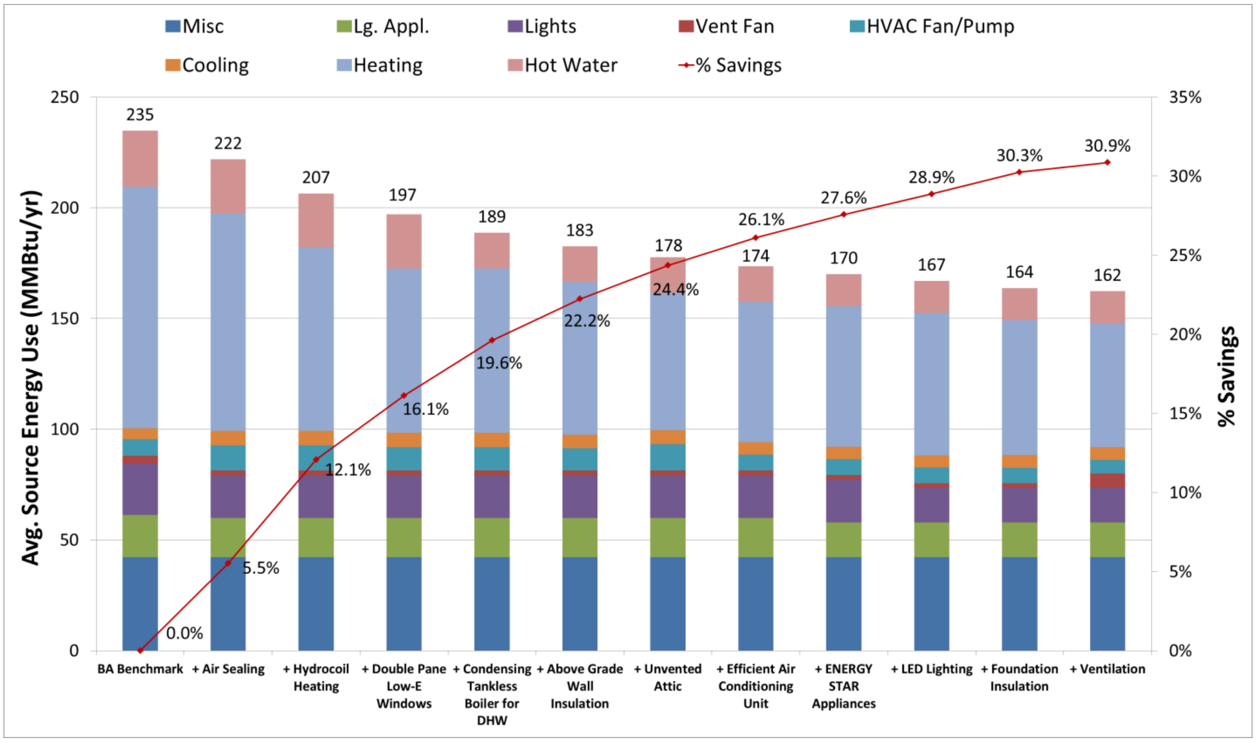


Figure 3. Cumulative contribution to total energy savings by measure and end use

3.2 Additional Design Considerations

In terms of water conservation, numerous design specifications were integrated into this project. They included on-site storm water management, an irrigation system with weather station controller (Figure 4), and low-flow toilets, showerheads, and faucets. To minimize hot water waste, a two-trunk structured plumbing configuration was used (Appendix) and an on-demand recirculation system (Figure 5) was installed for use in the bathrooms, kitchen, and laundry room.

Figure 4. (L) Gallery system for gutter rainwater; (R) irrigation weather station

(Preferred Builders Inc.)

Figure 5. On demand pump under a bathroom sink

(Preferred Builders Inc.)

To allow the home to age with the occupants, a first-floor bedroom was incorporated into the floor plan layout. This bedroom was designed to be Americans with Disabilities Act compliant. The accessibility design started at the front entry of the home, which was constructed to have a level walk-in to allow easy access for wheelchairs. The design continued to the first-floor bedroom bath, which includes a 60-in. turning diameter circle, an accessible vanity sink, and a roll-in shower, as shown in Figure 6.

Figure 6. Wheelchair accessible vanity and roll-in shower

(Preferred Builders Inc.)

In an effort to better educate the occupants, a whole-house electric monitoring system, E-Monitor by PowerDynamics, was installed in the home. This allows for detailed electrical monitoring of every electrical breaker circuit in this home. This provides the homeowners potentially valuable feedback on how they consume energy. But as noted in past studies, feedback devices may not save energy (Darby 2006). It is up to the homeowner to act based upon the information they receive. The homeowner may choose not to change his or her behavior at all, may change for a short period (while the novelty of the feedback device is new), and then revert back to old habits, or may permanently change the behavior. Without knowing how the homeowner will utilize this information, no savings were assumed for this device.

Finally, the builder provided an online owner's manual through HomeNav. This Web portal provides the homeowner with a resource that includes information on all the products in the home (model numbers, warranties, manuals, etc.), important contact information (emergency contacts, contractors' and utility information, etc.), and how to properly maintain this particular home.

4 A U.S. Department of Energy Challenge Home—Step-by-Step

As has been discussed in the previous sections, there was a lot of effort put into the design of this home. Yet even the best designs can still fail from quality control lapses during construction. Especially in very tight homes, the room for errors is drastically reduced as the ability for the home to compensate for errors has been diminished (e.g., lower drying potential for assemblies). As part of the effort to build and market a sustainable, energy-efficient home, the builder sought certification for the home under numerous national programs:

- U.S. Environmental Protection Agency's (EPA) ENERGY STAR Qualified Homes v3.0
- EPA's Indoor airPLUS
- EPA's Water Sense
- DOE's Challenge Home
- U.S. Green Building Council's LEED for Homes – Platinum
- National Association of Home Builder's National Green Building Standard – Emerald
- Institute for Business and Home Safety's FORTIFIED for Safer Living.

Requirement checklists for these certifications programs provided a lot of third-party verification throughout the construction process, but the builder must also be committed to a quality project. This builder took extensive photo documentation of the project at nearly every stage of construction.

A photo book of the key details needed to achieve these certifications is provided in Figure 7. This photo book is laid out to cover key components of the DOE Challenge Home (Table 4) with specific focus on the ENERGY STAR Qualified Homes v3.0 Thermal Enclosure System Rater Checklist and the Indoor airPLUS Verification Checklist.

Table 4. DOE Challenge Home Program Requirements

(Challenge 2012)

Area of Improvement	Mandatory Requirements
ENERGY STAR for Homes Baseline	☑ Certified under ENERGY STAR Qualified Homes Version 3
Envelope	☑ Fenestrations shall meet or exceed latest ENERGY STAR requirements ☑ Ceiling, wall, floor, and slab insulation shall meet or exceed 2012 IECC levels
Duct System	☑ Ducts located within the home's thermal and air barrier boundary
Water Efficiency	☑ Hot water delivery systems shall meet efficient design requirements (no more than 0.5 gal in distribution system)
Lighting and Appliances	☑ All installed refrigerators, dishwashers, and clothes washers are ENERGY STAR qualified ☑ 80% of lighting fixtures are ENERGY STAR qualified or ENERGY STAR lamps (bulbs) in minimum of 80% of sockets ☑ All installed bathroom ventilation and ceiling fans are ENERGY STAR qualified
Indoor Air Quality	☑ EPA Indoor airPLUS Verification Checklist and Construction Specifications
Renewable Ready	☑ EPA Renewable Energy Ready Home Solar Electric Checklist and Specifications ☑ EPA Renewable Energy Ready Home Solar Thermal Checklist and Specifications

Concrete with Krystol Internal Membrane chemical admixture incorporated (to create a waterproof concrete) arrives on site. Here, a worker is taking samples of the concrete. The gray canisters are filled with concrete and left at the jobsite till the next day so it is exposed to the same weather conditions as what was used on site. These samples are brought to a lab to measure the strength of the poured concrete.

Footings are poured. A key is applied.

IAP Moisture Control- Water-Managed Site and Foundation

1.1 **Site & foundation drainage: protected drain tile, & foundation floor drains.**

Drain tile at the exterior perimeter of the footing is protected by filter fabric and rock. This protects the foundation against water damage. There is an exterior sump pump chamber where footing drains discharge from. Drains discharge to town system.

IAP Radon
2.1 Approved radon-resistant features installed

Radon pipe from below slab to be extended through the roof.

The slab is prepared. Footing drains are in place and radon piping has been installed.

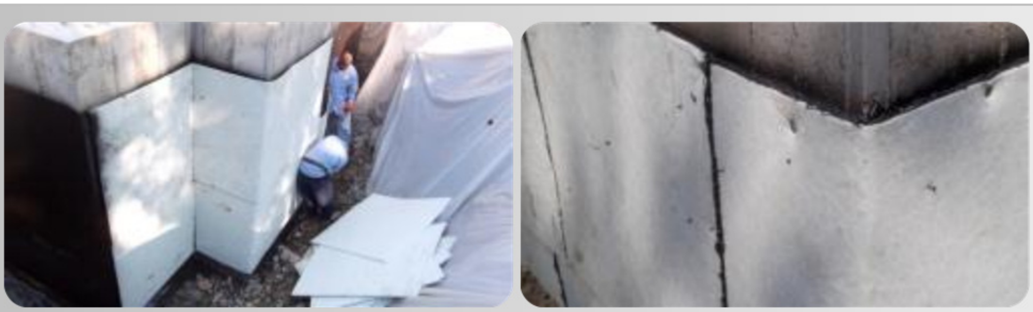
IAP Moisture Control- Water-Managed Site and Foundation
1.2 Capillary break below concrete slabs

Closed cell spray foam acts as a vapor retarder and a capillary break beneath the concrete slab. The IRC requires 6 mil polyethylene or approved (by building official) vapor retarder. ccSPF is a class II vapor retarder and with the addition of the Krystol Internal Membrane chemical admixture in the concrete, this system was approved by the local code official.

IAP Moisture Control- Water-Managed Site and Foundation

1.3 Foundation wall water-proofed

A waterproof membrane is applied to the below-grade foundation wall.



IAP Moisture Control- Water-Managed Site and Foundation

1.5 Continuous drainage plane behind exterior cladding, properly flashed to foundation.

Drain board on the exterior of the waterproof membrane keeps moisture away from the structure.

IAP Moisture Control- Water-Managed Site and Foundation

1.4 Basements insulated & conditioned

Closed cell spray foam exposure to UV results in yellow discoloration. Closed cell spray foam has been brought up 6” on wall to provide continuous thermal and moisture barrier. Radiant piping is located below the slab.

IAP Moisture Control- Water-Managed Site and Foundation

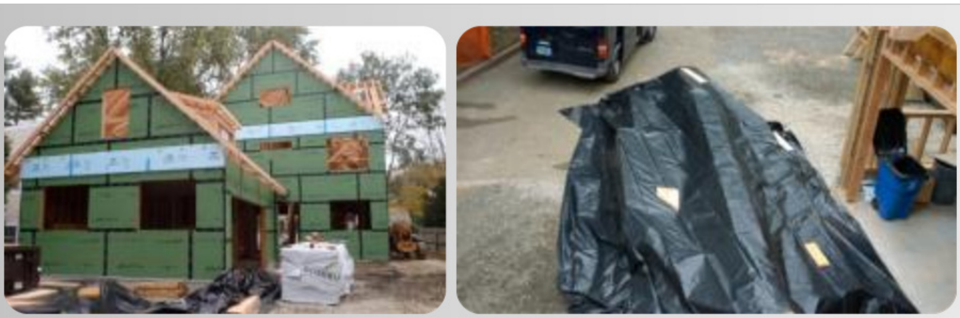
1.4 Basements insulated & conditioned

The interior of the foundation walls are framed and insulated with 3” closed cell spray foam. A gap between the foundation wall and the framing allows for the insulation to be continuous.

IAP Pests

3.1 Foundation joints & penetrations sealed, including air-tight sump covers.

Copper termite barrier extends over the rigid insulation where the foundation meets the above grade wall.



IAP Moisture Control- Interior Water Management
1.13 No wet or water-damaged materials enclosed in building assemblies

Materials were covered to avoid direct rain and the moisture content of building materials was checked prior to enclosing any assemblies.

IAP Pests
3.2 Corrosion-proof rodent/bird screens installed at all openings that cannot be fully sealed (e.g., attic vents)

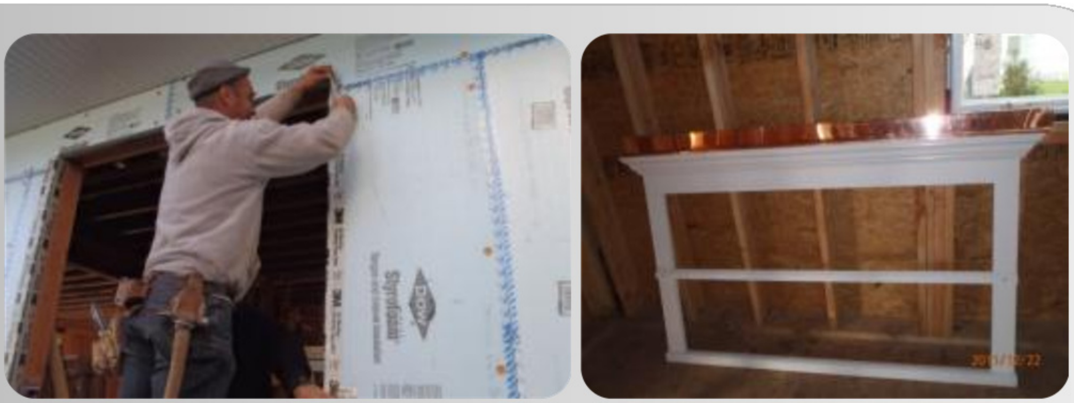
Insect screen at above-grade wall keeps pests from occupying the space between the drain board and the cladding. All inlets and exhausts also are installed with screens.

IAP Moisture Control- Interior Water Management
1.12 No vapor barriers installed on interior side of exterior walls with high condensation potential

Rigid insulation taped joints on the exterior of above-grade walls acts as the primary vapor barrier.

IAP Moisture Control- Water-Managed Wall Assemblies
1.5 Continuous drainage plane behind exterior cladding, properly flashed to foundation

A rain screen (yellow) is installed on above-grade walls over the exterior rigid insulation prior to the siding being installed. Though XPS is often used as the drainage plane, there was a concern with potential product shrinkage and the long-term durability of tapes.



IAP Moisture Control- Water-Managed Wall Assemblies
1.6 Window & door openings fully flashed

Flashing tape is installed on the exterior wall before window installation. Window trim has header flashing for additional water management.

IAP Moisture Control- Water-Managed Roof Assemblies
1.10 Ice flashing installed at eaves

Ice flashing is installed along the roof eaves. This will help prevent ice dams.

IAP Moisture Control- Water-Managed Roof Assemblies
1.8 Fully flashed roof/wall intersections (step & kick-out flashing) & roof penetrations

IAP Moisture Control- Water-Managed Roof Assemblies
1.9 Bituminous membrane installed at valleys & penetrations

Copper flashing protects extra susceptible junctures. A bituminous membrane (shown in black) is applied on the roof to seal the flashing to the walls.

IAP Moisture Control- Interior Water Management
1.11 Moisture-resistant materials/protective systems installed (i.e., flooring, tub/shower backing, and piping)

Closed cell spray foam insulation at wall behind bathtub will resist moisture damage.

TERC 3 Fully Aligned Air Barriers
3.1.1 Walls behind showers and tubs

The walls are insulated first with closed cell spray foam and then the tub is installed.

IAP Combustion Pollutants- Attached Garage Isolation
5.5 Common walls/ceilings (house & garage) air-sealed before insulation installed; house doors gasketed & closer installed

Closed cell spray foam insulation at garage wall ensures a seal to protect occupants against pollutants.

TERC 1 High-Performance Fenestration
1.2 Performance Path: Fenestration shall meet or exceed 2009 IECC requirements

Windows (U-0.28, SHGC-0.27) meet required values for climate zone 5.

DOE Challenge Home
Use high-performance windows that meet ENERGY STAR specifications.

Integrity Casement
Fiberglass – Wood
272 ARGON
CERTIFIED
ENERGY PERFORMANCE RATINGS
0.28
0.27
ADDITIONAL PERFORMANCE RATINGS
0.46

TERC 2 Quality-Installed Insulation
2.1 Ceiling, wall, floor, and slab insulation levels shall:
2.1.1 Meet or exceed 2009 IECC levels

2.2 All ceiling, wall, floor, and slab insulation shall achieve RESNET-defined Grade I installation or, alternatively, Grade II for surfaces that contain a layer of continuous, air impermeable insulation ≥ R-5 in Climate Zones 5 to 8

DOE Challenge Home
Meet 2012 International Energy Conservation Code levels for insulation.

All insulation was installed to Grade I levels. Insulation levels are greater than the IECC requirements.

R-13 of closed cell spray foam is under the basement slab. The interior of basement wall is furred out and insulated with R-20 of closed cell spray foam, and the exterior has R-3 of rigid insulation. The exterior 2x6 16"oc wood framed walls are insulated with 1.5" rigid insulation on the exterior and dense-packed blown insulation in the wall cavities for a total value of R-28.5. Joist bays and rims are insulated with rigid insulation on the exterior and 3" of closed cell insulation, for a value of R-28.5 as well. The floor above the garage is insulated with R-44 closed cell spray foam and R-42 in an exposed floor overhang. Although the attic is unfinished, the rafter bays are insulated with 5.5" of closed cell spray foam, topped with a fiberglass batt for an R-50 insulation value.

TERC 3 Fully Aligned Air Barriers
3.1.3 Attic knee walls

The air barrier (green) is on the exterior of the building (walls and roof). Tape (black) at the joints ensures a complete seal.

TERC 3 Fully-Aligned Air Barriers
3.1.5 Wall adjoining porch roof

The exterior walls are insulated at the eaves with continuous rigid insulation.

TERC 3 Fully-Aligned Air Barriers
3.1.8 Garage rim/band joist adjoining conditioned space

Rim joist are insulated on the interior with closed cell spray foam, which acts as a primary air barrier between the conditioned house and the garage.

During one of the inspections, the builder noticed some shrinkage of the closed cell spray foam in the rim/band joist area of the foundation wall. This thermal bypass was found through the use of an infrared camera. It is theorized that there was moisture on the foundation shelf. Water can react with the blowing agent to form CO_2, which may have pushed the foam off the surface as it was setting up.

TERC 3 Fully-Aligned Air Barriers
3.2.1 Floor above garage

R-44 closed cell spray foam is installed. All insulation penetrations are properly sealed.

TERC 4 Reduced Thermal Bridging
4.4 Reduced thermal bridging at above-grade walls separating conditioned from unconditioned space (rim / band joists exempted) using one of the following options:

4.4.1 Continuous rigid insulation, insulated siding, or combination of the two; ≥ R-5 in Climate Zones 5 to 8

Rigid insulation (blue) reduces thermal bridging of the wall framing.

TERC 4.4.5 Advanced framing
4.4.5b All headers above windows & doors insulated

Headers are insulated with closed cell spray foam.

TERC 4.4.5 Advanced framing
4.4.5c Framing limited at all windows and doors

Extra blocking has not been installed. This increases thermal bridging and decreases the overall wall R-value.

Also notice the covers over the roughed-in ductwork to prevent dust from entering the distribution system during construction.

TERC 4.4.5 Advanced framing
4.4.5d All interior / exterior wall intersections insulated to the same R-value as the rest of the exterior wall

Ladder blocking allows for closed cell spray foam to be applied in the wall cavity between the garage and interior space.

TERC 5 Air Sealing
5.1 Penetrations to unconditioned space fully sealed with solid blocking or flashing as needed and gaps sealed with caulk or foam

All penetrations are sealed to prevent infiltration. Owens Corning Energy Complete system was used to air seal in the wall cavities.

TERC 5 Air Sealing
5.1.1 Duct / flue shaft

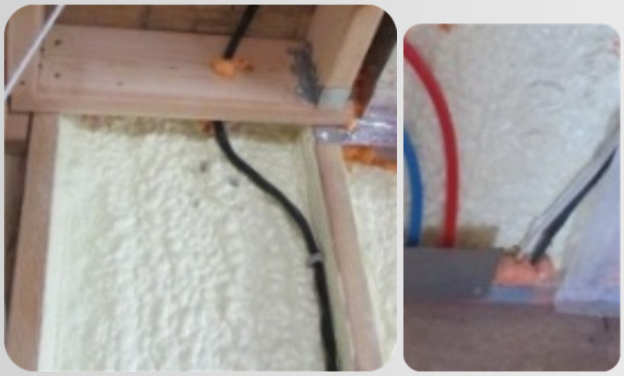
Where ductwork penetrates walls, the gap around it is sealed (orange).

TERC 5 Air Sealing
5.1.2 Plumbing/piping

When plumbing pipes penetrate walls or floors, the gap around it is sealed (orange).

TERC 5 Air Sealing
5.1.3 Electrical wiring

When wiring penetrates walls, the gap around it is sealed (orange).



TERC 5 Air Sealing
5.2.1 All sill plates adjacent to conditioned space sealed to foundation or subfloor with caulk, foam, or equivalent material. Foam gasket also placed beneath sill plate if resting atop concrete or masonry and adjacent to conditioned space

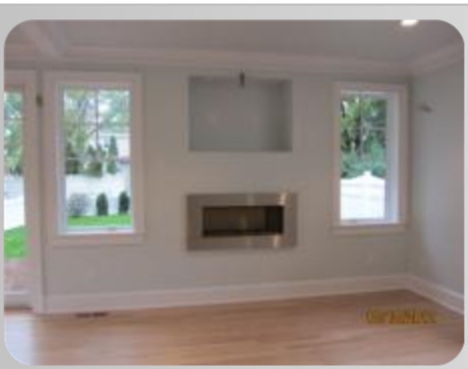
Air sealing the sill plate to the foundation wall prevents infiltration.

TERC 5 Air Sealing
5.2.4 Rough opening around windows & exterior doors sealed with caulk or foam

Foam (yellow) seals the gap between the rough opening and the window frame.

TERC 5 Air Sealing
5.2 Cracks in the building envelope fully sealed

Air sealing throughout the building process is necessary to prevent air movement in places that are hard to reach once construction is complete. A blower door test confirms this is a very tight building envelope.

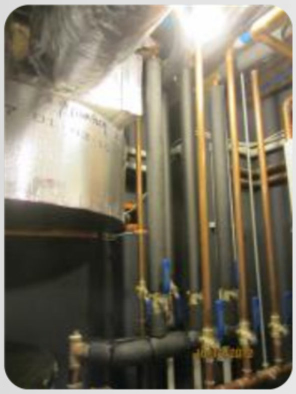


IAP Combustion Pollutants- Combustion Source Controls
5.2 Fireplaces/heating stoves vented outdoors & meet emissions/efficiency standards/restrictions

The fireplace's sealed doors meet the standards to prevent combustion pollutants from contaminating indoor air. The fireplace is vented directly to the outdoors.

DOE Challenge Home
Conserve water and energy through an efficient hot water distribution system that provides rapid hot water to the homeowner.

Pipe insulation minimizes heat loss of hot water traveling from the water heater to a faucet or showerhead.



DOE Challenge Home
Feature energy efficient appliances and fixtures that are ENERGY STAR qualified.

Energy saving information is found on Energy Guide labels

IAP HVAC
4.2 Duct system design documented & duct system tested

A duct blaster tests the total leakage of the distribution system. When combined with a blower door, duct leakage to outdoors (the energy penalty) can be determined. Leakage to outside was found to be less than 4% of total airflow.

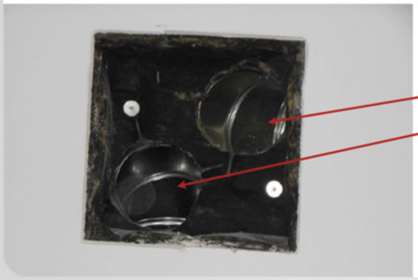
IAP HVAC
4.3 No air handling equipment or ductwork installed in garage; continuous air barrier required in adjacent assemblies

One duct had to run in the ceiling above the garage. To ensure a complete air barrier between the duct and the garage, the duct was encapsulated in spray foam.

Supply Run

IAP HVAC
4.4 Rooms pressure balanced (using transfer grills or jump ducts) tested

Jump ducts from the secondary bedrooms were run to a single register opening in the upstairs hallway. The central return is located in this same space to draw return air from the bedrooms.



Jumper duct in 2nd fl hallway to bedroom 2 & 3.

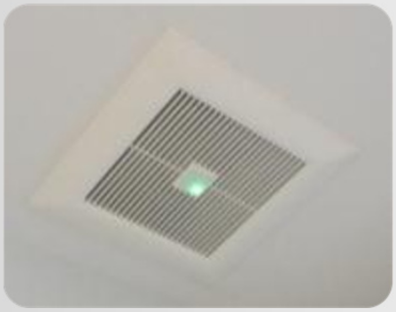
IAP HVAC
4.5 Whole house ventilation system installed to meet ASHRAE 62.2 requirements

HVAC Quality Installation Contractor Checklist
1. Whole-Building Mechanical Ventilation Design

An Energy Recovery Ventilator with its own dedicated distribution system meets ventilation requirements for healthy indoor air quality. This system includes a CO_2 sensor override located in the living room.

IAP HVAC
4.6 Local exhaust ventilation to outdoors installed for baths, kitchen, clothes dryers, central vacuum system, etc.

Kitchen exhaust is vented directly to outdoors, as is the clothes dryer exhaust. This fan has a built in humidity control sensor.



IAP HVAC
4.7 Central forced-air HVAC system(s) have minimum MERV 8 filter, no filter bypass, & no ozone generators

A MERV 13 filter was installed on each air handler with easy access for homeowners to replace the filters as part of their home maintenance.

IAP Combustion Pollutants- Combustion Source Controls
5.1 Gas heat direct vented; oil heat & water heaters power vented or direct vented

A sealed combustion tankless gas boiler is installed for health safety as well as increased efficiency.

IAP Combustion Pollutants- Attached Garage Isolation
5.6 Exhaust fan (minimum 70 cfm, rated for continuous use) installed in garage & vented to outdoors (controls optional)

An exhaust fan was installed in the garage to provide ventilation for a set period of time based on operation of the garage door.

TERC 5 Air Sealing
5.3.1 Doors adjacent to unconditioned space (e.g., attics, garages, basements) or ambient conditions gasketed or made substantially air-tight.

All of the glass and opaque doors are well sealed.

IAP Materials
6.2 Certified low-VOC or no-VOC interior paints & finishes used

Paint is low-VOC or no-VOC for better indoor air quality.

IAP Materials
6.1 Certified low-formaldehyde pressed wood materials used (i.e., plywood, OSB, MDF, cabinetry)

All wood materials have little formaldehyde.

IAP Moisture Control- Water-Managed Site and Foundation
1.1 Site & foundation drainage: sloped grade

The grade gradually slopes away from the house to keep storm water from accumulating and compromising the structure.

IAP Moisture Control- Water-Managed Roof Assemblies
1.7 Gutters/downspouts direct water a minimum of 5' from foundation

Gutters bring water to the drain tile below, and this is diverted away from the foundation and fed into the town storm water management system.

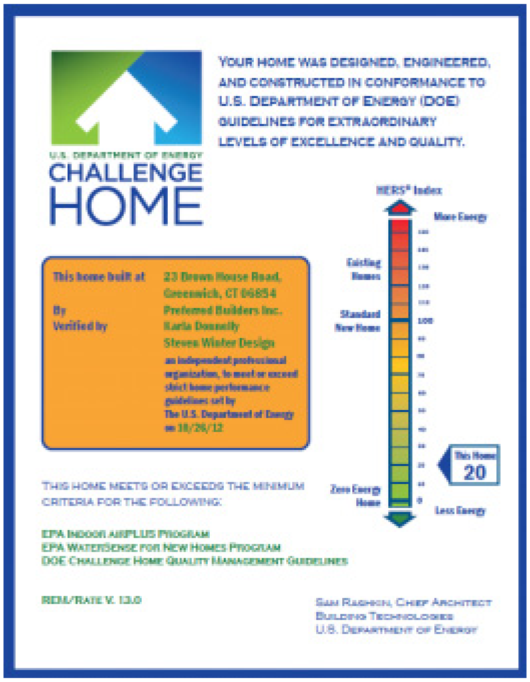
IAP Final
7.3 Completed checklist & other required documentation provided for buyer

The home earned an Indoor airPlus label and an ENERGY STAR v3.0 label.

Figure 7. Photo book of the Performance House

(Preferred Builders Inc.)

The end result of this builder's efforts was a DOE Challenge Home (Figure 8) that achieved a Home Energy Rating System Index Score of 20 (43 without PV, the minimum target was 55 for compliance). This home was also awarded the 2012 HOBI for Best Green Energy Efficient Home from the Home Builders & Remodelers Association of Connecticut and was the second place winner in the 2012 Connecticut Energy Efficiency Fund's Zero Energy Challenge. A short informational video of this project was created by one of the Zero Energy Challenge utility partners, Connecticut Light & Power.



U.S. DEPARTMENT OF ENERGY
CHALLENGE HOME

YOUR HOME WAS DESIGNED, ENGINEERED, AND CONSTRUCTED IN CONFORMANCE TO U.S. DEPARTMENT OF ENERGY (DOE) GUIDELINES FOR EXTRAORDINARY LEVELS OF EXCELLENCE AND QUALITY.

This home built at	23 Brown House Road, Greenwich, CT 06854
By	Preferred Builders Inc.
Verified by	Karla Donnelly Steven Winter Design
	an independent professional organization, to meet or exceed strict home performance guidelines set by The U.S. Department of Energy on 10/26/12

THIS HOME MEETS OR EXCEEDS THE MINIMUM CRITERIA FOR THE FOLLOWING:

EPA INDOOR AIRPLUS PROGRAM
EPA WATERSENSE FOR NEW HOMES PROGRAM
DOE CHALLENGE HOME QUALITY MANAGEMENT GUIDELINES

REM/RATE V. 13.0

SAM RASHKIN, CHIEF ARCHITECT
BUILDING TECHNOLOGIES
U.S. DEPARTMENT OF ENERGY

Figure 8. DOE Challenge Home Label

5 Short-Term Monitoring of Hydro-Coil Performance

The focus of the space heating research activity was to optimize the system efficiency of this condensing boiler with hydro-coil unit combination system and to compare performance to manufacturer's data. The system comprised the following components:

- Buderus GB142/24 wall-mounted condensing boiler
- Carrier Infinity FE4ANF002 communicating variable-speed fan coil
- Carrier HC3AXX017065AAA hot water coil-cased
- Grundfos Alpha 15-55F circulating pump.

The testing process of the hydro-coil system consisted of a one-day short-term monitoring session that examined the effect that altering the systems water temperature, water flow rate, and airflow rate had on its output performance. Performance metrics that were evaluated for this testing include total capacity of the system (TC), entering dry-bulb (EDB) and leaving dry bulb temperature (LDB) of air blown across the coil, and entering water temperature (EWT) and leaving water temperature (LWT) of fluid through the hydro-coil.

The EWT of the hydro-coil was adjusted through the BC10 basic controller (Figure 9 left image) on the Buderus GB142 tankless boiler. This controller utilizes a dial that allows the user to set the temperature adjustment between 0°F and 190°F. The unit's display screen provides for a dial resolution of 1°F. Additionally, instead of selecting a constant supply temperature, the temperature setting may also be positioned to "AUT." In this setting, the EWT will be adjusted based on the thermostat temperature and outdoor air temperature. The manufacturer supplies an outdoor reset heat curve that displays recommended programmable temperature settings for outdoor air temperatures between 0°F and 70°F that the control module will use when the setting is in "AUT" mode. For this short-term monitoring, the following settings were examined: 120°F, 130°F, 140°F, "AUT."

Figure 9. Hydro-coil system controls

The system water flow rate is controlled by a Grundfos Alpha circulator pump (Figure 9 center image). This pump has control options of constant speed, constant pressure, and proportional pressure. For this short-term monitoring, three constant-speed controls and one "AUTOADAPT" proportional-pressure control was examined. The three different constant speed controls which are available correspond to a low medium and a high setting at measured nominal flow rates of (I) 1.6 gpm, (II) 2.4 gpm, and (III) 4.2 gpm. Additionally, the pump can be set to an "auto" speed that maintains proportional pressure according to the manufacturer's defined performance curve. In this setting, the pump will adjust its performance based on the size of the system and the variations in heating load over time.

The airflow rate of the system was set through the Carrier Infinity Controls thermostat (Figure 9 right image). It offers adjustment between a low, medium, high, and auto setting. The "auto" setting dictates a fan mode where the fan will run in either heating or cooling speed based on the need to approach the desired set point. For the short-term testing done, the fan supplied (as measured with a multipoint pitot traverse within the filter slot of the air handler) 450 CFM (± 5 cfm) when heating high speed was called upon.

Table 5 provides details of the parameters and the monitoring equipment needed to determine the heating output of the hydro-coil forced-air heating system at various water flow and airflow rates and temperature set points. A data logger was used to take measurements every 5 s and output data every 1 min.

Table 5. Field Monitoring Equipment

Measurement	Equipment
Record and Output Measurements	Campbell-Scientific CR-10X Datalogger
Inlet and Outlet Water Temperatures (°F)	Omega ON-910-44006 NPT Pipe Plug Thermistor
Supply Air Temperature (°F) and Relative Humidity (%)	Humirel HTM2500 Probe
Hot Water Flow (gpm)	Omega FTB4607 Low Flow, Turbine-Type Flow Meter
Air Handler Flow (cfm)	Energy Conservatory TrueFlow Air Handler Flow Meter

5.1 Analysis

To determine the heat extracted from the hydro-coil system, the following equation was utilized on the water side measurements:

$$Q_h = (\Delta T_{T_s - T_r} \times \dot{V} \times C_p \times \rho)$$

Where:

Q_h = useful heat extracted from system (Btu/h)

$\Delta T_{Ts\text{-}Tr}$ = T supply minus T return (°F) into and out of the hydro-coil/air handler

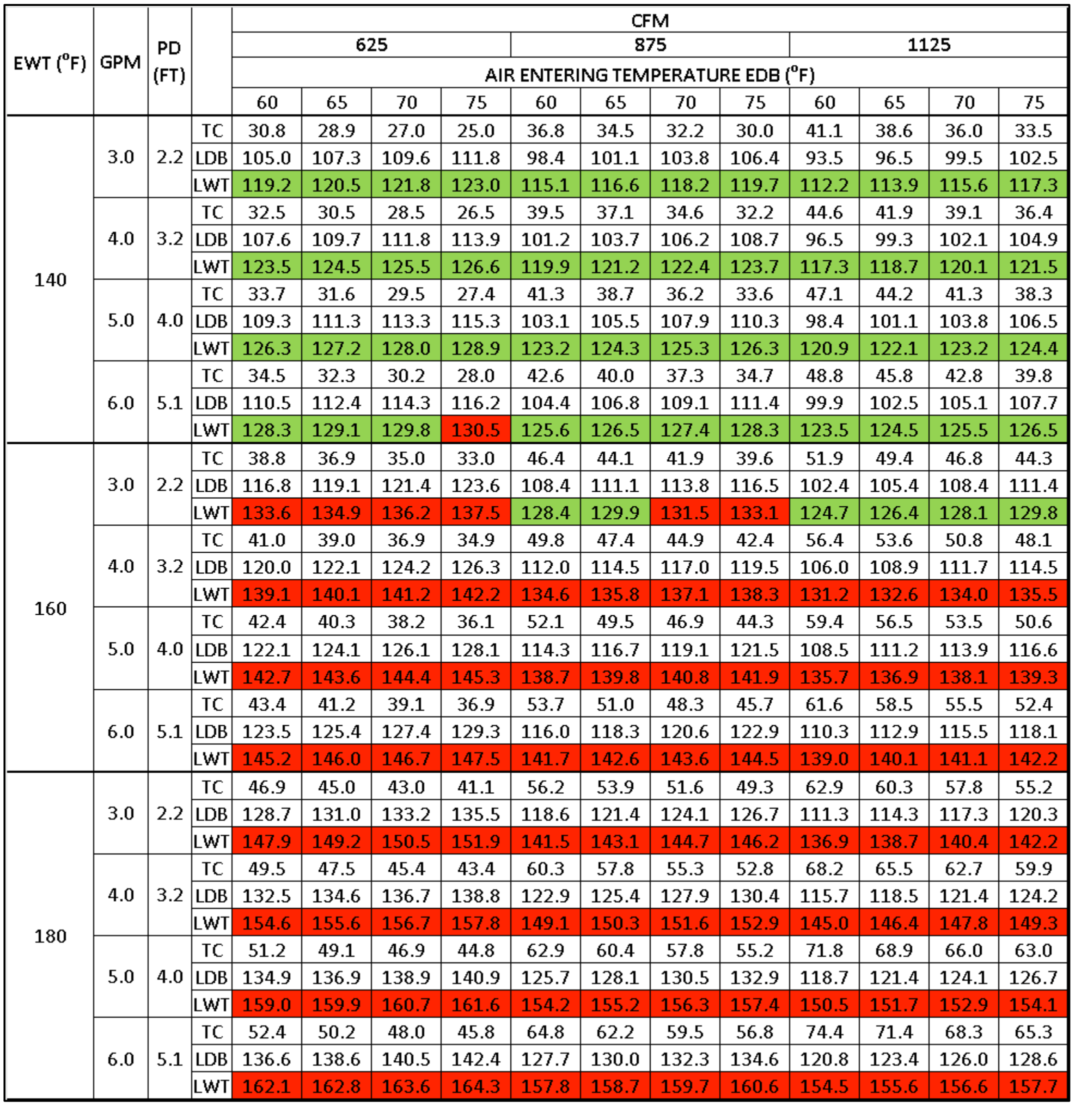
$\dot{V}$ = volumetric flow rate (ft^3/h)

C_p = specific heat of water/air (Btu/lbm·°F)

ρ = density of water/air (lbm/ft^3)

5.2 Results

One goal of testing this hydro-coil system was to verify that the unit performs to the manufacturer's rated heat output capacities and temperature conditions at various configurations. In order for these systems to work at optimal performance, the LWT that returns to the boiler must be a low enough temperature to allow condensation of the combustion vapors. This means that LWT should be less than 130°F for peak efficiency to be obtained (Arena 2012). Figure 10 displays the manufacturer's hydro-coil rated performance specifications. LWT values are color-coded based on the boiler's potential to utilize condensation heat recovery. LWTs in green indicate conditions (< 130°F) where vapor condensation is likely to occur and values highlighted in red indicate conditions (> 130°F) where condensation is unlikely to occur.



EWT (°F)	GPM	PD (FT)		CFM											
				625				875				1125			
				AIR ENTERING TEMPERATURE EDB (°F)											
				60	65	70	75	60	65	70	75	60	65	70	75
140	3.0	2.2	TC	30.8	28.9	27.0	25.0	36.8	34.5	32.2	30.0	41.1	38.6	36.0	33.5
			LDB	105.0	107.3	109.6	111.8	98.4	101.1	103.8	106.4	93.5	96.5	99.5	102.5
			LWT	119.2	120.5	121.8	123.0	115.1	116.6	118.2	119.7	112.2	113.9	115.6	117.3
	4.0	3.2	TC	32.5	30.5	28.5	26.5	39.5	37.1	34.6	32.2	44.6	41.9	39.1	36.4
			LDB	107.6	109.7	111.8	113.9	101.2	103.7	106.2	108.7	96.5	99.3	102.1	104.9
			LWT	123.5	124.5	125.5	126.6	119.9	121.2	122.4	123.7	117.3	118.7	120.1	121.5
	5.0	4.0	TC	33.7	31.6	29.5	27.4	41.3	38.7	36.2	33.6	47.1	44.2	41.3	38.3
			LDB	109.3	111.3	113.3	115.3	103.1	105.5	107.9	110.3	98.4	101.1	103.8	106.5
			LWT	126.3	127.2	128.0	128.9	123.2	124.3	125.3	126.3	120.9	122.1	123.2	124.4
	6.0	5.1	TC	34.5	32.3	30.2	28.0	42.6	40.0	37.3	34.7	48.8	45.8	42.8	39.8
			LDB	110.5	112.4	114.3	116.2	104.4	106.8	109.1	111.4	99.9	102.5	105.1	107.7
			LWT	128.3	129.1	129.8	130.5	125.6	126.5	127.4	128.3	123.5	124.5	125.5	126.5
160	3.0	2.2	TC	38.8	36.9	35.0	33.0	46.4	44.1	41.9	39.6	51.9	49.4	46.8	44.3
			LDB	116.8	119.1	121.4	123.6	108.4	111.1	113.8	116.5	102.4	105.4	108.4	111.4
			LWT	133.6	134.9	136.2	137.5	128.4	129.9	131.5	133.1	124.7	126.4	128.1	129.8
	4.0	3.2	TC	41.0	39.0	36.9	34.9	49.8	47.4	44.9	42.4	56.4	53.6	50.8	48.1
			LDB	120.0	122.1	124.2	126.3	112.0	114.5	117.0	119.5	106.0	108.9	111.7	114.5
			LWT	139.1	140.1	141.2	142.2	134.6	135.8	137.1	138.3	131.2	132.6	134.0	135.5
	5.0	4.0	TC	42.4	40.3	38.2	36.1	52.1	49.5	46.9	44.3	59.4	56.5	53.5	50.6
			LDB	122.1	124.1	126.1	128.1	114.3	116.7	119.1	121.5	108.5	111.2	113.9	116.6
			LWT	142.7	143.6	144.4	145.3	138.7	139.8	140.8	141.9	135.7	136.9	138.1	139.3
	6.0	5.1	TC	43.4	41.2	39.1	36.9	53.7	51.0	48.3	45.7	61.6	58.5	55.5	52.4
			LDB	123.5	125.4	127.4	129.3	116.0	118.3	120.6	122.9	110.3	112.9	115.5	118.1
			LWT	145.2	146.0	146.7	147.5	141.7	142.6	143.6	144.5	139.0	140.1	141.1	142.2
180	3.0	2.2	TC	46.9	45.0	43.0	41.1	56.2	53.9	51.6	49.3	62.9	60.3	57.8	55.2
			LDB	128.7	131.0	133.2	135.5	118.6	121.4	124.1	126.7	111.3	114.3	117.3	120.3
			LWT	147.9	149.2	150.5	151.9	141.5	143.1	144.7	146.2	136.9	138.7	140.4	142.2
	4.0	3.2	TC	49.5	47.5	45.4	43.4	60.3	57.8	55.3	52.8	68.2	65.5	62.7	59.9
			LDB	132.5	134.6	136.7	138.8	122.9	125.4	127.9	130.4	115.7	118.5	121.4	124.2
			LWT	154.6	155.6	156.7	157.8	149.1	150.3	151.6	152.9	145.0	146.4	147.8	149.3
	5.0	4.0	TC	51.2	49.1	46.9	44.8	62.9	60.4	57.8	55.2	71.8	68.9	66.0	63.0
			LDB	134.9	136.9	138.9	140.9	125.7	128.1	130.5	132.9	118.7	121.4	124.1	126.7
			LWT	159.0	159.9	160.7	161.6	154.2	155.2	156.3	157.4	150.5	151.7	152.9	154.1
	6.0	5.1	TC	52.4	50.2	48.0	45.8	64.8	62.2	59.5	56.8	74.4	71.4	68.3	65.3
			LDB	136.6	138.6	140.5	142.4	127.7	130.0	132.3	134.6	120.8	123.4	126.0	128.6
			LWT	162.1	162.8	163.6	164.3	157.8	158.7	159.7	160.6	154.5	155.6	156.6	157.7

Figure 10. Condensation potential based on leaving water temperature of the hydro-coil

(Recreated from Carrier 2007, courtesy of Carrier Corporation)

When an outdoor reset is used with the boiler's "AUT" mode, the installing technician should generally program the outdoor reset conditions to match the manufacturer's recommended heating curve. For the condensing boiler used in this study, the recommended heating curve is shown in Figure 11. As indicated by the heating curve chart, the boiler supply water temperature (or EWT) should be set at minimum cut-in temperature of 150°F when paired with a hydro-air system. With a 150°F to 190°F EWT, there is little chance of the boiler working in its optimal condensation mode. Whether by design or simply an accident, the outdoor reset control for this system was set to a radiator schedule rather than the hydro-air schedule.

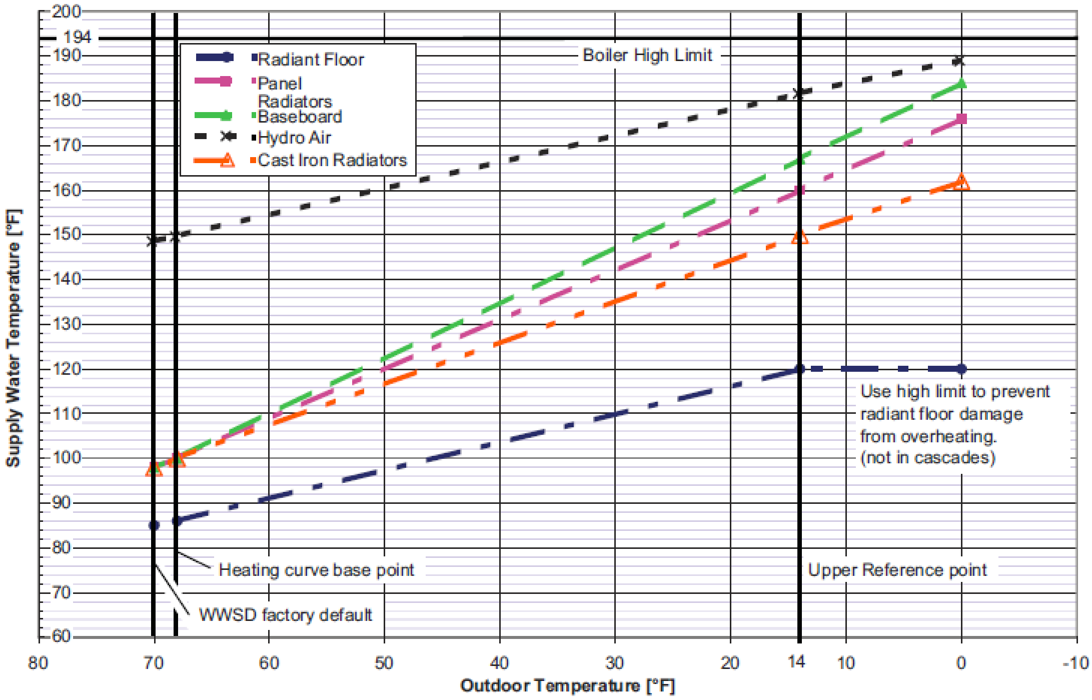


Figure 11. Buderus GB142 heating curve chart

(courtesy of Bosch Thermotechnology Corp. [2012])

Short-term data monitoring was performed while experimentally varying the EWT and water flow rate through the coil; maintaining a fairly constant air flow at a rate of 450 cfm (high fan speed setting for heating as configured by the HVAC contractor) and an EDB temperature of ~70°F. The system performance was evaluated by examining the output characteristics of total capacity, leaving dry bulb of air blown across the coil, and leaving water temperature of fluid exiting the coil. The results from these tests are provided in Table 6. It should be noted that the LWT does not exceed 130°F until both the boiler set point and water flow rate at set high (150°F and 2.8+ gpm, respectively).

In order to compare manufacturer specifications to results from short-term test data, rated capacities were extrapolated to a predicted performance at 450 cfm. Figure 12 shows a plot that contains monitoring results and manufacturer rated capacity at various fluid flow rates with a constant EWT of 140°F and EDB of 70°F. As displayed in the plot, the experimentally determined capacities found during short-term test were generally slightly less (on average, 13%) than the spec sheet-extrapolated capacity. Still the system met the heating demands of this low-load home (heating design load: 15,576 Btu/h for the first floor/basement and 15,196 Btu/h for the second floor) while allowing the boiler to achieve condensing and the associated higher efficiency.

Table 6. Short-Term Monitoring Results

EWT(°F) Setting	GPM	450 CFM, EDB 70°F		EWT(°F) Setting	GPM	450 CFM, EDB 70°F	
120	1.6	TC	14.4	140	1.6	TC	20.3
120	1.6	LDB	95.9	140	1.6	LDB	107.3
120	1.6	LWT	102.6	140	1.6	LWT	116.1
120	2.8	TC	15.7	140	2.8	TC	23.4
120	2.8	LDB	100.9	140	2.8	LDB	113.4
120	2.8	LWT	107.1	140	2.8	LWT	125.4
120	4.2	TC	17.7	140	4.2	TC	N/A
120	4.2	LDB	100.3	140	4.2	LDB	N/A
120	4.2	LWT	111.3	140	4.2	LWT	N/A
130	1.6	TC	17.2	150	1.6	TC	22.4
130	1.6	LDB	101.4	150	1.6	LDB	113.3
130	1.6	LWT	109.2	150	1.6	LWT	122.3
130	2.8	TC	19.3	150	2.8	TC	24.3
130	2.8	LDB	102.5	150	2.8	LDB	118.2
130	2.8	LWT	113.5	150	2.8	LWT	130.6
130	4.2	TC	21.0	150	4.2	TC	26.1
130	4.2	LDB	107.9	150	4.2	LDB	121.0
130	4.2	LWT	120.4	150	4.2	LWT	134.9

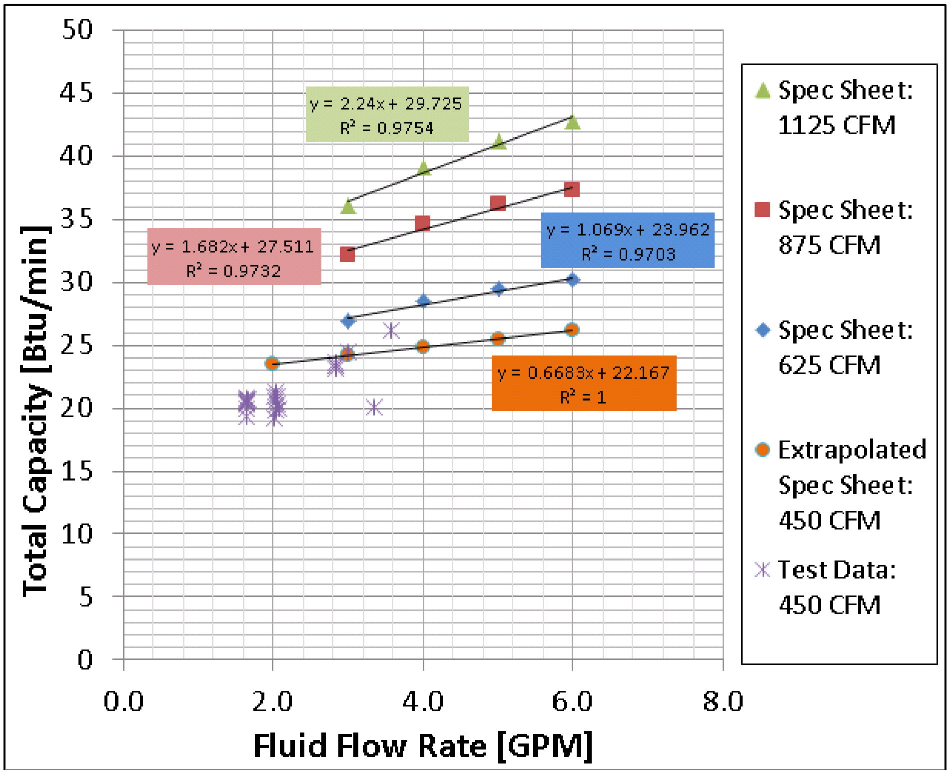


Figure 12. Short term testing results of AHU capacity at EWT of 140°F and EDB of 70°F

6 Project Results

Implementing all the efficiency measures of the BA solutions package brings the energy saving of the as-built home to 30.9% (excluding solar PV) compared to the BA Benchmark. CARB's solution package reduced utility costs significantly, but alternative solutions to achieve the same energy savings at a lower first cost are potentially possible. It should be noted that the DOE Challenge Home certification requires insulation levels to meet the 2012 IECC requirements, which are more stringent than the BA Benchmark base case specifications (2009 IECC). Based on the BEopt analysis, the solution package reduced utility costs by $913/yr, but increased mortgage costs by $1,143/yr. The net result was source energy savings of 73 MMBtu/yr, but with an increase in annualized energy related costs of $230/yr over the BA Benchmark reference.

Looking at specific costs of the builder, a more detailed cost analysis was performed. A common method of determining cost-effectiveness was utilized: savings-to-investment ratio (SIR). A SIR is the annual savings resulting from energy efficiency measure for the lifetime of the measure divided by the first cost of those implemented measures. The standard is for the SIR to be 1 (100%) or greater to be deemed a cost-effective efficiency measure or package. In the case of a solutions package, there are varying lifetimes for the various measures. Most mechanical equipment has an expected 15-yr serviceable lifespan. For building shell components, the lifetime of these components was limited to 30 years. The SIR analysis for the as-built home is provided in Table 7.

Table 7. Incremental Cost and SIR by Component

Component	Basecase Specification	Improved Specification	Incremental Cost Difference	Savings/year	Lifetime	Simple Lifetime Savings	SIR
Foundation Walls	Interior rigid insulation (R-10)	3/4" rigid on exterior (R-5) and 3"closed-cell spray polyurethane foam (ccSPF) on the interior walls (R-18)	$2,688	$40	30	$1,186	0.27
Foundation Slab	R-10 rigid under slab	R-13 ccSPF under slab	$1,661				
Above Grade Wall Assembly	Framed 2x6 walls @ 24"o.c. w/ R-20 blown cavity insulation	Advanced framed 2x6 walls @ 24" o.c. with 1.5" of XPS (R-7.5) over sheathing and blown cavity insulation (R-21)	$9,444	$296	30	$8,885	0.50
Ceiling/Attic Assembly	Vented attic, R-38 @ ceiling plane, standard asphalt shingles	Unvented attic with 5.5" ccSPF (R-36) plus 3.5" foil-faced batt (R-13) in between rafters.	$6,377				
Additional Air Sealing	-	Owens Corning Energy Complete	$1,900				
Windows	Dual pane, low-e windows w/ vinyl frame (U-0.35 / SHGC-0.35)	Dual pane, low-e windows w/ vinyl frame (U-0.28 / SHGC-0.27)	$0	$121	30	$3,619	N/A
Ventilation	-	Energy Recovery Ventilator (ERV) with CO_2 override control	$3,834	$4	15	$63	0.02
Space Conditioning & Water Heating	Two gas furnaces (AFUE 78%). Two 2.0-ton air conditioners (SEER 13). Typical duct sealing. Natural gas water heater (0.58 EF)	Two hydro-coils with variable-speed fan coils. Two 1.5-ton air conditioners (SEER 16.5). Extensive duct sealing. Natural gas wall-mounted boiler (96% AFUE)	$13,900	$362	15	$5,429	0.39
Lighting	100% incandescent lighting	~100% LED lighting	$7,003	$52	15	$775	0.11
Appliances	Standard clothes washer and exhaust fans	ENERGY STAR clothes washer and exhaust fans	$530	$46	15	$696	1.31
Solar	none	7.5 KW PV	$29,271	$1,714	25	$42,852	1.46

Excluding Solar	**Total Upgrade Cost :**	$47,337
	CT Incentives:	$7,283
	Adjusted Upgrade Cost:	$40,054
Including Solar	**Total Upgrade Cost :**	$76,608
	CT Solar Incentives:	$14,063
	Adjusted Upgrade Cost:	$55,263

The SIR for the complete solution (over a 15-yr savings period, so that anticipated equipment replacements are not an issue) without solar PV is only 0.29, so from a purely energy efficiency perspective, this solutions package is not cost neutral. If the solar electric system is included as part of the overall package, the SIR is 0.52. In this case, the solutions package with solar is better, but still not cash positive. In addition, there are a tremendous amount of state incentives being allocated for energy-efficient home projects such as this one. If the state incentives are included in the cost analysis, the SIR increases to 0.34 without solar and 0.72 with solar. The largest first cost that doesn't translate in to equivalent energy savings was the inclusion of LEDs throughout the home. Swapping the LEDs for screw-in CFLs would increase the SIR of the solutions package without solar or incentives to 0.34. Including solar and incentives, the SIR for the comparable CFL solution package would be 0.82.

This simple cost metric still excludes the value of improved comfort, durability, and indoor air quality associated with the implemented measures. The selection processes for nearly all the building components were impacted based on these other metrics:

- Tighter envelopes (by providing a complete interior air barrier through the specifications of the building shell) ensure thermal comfort while reducing energy consumption.
- Tightly built homes require mechanical ventilation to maintain acceptable indoor air quality by providing fresh air and diluting indoor pollutants. An ERV helps minimize the energy penalty associated with whole-house ventilation. Efficiency must not be achieved at the expense of the homeowner health (e.g., sick building syndrome).
- The sealed combustion boiler minimizes the potential for carbon monoxide poisoning.
- Duct leakage can lead to pressure imbalances within homes. Such imbalances not only can affect comfort and efficiency, but can also impact health and durability. Return side leaks can bring unwanted contaminants into the air stream, while supply side leakage can impact comfort (due to insufficient space conditioning leading to temperature fluctuations) in individual rooms.
- LEDs were selected to provide efficient lighting, while also eliminating the mercury concerns that the builder had with CFLs. As this home was being promoted as a green, sustainable home, the builder thought that LEDs were a necessary expense.

The true test of market viability is whether the builder will repeat this solution package in future construction projects. In this case, the builder sees the inherent value (not just focused on energy efficiency, but accounting for safety and health, reduced callbacks, durability, and comfort) of this solution package and will continue to implement this package in future homes.

7 Conclusions

The overarching research focus was to identify and vet a viable solution package that can be readily implemented in the cold climate zone for new construction single-family detached homes to achieve 30% source energy savings compared to a comparable 2009 IECC code-built home.

The primary questions addressed by this research were:

- What solution package can be readily implemented in a cold climate home to achieve 30% greater source energy savings compared to the BA House Simulation Protocols for new construction?
  - The building shell needs to be constructed in a manner in which the thermal, air, and moisture barriers are continuous. The key points are the transitions between the foundation, above-grade walls, and the roof. For the above-grade walls, 1.5 in. of XPS rigid insulation was applied to the exterior of the sheathing and taped at the seams to provide the continuous barriers. To ensure optimal performance, a secondary drainage plane was installed over the rigid insulation, and spot-applied low-expanding spray foam provided a flexible air seal in the wall assembly. The wall cavity could then be filled with lower cost blown insulation, rather than completely with spray polyurethane foam. To continue these barriers in the foundation, ccSPF was used on the interior of the poured concrete walls, under the basement slab, and in the rim/band joist areas. Finally, the roof deck was insulated with ccSPF. To meet code requirements, a thermal or ignition barrier was required over the ccSPF exposed in the attic. Rather than use a more expensive intumescent coating, exposure-rated foil-faced fiberglass batts were installed against the ccSPF and inset stapled to the rafters.

    The mechanical systems focused on a simplified system to provide heating and hot water as efficiently as possible. For this, a condensing tankless boiler was installed to provide domestic hot water and feed two hydro-coil fan units. Ductwork was designed to be as compact as possible to minimize the duct sealing effort. To provide whole-house ventilation, a highly efficient ERV was installed with its own dedicated ductwork and included a runtime controller and carbon dioxide override controller to increase ventilation automatically when occupancy increased.
- Is that solution package commercially viable? Where are opportunities to reduce costs in this solutions package?
  - For this class of home, achieving 30% source energy savings while maintaining traditional systems and features expected by homeowners is past the point of diminishing returns on investment at current market costs. Only when solar site generation and local incentives are also included into the economic analysis does this solution package approach cost neutrality.
  - The conversion of the attic to an unvented assembly allowed for the second-floor mechanical system and ductwork to be located in the conditioned space, but insulating at the roof deck was more costly than blowing loose-fill insulation at

    the ceiling plane of a vented attic. If the home design could have changed, to allow for mechanicals to be within the conditioned space with a vented attic, this could have reduced incremental costs by more than $6,000 with similar performance results.

    If energy efficiency and annualized energy-related costs were the only criteria, the LEDs could be replaced with lower cost screw-in CFL lighting. This could have reduced incremental costs by more than $7,000 with similar performance results.

    For whole-house ventilation, an exhaust-only ventilation strategy with an enhanced bathroom exhaust fan could have been installed to comply with ASHRAE 62.2-2010 ventilation requirements for a savings of $3,800 and just slightly lower performance.

    Finally, more typical rigid insulation could have been used under the foundation slab rather than ccSPF. This would have saved an additional $1,600 with similar performance results.

    In all, these changes would result in a SIR of greater than 1 if including local incentives or solar, but would have required the builder to make changes to his overall goals (beyond energy efficiency) and therefore, were not pursued.

- What are the major gaps to achieving this solution package at a production scale (cost, risk adversity, implementation complexity, etc.)?
    - Substituting LEDs for CFLs is a very high cost premium, even though the energy savings aren't significant. With greater market adoption, it is anticipated that the cost of LEDs will continue to drop. In addition, the cost for ccSPF fairly high compared to batt insulation. Unfortunately, the quality, performance, and consistency of installation are not accounted for in the valuing of these insulations.

In addition to these primary whole-house research questions, CARB performed a short-term evaluation of the hydro-coil heat system to quantify its performance. The hydro-coil system provided an advantage in HVAC equipment sizing for this low-load home, because the output capacity delivered a wide modulation range. Short-term testing determined that the system capacity of the boiler/hydro-coil could range from approximately 14 kBtu/h to 24 kBtu/h. The goal of this testing was to answer the following research questions:

- How does the hydro-coil system used in this test home compare to manufacturer's rated performance (capacity and water/air temperatures)?
    - Due to lower air handler flow than the manufacturer's data, rated capacities had to be extrapolated. The experimentally determined capacities found during short-term test were generally slightly less (on average, 13%) than the spec sheet-extrapolated capacity. Still the system met the heating demands of this low-load home (heating design load: 15,576 Btu/h for the first floor/basement and 15,196 Btu/h for the second floor).
- Does the condensing boiler supplying the heat to the hydro-coil system achieve suitable return temperatures to actually condense?

  - From the short-term testing data, the LWT did not exceed 130°F (therefore low enough to promote condensation of combustion vapors) until both the boiler set point and water flow rate were set high (150°F and 2.8+ gpm, respectively). More detailed monitoring would be needed to confirm boiler efficiency rates, but this limited dataset suggests that the system, as configured, should allow the condensing boiler to achieve near optimal performance.

Overall, the builder was extremely happy with the end result of this project. His final thought during the project debrief was *"I can not be happier with the comfort levels in the house."* In addition, CARB has worked with several builders in this climate region that have found this solution package (or very comparable alternatives) to be viable for their businesses. One builder had the following to say about the value of this level of energy efficient home:

> People have all sorts of misconceptions about the sacrifices that they feel they have to make in high performance homes and it is completely untrue. It is exactly the opposite. The even temperatures, the lack of drafts, the feeling of warmth, comfort, and right levels of humidity and fresh air…they are unrivaled. Comfort is something you have never experienced properly in a home until you have a high performance home.
>
> – Michael Trolle, BPC Green Builders (Source: CT Zero Energy Challenge 2012)

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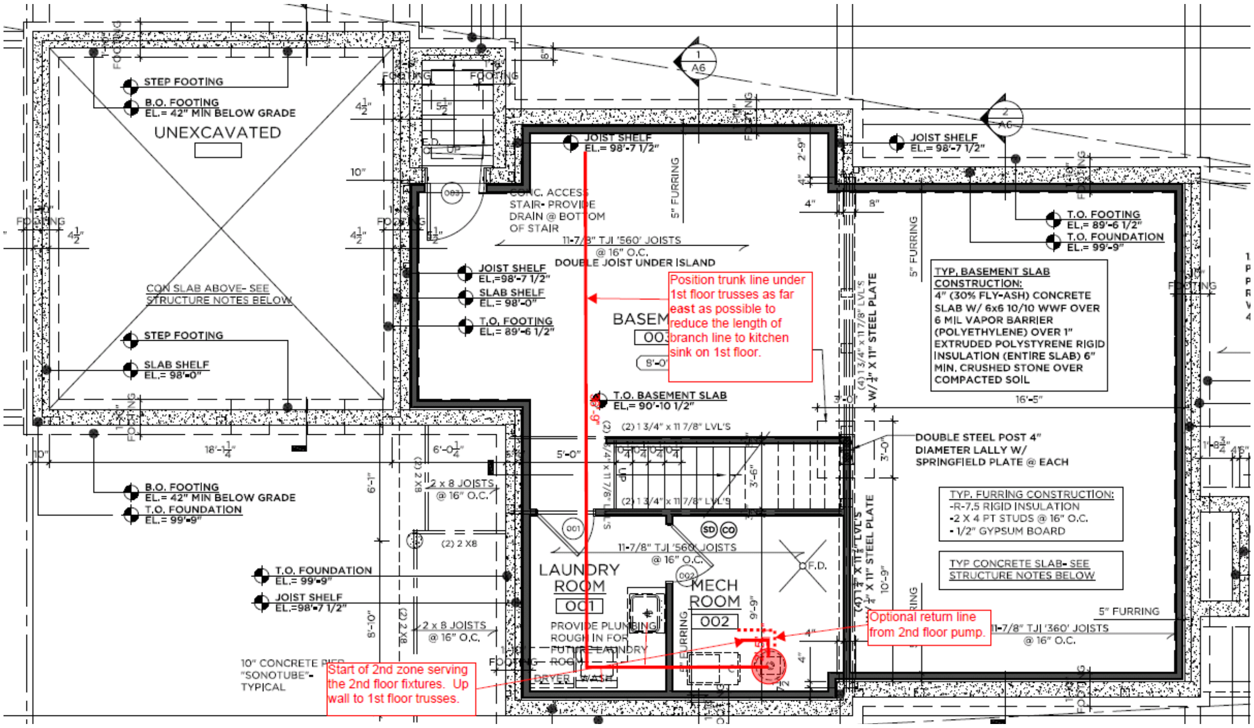
Appendix: Floor Plans

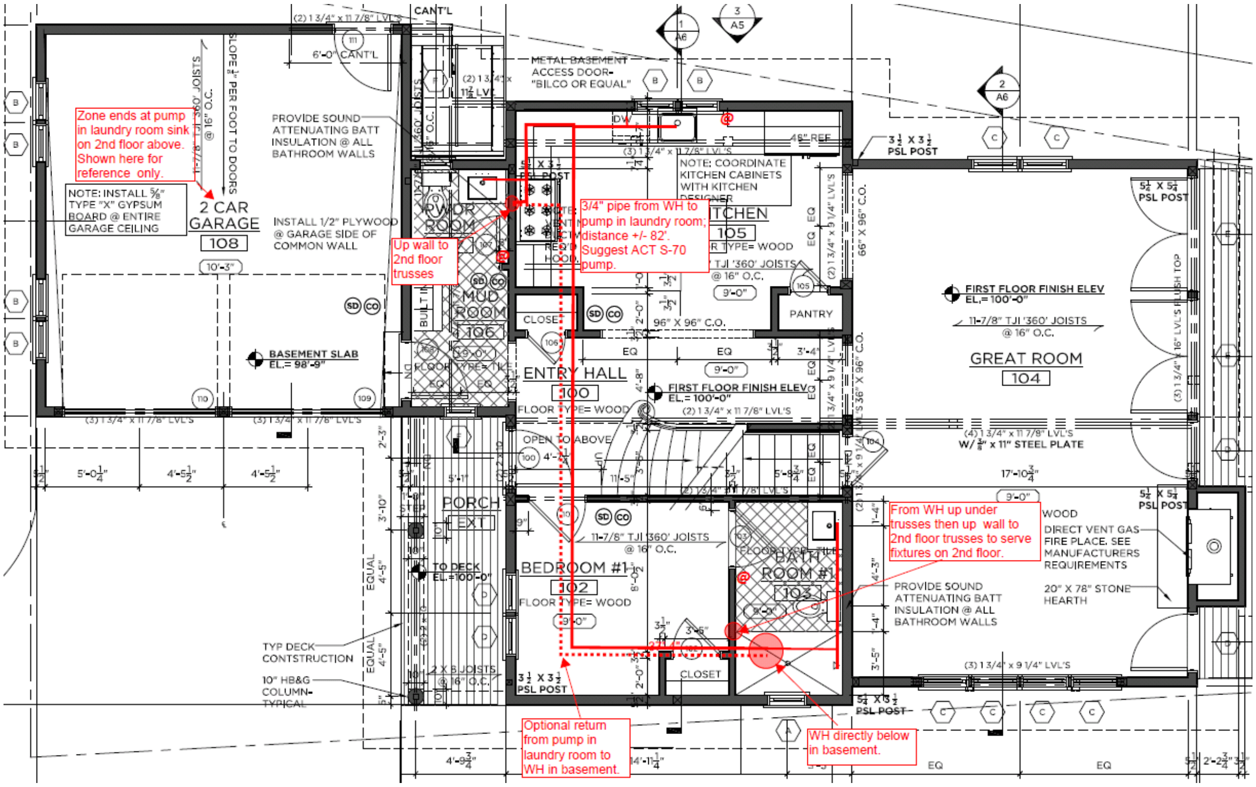


Position trunk line under 1st floor trusses as far east as possible to reduce the length of branch line to kitchen sink on 1st floor.

Optional return line from 2nd floor pump.

Start of 2nd zone serving the 2nd floor fixtures. Up wall to 1st floor trusses.

Figure 13. Basement floor plan



Zone ends at pump in laundry room sink on 2nd floor above. Shown here for reference only.

Up wall to 2nd floor trusses

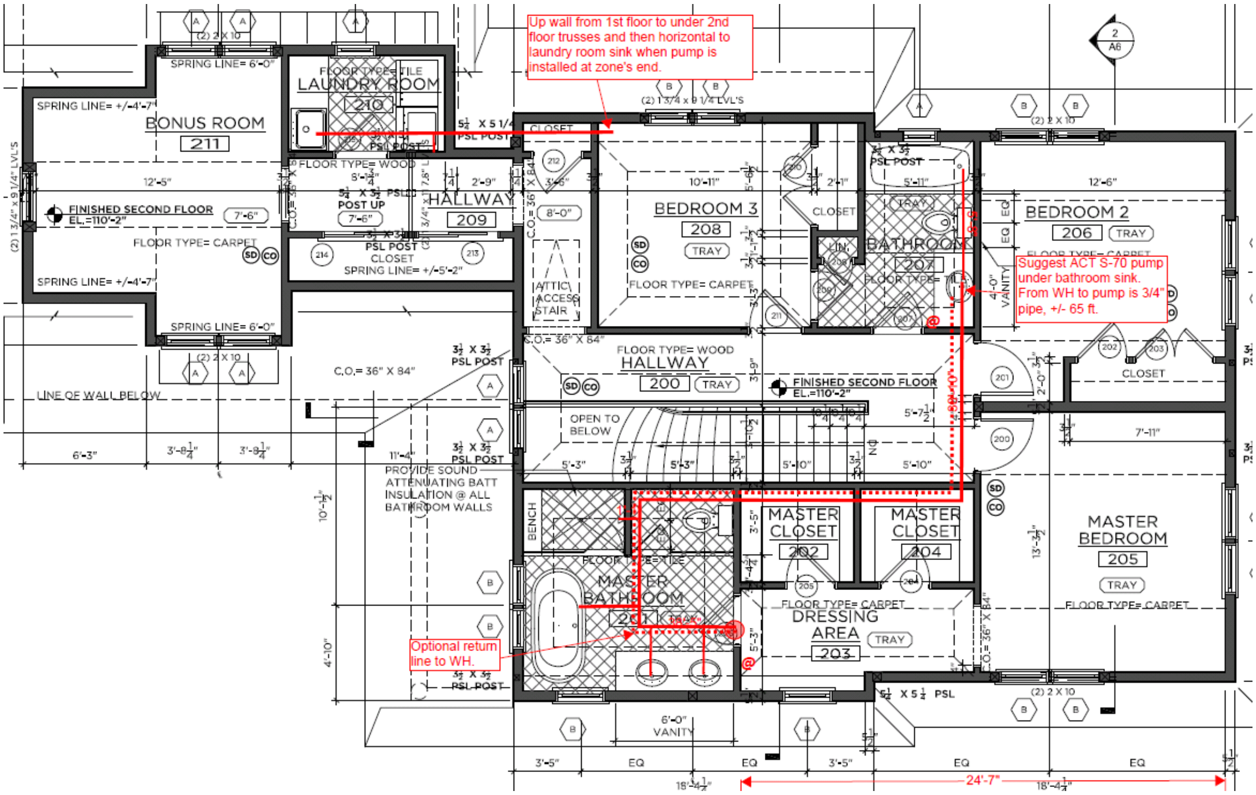
3/4" pipe from WH to pump in laundry room; distance +/- 82'. Suggest ACT S-70 pump.

From WH up under trusses then up wall to 2nd floor trusses to serve fixtures on 2nd floor.

Optional return from pump in laundry room to WH in basement.

WH directly below in basement.

Figure 14. 1st floor plan


Up wall from 1st floor to under 2nd floor trusses and then horizontal to laundry room sink when pump is installed at zone's end.

Suggest ACT S-70 pump under bathroom sink. From WH to pump is 3/4" pipe, +/- 65 ft.

Optional return line to WH.

Figure 15. 2nd floor plan

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