BUILDING TECHNOLOGIES PROGRAM

# Draft Technical Report: Winchester/Camberley Homes NCTH

*Short Term Testing*
*Mixed Humid Climate*

D. Mallay, J. Wiehagen, A. Wood

December 2011

**Prepared by the NAHB Research Center**
**For the U.S. Department of Energy Building Technologies Program**

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***Short Term Testing***
***Mixed Humid Climate***

Prepared for:

Building America

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Prepared by:

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400 Prince George's Blvd

Upper Marlboro, MD 20774



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# Definitions

| | |
|---|---|
| NAHB | National Association of Home Builders |
| DOE | United States Department of Energy |
| ACCA | Air Conditioning Contractors of America |
| WHI | Winchester Homes, Inc. and its Camberley Homes division |
| IECC | International Energy Conservation Code |
| NCTH | New Construction Test House |
| NGBS | National Green Building Standard ANSI ICC 700-2008 |
| ECM | Electrically Commutated Motor |
| SPF | Spray Polyurethane Foam |
| ADA | Airtight Drywall Approach |
| MERV | Minimum Efficiency Reporting Value (for media type air filters) |

# Executive Summary

The NAHB Research Center partnered with Winchester/Camberley Homes on a new construction test house in Silver Spring, MD in the mixed humid climate. The goals for this house were to improve energy efficiency by 30% over the Building America B10 benchmark by developing and implementing an optimized framing, air sealing, insulation, and space conditioning system designs that could be cost effectively and reliably constructed on a production basis using quality management practices. The test house was completed in June 2011. The intent of this report is to outline the features of this house, discuss the implementation of the energy efficient design, and report on short-term testing results.

# 1 Introduction

## 1.1 Background

A new construction test house was built in the Poplar Run subdivision in Montgomery County, MD, a suburb of Washington DC as shown in Figure 1. This subdivision will eventually site 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 New Construction Test House**

## 1.2 Overview

With the support of the DOE Building America Program, 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 and climate zone four of Silver Spring, MD. The three-story, Victorian-style house was completed in 2011. Additionally, it was built to be the builder's model home.

The three-story design had 3,228 square feet of conditioned floor area above grade, including a 605 square foot finished third floor with a sitting room, full bath, and fourth bedroom. A finished basement brought the total to 4,441 finished square feet. The finished third floor and basement were included builder options. Ceilings were nine feet for the first floor and basement, eight feet for the second floor, and eight 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 performance goals for this house were to improve energy efficiency by 30% over the Building America B10 benchmark by developing and implementing an 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 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 IECC[1]
- 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 100% in conditioned space, reducing duct run lengths and eliminating 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 ICC 700-2008 NGBS Silver Level Green Certification

The intent of this report is to outline the features of the house, discuss construction and installation, and report on short term characterization testing. Long term monitoring will be detailed in a future report.

# 2 Design Development

## 2.1 Design Process & Energy Simulations

The thermal envelope was completely redesigned from standard specifications and a set of high performance construction features was developed for a 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. Simulated energy savings, using BEopt v1.1, were detailed and presented in the Research Center's Test Plan (Test Plan)[2] for this research project. Through BEopt software optimization and other analyses, a set of options that provided the highest energy savings for the lowest investment costs was determined.

[1] http://www1.eere.energy.gov/buildings/building_america/program_goals.html
[2] *Test Plan: Environmental, Energy, and Moisture Monitoring for Winchester./Camberley Homes' NCTH*, NAHB Research Center, July 2011

## 2.2 Cost Analysis

This project, the development of a new line of production homes, began with the builder's commitment to include high performance home features, significantly exceeding current energy code requirements. The first decision that WHI made in the design process was to start from scratch with the design rather than modify an existing model with new features. Closely coupled with this decision was the approach to develop a product line with high performance energy features that would be integrated into the plan development process. As a result WHI completed an extensive, in house, cost analysis at the design level. This allowed WHI to choose specific systems over other options (e.g. business as usual vs. 2x4 with exterior rigid foam vs. 2x4 with cavity spray foam, etc.). In addition, the Research Center also completed a preliminary cost analysis presented in the Research Center's Test Plan (Test Plan)[3].

Based on the builder's construction and cost analysis, the selection of high performance home features to achieve 30% energy savings over the 2009 IECC, the plans, product selection, insulating and air sealing approaches, and the design and efficiency of the HVAC system, all are designed new to perform as an integrated system. The builder's analysis will not only include verification of higher levels of energy and comfort performance but also cost containment from such changes where synergistic benefits such as reduced material and labor costs, are identified. Expectation of these benefits has led the builder's design team to develop similar models for the product line, all including the high performance home features.

Additional cost analysis is planned for the long-term monitoring test report to more fully understand the incremental costs. Currently WHI is completing three additional houses of similar design as outlined in Section 8.1 below. Once complete, the Research Center will work with WHI to finalize the preliminary analysis. This is important because understanding the cost approach by a builder is not a straight forward analysis. This test house is particularly complex because of the redesign aspect of this project. As a result, there is not a reference point for "builder standard practice" as the homes are a new product line and unique to the builder.

## 2.3 Cost Effective Energy Solutions

The project planning stage included four builder-directed design review meetings conducted at the Research Center. Attendees included the project manager, operations manager, 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, one early-on decision was that wall panels would have structural sheathing without foam on the exterior, due to structural and cladding attachment concerns. Based on this decision and recognizing future need for higher insulation levels for this climate zone, a nominal 2" x 4" wall cavity would require much higher density insulations such as closed cell SPF insulation. Evaluating the cost for a 2" x 4" wall with SPF, this option was ruled out in favor of a 2" x 6" 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 non-structural nailers where possible, and other advanced framing techniques to increase room

[3] *Test Plan: Environmental, Energy, and Moisture Monitoring for Winchester./Camberley Homes' NCTH*, NAHB Research Center, July 2011

for insulation and provide for a higher level of air sealing. To avoid non-standard length studs and maintain ceiling heights, and allow for a flexible floor framing layout, a conventional second top plate was included in this new design. The construction of the wall design using the advanced framing described above is shown in Figure 2.

**Figure 2. Advanced Wall Framing**

Another example of this iterative design process was the early-on decision to install the entire HVAC system in conditioned space, in order to reduce energy losses. This required redesigning the floor plan and floor joist framing to accommodate a central duct chase to serve all four levels. Additionally, a bulkhead along the first floor ceiling to conceal the supply trunks serving the second and third floors was not acceptable architecturally. To achieve these design goals, an engineered floor system designed by component for the specific house layout, was used as shown in Figure 3. The engineered floor joists coupled with specialized design software allows for a precise location for mechanicals through the floor system and precut at the factory. The size of the main duct chase was based on the required duct dimensions. The supply trunks would be installed perpendicularly through the second floor engineered joists, so that all supply duct serving the upstairs would be above the first floor ceiling plane. This high level integration of structural and mechanical systems required a complete duct design during the planning stage to size the chase and so that rectangular openings in the joists could be accurately cut at the factory. Similar planning was necessary for the plumbing and sprinkler piping which also ran through the floor joists as needed.

**Figure 3. Supply Trunk through Floor Joists & Central Duct Chase**

This iterative approach to evaluating benefits and trade-offs 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. The summary of the design is detailed in Table 1.

**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 & consistency of installation |
| Improved HVAC System Efficiency | ○ Reduced the number of equipment systems from the traditional two HVAC systems to one<br>○ Redesigned floor plan, framing, & ducts to locate entire system in conditioned space for significant energy savings<br>○ Improved equipment operating efficiencies<br>○ Improved ventilation, filtration, and occupant comfort |
| Quality Assurance & Control | ○ Planning stage design reviews included practical input from WHI, vendors, & trade partners<br>○ Developed construction details & specifications<br>○ Established construction monitoring points (reviews, inspections, & tests) |
| Repeatable Design | ○ Specified features optimized performance, cost, & practical implementation |

Many of the new construction details were included in the drawing package. Goals and expectations for the trade contractors were mutually agreed upon, and site reviews, inspections, and tests were scheduled for quality assurance. The level of effort invested during the planning stage was 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, openings, and allowing as much insulation as possible in the exterior walls and attic while maintaining the Victorian-style architecture. 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 | ○ 2x4 frame, 16" on center<br>○ R-13 batt insulation | ○ 2x6 frame, 24" on center<br>○ Structural rim headers<br>○ Reduced framing<br>○ R-24 blown fiberglass insulation<br>○ Continuous drywall method |
| Air Sealing | ○ Bottom plates sealed at deck<br>○ Penetrations sealed<br>○ Window rough openings sealed | ○ Same as standard practice plus:<br>○ Sealed frame at all critical areas (see table below) using spray applied, water soluble, elastomeric sealant<br>○ Airtight Drywall Approach<br>○ House wrap installed as air barrier |
| Windows | ○ U-0.35, SHGC-0.35 | ○ Low-e, U-0.31, SHGC-0.28 |
| Doors | ○ n/a | ○ U-0.35, SHGC-0.36 |
| Roof/attic (vented) | ○ Standard truss, 1 ft overhang<br>○ R-38 blown fiberglass | ○ Raised heel truss, 2 ft overhang<br>○ R-49 blown fiberglass insulation, full depth at eaves & sloped ceilings<br>○ Ice & water shield at eaves & valleys<br>○ Drip edges at eaves & rakes |

## 3.1 Framing

Floor framing was optimized using I-joists, 24" on center as shown in Figure 4. The reduced cost of fewer floor joists was partly offset by selecting 7/8" floor decking (instead of ¾") to ensure rigid floors. Floor joists and rim boards were cut to exact length and numbered at the factory for efficient installation. Cutouts through the joists for the HVAC duct, plumbing, and sprinkler piping were also made at the factory.

**Figure 4. Floor Framing**

Factory built wall panels shown in Figure 5 were redesigned to reduce thermal bridging and increase insulation volume. Walls were 2” x 6” wood frame, 24” on-center, with ½” 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 improve thermal performance. Second top plates and house wrap were installed in the field. Cladding was fiber cement siding.

**Figure 5. Wall Panels**

The continuous drywall method was specified to reduce, further, framing air losses. All interior partition walls were installed 1” 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” from the poured foundation. In the attic, raised heel roof trusses with two-foot overhangs shown in Figure 7, accommodated full depth insulation and insulation baffles at the eaves and notably at the third floor sloped ceilings.


**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, it was essential to identify critical areas for air sealing. The air sealing design was considered complex to air seal primarily due to the third floor and turret as detailed 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 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, were all adjacent to the same attic. 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. The critical areas to apply the sealant to ensure that the house was well sealed is outlined in Table 3 and shown in Figure 11.

**Table 3. Critical Areas to Apply Sealant**

| Critical Area | Specific Location for Sealant |
|---|---|
| Exterior Walls | Stud cavities: top & 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 |

| Critical Area | Specific Location for Sealant |
|---|---|
| | Electrical boxes and other exterior penetrations |
| Partition Walls | Face of top plates adjacent to a vented attic |
| Rim Areas | Rim board at floor deck & 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 & 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 & 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 & door rough openings on exterior walls |
| | Electrical boxes in exterior walls |

**Figure 11. Air Sealing**

An additional air sealing strategy was to install house wrap 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" 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" 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, wall cavities (above grade) 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, as these walls had been installed with a ¾” gap between panels. Basement walls were insulated using R-13 fiberglass batts. Attic insulation, including the sloped ceilings of the third floor, was increased to R-49. This was accomplished 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, U-0.31, SHGC-0.28. The installed insulation and fenestration is detailed in Figure 13.

**Figure 13. Wall & Attic Insulation**

# 4 Systems

The system design included heating, cooling, duct, ventilation, plumbing, and lighting. The goal of the system 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 allowing the installation of one HVAC system 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 | (2) 80% AFUE natural gas furnaces (one in vented attic & one in basement) | (1) 92.5% AFUE natural gas furnace with 2-stage gas valve & ECM air drive, installed in basement |
| Cooling | (2) 13 SEER systems | (1) 15 SEER system |
| Thermostat | Programmable | Programmable with integral humidistat and controls to run the cooling system in dehumidification mode |
| HVAC Duct | (1) flexible, insulated duct system in vented attic & (1) metal duct system in basement | (1) system 100% in conditioned space with supply trunk balancing dampers. Simplified central return with one grille per level & bedroom transfer grilles |
| Filtration | Standard 1” filter | MERV 10 high efficiency pleated filter |
| Ventilation | (1) bath exhaust fan with programmable control | Supply type central fan integrated fresh air ventilation system with damper & control |
| Plumbing | 65 gallon natural gas water heater, EF 0.55; CPVC branch & tee piping | 50 gallon, power vent, natural gas water heater, EF 0.74; PEX manifold piping |
| Lighting | 50% CFL | 80+% CFL |

## 4.1 HVAC System

The HVAC system was designed so all equipment and duct would be in conditioned space in order to significantly reduce distribution energy loss. Standard WHI practice utilized two independent systems, one in the attic (furnace and ducts) to condition the second and third floors, and a second in the basement to condition the first floor and basement. The new design called for one system instead of two; the expected result was an equipment cost savings.

High efficiency equipment was specified: a 16 SEER cooling system and a 92.5% AFUE natural gas furnace. The furnace shown in Figure 14 was direct vent (two-pipe and using outdoor air for combustion) with a two-stage gas valve and 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, however in low-heat mode, the output matched much more closely to the calculated load. The programmable thermostat with 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 ACCA Manual J, Manual S, Manual T, and Manual D recommendations.

**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 Air Velocity for Noise Control recommendations and acoustically lined in order to ensure quiet operation, an important consideration with the furnace installed in the basement directly below the first floor return grille.

The vertical section of the supply trunk duct serving the second and third floors was also installed in the chase as shown in Figure 14. The horizontal sections were installed through the factory cut openings in the second floor joists 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 supply trunk was installed in a more conventional manner: perpendicular to and under the first floor joists, and therefore required a bulkhead 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 capable of meeting ASHRAE Standard 62.2 ventilation recommendations. 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. 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. Additionally, the source location of outdoor air was known, unlike exhaust only systems that rely on makeup air infiltrating through the house envelope.

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. A central humidifier was installed due to a concern that the abundant wood floors and trim may dry too much during the heating season and crack.

Bath exhaust fans were ENERGY STAR and rated to be quiet (0.8 sone at 0.1 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 also capable of being programmed for supplemental ventilation, if desired.

## 4.2 Plumbing

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


**Figure 16. High Efficiency Water Heater**

### 4.3 Lighting and Appliances

High efficiency lighting was increased to over 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 an efficient and accurate installation of the numbered joists and rim boards shown in Figure 17 and Figure 18. 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 numbered wall panels shown in Figure 19 and Figure 20 were installed quickly. The roof trusses and framing were also numbered for efficient installation. After framing was complete, WHI staff observed, and had corrected, some rim, header, and wall nailing issues. The 7/8" floor decking installed over the 24" on center floor joists resulted in an observably stiff floor without visible deflection.

**Figure 17. Floor Framing**

**Figure 18. Floor Framing & Wall Panels**

**Figure 19. Wall Panels**

Figure 20. Wall Panels & 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 A), however the three-dimensional aspect of the boundary made an on-site review, just prior to air sealing, imperative. This review included the framing contractor (responsible for installing the air barriers) and insulation contractor (responsible for sealing the air barriers) as they needed to coordinate their efforts.

After air sealing, a walk-through showed that the majority of critical areas had been sealed. In light of the high expectations for this house, a number of areas were required to be touched-up prior to 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 to criticize the product or trade contractors; rather, it was intended to highlight the challenge of identifying a continuous thermal and air barrier with such a complicated 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. An example of the complexity of air sealing these areas is shown in Figure 21.

Figure 21. Air Sealing at Blocking Below Third Floor Knee Wall & Knee Walls

Sealant was not consistently applied to the faces of the bottom plates of exterior walls (bottom plates were sealed at the floor deck) or faces of rough framing around windows and doors, in accordance with the ADA, because the contractor and did not consider this necessary. Sealant was applied in the gap between the rough framing and the windows and doors, however these gaps may have been more effectively sealed using low expansion spray foam insulation instead. Sealant applied to the interior faces of the bottom cords of second and third floor roof trusses, while not detrimental, was not considered, by the Research Center, necessary. The sill plate at the foundation wall was difficult to reach and inspect because the basement wall framing had already been installed, therefore the sill plate was sealed from the exterior.

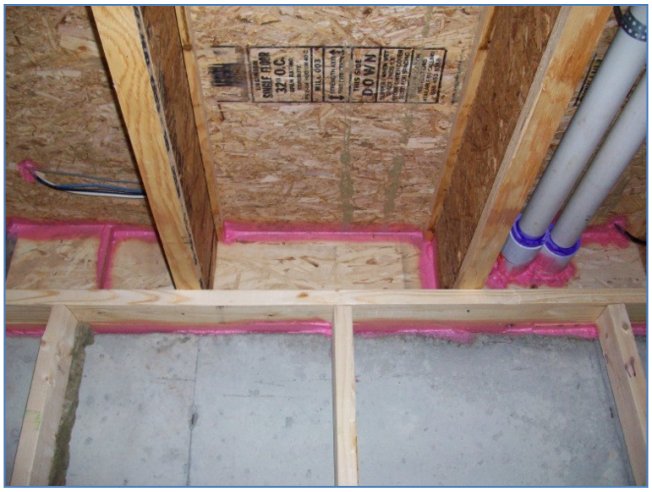


**Figure 22. Air Sealing at Basement Rim Area**

**Figure 23. Installing Wall Cavity Blown Insulation & Checking Density**

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 these were challenging or overlooked, but an effort to correct all of these areas was not considered critical due to the use of the sealant as the primary air sealing strategy.

To insulate the wall cavities, netting was stapled to the faces of all wall framing. Next, the loose fiberglass insulation was blown into each cavity, using a hose from the truck outdoors, through one slit in the netting (see Figure 23). Wall cavity density was measured as the work progressed to ensure the target insulation levels were achieved (see figure 13). For attic insulation, netting was installed at the ceiling plane where fiberglass batts had not already been installed, and then loose fiberglass was blown into these areas. All wall and ceiling insulation was complete before drywall installation.

### 5.3 HVAC

Cutting an opening through the structural rim boards to allow the trunk to be slid into place was not acceptable. Therefore the trunks were installed in sections, through the joist cutouts, as the framing trade partner installed the first floor joists. Although this integrated duct and floor joist design eliminated the first floor bulkhead, it did require significant design stage coordination between the HVAC trade contractor and floor joist vendor, as well as an additional site trip by the HVAC contractor.

**Figure 24. Installing HVAC Trunk through Floor Joists**

The electronic zone dampers originally specified were eliminated due to cost. 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 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), however not between the second and third floors.

All ducts were sealed with mastic as planned. A rough duct leakage test, before the furnace was installed, indicated higher than expected leakage. A second rough test was conducted using theatrical smoke with the HVAC contractor present in order to identify, visually, the leakage areas in need of repair. After additional mastic was applied to these areas, a third rough test measured the improvement (see section 7.1 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 TXV) had not been rated by AHRI (the condenser and coil are a rated AHRI match, but they had not been additionally rated with this furnace).

# 6 Testing

## 6.1 Test Plan

Testing and long term monitoring plans for the NCTH were detailed in the Test Plan. Many of the energy efficiency features incorporated into the home design were new to the builder and trade contractors. As a model home for the Poplar Run subdivision, the house will likely see extremes in energy usage due to the anticipated additional heating, cooling, lighting, and miscellaneous loads. The products and methods will be evaluated in order to report on the research questions posed in the Test Plan in a future long-term monitoring report.

## 6.2 Research Questions

Use of this NCTH for testing and evaluation 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, trades or manufacturer partners?

To answer all but the last question, the following research measurements detailed in Table 5 will be made:

**Table 5. Research Measurements and Equipment**

| Measurement | Equipment | Test Type |
|---|---|---|
| Infiltration Rate | Blower door apparatus | Short-term characterization test |
| Duct Loss | Duct blaster apparatus | 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/MC | Omnisense Gateway connected to protected website | Long-term monitoring |
| Data Recording – Energy, runtime, etc. | Campbell Scientific data logger, modem | Long-term monitoring |

Short-term test results are detailed in the following section. Long-term monitoring will be detailed in a future report after at least one year of monitored data has been collected.

# 7 Performance Testing

## 7.1 Short-term characterization testing

An intermediate blower door test (shown in Figure 25), performed after drywall 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, 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.

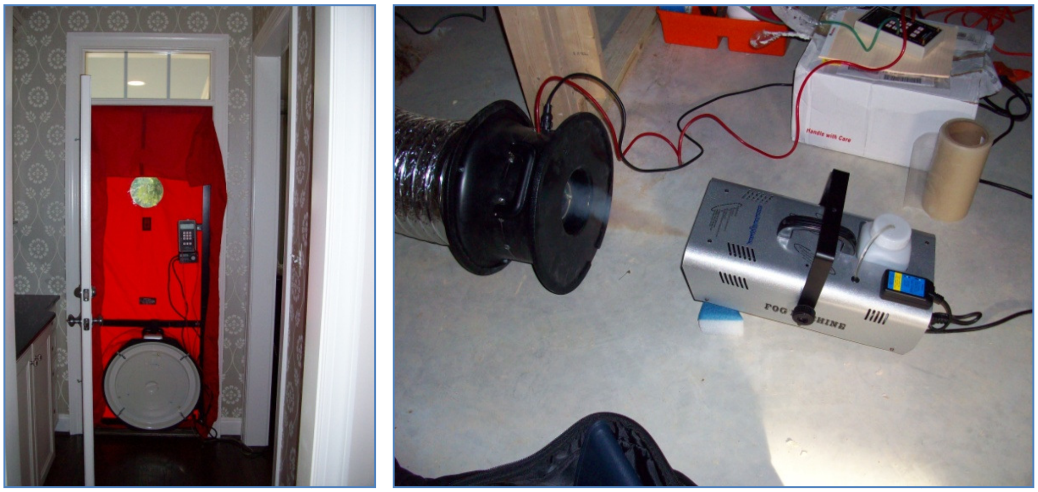


**Figure 25. Blower Door Test Apparatus & Duct Test using Theatrical Smoke**

**Table 6. Characterization Testing: House Leakage**

| Performance Metric | NCTH | | | Units |
|---|---|---|---|---|
| House Size | 4,441 | | | SF finished area |
| | 4,568 | | | SF conditioned area |
| House Volume | 41,847 | | | CF |
| Infiltration | *Test 1*[A] | *Test 2*[B] | *Final* | |
| | 2,400 | 1,380 | 1,335 | CFM50 |
| | 3.4 | 2.0 | 1.9 | ACH50 |
| | 0.17 | 0.10 | 0.10 | ACH nat |
| | 0.53 | 0.30 | 0.29 | CFM50/SFcfa |

[A] Prior to trim and sealing of all penetrations but after sheetrock installation
[B] After access panels and other knee walls from the 3rd floor room to the attic were sealed
[C] Final after all finishes complete

A series of 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 and therefore leakage to the outdoors could not be measured. After the furnace was installed, final duct testing indicated excessive total leakage; the difference between the rough and final leakage results was higher than expected from furnace leakage alone. Duct leakage to outdoors, as expected, was relatively low as shown in Table 7.

**Table 7. Characterization Testing: Duct Leakage**

| Performance Metric | NCTH | | | | Units |
|---|---|---|---|---|---|
| House Size | 4,441 | | | | SF finished area |
| | 4,568 | | | | SF conditioned area |
| 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 | CFM25/100SFcfa |
| | n/a | n/a | n/a | 43 | CFM25 to outdoors |

(A) All three rough duct tests were conducted after ducts sealed using mastic, before furnace installation, and before house was ready for blower door test, therefore duct leakage to outdoors was not available
(B) Higher leakage results of test 2 were due to use of existing tape from test 1 as this test was performed using theatrical smoke for demonstration purposes (tape may have become loose in some areas)
(C) Test 3 was conducted after additional duct sealing using mastic
(D)Final test conducted after furnace installation and house was complete

## 7.2 HVAC Testing

The manufacturer's regional technical representative assisted with the startup of the heating and cooling equipment. The gas furnace was initially found to consume gas at a rate much higher than specified (based on the clocking the meter method) for the equipment size. The furnace gas manifold pressures were adjusted accordingly, and brought into the range per the manufacturer's specifications. The thermostat was found to require calibration as well. The cooling system charge had been accurately weighed-in by the HVAC contractor, the measured sub-cooling was within range for this TXV system, and the system appeared to be cooling adequately. Despite this, the technical representative made additional measurements (including super-heat) and, along with an accurate furnace air flow measurement by Research Center staff using a flow grid, was able to calculate that the nominal 4-ton system was under-cooling by 9,000 Btuh (3/4 of a ton), and therefore running considerably longer than necessary. A relatively simple adjustment (to the TXV sensing bulb) corrected the problem. This situation, where the refrigerant charge was installed and checked per industry standards, but still resulted in the cooling system operating very inefficiently, likely would have gone unnoticed if it were not for the manufacturer representative's thorough commissioning effort.

Temperature variations by level measured during the cooling season varied by time of day but typically ranged from one to three degrees F. The measured results were best when the two downstairs dampers were ½ closed. The duct design appeared to be performing very well, particularly considering the four level design of the house. The Test Plan includes long-term monitoring of indoor temperatures and relative humidity. 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) | | |
|---|---|---|---|
| | *Jun 21, 8 am* | *Jun 21, 4 pm* | *Aug 17, 1 pm* |
| 1st floor at thermostat | 70.6 | 71.6 | 72.2 |
| 2nd floor master bedroom | 70.4 | 71.6 | 72.1 |
| 3rd floor bedroom | 70.7 | 72.6 | 73.5 |
| Basement recreation room | 69.7 | 70.9 | 72.3 |

The ventilation air 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. Lower than expected ventilation may be attributed to the low pressure drop return duct design; the Research Center plans to investigate ventilation air flow improvement, and performance will be monitored as part of the Test Plan.

Bath exhaust fan airflows tested significantly less than rated. Upon investigation, an unnecessary control that limited air flow had been incorrectly installed. Removing this control improved air flows considerably; however the flows are still below factory ratings. The Research Center continues to investigate the cause and solution of this issue. Additionally, the effect on house pressure of a 600 CFM, adjustable flow, kitchen range exhaust hood will be measured.

# 8 Summary

## 8.1 Overview

The design and implementation goals for this test house were achieved. The cost effective enhancements, including the optimized framing, air sealing, HVAC system, and water heater and plumbing, as reported, have been adopted by WHI for at least three additional houses of similar design as shown in Figure 26.


**Figure 26. Three Additional Houses Built Using the NCTH Cost Effective Features**

## 8.2 Gaps and Lessons Learned

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.

The optimized wall framing provided 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, after a brief learning curve period, made for efficient installation.

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 house wrap was not completed), and the ADA was not completely implemented. These details, sealing the top and bottom of the house wrap and the faces of the bottom plates and rough framing for the ADA, were not included in the subsequent three houses. Intermediate house leakage testing in order 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.

Installing the entire heating and cooling system in conditioned space resulted in significant estimated energy savings, and 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 had to be integrated with a redesigned floor plan and joist layout in order to accommodate the central duct chase. This chase was critical to install the entire system in conditioned space including the simplified return ducts and upstairs supply trunk, and additionally was utilized for plumbing piping. The upstairs supply trunks integrated into the second floor joists required significant design stage coordination, though this step could be eliminated if an acceptable bulkhead to conceal this duct could be designed into the architectural plans.

The final duct leakage test measured an additional 253 CFM compared to the rough test conducted before furnace installation. This could 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 vast majority of duct was concealed with drywall and therefore further testing would not be 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.

It is expected that the additional costs of higher efficiency heating and cooling equipment would be more than offset by installing one system instead of two and a simplified duct system. The startup of the furnace and air conditioning system highlighted how critical a thorough commissioning procedure is to ensure the optimum actual equipment performance and operating cost expectations. The gas valve on the furnace was not accurately set at the factory; this is not uncommon (for all brands) and is why manufacturer's installation instructions state that the gas meter must be clocked (to measure gas consumption) and gas valves must be adjusted, if necessary, within manufacturer's specifications, for safe and efficient operation. 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, in order to isolate any potential temperature difference between the chase and house. The thermostat did require a two-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, initially, very inefficiently; an adjustment was required for the system to perform as rated. A written commissioning report is always important to document that the entire HVAC system was properly installed and that the field performance is within manufacturer's limits of rated performance. A thorough commissioning procedure is even more critical with multi-stage and variable capacity equipment and thermostats that control humidity and ventilation.

The performance of the bath exhaust fans indicated the need to pay more attention to the vent layout, component selection, and installation. The measured ventilation air flow highlighted a need for an improved method of duct design to accurately control the introduction of fresh air. Plumbing piping could be optimized, potentially, by identifying more direct routes and reduced diameter piping to some fixtures.

Scheduled site reviews and inspections would still be recommended for subsequent houses to ensure all framing, sealing, and mechanical systems are installed as designed.

### 8.3 Next Steps

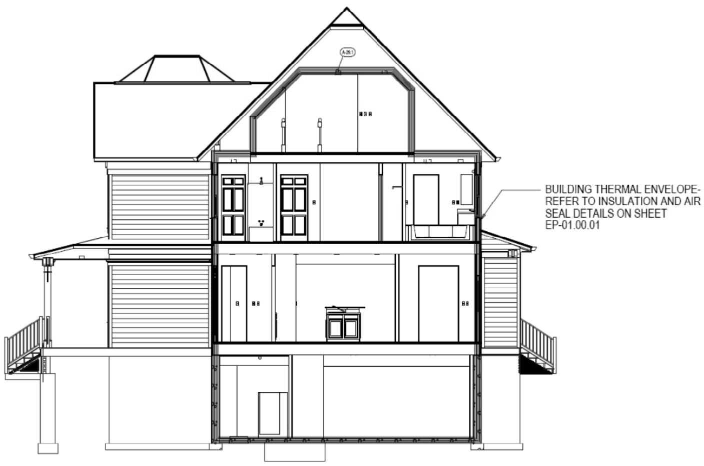
The Research Center, working with WHI, plans to prepare a cost and payback analysis, investigate open items identified in the above testing section, and prepare a long-term monitoring report for this NCTH research project.


**Figure 27. Completed Test House**

# Appendix A: Complexity of the Home's Thermal Boundaries

Winchester Homes Inc. (WHI)'s Camberley Homes
Poplar Run Subdivision, Poplar Run Community, Silver Spring, MD
Victorian Model

Thermal Boundaries on house plans:




THERMAL ENVELOPE
BUILDING SECTION A-A    SCALE: 1/8" = 1'-0"


THERMAL ENVELOPE
BUILDING SECTION B-B    SCALE: 1/8" = 1'-0"


THERMAL ENVELOPE

BUILDING SECTION C-C SCALE: 1/8" = 1'-0"

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*Test Plan: Environmental, Energy, and Moisture Monitoring for Winchester/Camberley Homes' NCTH*, NAHB Research Center, July 2011.

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