BUILDING TECHNOLOGIES PROGRAM

Winchester/Camberley Homes New Construction Test House Design, Construction, and Short-Term Testing in a Mixed-Humid Climate

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NAHB Research Center Industry Partnership

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Winchester/Camberley Homes New Construction Test House
Design, Construction, and Short-Term Testing in a Mixed-Humid Climate

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Definitions

ACCA	Air Conditioning Contractors of America
ACH	Air changes per hour
ADA	Airtight drywall approach
AFUE	Annual fuel utilization efficiency
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
ANSI	American National Standards Institute
Btu	British thermal unit
CFL	Compact fluorescent lighting
CPVC	Chlorinated polyvinyl chloride
ECM	Electrically commutated motor
EF	Energy factor
ERV	Energy recovery ventilator
ft^2	Square foot
h	Hour
HRV	Heat recovery ventilator
ICC	International Code Council
IECC	International Energy Conservation Code
iwg	Inches of water gauge pressure
Low-e	Low-emissivity
MBtu	Thousand Btu
MERV	Minimum efficiency reporting value (for media-type air filters)
NAHB	National Association of Home Builders
NCTH	New construction test house
NGBS	National Green Building Standard (ANSI ICC 700-2008)
OSB	Oriented strand board
PEX	Cross-linked polyethylene
SEER	Seasonal energy efficiency ratio
SHGC	Solar heat gain coefficient
SPF	Spray polyurethane foam
TXV	Thermostatic expansion valve
WHI	Winchester Homes, Inc. and its Camberley Homes division

Executive Summary

The NAHB Research Center partnered with production builder Winchester/Camberley Homes to build a new construction test house (NCTH) with the support of the U.S. Department of Energy Building America Program.[1] This single-family detached house, located in the mixed-humid climate zone of Silver Spring, Maryland, was completed in June 2011. The primary goal for this house was to improve energy efficiency by 30% over the Building America B10 benchmark by developing and implementing an optimized energy solutions package design that could be cost effectively and reliably constructed on a production basis using quality management practices.

This report outlines the features of the house, discusses the implementation of the energy efficient design, and reports on the short-term testing results. During the interactive design process of this project, numerous iterations of the framing, air sealing, insulation, and space conditioning systems were evaluated for energy performance, cost, and practical implementation. The final design featured numerous advanced framing techniques and high levels of insulation. In addition, the HVAC system was built entirely within conditioned space. Short-term testing confirmed a very tight thermal envelope and efficient and effective heating and cooling. Relevant heating, cooling, humidity, energy, and wall cavity moisture data will be collected and presented in a future long-term report.

[1] See http://www1.eere.energy.gov/buildings/building_america/program_goals.html for more information.

1 Introduction

1.1 Overview

With the support of the U.S. Department of Energy Building America Program (see footnote 1), as part of the NAHB Research Center Industry Partnership, the NAHB Research Center (Research Center) partnered with production builder Winchester Homes, Inc. (WHI) and its Camberley Homes division to build a new construction test house (NCTH). This single-family detached house is located in the mixed-humid region (climate zone four) of Silver Spring, Maryland. The three-story (four levels including a basement) Victorian-style house, built as a model home, was completed in 2011.

This report outlines the energy efficiency features of the house, discusses construction and installation, and reports on short-term characterization testing. Long-term monitoring and additional cost analysis will be detailed in a future report.

1.2 Background

The NCTH, shown in Figure 1, was built in the Poplar Run subdivision in Montgomery County, Maryland, a suburb of Washington, D.C. This subdivision will eventually contain 700 homes, 100 of which are expected to incorporate the energy efficient design of this house. Based on consumer acceptance and measured performance of this research project, some of the remaining 600 homes may also include these advanced energy features.

Figure 1. Winchester/Camberley NCTH

The three-story design had 3,228 ft^2 of conditioned floor area above grade, including a 605 ft^2 finished third floor with a sitting room, a full bath, and a fourth bedroom. A finished basement brought the total to 4,441 finished ft^2. The finished third floor and basement were included builder options. Ceilings were 9 feet for the first floor and basement, 8 feet for the second floor, and 8 feet or sloped for the third floor. Above-grade walls were frame construction; basement foundations were poured and mostly below grade. All attic areas were vented. A unique design feature of this home was the octagonal, three-story turret that housed the open stairwell connecting the basement to the second floor. Access to the third floor was by a separate stairway. The garage was not attached to the house.

1.3 Goals

The primary performance goal for this house was to improve energy efficiency by 30% over the Building America B10 benchmark by developing and implementing optimized framing, air sealing, insulation, and space conditioning system designs that could be cost effectively constructed on a production basis using quality management practices. The Building America goals align well with the builder's long-term goals for performance and construction quality. Specific goals for the NCTH were established during the planning phase:

- Develop and implement a durable design that improved energy efficiency by at least 30% over a comparable house that meets the 2009 International Energy Conservation Code (IECC; see International Code Council [ICC] 2009).
- Create a tight thermal boundary and increase insulation levels to be in accordance with expected higher levels in future editions of energy codes or from consumer demand.
- Develop an envelope design that would be flexible in adapting to higher insulation levels without costly architectural or structural redesign efforts.
- Optimize the wall design to improve thermal performance and minimize the potential for moisture accumulation inside the wall cavity while controlling cost increases.
- Design the HVAC system to be located entirely in conditioned space to significantly reduce energy losses (leakage and convection losses from equipment and ducts) to unconditioned space, reduce duct run lengths, and eliminate the need for a second system.
- Design the HVAC system to ensure occupant comfort in this four-level design.
- Develop a cost-effective integrated design that extracts construction efficiencies across building systems that could be constructed on a production basis using quality management practices.
- Develop a test and monitoring plan to evaluate energy use, heating and cooling distribution, and wall moisture performance.
- Earn the American National Standards Institute (ANSI)/ICC 700-2008 (2009) National Green Building Standard (NGBS) Silver Level Green Certification.

2 Design Development

2.1 Design Process and Energy Simulations

The builder was committed to including high performance home features to significantly exceed current energy code requirements and decided to develop a new product line that integrated the energy features instead of modifying an existing model. The thermal envelope was completely redesigned from standard specifications and a set of high performance construction features was developed for the new house design. The final energy efficiency solution package represented months of development by the Research Center, WHI staff, trade contractor professionals, manufacturers, and product suppliers. The design process involved technical input, energy modeling, and optimization by the Research Center and input on costs and other practical factors by team members. Energy savings were simulated using BEopt v1.1.[2] Through BEopt software optimization and other analyses, a set of options that provided the highest predicted energy savings for the lowest investment costs was determined. These energy simulations are detailed in Appendix A and indicate that the Building America energy savings goal was met.

2.2 Cost Analysis

During the design process, WHI completed an extensive in-house cost analysis, which allowed the builder to choose specific systems over other options (e.g., business as usual versus 2 × 4 with exterior rigid foam versus 2 × 4 with cavity spray foam, among others). This analysis included energy performance, occupant comfort, and synergistic cost containment benefits such as reduced material and labor costs. The high performance features were selected and designed to perform as an integrated system.

A detailed cost analysis is planned for the future long-term monitoring test report for this project. WHI is currently completing three additional houses of similar design that include the energy savings features of the NCTH. Once these are complete, the Research Center will work with WHI to finalize the cost analysis, allowing investigators to more fully understand the incremental costs. Understanding a builder's cost approach is not necessarily a straightforward analysis because of the pricing structure for the different materials and the lack of comparative pricing for the framing system. Additionally, there is no reference point for "builder standard practice" because the homes are a new product line and unique to the builder.

2.3 Energy Solutions Package

The project planning stage included four builder-directed design review meetings conducted at the Research Center. Attendees included the project manager, the operations manager, the site superintendent, design and purchasing personnel, structural engineers, floor component and wall panel vendors, and trade contractors. Numerous iterations of the framing, air sealing, insulation, and HVAC systems were evaluated for energy performance, cost, and practical implementation.

For example, the meeting participants decided early in the process that wall panels would have structural sheathing without foam on the exterior. The builder was concerned about the structural durability of foam sheathing products without oriented strand board (OSB) and the durability of cladding attachment over rigid foam with or without OSB. Based on this decision and recognizing the need for higher insulation levels for this climate zone in the future, a nominal

[2] See http://beopt.nrel.gov/ for more information.

2-in. × 4-in. wall cavity would require higher density insulation such as closed-cell spray polyurethane foam (SPF) insulation. After evaluating the cost for a 2-in. × 4-in. wall with SPF, this option was ruled out in favor of a 2-in. × 6-in. frame wall with batt or blown insulation. Once this decision was made, the wall panels were redesigned to optimize performance, including engineered structural rim boards, elimination of nonstructural nailers where possible, and other advanced framing techniques (detailed in Table 2) to increase room for insulation and provide a higher level of air sealing. To avoid nonstandard length studs and maintain ceiling heights, a conventional second top plate was included in this new design. Figure 2 shows the construction of the wall design using this advanced framing technique.

Figure 2. Advanced wall framing

Another example of this iterative design process was the early decision to install the entire HVAC system in conditioned space to reduce energy losses. This required redesigning the floor plan and floor framing to accommodate a central duct chase to serve all four levels. This chase was sized to accommodate the vertical sections of the supply and return trunk ducts within. Additionally, a bulkhead along the first floor ceiling to conceal the supply trunks serving the second and third floors was not architecturally acceptable.

As a result, the horizontal sections of the supply trunks serving the upstairs (second and third floors) were integrated within the second-floor framing (installed perpendicularly through factory cutouts through the floor joists) so that all of this upstairs duct would be above the first-floor ceiling plane. A bulkhead at the first floor ceiling would not be required. The supply trunks serving the downstairs (first floor and basement) were installed in the basement in a more conventional manner (below and perpendicular to the first-floor joists) because a bulkhead to conceal this duct was deemed acceptable in finished portions of the basement.

Specialized design software was used to prepare accurate drawings showing exact locations of the mechanicals (including plumbing and sprinkler piping) within the floor system, including the central duct chase. These drawings were then used at the factory to number and cut all joists and rim boards to exact lengths, and to precisely cut openings through the I-joists as required. Figure 3 shows the central duct chase and integrated duct and floor-joist design. This high-level integration of structural and mechanical systems required a complete duct design during the planning stage to size the chase and joist openings. Similar planning was necessary for the plumbing and sprinkler piping.

Figure 3. Supply trunk through floor joists and central duct chase

This iterative approach to evaluating benefits and trade-offs of alternative designs was applied to insulation and air sealing products and methods, floor and truss framing, windows, HVAC equipment, and the water heater and plumbing distribution system. Table 1 summarizes the design, and Table 2, Table 3, and Table 4 give additional details.

Table 1. Cost-Effective Energy Solutions Summary

Design Consideration	Solution
Increased Insulation	• Optimized framing to increase thermal performance
Improved Air Sealing	• Detailed strategy balanced with cost and consistency of installation
Improved HVAC System Efficiency	• Reduced the number of equipment systems from the traditional two HVAC systems to one • Redesigned floor plan, framing, and ducts to locate entire system in conditioned space for significant energy savings • Improved equipment operating efficiencies • Improved ventilation, filtration, and occupant comfort
Quality Assurance and Control	• Included practical input from WHI, vendors, and trade partners during planning stage design reviews • Developed construction details and specifications • Established construction monitoring points (reviews, inspections, and tests)
Repeatable Design	• Specified features that optimized performance, cost, and practical implementation

Many of the new construction details were included in the drawing package. Goals and expectations for the trade contractors were mutually agreed on, and site reviews, inspections, and tests were scheduled for quality assurance. The level of effort invested during the planning stage was considered important for the successful design and implementation of the solution package for this test house as well as subsequent houses.

3 Thermal Envelope

The thermal envelope design consisted of an integrated framing package with considerations for air sealing and openings. The package also maintained the Victorian architectural style while allowing as much insulation as possible in the exterior walls and attic. Table 2 shows the thermal envelope design compared with standard regional practice.

Table 2. Thermal Envelope

Feature	Standard Practice	NCTH
Foundation	• R-10 walls	• R-13 walls
Walls	• 2 × 4 frame, 16 in. on center • R-13 batt insulation	• 2 × 6 frame, 24 in. on center • Structural rim headers • Reduced framing • R-24 blown fiberglass insulation • Continuous drywall method
Air Sealing	• Bottom plates sealed at deck • Penetrations sealed • Window rough openings sealed	• Same as standard practice plus the following: ▪ Sealed frame at all critical areas (see Table 3) using spray-applied, water-soluble, elastomeric sealant ▪ Airtight drywall approach ▪ House wrap installed as air barrier
Windows	• U-value = 0.35, SHGC = 0.35	• Low-e, U-value = 0.31, SHGC = 0.28
Doors	• n/a	• U-value = 0.35, SHGC = 0.36
Roof/Attic (Vented)	• Standard truss, 1-ft overhang • R-38 blown fiberglass	• Raised heel truss, 2-ft overhang • R-49 blown fiberglass insulation, full depth at eaves and sloped ceilings • Ice and water shield at eaves and valleys • Drip edges at eaves and rakes

Notes: Low-e, low-emissivity; SHGC, solar heat gain coefficient

3.1 Framing

Floor framing was optimized using I-joists, 24-in. on center as shown in Figure 4. The reduced cost of fewer floor joists was partly offset by selecting ⅞-in. floor decking (instead of ¾-in.) to ensure rigid floors. Floor joists and rim boards were cut to exact lengths and numbered at the factory for efficient installation. Cutouts through the joists for the HVAC duct, the plumbing, and the sprinkler piping were also made at the factory.

Figure 4. Floor framing

The factory-built wall panels shown in Figure 5 were redesigned to reduce thermal bridging and increase insulation volume. Walls were 2-in. × 6-in. wood frame, 24 in. on center, with ½-in. OSB sheathing. Structural rim headers eliminated first-floor headers and jack studs; unnecessary blocking, studs, and cripples were also eliminated. Second-floor headers were engineered to minimize dimensions to reduce initial cost, reduce thermal bridging, and increase wall insulation. Second top plates and a house wrap were installed in the field. Cladding was fiber cement siding.

Figure 5. Wall panels

The continuous drywall method was specified to further reduce framing air losses. All interior partition walls were installed 1 in. from the exterior walls, allowing the wallboard to be slid through this space along the exterior walls shown in Figure 6. These walls were structurally attached using metal plates above the top plates. Electric and plumbing trade partners' specifications required that electric wiring or pipes were not to be installed in this space.

Figure 6. Continuous drywall method

In the basement, wood frame walls were site-built and held 1 in. from the poured foundation. In the attic, raised heel roof trusses with the 2-ft overhangs shown in Figure 7 accommodated full-depth insulation and insulation baffles at the eaves and notably at the sloped ceilings of the third floor.

Figure 7. Raised heel truss with increased overhang at eaves

3.2 Air Sealing

To achieve very low infiltration rates given the frame walls and complex thermal boundary, identifying critical areas for air sealing was essential. This house design was considered architecturally complex to air seal primarily because of the third floor and turret as shown in Figure 8, Figure 9, and Figure 10. The third floor had front and rear knee wall attics, partially sloped ceilings, and a separate attic above the flat ceiling. The top of the turret and the third floor were separated by the front attic. Additionally, the following were all adjacent to the same attic: the stairs to the third floor, the HVAC chase, a knee wall framed cavity, a gable knee wall for a second-floor bedroom with a cathedral ceiling, and two closets with lower ceilings. This complex design created the need for the installation and sealing of numerous air barriers including the blocking of floor joists below third-floor knee walls.

Figure 8. Complex thermal air boundary (1 of 3)

Figure 9. Complex thermal air boundary (2 of 3)

Figure 10. Complex thermal air boundary (3 of 3)

The primary air sealing strategy was to create an effective air barrier exterior to the insulation. A secondary strategy was to provide an interior air barrier using the airtight drywall approach (ADA). The product selected for both was a spray-applied, low-expanding, water-soluble, elastomeric sealant (sealant) applied at all critical area seams of the wood frame. Table 3 outlines the critical areas where the sealant was applied, and Figure 11 shows examples of air sealing.

Table 3. Critical Areas to Apply Sealant

Critical Area	Specific Location for Sealant
Exterior Walls	Stud cavities: top and bottom plates at sheathing
	Stud cavities: studs at sheathing seams
	Face of top plates, between top plates
	Face of studs at wall panel connections
	Bottom plates at floor deck
	Electrical boxes and other exterior penetrations
Partition Walls	Face of top plates adjacent to a vented attic
Rim Areas	Rim board at floor deck and top/sill plate
	Floor-joist air barriers below third-floor knee walls
	Sill plates at the foundation
	Basement frame wall cavity, top plates at foundation wall
Knee Wall Air Barriers	Third floor, front and rear
	Third-floor stairs
	Gable knee wall of second floor, front bedroom cathedral ceiling
	Portions of turret walls
Framed Cavity Air Barriers	Behind the fireplace
	Behind tubs at exterior walls
	HVAC chase, wall and sloped ceiling
	Closet ceilings adjacent to attic
	Knee wall cavity created by second knee wall
Additional Areas for ADA	Face of bottom plates
	Face of window and door rough openings on exterior walls
	Electrical boxes in exterior walls

Figure 11. Air sealing

As a tertiary air sealing strategy, house wrap was installed as a secondary exterior air barrier, which also serves as the drainage plane. All house wrap seams were taped, and the top and bottom edges were sealed to the frame. To seal the bottom edge, first flashing tape was applied to the sheathing with a 1-in. overhang below the sill plate, and then house wrap was shingled over and sealed to the flashing tape as shown in Figure 12. To seal the top edge, house wrap was held 2 in. from the top of the sheathing and then covered with flashing tape. The flashing tape was also mechanically secured with staples.

Figure 12. House wrap installed as air barrier

Windows and doors were installed and flashed in a conventional manner per manufacturer instructions. Attic access panels and ceiling penetrations adjacent to attics, including electrical boxes, speakers, and recessed lights, were sealed after drywall using gaskets, foam, or caulk.

3.3 Insulation and Fenestration

After air sealing, above-grade wall cavities were netted and blown using R-24 dense-pack fiberglass insulation. The triangular voids between the wall panels of the octagonal turret were filled using spray foam insulation from a can because these walls had been installed with a ¾-in. gap between panels to allow for the installation of the spray foam. Basement walls were insulated using R-13 fiberglass batts. Attic insulation, including the sloped ceilings of the third floor, was increased to R-49 by using fiberglass batt insulation in some sloped ceiling locations and blown fiberglass insulation in other locations. Attic insulation in a few locations was installed before drywall using netting because access to these attic areas would be very limited after drywall installation. Windows were double hung, vinyl, and improved to low-e, a U-value of 0.31, and an SHGC of 0.28. Figure 13 shows the installed insulation and fenestration.

Figure 13. Wall and attic insulation

4 Systems

The systems design included heating, cooling, duct, ventilation, plumbing, and lighting. The goal of the systems design was to improve equipment operating efficiencies, ventilation, filtration, and occupant comfort. Two significant design details for the test house systems include (1) locating the ducts entirely in conditioned space and designing the duct location in conjunction with the framing design and (2) properly sizing the HVAC system given the thermal envelope of the house, which allowed one HVAC system to be installed where typical regional practice would install two systems. Table 4 outlines the systems for the WHI test house.

Table 4. Systems

System	Standard Practice	NCTH
Heating	Two 80% AFUE natural gas furnaces (one in vented attic and one in basement)	One 92.5% AFUE natural gas furnace with two-stage gas valve and ECM air drive, installed in basement
Cooling	Two 13 SEER systems	One 15 SEER system
Thermostat	Programmable	Programmable with integral humidistat and controls to run the cooling system in dehumidification mode
HVAC duct	One flexible, insulated duct system in vented attic and one metal duct system in basement	One system 100% in conditioned space with supply trunk balancing dampers. Simplified central return with one grille per level and bedroom transfer grilles
Filtration	Standard 1-in. filter (MERV 1–4)	MERV 10 high-efficiency pleated filter
Ventilation	One bath exhaust fan with programmable control	Mechanical ventilation with damper and control
Plumbing	65-gal natural gas water heater, EF = 0.60; CPVC branch and tee piping	50-gal, power vent, natural gas water heater, EF = 0.74; PEX manifold piping
Lighting	50% CFL	80+% CFL

Notes: AFUE, annual fuel utilization efficiency; ECM, electrically commutated motor; SEER, seasonal energy efficiency ratio; MERV, minimum efficiency reporting value; EF, energy factor; CPVC, chlorinated polyvinyl chloride; PEX, cross-linked polyethylene; CFL, compact fluorescent lighting

4.1 HVAC System

The HVAC system was designed so that all equipment and ductwork would be located within conditioned space to significantly reduce equipment and distribution energy losses resulting from conduction and leakage. Standard WHI practice used two independent systems—one in the basement to condition the first floor and basement, and a second in the attic (furnace and ducts) to condition the second and third floors. This approach, common in this region, provides effective heating and cooling comfort (two independent zones) and is simple to install (no supply ducts running between floors). The additional equipment costs are typically considered a tradeoff to the expectation of satisfactory occupant comfort and expediency. Installing two systems expedites the design stage and does not require site efforts to integrate the systems within conditioned space, but one system could often easily meet the heating and cooling load calculations. The WHI NCTH design was a single HVAC and duct system located in the conditioned space with the expected result, in addition to energy savings, of equipment cost savings.

High-efficiency equipment was specified: a 15 SEER cooling system and a 92.5% AFUE natural gas furnace. The furnace shown in Figure 14 was direct vent (a two-pipe design that uses outdoor air for combustion) with a two-stage gas valve and an ECM air drive. The furnace was selected based on the cooling air flow requirements. In high-heat mode the furnace output was much higher than the design load; in low-heat mode, however, the output matched much more closely with the calculated load. The programmable thermostat with its integral humidistat had the capability of running the furnace in dehumidification mode (reduced blower speed) to improve moisture control during the cooling season. Electronic zone dampers were specified to ensure occupant comfort in this four-level house design. Load calculations, equipment selection, and duct design were in accordance with the recommendations of the Air Conditioning Contractors of America's (ACCA's) Manual J (2006), Manual S (2004), Manual T (1992), and Manual D (2009).

Figure 14. Furnace and first-floor return grille at central chase

The centrally located duct chase shown in Figure 14 served all four levels. A simplified return duct system, consisting of one central return per level, was installed in the chase. Bedroom transfer grilles, baffled to minimize light and noise, provided a return air pathway. The return duct was intentionally sized in accordance with ACCA Manual D, Table A1-1, Air Velocity for Noise Control recommendations and acoustically lined to ensure quiet operation, an important consideration with the furnace installed in the basement directly below the first-floor return grille.

Figure 14 shows how the vertical section of the upstairs (second and third floors) supply trunk duct was also installed in the chase. The horizontal sections of the upstairs supply trunk duct were integrated within the second-floor framing as shown in Figure 15. Supply branch ducts were installed between the joists, and vertically through interior walls for the third floor, to perimeter floor registers.

Figure 15. HVAC supply trunk installed in second-floor framing

The downstairs (first-floor and basement) supply trunk was installed in a more conventional manner: below and perpendicular to the first-floor joists. As a result, a bulkhead was required to conceal this trunk in the finished portions of the basement. Supply branch ducts were installed between floor joists to perimeter floor registers on the first floor and ceiling registers in the basement. All ducts were sealed using mastic.

Fresh air ventilation for moisture control and indoor air quality was provided using a supply-type central fan-integrated design. The design is capable of meeting ASHRAE Standard 62.2 ventilation recommendations (ASHRAE 2010). An insulated metal duct delivered outdoor air to the HVAC return plenum through a motorized damper opened or closed by an electronic control. This design allowed outdoor air to be filtered, conditioned, and well distributed during a call for heating or cooling, and the source of outdoor air would be known (unlike exhaust-only systems that rely on makeup air infiltrating through the house envelope). The ventilation control would also activate the damper and furnace blower when the heating or cooling run times did not satisfy the desired ventilation rate. A balanced ventilation system based on the use of an energy recovery ventilator (ERV) or heat recovery ventilator (HRV) was ruled out as too costly. The expectation for the selected supply-type ventilation was that positive house pressure would not be excessive and would tend to be alleviated via exhaust fan ducting, in effect providing a partially balanced system. As such, the system would not contribute to potential moisture drive into the wall cavities.

A high-efficiency (MERV 10), media-type, pleated air filter was installed to improve air quality. The filter cabinet had a gasketed access door and its location adjacent to the furnace allowed for simple filter replacement. Because the builder was concerned that the abundant wood floors and trim might dry too much and crack during the heating season, a central humidifier was installed.

Bath exhaust fans were ENERGY STAR and rated to be quiet (0.8 sone at 0.1 in. of water gauge pressure [iwg] static pressure). Wall switches with timers were installed for these fans to ensure adequate moisture removal. These switches had a 20-minute fan-on delay and were capable of being programmed for supplemental ventilation, if desired.

4.2 Plumbing

Domestic hot water was provided by the 50-gallon, natural gas, power vented water heater shown in Figure 16. The estimated EF was 0.74 (manufacturers are not required to provide EF ratings for units with inputs exceeding 75,000 Btu/h). The water heater was centrally located, low-flow plumbing fixtures were installed, and a PEX manifold distribution system was installed to minimize energy and water use.

Figure 16. High-efficiency water heater

4.3 Lighting and Appliances

High-efficiency lighting was increased to more than 80% of total lighting by specifying dimmable fluorescents in recessed fixtures and fluorescent lamps in other standard fixtures. Recessed lighting fixtures were upgraded to sealed units to reduce air leakage (the incremental cost was attributed to the lighting option budget). Appliances were all ENERGY STAR rated. Additionally, the house design included one natural gas direct vent fireplace with a sealed glass panel.

5 Implementation

5.1 Framing

The floor component manufacturer conducted an on-site installation review the morning of floor framing to ensure that the numbered joists and rim boards shown in Figure 17 and Figure 18 were efficiently and accurately installed. Two components were missing from the delivery and some minor field modifications were required, but this did not appear to affect the construction schedule. The floors and numbered wall panels shown in Figure 19 and Figure 20 were installed in 2 days. The roof trusses and framing were also numbered for efficient installation. After framing was complete, WHI staff observed and corrected some rim, header, and wall nailing issues. The ⅞-in. floor decking, which was installed over the 24-in. on center floor joists, resulted in an observably stiff floor.

Figure 17. Floor framing

Figure 18. Floor framing and wall panels

Figure 19. Wall panels

Figure 20. Wall panels and trusses

5.2 Air Sealing and Insulation

The primary air sealing challenge was the difficulty of identifying a continuous thermal and air sealing boundary for this complicated house design. A notable effort was made to include the air sealing boundary on the drawings (see Appendix B); however, the three-dimensional aspect of the boundary made an on-site review, just before air sealing, imperative. This review included the framing contractor (responsible for installing the air barriers) and insulation contractor (responsible for sealing the air barriers) because they needed to coordinate their efforts.

After air sealing, a walk-through showed that the majority of critical areas had been sealed. Because of the high expectations for this house, a number of areas needed to be touched up before installing insulation, including portions of top plates and header cavities, and portions of air barriers at knee walls, joist blocking, and framed cavities. Identifying areas that needed to be touched up was not intended as criticism of the product or trade contractors; instead, it was intended to highlight the challenge of identifying a continuous thermal and air barrier with such an architecturally complex design. A key advantage of using a product and method such as this sealant was the ability to visually inspect after air sealing and, if necessary, make corrections before insulation and drywall installation. Figure 21 shows an example of the complexity of air sealing these areas.

Figure 21. Air sealing at blocking below third-floor knee wall and knee walls

Sealant was not consistently applied to the faces of the framing at the bottom plates and around windows and doors (although bottom plates were sealed at the floor deck). These areas were specified to be sealed in accordance with the ADA, but the contractor did not consider this necessary. Although sealant was applied in the gap between the rough framing and the windows and doors, these gaps might have been more effectively sealed using low-expansion spray foam insulation instead. Research Center personnel did not consider it necessary to apply sealant to the interior faces of the bottom cords of second- and third-floor roof trusses (although it would not have been detrimental). The sill plate at the foundation wall could not be sealed from the interior because the basement wall framing had already been installed (see Figure 22); instead, sealant was applied from the exterior at this critical area.

Figure 22. Air sealing at basement rim area

Sealing the house wrap to function as a secondary exterior air barrier was initially considered a simple, additional method to reduce infiltration. During construction, some areas of the house wrap were not completely air sealed as planned because they were challenging or overlooked, but an effort to correct all of these areas was not considered critical because the sealant was used as the primary air sealing strategy.

To insulate the wall cavities, netting was stapled to the faces of all exterior wall framing. Next, the loose fiberglass insulation was blown into each cavity, using a hose from a truck outdoors, through one slit in the netting (see Figure 23). Wall cavity density was measured as the work progressed to ensure that the target insulation levels were achieved (see Figure 23). For attic insulation, netting was installed at the ceiling plane where fiberglass batts had not already been installed. Next, loose fiberglass was blown into these areas. All wall and ceiling insulation was complete before drywall installation.

Figure 23. Installing wall cavity blown insulation and checking density

5.3 HVAC

During the design phase, the participants did not consider it acceptable to cut openings through the second-floor structural rim boards to allow the upstairs supply trunks to be slid into place. For this reason, the HVAC trade contractor installed these trunks in sections, through the joist cutouts, as the second-floor joists were being installed. This implementation approach required an additional site trip for the HVAC contractor.

Figure 24. Installing HVAC trunk through floor joists

The electronic zone dampers originally specified were eliminated as too costly. Manual dampers, accessible from the furnace room, were installed instead in the three supply trunks. Two trunks, one for the front and one for the rear, supplied the first floor and the basement. The third trunk was dedicated to the second and third floors. This allowed air flow balancing between the two lower levels (first floor and basement) and the two upper levels (second and third floors), but not between the second and third floors.

All ducts were sealed with mastic as planned. Before the furnace was installed, a rough duct leakage test indicated higher than expected leakage. A second rough test was conducted using theatrical smoke. The HVAC contractor was on site to visually identify the leakage areas in need of repair. After additional mastic was applied to these areas, a third rough test measured the improvement (see Section 6.3 for test results).

A standard efficiency, nominal 13 SEER cooling system was installed instead of the 15 SEER that was originally specified. This substitution was the result of a contract-related decision between the WHI purchasing department and the HVAC contractor. The ECM in the furnace typically improves the rated SEER, and although this system is likely operating above 13 SEER, this equipment combination (gas furnace, condensing unit, evaporator coil, and thermostatic expansion valve [TXV]) had not been rated by the Air-Conditioning, Heating, and Refrigeration Institute (AHRI). Note that the condenser and the coil are a rated AHRI match, but they had not been additionally rated with this furnace.

6 Testing

6.1 Test Plan

Many of the energy efficiency features incorporated into the house design were new to the builder and trade contractors. As a model home, the house will likely see extremes in energy usage that result from the anticipated additional heating, cooling, lighting, and miscellaneous loads. Using this NCTH for testing and evaluating products and methods is critical in addressing the following research questions:

- Based on the redesigned single-zone duct air delivery system, how consistent are the interior temperatures on each of the four levels of the home and how do these temperatures change throughout the day during summer peak cooling days and winter peak heating days?
- Is the measured energy use for heating and cooling consistent with modeled estimates given similar ambient weather conditions?
- Are the HVAC elements—furnace, compressor, thermostat, humidifier, and fresh air supply damper—operating as designed and in an optimal manner?
- How do the wall cavity environmental conditions change with seasonal interior and exterior conditions and are the sheathing moisture characteristics within expected swings?
- How do the wall cavity moisture characteristics compare with modeled results in WUFI software?
- Is there anecdotal evidence of the marketplace response to the costs, features, and interior conditions of the house from the builder, potential buyers, trade contractors, or manufacturers?

To answer all but the last question, a team will take the research measurements detailed in Table 5. Feedback from WHI will be used to evaluate the last question.

Table 5. Research Measurements and Equipment

Measurement	Equipment	Test Type
Infiltration Rate	Minneapolis Model 3 blower door and DG700 manometer	Short-term characterization test
Duct Loss	Minneapolis Series B duct blaster and DG700 manometer	Short-term characterization test
Air Handler and Duct Flow Rates	Trueflow grid, balometer, hot wire anemometer	Short-term characterization test
Temperature, Humidity, Moisture Content	Omnisense S-900 wireless sensor	Long-term monitoring
Electric Energy	Watt Node transducers and associated current transformer sizes	Long-term monitoring
Gas Valve On-Time	Low-current switch	Long-term monitoring
Data Recording—Temperature/Humidity/ Moisture Content	Omnisense Gateway connected to protected website	Long-term monitoring
Data Recording—Energy, Runtime, and Others	Campbell Scientific data logger, modem	Long-term monitoring

Short-term test results are detailed in the following sections. Long-term monitoring will be detailed in a future report after collecting at least 1 year of monitored data.

6.2 Infiltration Testing

An intermediate blower door test (shown in Figure 25), performed after drywall installation but before trim, floors, and ceiling penetrations were sealed, identified one significant leakage area. A short wall built in front of a third-floor knee wall to increase ceiling height created a framed cavity, common to the HVAC chase, that resulted in significant leakage from the attic at the angled top plate and sloped ceiling. A second intermediate test, conducted after this area was re-sealed and the house was substantially complete except for the sealing of all ceiling penetrations, showed a significant improvement. Final testing measured an additional improvement for the completed house as detailed in Table 6.

Figure 25. Blower door test apparatus and duct test using theatrical smoke

Table 6. Characterization Testing: House Leakage

Performance Metric	NCTH			Units
House Size	4,441			Finished area (ft^2)
	4,568			Conditioned area (ft^2)
House Volume	41,847			ft^3
Infiltration	Test 1[a]	Test 2[b]	Final[c]	
	2,400	1,380	1,335	CFM50
	3.4	2.0	1.9	ACH 50
	0.17	0.10	0.10	ACH natural
	0.53	0.30	0.29	CFM50

[a] Before trim and sealing of all penetrations but after sheetrock installation
[b] After access panels and other knee walls from the third-floor room to the attic were sealed
[c] Final after all finishes complete
Notes: CFM, cubic feet per minute; CFM 50, cubic feet per minute at 50 Pa; ACH 50, air changes per hour at 50 Pa

6.3 Duct Leakage Testing

Several rough duct leakage tests were conducted before the furnace was installed. The first test indicated higher than expected leakage. A second test, using theatrical smoke (shown in Figure 25), identified leakage areas, and a third test measured the improvement after additional mastic was applied. During the rough tests, the house was not ready for a blower door test, so leakage to the outdoors could not be measured. After the furnace was installed, the final duct leakage test measured an additional 253 cfm compared to the previous rough test. This may be largely attributed to the furnace, coil, and air cleaner cabinets. Sealing registers and grilles to finished floors and walls during final testing may also allow additional leakage between these surfaces, compared to sealing these areas during a rough test. The majority of the ductwork was concealed with drywall, so further testing and repair was not practical. An additional rough test conducted after the installation of the furnace, filter, and coil, but before drywall, would have provided a valuable incremental test result. Duct leakage to outdoors, as expected, was relatively low. Table 7 summarizes the duct leakage testing results.

Table 7. Characterization Testing: Duct Leakage

Performance Metric	NCTH				Units
House Size	4,441				Finished area (ft^2)
	4,568				Conditioned area (ft^2)
Duct Leakage	Rough 1[a]	Rough 2[a,b]	Rough 3[a,c]	Final[d]	
	209	248	183	436	CFM25 total
	4.6	5.4	4.0	9.5	CFM25/100 ft^2
	n/a	n/a	n/a	43	CFM25 to outdoors

[a] All three rough duct tests were conducted after ducts were sealed using mastic, before the furnace was installed, and before the house was ready for a blower door test, so duct leakage to outdoors measurements were not available.
[b] The higher leakage results of Test 2 were due to use of existing tape from Test 1, which may have come loose in some areas. Test 2 was performed using theatrical smoke for demonstration purposes.
[c] Test 3 was conducted after additional duct sealing using mastic.
[d] The final test was conducted after the furnace was installed and the house was complete.

6.4 HVAC Equipment Testing (Startup)

The manufacturer's regional technical representative assisted with the startup of the heating and cooling equipment. The gas furnace initially consumed gas at a much higher rate (based on the clocking the meter method) than specified by the equipment nameplate. The furnace gas manifold pressures were adjusted accordingly per the manufacturer's specifications. Typically, gas furnace installation instructions state that the gas consumption must be measured and burner orifices checked as part of a proper startup. As a result, gas valve adjustments are routinely required (for any brand). The thermostat was installed on a wall common to the duct chase; this makes sealing the hole for the control wiring behind the thermostat—a conventional practice—more critical because it helps to isolate any potential temperature difference between the chase and house. The thermostat required a 2-degree calibration.

For the cooling system, despite an accurate air flow measurement and refrigerant charge in accordance with industry standards, the system was shown to be operating very inefficiently at first. The HVAC contractor had accurately weighed in the refrigerant, the measured subcooling was within range for this TXV system, and the system appeared to be cooling adequately. Despite these factors, based on additional measurements (including superheat) and an accurate furnace air flow measurement by Research Center staff using a flow grid, the technical representative calculated that the nominal 4-ton system was undercooling by 9,000 Btu/h (¾ of a ton), and therefore running considerably longer than necessary. The factory-installed TXV sensing bulb was relocated (a relatively simple adjustment), which corrected the problem.

6.5 HVAC Duct Distribution Testing

Temperature variations by level measured during the cooling season varied by time of day but typically ranged from 1°–3°F (see Table 8). The measured results were best when the two downstairs dampers were half-closed. Based on temperature measurements and perceived comfort, the duct design appeared to be performing very well, particularly considering the four-level design of the house. Long-term monitoring of indoor temperatures and relative humidity results will be presented in a future report. The effectiveness of the bedroom transfer grilles as a low-pressure, return air pathway was not measured because these interior doors had not been installed in the model home.

Table 8. Example Measured Temperature by Level

Location	Temperature (°F)		
	June 21, 8:00 a.m.	June 21, 4:00 p.m.	August 17, 1:00 p.m.
First Floor at Thermostat	70.6	71.6	72.2
Second-Floor Master Bedroom	70.4	71.6	72.1
Third-Floor Bedroom	70.7	72.6	73.5
Basement Recreation Room	69.7	70.9	72.3

6.6 Ventilation Testing

The fresh air ventilation flow, measured using a hot wire anemometer, was less than expected, even in the cooling mode (when the fan should be drawing the most air). One subsequent measurement in the heating mode showed an unexpected improvement, although the flow was still less than anticipated. This lower flow required the controls to open the damper for more minutes per hour to meet ASHRAE Standard 62.2 recommendations (ASHRAE 2010).

Bath exhaust fan air flows initially tested significantly less than rated. An investigation revealed that an unnecessary control that limited air flow had been installed. Removing this control improved the air flows considerably, although they were still below the nominal factory ratings.

7 Gaps and Lessons Learned

7.1 Overview

The level of effort invested during the planning stage was considered important to the successful design and implementation of the energy features for this research project. The energy efficiency features were selected for durability, practical and repeatable installation, and cost effectiveness.

7.2 Framing

The floor-framing members were individually engineered to accommodate the floor plan, central duct chase, and integrated HVAC supply duct. The optimized wall framing improved thermal performance. Inspections showed a number of nailing and blocking issues that were addressed in the field and should be added to the framing contractor's scope of work for subsequent houses. The floor framing design resulted in a rigid floor, and the numbered joists and rim boards made for efficient installation after a brief learning curve period.

7.3 Air Sealing

The sealant product and method, including being able to inspect the application before proceeding, resulted in a high level of air sealing. The installation of house wrap as a secondary exterior air barrier was not completely accomplished (sealing the top and bottom of the house wrap was not completed), and the ADA was not completely implemented (sealing the faces of the bottom plates and rough framing around windows and doors); these details were not included in the subsequent three houses. Intermediate house leakage testing to identify the incremental effect of both was not possible because the house wrap, sealant, and drywall were installed before an intermediate blower door test could be performed.

7.4 HVAC

Installing the entire heating and cooling system in conditioned space resulted in significant estimated energy savings. This, in fact, is one of the first design decisions that must be made in order to perform accurate heat loss and gain calculations, select equipment, and design the distribution system. The redesigned duct system was integrated with the redesigned floor plan and joist layout to accommodate the central duct chase. This chase was critical to installing the entire system in conditioned space and was also used for plumbing piping. The integrated upstairs duct and floor system required significant effort and site coordination at the design stage. A different approach to implementing this design could be to cut an opening through the engineered rim board at the factory to accommodate the field installation of the duct after framing was complete. For an opening required over a window, a conventional header could be installed. As an alternative, the integrated duct and floor design could be eliminated by installing this duct conventionally (below and perpendicular to the floor joist) with a bulkhead if the design aligned with the architectural plan.

Duct leakage to outdoors was presumably through leakage points in the air barrier in areas that could communicate with the ducts (e.g., at the rim areas or at the top of the central duct chase). Because the leakage to the outdoors was minimal, the energy penalty was not considered significant, although the total duct leakage is still a cause for concern.

Bath exhaust fan air flows that test below the nominal fan ratings may be widespread (not limited to this project) and may be partially caused by a lack of manufacturer guidance for duct design.

Testing indicated a need to investigate improved exhaust fan ducting layout and component selection. Performance can be diminished by excessive duct static pressure; performance might be improved by using different duct or fittings (e.g., a larger diameter pipe or a less restrictive vent hood). The Research Center continues to investigate the cause and solution of this issue. Additionally, the effect of a 600-cfm adjustable flow kitchen range exhaust hood on house pressure will be measured.

Lower than expected fresh air ventilation flow may be attributed to the return duct design. The return duct was sized to reduce air velocity and associated noise in accordance with ACCA Manual D recommendations (ACCA 2009). This, however, resulted in a low-pressure-drop design that might indicate a need for a larger diameter fresh air duct. An overly restrictive intake hood may have contributed as well. The test results highlighted a need for additional ducting considerations for this supply-type ventilation design, in some cases, to ensure sufficient ventilation. The Research Center plans to investigate ventilation air flow improvement methods and monitor the long-term performance of this system.

The additional costs of higher efficiency heating and cooling equipment are expected to be more than offset by installing one system instead of two, and by using a simplified duct system. The startup of the furnace and air-conditioning system, notably the calibration adjustments that both required, highlighted how critical a thorough commissioning procedure and written report are to ensure the equipment is operating safely and efficiently.

7.5 Plumbing

There may be an opportunity to further optimize the plumbing piping by identifying routes that are more direct and running reduced diameter piping to some fixtures.

7.6 Energy Simulations and Cost Effectiveness

The Research Center plans to evaluate the effect of builder substitutions in the implemented design on the 30% simulated energy savings goal. In addition, working with WHI, the Research Center plans to evaluate the cost effectiveness of the energy features presented in this report; much of the cost information was not available when the report was written. These simulation and cost details will be presented in the next report.

7.7 Quality Assurance

Scheduled design reviews, site reviews, and inspections are still recommended for subsequent houses to ensure that all framing, air sealing, insulation, and mechanical systems are designed and installed to optimize performance goals.

8 Summary

8.1 Overview

The specific energy efficiency goals established during the planning stage for this NCTH were largely achieved. The project may have fallen short of the 30% energy efficiency goal because of builder substitutions. All of the permanent features, though, including optimized framing, insulation, windows, plumbing piping, and a single HVAC system with interior ducts were implemented. The substituted features (e.g., the cooling system condensing unit) may be easily changed in future homes. WHI considered all the permanent features to be cost effective, and the builder incorporated them into at least three additional houses of similar design as shown in Figure 26.

Figure 26. Three additional houses built using the NCTH features

The thermal envelope design successfully incorporated advanced framing techniques and high insulation levels. Short-term testing indicated a very tight thermal envelope. The HVAC system was successfully installed entirely within conditioned space, and short-term testing indicated that the heating and cooling system was operating efficiently and effectively. The completed NCTH is shown in Figure 27.

Figure 27. Completed test house

8.2 Next Steps

The Research Center plans to work with WHI to prepare a cost analysis, investigate open items identified in the Gaps and Lessons Learned section, and prepare a long-term monitoring report for this NCTH research project. That report will address the long-term goals and research questions presented in this report.

References

ACCA (2009). *Manual D, Residential Duct Systems.* 3rd Edition. Arlington, VA: ACCA.

ACCA. (2006). *Manual J, Residential Load Calculations.*8th Edition. Arlington, VA: ACCA.

ACCA (2004). Manual S, Residential Equipment Selection. Arlington, VA: ACCA.

ACCA (1992). Manual T, Air Distribution Basics for Residential and Small Commercial Buildings. Arlington, VA: ACCA.

American National Standards Institute (ANSI)/ICC 700-2008 (2009) National Green Building Standard (NGBS)

ASHRAE (2010). "ANSI/ASHRAE Standard 62.2-2010, Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings." Atlanta, GA: ASHRAE.

ICC. (2009). 2009 International Energy Conservation Code. Washington, DC: ICC.

Appendix A Energy Simulations

The NCTH as built with both the optional finished basement and third floor was 30% over the Building America B10 benchmark excluding any size adjustment factor. The preliminary energy simulations included both cost optimization and source energy savings analyses. Through optimization, BEopt produced a set of options that provided the highest energy savings for the lowest investment costs, within the limits of the software and cost data. Figure 28 graphically depicts the simulation results.

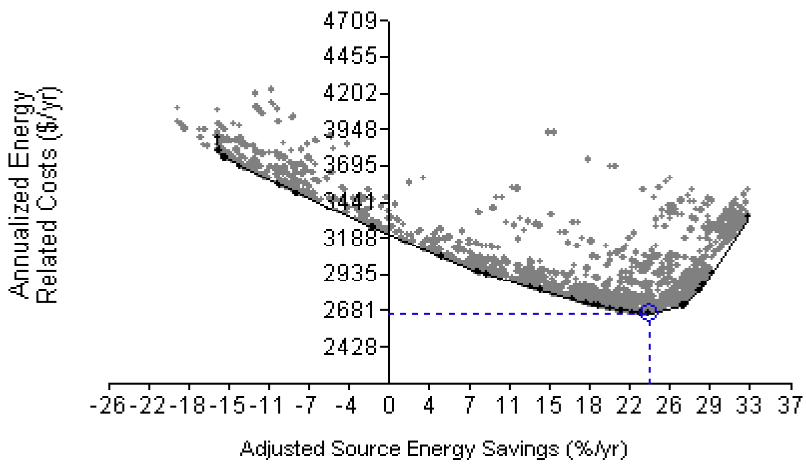

Figure 28. BEopt simulation results

The “swoosh” shape of the graph indicated that the minimum annualized energy cost occurred at source energy savings of approximately 24% (indicted by blue dotted lines). Before reaching the minimum cost point, investment in energy savings measures decreased annualized energy costs (mortgage plus utilities) at a roughly linear rate. Just beyond the minimum (after about 27% source energy savings), additional energy savings were attainable, but the investment needed to attain incremental efficiency gains rose sharply. For example, meeting the project goals of 30% energy savings required approximately a 10% higher annualized energy cost than would reaching 27% savings. The results indicated that, for this home design in the Washington, D.C., area, the maximum practical energy savings for production builders is near the 30% level. Attaining higher energy savings requires a better understanding of and experience with new technologies and construction methods, along with the benefits of efficiency investments.

The second simulation analysis consisted of preliminary source energy savings estimates. Although the test home was anticipated to reduce the home’s energy consumption by 30% over the B10 benchmark, the as-built design (which will serve as a model home and, as such, includes nearly 2,000 ft^2 of optional conditioned space) was subject to a size penalty that reduced overall projected savings. Because of the additional conditioned space, the Building America Program administers a penalty (which is manifested in a source energy reduction for the B10 benchmark design). Figure 29 shows source energy use for the B10 benchmark and the final house design. The size penalty reduced theoretical source energy savings by about 7%.

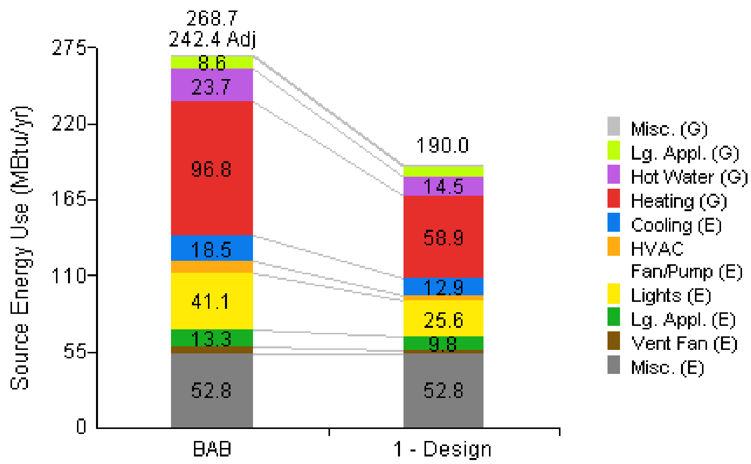

Figure 29. Source energy savings for energy efficient design compared to the B10 benchmark

(Adjusted source energy use includes a penalty for the energy efficient design's additional square footage)

The preliminary cost savings, which were not subject to a size penalty, were estimated to be about $1,100 per year. Figure 30 depicts the components of these savings.

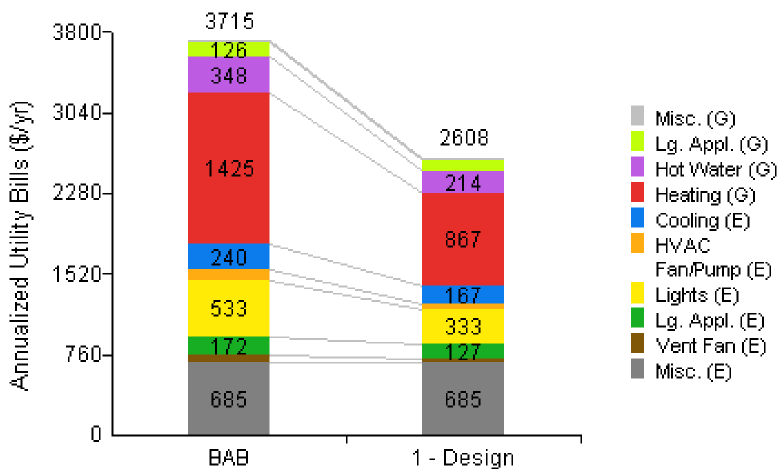

Figure 30. Annualized utility bill comparison for B10 benchmark and energy efficient design

For a house with the same energy efficiency solution package but without the 700-ft^2 above-grade finished attic space or the 1,300-ft^2 finished basement, a 30% source energy savings (with a 1% size penalty) was predicted. Results are shown in Figure 31 and Figure 32.

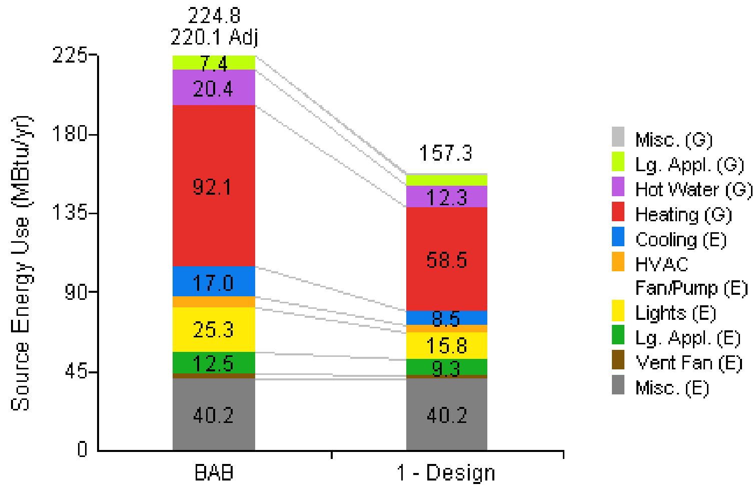

Figure 31. Source energy use for B10 benchmark and energy efficient design

(For house without finished third-floor and without finished basement)

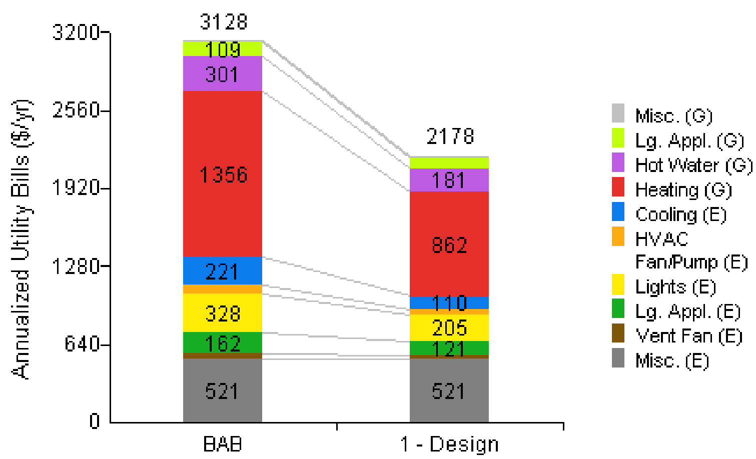

Figure 32. Annual utility bills

(For house without finished third-floor and without finished basement)

Appendix B Complexity of the Home's Thermal Boundaries

WHI's Camberley Homes
Poplar Run Subdivision, Poplar Run Community, Silver Spring, Maryland
Victorian Model

Figure 33 through Figure 35 show three different views of the house's thermal boundary.

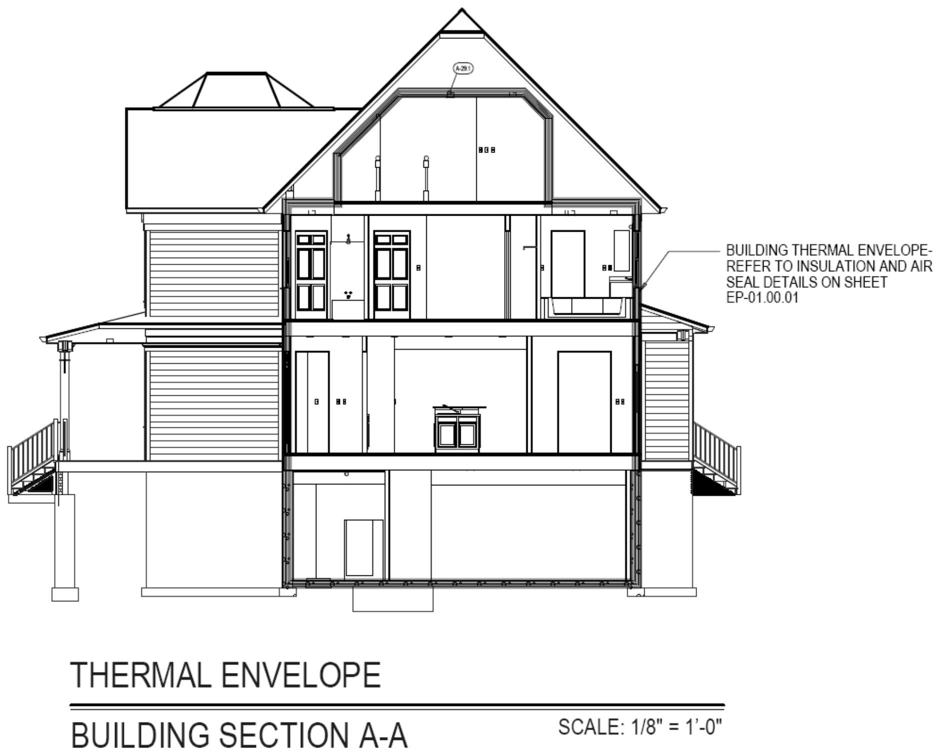

Figure 33. NCTH thermal envelope, Section A-A

Figure 34. NCTH thermal envelope, Section B-B

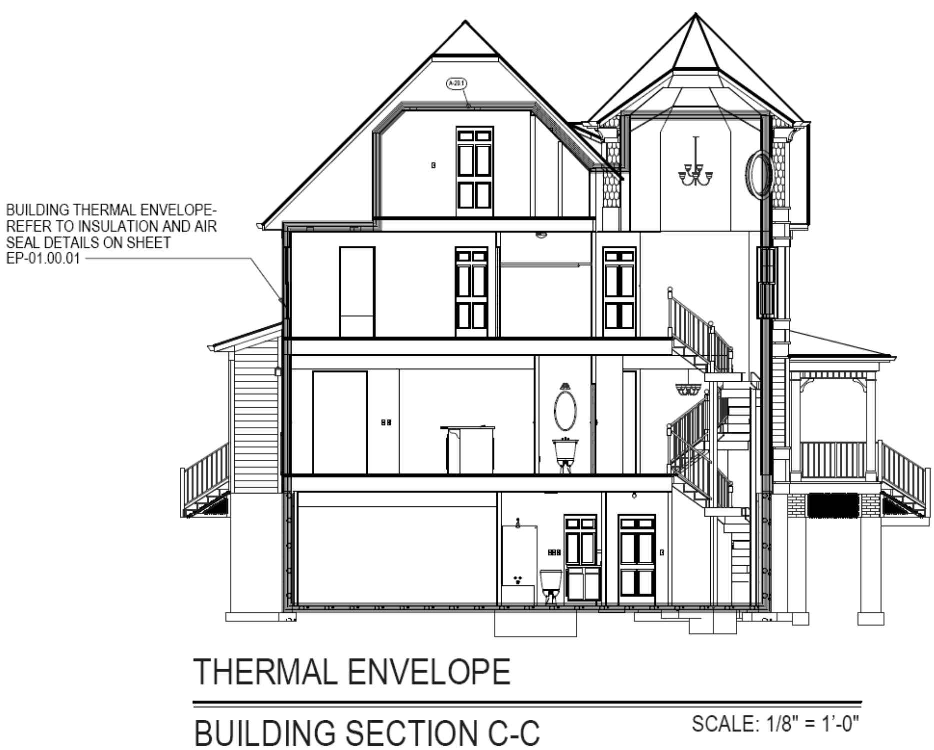

Figure 35. NCTH thermal envelope, Section C-C

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