Performance Verification of Production-Scalable Energy-Efficient Solutions

Winchester/Camberley Homes
Mixed-Humid Climate

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Partnership for Home Innovation

July 2014

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Definitions

ACH50	House Air Changes per Hour At 50 Pascals Pressure
AFUE	Annual Fuel Utilization Efficiency
AGW	Above Grade Wall
BA	Building America
CFA	Conditioned Floor Area
CFM25	Cubic Feet per Minute at 25 Pascals Pressure
CFM50	Cubic Feet per Minute at 50 Pascals Pressure
DPT	Dew Point Temperature
ECM	Electronically Commutated Motor
MC	Moisture Content (of either wood framing or wood sheathing)
NCTH	New Construction Test House
OSB	Oriented Strand Board
RH	Relative Humidity
SEER	Seasonal Energy Efficiency Ratio
T	Temperature
WHI	Winchester Homes, Inc.
WUFI	Wärme und Feuchte instationär

Executive Summary

Winchester/Camberley Homes collaborated with the Building America program and its Partnership for Home Innovation to develop a new set of high performance home designs that could be applicable on a production scale. The new home designs are to be constructed in the mixed-humid climate zone 4 and could eventually apply to all of the builder's home designs to meet or exceed future energy codes or performance-based programs. However, the builder recognized that the combination of new wall framing designs and materials, higher levels of insulation in the wall cavity, and more detailed air sealing to achieve lower infiltration rates changes the moisture characteristics of the wall system. In order to ensure long-term durability and repeatable successful implementation with few callbacks, this report demonstrates through measured data that the wall system functions as a dynamic system, responding to changing interior and outdoor environmental conditions within recognized limits of the materials that make up the wall system. A similar investigation was made with respect to the complete redesign of the heating, cooling, air distribution, and ventilation systems intended to optimize the equipment size and configuration to significantly improve efficiency while maintaining indoor comfort. Recognizing the need to demonstrate the benefits of these efficiency features, the builder offered a new house model to serve as a test case to develop framing designs, evaluate material selections and installation requirements, changes to work scopes and contractor learning curves, as well as to compare theoretical performance characteristics with measured results.

In the production environment, the impact of the home redesign is significant both in cost and time. As interest in energy savings and environmental performance increases, and as building code requirements become more stringent, these new demands are now leading to large changes in envelope design, material selections, and performance metrics. When in previous enhancements the performance of the home could be increased through higher efficiency materials or systems, new building requirements are leading to a revamping of the entire building envelope and the space conditioning system. The evolving requirements are of such significance that design changes now must consider much more than a static insulation level or the rated efficiency of equipment, and begin to combine material properties with installation specifications, long-term durability assessments, and energy consumption estimates. This project is unique in that it lays the groundwork for higher performing wall designs that can be more easily modified to achieve a further increase in thermal performance levels without major redesign efforts. In addition, performance results lend confidence in achieving stringent energy efficiency goals while maintaining durability. This project also demonstrates a reasonable and achievable heating, ventilation, and air conditioning design, installation, and commissioning that satisfies enhanced performance goals, including occupants' comfort, and can be used in high performance house designs by the production builder.

Highlighted findings and lessons learned from the project include:

- Clear a pathway to the successful integration of an advanced wall design using 2 × 6 lumber, standardized rim header[1] layout, optimized framing members,[2] offset interior

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[1] The rim header uses an engineered rim board design coupled with floor framing support specifications over openings to provide the header support. See NAHBRC 2012 for a detailed description of rim header testing. A methodology to prescriptively implement rim headers in the building code is underway.

walls,[3] and wood structural sheathing by the architect, panel fabricator, and trade contractor.

- The advanced wall design exceeds minimum building code requirements for climate zones 1–5 both on a performance and a prescriptive basis and can be more easily modified for other higher performance solutions without large redesign costs.
- The durability of the wall cavity design in terms of the measured moisture characteristics in the cavity shows cyclic moisture content of 6%–18% with all wall orientations showing less than 10% moisture content in the summer months.
- The four floor level temperature gradient during a hot summer period showed modest temperature differences, less than 3°F between the main living areas of the house, and about 6°F when including the basement.
- The design and installation of the exhaust and ventilation fan systems require further refinement to consistently achieve rated flow rates.
- More coordination between the framing and heating, ventilation, and air conditioning trade contractors is necessary to decrease the complexity of installing the duct system with an engineered floor system.

This report outlines an advanced wall system design and installation, air sealing details, and the design and installation of the space conditioning and ventilation systems for a high performance home. The measured performance from tests on these systems indicates that the designs and installation methods are sufficiently mature to be incorporated by production builders in new home designs. The lessons learned from the test house show areas where particular attention should be made to avoid performance problems or the need for call-back repairs. The test house construction and test results can be used by builders as a basis to revise current home designs for a high performance home option in climate zones 3, 4, and 5. Researchers may use this report to add to the growing base of information on wall system moisture performance and for improvement of design tools to assess moisture characteristics in advanced wall systems.

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[2] Optimized framing includes 24-in. o.c. studs, 2-stud corners, and reduced use of cripple framing.
[3] Offset interior walls is a design methodology to move interior walls perpendicular to exterior walls 1 in. from the exterior walls providing space for a continuous sheet of gypsum board on the exterior wall.

1 Introduction

1.1 Overview

With the support of the U.S. Department of Energy Building America (BA) program, as part of the Partnership for Home Innovation, Home Innovation Research Labs (Home Innovation) 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 climate (U.S. Department of Energy climate zone 4) of Silver Spring, Maryland. The three-story, Victorian-style model home was completed in 2011.

The goals shared by the builder and the BA program for the test house were to design, construct, and verify/evaluate the advanced high performance features of a production home design in the mixed-humid climate.

This report details and summarizes the design features and the construction obstacles and provides verification testing results performed since the home's completion. Testing results are used to evaluate technologies and system designs where sufficient data are available. The testing summary covers wall moisture characteristics, heating, ventilation, and air conditioning (HVAC) system performance characteristics, ventilation system operation, and additional infiltration testing. Whole-house energy usage and heating and cooling energy data are compared to simulation estimates.

1.2 Background

The NCTH, pictured in Figure 1, was built in the Poplar Run subdivision in Montgomery County, Maryland, a suburb of Washington, D.C. Poplar Run will eventually include 700 homes. After gauging consumer acceptance of the advanced energy features in the test home, the builder will consider incorporating similar advanced energy features in some of the current designed 600 homes as well as use the developed approaches as a design methodology for new home designs.

Figure 1. Winchester/Camberley NCTH

The three-story design has 3,228 ft^2 of conditioned floor area (CFA) above grade, including a 605-ft^2 finished third floor with a sitting room, full bath, and bedroom. A finished basement brings the total finished area to 4,441 ft^2. Ceilings are 9 ft high for the first floor and basement, 8 ft high on the second floor, and 8 ft or sloped on the third floor. Above grade walls (AGWs) are wood-frame construction; the basement foundation is poured concrete and mostly below grade. All attic areas are vented. A unique design feature of this home is the octagonal, three-story turret containing an open stairwell that connects the basement to the second floor. Access to the third floor is by a separate stairway. The garage is detached from the house.

Since completion, the house has been open as a model for the development. Energy loads for the model home include multiple computers, digital TV displays operating continuously, lamps operating when sales staff are present, and space conditioning. The garage is configured as a field office for construction and sales and is outfitted with a heating and cooling system, computers, and other office equipment.

1.3 Test House Design and Construction Goals

The original performance goals for this house,[4] developed jointly by the builder and Home Innovation, was to improve energy efficiency by 30% over the current BA 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. This performance goal aligns well with the goals of the BA program.[5] Specific goals that the NCTH established during the planning phase include:

- Develop and implement a durable design that improves energy efficiency by at least 30% over a comparable house that meets the 2009 International Energy Conservation Code (IECC 2009).
- Create a tight thermal boundary.
- Install insulation at levels that will be in accordance with future anticipated consumer demand and building code requirements.
- Develop an envelope design that can be adapted 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 incremental cost.
- Design the HVAC system to be located entirely in conditioned space to significantly reduce energy losses to unconditioned space, reduce duct lengths, and meet the home’s heating and cooling needs with a single HVAC system.
- Design the HVAC system to ensure occupant comfort in terms of temperature consistency, throughout the four-level home.
- Develop a cost-effective, integrated design that extracts construction efficiencies across building systems, such as reduced labor time for numerous trades when

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[4] Final Technical Report: Winchester/Camberley Homes NCTH – Design, Construction, & Short-term Testing, NAHB Research Center for the DOE Building America Program, March 2012.

[5] See DOE 2011

working with optimized framing systems, and which could be constructed on a production basis using quality management practices.

- Develop a test and monitoring plan to evaluate energy use, heating and cooling air distribution, and wall moisture performance.
- Earn Silver Certification under the National Green Building Standard (NGBS 2008).

2 Test House Energy Features

2.1 Design Process and Energy Simulations

WHI is committed to building a line of high performance homes that exceed current energy code requirements and look toward meeting future more stringent code requirements. Cost efficiencies in meeting such goals were achieved by developing a new product line that integrated the energy features rather than to modify an existing model. The team completely redesigned the NCTH thermal envelope from standard specifications and added a set of newly developed high performance construction features. The final energy efficiency solution package represented months of collaborative development among WHI and Home Innovation staff, trade contractor professionals, manufacturers, and product suppliers. The design process involved technical design input, laboratory testing, energy modeling and optimization, cost comparisons and other practical factors by team members. Energy savings were simulated using Building Energy Optimization™ (BEopt™) v1.0.1. 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, detailed in Appendix A, indicate that the BA energy savings goal was met based on modeling outputs.

2.2 Construction and Energy Features

WHI completed an extensive in-house cost analysis to select high performance home features. The cost analysis, along with the BEopt simulations and practical input based on the combined experience of the project team, allowed the builder to choose systems—based on wide-ranging factors including occupant comfort, constructability, durability, reliability, energy performance, and synergistic cost containment benefits such as reduced material and labor costs—that would perform as an integrated system.

The performance and cost analysis framework generally focused on meeting anticipated energy savings requirements in a manner that limited incremental cost and provided reliable and tangible results for the builder and homebuyer.

Constructability was a very important factor in the builder's decision-making process. Selected technologies, construction methods, and performance testing are all aspects of acute attention since the trade contractors must be able to incorporate any design changes in a manner that produces high quality outcomes and enhanced consumer satisfaction while minimizing code compliance failures and risks from negative long-term performance issues.

Based on the lessons learned through the NCTH design and installation process, the builder is planning incremental changes to existing house designs to incorporate high performance features. However, redesigning existing plans is often more challenging than working from a clean slate. The complexity of redesign extends to sales staff and homebuyers, who may not understand the difference between the layout of the model home and the redesigned model, particularly when interior walls are significantly changed.

2.3 Strategies To Achieve New Construction Test House Goals

During the design process, the project team identified design strategies that would meet the project goals of increased performance, constructability, durability and reliability. A summary of the project's guiding design strategies is outlined in Table 1.

Table 1. High Performance Home Design Strategies

Design Strategy	Solution Approach
Increased AGW Insulation	• Enhanced and 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 HVAC systems from two 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	• Planning stage design reviews included practical input from WHI, vendors, and trade partners • Developed construction details and specifications • Established construction monitoring points (reviews, inspections, and tests)
Repeatable Design	• Specified features that optimized performance, cost, and practical implementation

Adherence to the design strategies provided both the guidance for technology and system selection as well as a metric for outcome evaluation.

3 High Performance Solution Package

Design solutions selected for the NCTH are summarized in Table 2 and Table 3. Major changes to improve the energy performance were centered on the envelope and HVAC systems. A more complete detail of the design changes is documented in two research reports.[6,7]

Table 2. Thermal Envelope Improvements

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 • Rim headers (DeRenzis et al. 2012) • Reduced framing • R-24 blown fiberglass insulation • Offset interior walls[8]
Air Sealing	• Bottom plates sealed at deck • Penetrations sealed • Window rough openings sealed • Panel joints and corners caulked	• Same as standard practice plus: • Sealed frame at all critical areas using spray applied, elastomeric sealant[9] • Airtight drywall approach[10] • House wrap installed as air barrier
Windows	• U-0.35, solar heat gain coefficient 0.35	• Low-e, U-0.31, solar heat gain coefficient 0.28
Doors	• N/A	• U-0.35, solar heat gain coefficient 0.36
Roof/Attic (Vented)	• Standard truss, 1-ft overhang • R-38 blown fiberglass • Ice and water shield at eaves and valleys • Drip edges at eaves and rakes	• 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

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[6] *Final Technical Report: High-R Walls for New Construction Structural Performance Integrated Rim Header Testing*, NAHB Research Center for the DOE Building America Program, April 2012.

[7] *Final Technical Report: Winchester/Camberley Homes NCTH – Design, Construction, and Short-term Testing*, NAHB Research Center for the DOE Building America Program, March 2012.

[8] Offset interior walls allow for a layer of continuous gypsum board to be used on exterior walls even where interior walls intersect.

[9] One method for air sealing of the exterior wall framing is to apply an air sealing material to the front edges of top and bottom plates, to picture frame the cavity, and around openings. The material is generally non-expanding and offers no direct R-value to the wall.

[10] The airtight drywall approach is an air sealing methodology to reduce air leakage from the interior of the house through separations in the drywall where it is attached to the framing members.

Table 3. Mechanical System Improvements

System	Standard Practice	NCTH
Heating	(2) 80% AFUE[a] natural gas furnaces (one in vented attic and one in basement)	(1) 92.5% AFUE natural gas furnace with 2-stage gas valve and ECM[b] air drive, installed in basement
Cooling	(2) 13 SEER[c] systems	(1) 14-15 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 and (1) metal duct system in basement	(1) Single 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[d] 1-4)	High efficiency pleated filter (MERV 10)
Mechanical Ventilation	(1) Bath exhaust fan with programmable control	Supply type central fan integrated (ducted to the return) with damper and control[11]
Plumbing	65-gallon natural gas water heater, EF[e] 0.57; CPVC[f] branch and tee piping	50-gallon, power vent, natural gas water heater, EF 0.74 (est.); PEX[g] manifold piping
Lighting	50% compact fluorescent lamps	80%+ compact fluorescent lamps

[a] Annual fuel utilization efficiency
[b] Electronically commutated motor
[c] Seasonal energy efficiency ratio
[d] Minimum efficiency reporting value
[e] Energy factor
[f] Chlorinated polyvinyl chloride
[g] Cross-linked polyethylene

The referenced reports provide background for the design solutions employed in this NCTH and describe implementation and construction issues discovered during site visits and in discussion with the builder and trade contractors.

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[11] The ventilation system was initially set to operate at 60% of the ASHRAE 62.2 (ASHRAE 2010) ventilation rate for the house.

4 Verification Testing

While many of the energy efficiency features incorporated in the NCTH design were familiar to the builder and trade contractors, they were not standard practice. As a result, Home Innovation developed a short-term verification testing plan to ensure that test results matched expected performance levels. For durability and confidence in the system performance, Home Innovation established a longer-term testing plan to provide field data to demonstrate ongoing reliability and energy savings.

4.1 Test Plan

Testing and evaluating the design strategies employed in the NCTH are critical for understanding the reliability of the systems and if systems were successfully integrated into the finished product. Short- and long-term field tests address the following research questions:

- Based on the redesigned single-zone ducted air delivery system, how consistent are the interior temperatures on each of the four levels of the home? How do interior temperatures change throughout the day under summer and winter peak load conditions?
- Is measured energy use for space conditioning consistent with modeled estimates under similar ambient weather conditions?
- Are the HVAC elements including furnace, compressor, thermostat, humidifier, fresh air supply damper, and exhaust fans operating as designed and in an optimal manner?
- How do the wall cavity environmental conditions change with seasonal interior and exterior conditions? Are sheathing moisture characteristics within expected swings?
- How do the wall cavity moisture characteristics compare with estimated or modeled results?
- Is there anecdotal evidence of market response to the costs, features, and interior conditions of the house from the builder, potential buyers, trade contractors, or manufacturer partners?

To answer all but the last question, the research measurements detailed in Table 4 will be taken. Builder feedback will be used to evaluate the last question.

Initial short-term test results, reported previously (see footnote 5 above), are summarized here to add context to the long-term and repeat test results.

Table 4. Research Measurements and Equipment

Measurement Parameter	Test Measurement	Test Purpose
House Infiltration Rate	Blower door test and diagnostic evaluation	• After drywall – assess primary leakage paths and remediate • At construction completion – document overall infiltration rate and locate remaining major leakage paths
HVAC Duct Tightness and Overall Duct System Performance	Duct blaster test; air handler and diffuser flow rates	• Duct system rough-in – assess leakage and remediate; repeat tests • At construction completion – characterize overall air delivery system
Ventilation and Exhaust Fan System Performance	Balometer, hot wire anemometer, and pressure measurements	• At construction completion – measure supply ventilation airflow rate and exhaust fan flow rates. Measure house depressurization during exhaust fan operation
Whole-House Electric	Energy transducer and recording devices	• Record whole-house electricity use • Identify a demand profile
Space Conditioning Equipment	Energy transducer and recording devices	• Document the operation of the HVAC system relative to interior set points and exterior ambient drivers
Indoor Environment	Temperature/relative humidity (T/RH) sensors located on each floor and on the exterior of the home	• Analyze the operation of the HVAC system relative to interior and exterior T/RH drives • Document the operation of the supply ventilation and humidification systems • Analyze T stratification through the four-level home • Assess ventilation performance
Wall Cavity Environment	T/RH/moisture content (MC) sensors placed in wall cavities of basement, first, second, and third floors, and roof	• Monitor wall cavity conditions and sheathing MC in high thermal value wall system with elastomeric air seal • Characterize the diurnal and seasonal moisture performance • Provide data for comparison with moisture models
Other	Repeat tests	• Additional short-term tests may be added based on ongoing analysis and/or field performance of similar other homes for comparison

4.2 Infiltration Testing

At various points during construction, Home Innovation conducted whole-house infiltration testing using a blower door to identify particular areas, if any, where remediation is likely to be necessary to meet whole-house infiltration criteria in the production environment.

The first infiltration test was performed after drywall but before trim, floors, and ceiling penetrations were sealed. This test identified a significant leakage area in a third floor kneewall adjacent to a common HVAC chase that resulted in significant airflow between the attic and conditioned space at the angled top plate and sloped ceiling. This detail will require particular attention in all future air sealing efforts. A second infiltration test was conducted after further air sealing and the house was substantially complete except for the sealing of all ceiling penetrations. This test showed a significant reduction in air infiltration over the initial test. A final test was performed after completion; this test showed further reductions in air leakage. Finally, another air infiltration test was performed after 14.5 months of home operation to document any air leakage changes following heating and cooling cycles. Table 5 summarizes infiltration test results.

Table 5. Characterization Testing: House Leakage

Performance Metric	NCTH				Units
House Size	4,441				ft^2 finished area
	4,568				ft^2 conditioned area
House Volume	41,847				ft^3
Infiltration	**Test 1[a]**	**Test 2[b]**	**Final 1[c]**	**Final 2[d]**	
	2,400	1,380	1,335	1,365	CFM50
	3.4	2.0	1.9	2.0	ACH50
	0.17	0.10	0.10	0.10	ACH natural
	0.53	0.30	0.29	0.30	CFM50/ft^2 CFA

[a] Prior to trim and sealing of all penetrations but after sheetrock installation
[b] After access panels and other kneewalls from the third-floor room to the attic were sealed
[c] Final after all finishes complete
[d] 14.5 months following Final 1

The air infiltration measurement results indicate that the air sealing effort was successful in achieving the builder's goal of no more than 3 ACH50. In addition, leakage areas that needed special detailing were identified. Leakage areas that were identified included the attic room kneewall framing, duct chase and closet framing adjacent to attic spaces, and ceiling penetrations adjacent to the attic. The builder used an elastomeric water-based foam product to air seal these areas as outlined in the previous report (see footnote 5). Based on the complexity of the framing, it was generally understood that use of such a product was highly advantageous to attain reliable air sealing that meets performance goals.

Home Innovation conducted infiltration tests on models that include energy efficiency features similar to the NCTH but that have different layouts (models H2, H3, H4). The CFA of each model is within 4% of the NCTH. Two of the three models have an attic room and none has the complex turret design. The models were insulated and air sealed using the same approaches as the NCTH.

During construction, these three models were not subject to the high level of scrutiny imposed on the NCTH, but all four models were air sealed by the same contractor. The H2, H3, and H4 models tested between 2.3 and 2.4 ACH50, providing anecdotal evidence of reliable and repeatable air sealing approaches to complex house designs.

As a comparison, the builder subsequently constructed a home (model B17) that has the same floor plan as model H3 but that was air sealed with caulking and spray foam rather than with elastomeric spray materials. Note that the model H3 and B17 does not have the large turret that is a design element in the NCTH. The turret adds multiple corner and angle joints constructed over three stories in height and presents a significant challenge to air sealing aside from the rest of the home. In model B17, the sealing contractor employed its customary practice of sealing window rough framing openings and other framing penetrations with spray foam, and caulking bottom plates at the deck, between top plates and panel joints. Infiltration testing showed that model B17 (which was insulated with batt insulation in the walls rather than packed fiberglass as was in model H3) tested at 3.1 ACH50, or about 30% higher than model H3. Whole-house air infiltration results, however, were close to the 3.0 ACH50 target air sealing level). Furthermore, during the air infiltration test in B17, air leakage around exhaust fans was measured at a total of 135 CFM (across five exhaust fans). If just half of this leakage was eliminated due to air sealing at the gypsum/fan interface, infiltration in B17 would be reduced to 3.0 ACH50. Yet, even though this result meets the builder's infiltration goals, there remains the issue of consistently achieving satisfactory results on a production basis. From this example, it appears that standard air sealing methodologies can achieve what are considered low air infiltration levels. It remains to be demonstrated, however, if standard air sealing methods can achieve the required levels consistently and without remediation costs after the home is substantially complete.

4.3 Heating and Cooling System Design and Duct Leakage Testing

To dramatically reduce equipment and distribution energy losses due to conduction and air leakage, the HVAC system was designed to incorporate all equipment and ducts within conditioned space. Standard builder practice was to install two HVAC systems, one in the basement and one in the attic. While the two-system approach is common in the region, simple to install (no supply ducts running between floors), and creates two independent zones for improved comfort, its benefits are more pronounced in conventional home designs for which comfort and efficiency are not factored into the whole-house design. In high performance homes like the NCTH, a single, well-designed HVAC system can eliminate the need for additional equipment costs without sacrificing performance and comfort.

Load calculations, equipment selection, and duct design were made in accordance with Air Conditioning Contractors of America Manual J (ACCA 2006), Manual S (ACCA 2004), Manual T (ACCA 2009a), and Manual D (ACCA 2009b) standards. The project team selected a single HVAC and duct system located in the conditioned space with a 15 SEER cooling system and a 92.5% AFUE natural gas furnace. The direct-vent furnace, which uses outdoor air for combustion and exhausts combustion air through a separate pipe, has a two-stage gas valve and ECM blower motor. The furnace was selected based on the cooling airflow requirements; in high-heat mode the furnace output is much higher than the design load, in low-heat mode, the furnace capacity matches design load well; the team anticipated that the furnace will operate primarily in low heat mode. During the cooling season, the programmable thermostat with integral humidistat can operate the furnace in dehumidification mode (reduced blower speed) to improve humidity control.

In the NCTH, a series of preliminary duct leakage tests were conducted before furnace installation (see Table 6). The first test indicated higher than expected leakage. A second test, using theatrical smoke, identified leakage areas, and a third test measured the improvement after additional duct mastic was applied. During the preliminary 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, the final duct leakage test was more than double that measured in the last preliminary test. A portion of this increase may be attributed to additional leakage through the furnace, coil, and air cleaner cabinets. Additional leakage, likely a larger portion, may also be attributed to different duct testing protocols for the preliminary and final tests. During preliminary tests, outlets were sealed by adhering the masking material directly to the metal ducts. During final testing registers and grilles were sealed to finished floors and walls, which may have allowed additional leakage between these surfaces, particularly the gaps between the drywall and the metal duct at return grilles. Because the majority of duct was concealed behind drywall, further testing and repair were impractical. 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 for a tight home with ducts in conditioned space, was relatively low, less than 4% of air handler flow and less than 1 CFM25/100 ft^2 CFA. Duct leakage testing results are summarized in Table 6.

Table 6. Characterization Testing: Duct Leakage

Performance Metric	NCTH				Units
House Size	4,441				ft^2 finished area
	4,568				ft^2 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	CFM25/100ft^2 CFA
	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

4.4 Conditioned Air Distribution Testing

The ability of the single-zone, HVAC system with programmable thermostat/humidistat to operate as designed and provide adequate comfort was of significant interest to the project. Therefore, this testing sought to evaluate those HVAC design approaches that differed significantly from those of standard builder practice and to determine if the new approach matches the comfort levels achieved by the builder’s conventional two-system approach. The NCTH improvements are designed to enhance energy efficiency while limiting cost increases; however, it is critical that the system can provide acceptable comfort to the occupants through outdoor seasonal extremes.

One evaluation of comfort is temperature variations between levels in a multistory home. Since the NCTH contains three stories above grade plus a conditioned basement, the challenge for the single-zone duct delivery system is to provide a balanced temperature profile between levels.

During the commissioning period, airflow at each diffuser was measured and dampers were adjusted. Measurements during one cooling period indicated that the temperatures on different levels of the home varied by time of day but typically were within 1°–3°F (see Table 7). Measured results were best when the two dampers for the lower levels were halfway closed. Based on temperature measurements and perceived comfort of the sales and builder staff, the duct design appears to be performing very well, particularly considering the four-level design. The effectiveness of the bedroom transfer grilles to provide a low pressure, return air pathway was not measured because interior doors were not installed at the time of testing.

Table 7. 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.
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

Figure 2 depicts 15-minute average temperature data for 3 days in July and depicts cooling system operation. The 3-day period experienced extremely hot weather; the third day was a Saturday for which the home may have had many visitors and more introduction of outdoor air.

Figure 2 shows the temperature difference between floors. At times, generally when the air conditioner compressor was off, there was up to a 4°F differential between the first (blue) and third (green) floors. In general, the second floor (red) was slightly cooler than the first floor, likely due to higher internal gains and solar gain through windows. The air handler fan operates continuously,[12] so air is being mixed, but the temperature deviation in the third floor attic room is larger than the other floors. This is likely due to heat gain through the partially-cathedralized ceiling. Yet, the temperature profile shows that all above-grade floors trend together and respond similarly to the cooling equipment operation. Average temperatures for each level during the 3-day period, shown in Table 8, are within about 2°F with a wider separation in the basement area (indicating that, in summer, little cooling is needed in the basement). The outdoor temperature averaged 89°F and the attic temperature averaged even warmer (which is a driver for increasing temperature in the third floor room, in particular).

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[12] The fan-only mode in the NCTH was set approximately 200 CFM higher than the standard fan only mode to maintain a higher level of mixing in the sales model. The effect of this detail on floor-floor temperature variations was not tested.

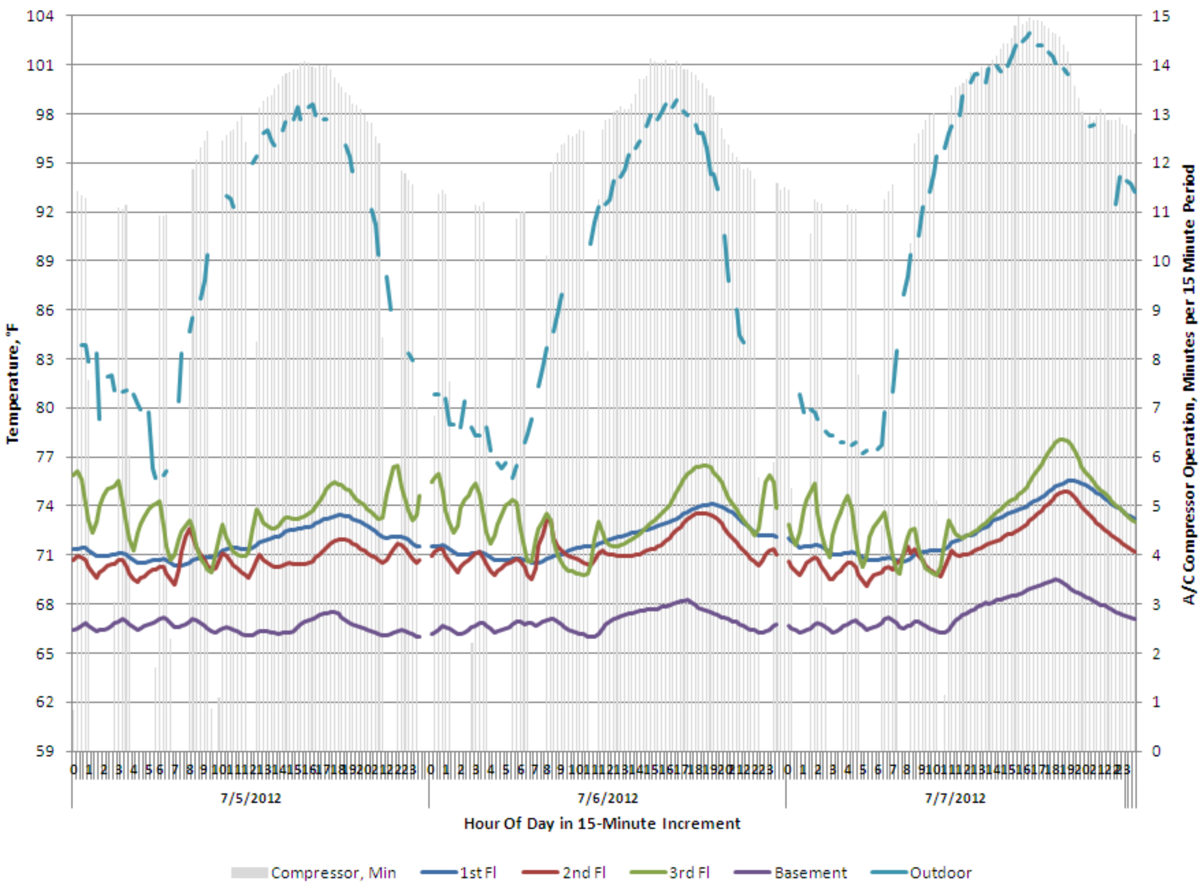

Figure 2. Indoor temperature profile during an extreme cooling period

Table 8. Average Temperatures for 3-Day Period, July 5–July 7, 2012

Temperature Measurement Location	Average Temperature, °F
1st Floor (in Room With Thermostat)	72.1
2nd Floor (in Master Bedroom)	71.2
3rd Floor Attic Room	73.4
Basement Recreation Area	67.0
Basement Utility Room (HVAC Equipment Location)	65.7
Attic Space (Above Insulation, Vented)	96.1
Outdoor	89.0

Figure 3 depicts indoor temperatures for a 16-month period spanning two cooling seasons and one heating season. The first floor is highlighted in red, the second in black, and the third in green. The gray line, read on the right axis, represents the maximum temperature difference between the first, second, and third floors only. Temperature different between floors is highest in the heating season and during very hot periods in the cooling season.

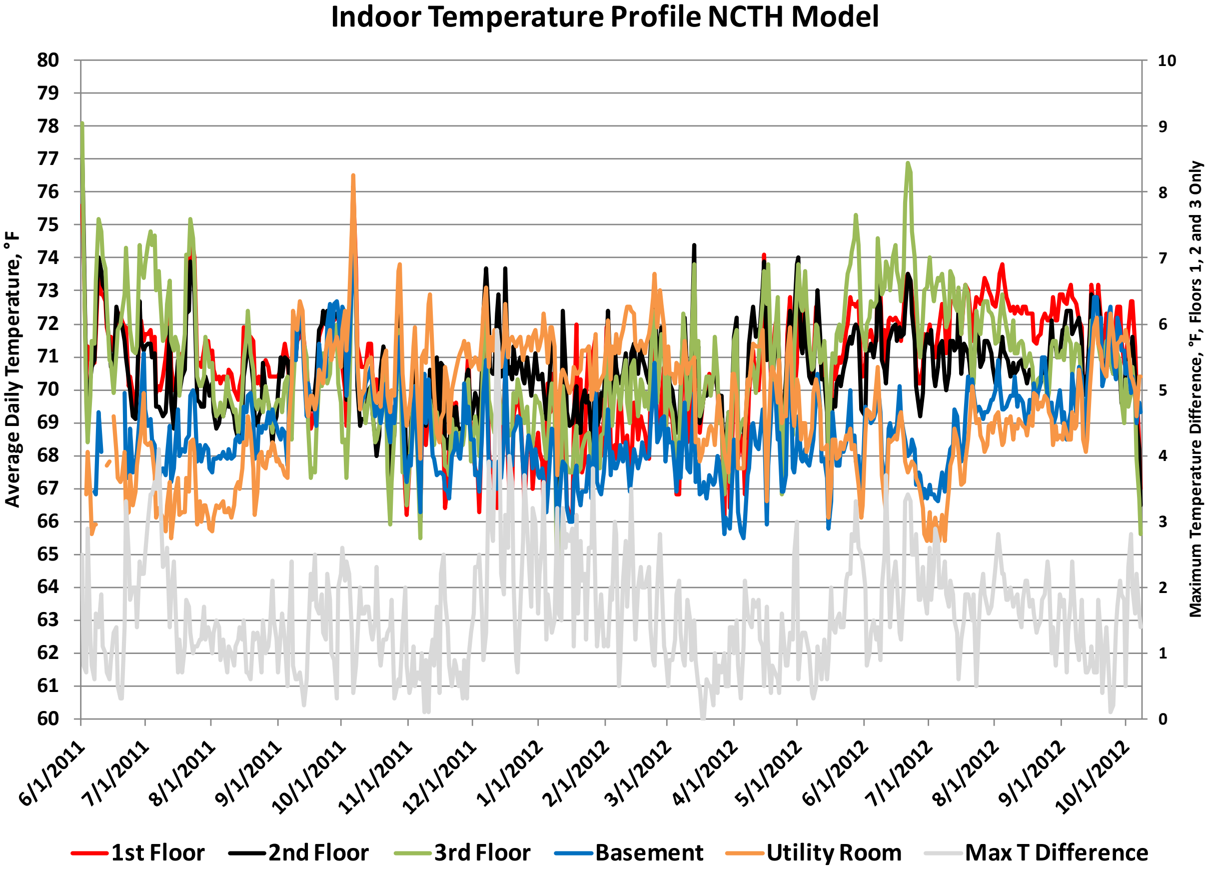

Figure 3. Indoor temperature profile for 16-month monitoring period

The temperature profile indicates that the duct design and operation of the heating and cooling system produces modest temperature difference between floors. The design team had originally considered installing a thermostat-controlled zoned damper system to minimize temperature differences between floors, but it appears that the current design, with the continuous operation of the ECM fan motor, produces acceptably consistent temperatures across levels of the home.

4.5 Ventilation and Exhaust Fan Testing

Fresh air ventilation flow, measured using a hot wire anemometer, was lower than expected, even in the cooling mode when the fan should be drawing the most air (the cooling mode fan operation is the highest fan speed). One subsequent measurement in the heating mode showed an unexpected improvement, although the flow was still less than anticipated. Incoming ventilation air was measured between about 35 CFM and 70 CFM depending on the air handler operation. Daily average operation of the fresh air inlet damper has indicated a consistent airflow at all times of the year. The controller was set to operate the fresh air damper for 60% of the time. Monitoring equipment, which provided the status of the ventilation damper (open or closed), verified that the control was operating as intended.

Bath exhaust fan airflows initially tested significantly less than rated. Upon investigation, it was determined that an unnecessary control which limited airflow had been installed. Removing this control improved the airflows considerably; however, all tested below the nominal factory ratings. Table 9 shows the results of exhaust fan measurements compared with factory ratings after the unnecessary control was removed.

Table 9. Exhaust Fan Ratings and Operation

Fan Location	Rated Airflow, CFM	Measured Airflow, CFM
Basement Bath	80	63
Powder Room	50	39
Master Bath (Main)	110	50
Master Bath WC	80	11
Hall Bath	80	42
Loft Bath	80	59
Range Exhaust	600	500

The results in Table 9 are not atypical from exhaust fan test results in other homes. The results clearly indicate that the design and installation of exhaust fans remains in need of improvement. At this time, however, there is no standard practice for verifying installed exhaust fan flow.

4.6 Wall Cavity Moisture Performance

Early investigations into the use of 2 × 6 framing in high performance home construction raised awareness of the importance of understanding the moisture characteristics of the wall cavity and designing the wall system to accommodate the natural movement of moisture in the wall cavity system. Members of the project team therefore, expressed interest in developing a more detailed understanding of the actual moisture characteristics in the wall cavity and additionally within the home. For this reason, and to add to ongoing field research on moisture characteristics in occupied homes, a more in-depth analysis of the moisture properties of the 2 × 6 framed wall system is underway at NCTH.

To evaluate the wall cavity moisture characteristics in the NCTH, sensors were installed at the interior sheathing surface. The sensors measure surface T/RH and the moisture content (MC) of the sheathing. (Refer to Appendix B for a description of the sensors and the calibration analysis used in the data processing.)

Wall cavity sensors were installed in selected wall cavities on the three AGW areas (22 sensors), in the band area of the basement (2), in the attic space (1), and in selected roof sheathing areas (2). Indoor sensors were located on all four levels of the home and one exterior sensor was located near the garage. Sensors were installed in all orientations. One of the first-floor sensors was located in a northwest-facing wall section constructed of fully insulated, double 2 × 6 framing (nominal R-46).

In addition to the wall cavity sensors, indoor T/RH measurements were also taken on each level of the home. These indoor measurements provide data that can be used to document the cyclic interior moisture levels in various seasons based on the actual use of the home and the operation of mechanical equipment (heating, cooling, ventilation, fans).

4.6.1 Sheathing Condensation Potential

The project team was interested in the moisture characteristics of the 2 × 6 wall system developed for the high performance home design. Using a standard simplified condensation potential methodology, Home Innovation conducted an initial evaluation of the theoretical potential condensation characteristics in the wall cavity based on estimated interior temperature and humidity conditions and historical average weather data.[13] The methodology assumes that the moisture in the wall cavity is directly based on the interior moisture conditions, regardless of the permeability characteristics of interior wall layers. The method uses standard calculations to determine wall sheathing temperature based on the level of insulation in the cavity.

Condensation is possible when the dew point temperature (DPT) of the air is higher than the surface temperature of the sheathing. In the heating season, the interior air T/RH directly affects the wall cavity moisture characteristics and the potential for increased MC of the sheathing. The configuration of the wall cavity, including interior vapor retarders, cavity insulation materials, and sheathing materials, will affect the ability of the wall cavity to handle the moisture load that enters the wall cavity through air leakage or diffusion.

To determine the potential for condensation on the interior surface of the sheathing, the surface temperature can be calculated using exterior and interior temperature conditions and the R-value of the insulation materials. The temperature at the interior surface of the sheathing is a function of the relative insulation levels to the interior and exterior of the sheathing surface at the interior of the cavity (see Figure 4) and the indoor and outdoor environmental conditions. For the cavity path, the temperature at any surface in the path is derived from the formula[14]:

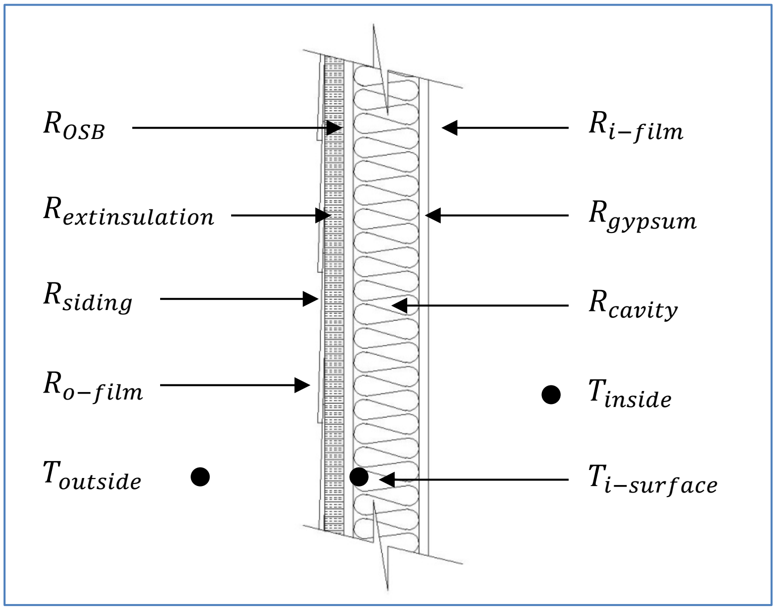

Figure 4. Graphical description of sheathing temperature calculation

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[13] Building Science Corporation, Guide to Insulating Sheathing, Revised January 2007. See also Insight issue May 2011 (rev), www.buildingscience.com for a discussion on the actual condensing surface compared with calculations of the condensing plane within a wall cavity.

[14] The calculation of the temperature at any point in the thermal pathway is based on well-known physical principles of heat or current flow across a resistance.

$$T_{surface\ a} = \left[\left(\frac{sum\ R_{values\ a-o}}{sum\ R_{values\ i-o}}\right) \times \Delta T_{i-o}\right] + T_o$$

where:

$T_{surface\ a}$ ≡ temperature of the surface of interest

$R_{values\ a-o}$ ≡ sum of the path R-value from surface of interest to the exterior

$R_{values\ a-o}$ ≡ sum of the path R-value from the inside surface to the outside surface

ΔT_{i-o} ≡ Air temperature difference from the inside to the outside

T_o ≡ Outside air temperature,

and where: Temperature is in °F and R-value is in $ft^2 \cdot h \cdot °F/Btu$.

For the NCTH located in climate zone 4, the potential for condensation based on monthly average outdoor temperatures is graphed in Figure 5. The wall system used for the dew point calculations is a 2 × 6 framed wall with R23 cavity insulation, exterior oriented strand board (OSB) sheathing and fiber cement siding, and interior gypsum with two coats of paint.

The green line represents the DPT of the indoor air at assumed winter conditions of 71°F and 47% RH. Curved lines represent the temperature at the sheathing for average monthly exterior temperatures, of various wall sections. The blue dotted line represents the actual monthly average temperature for the measurement period.

Under the assumed winter conditions, it is clear the potential for condensation on the interior sheathing surface exists during most of the winter heating season.

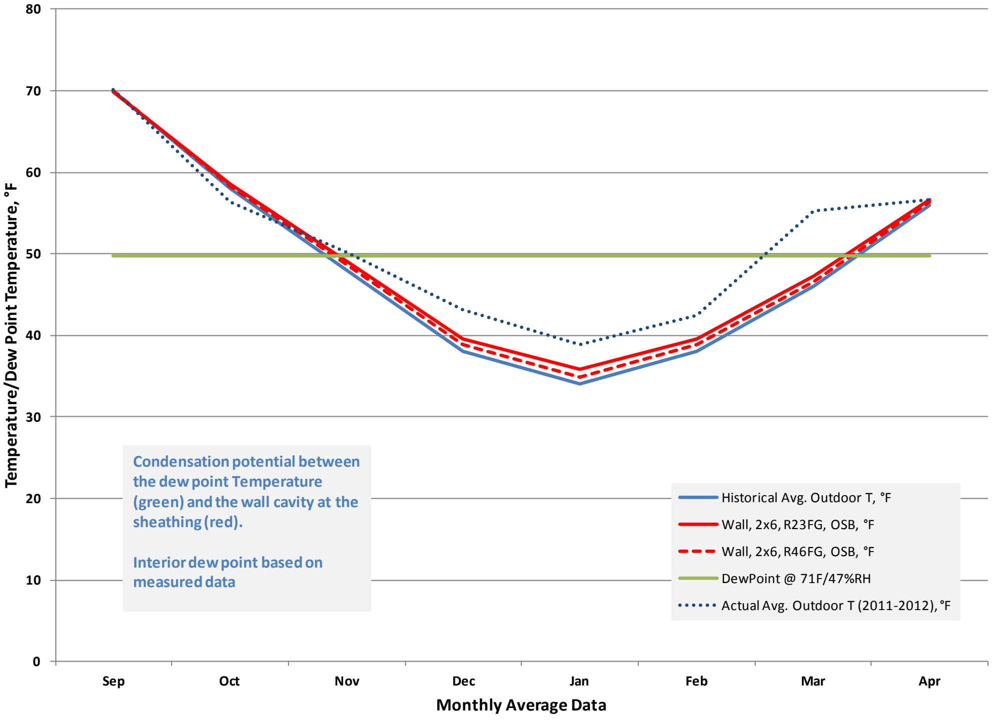

Figure 5. Theoretical condensation potential at interior surface of sheathing

The difference between the actual sheathing temperatures and concurrent DPT for a full winter heating season are charted in Figure 6, based on moisture sensor readings of T/RH and calculations of DPT. When the DPT at the sheathing is higher than the sheathing temperature, the potential for condensation exists. In Figure 6, this condition is depicted by sheathing temperature difference (T-DPT) that dips below the green line.

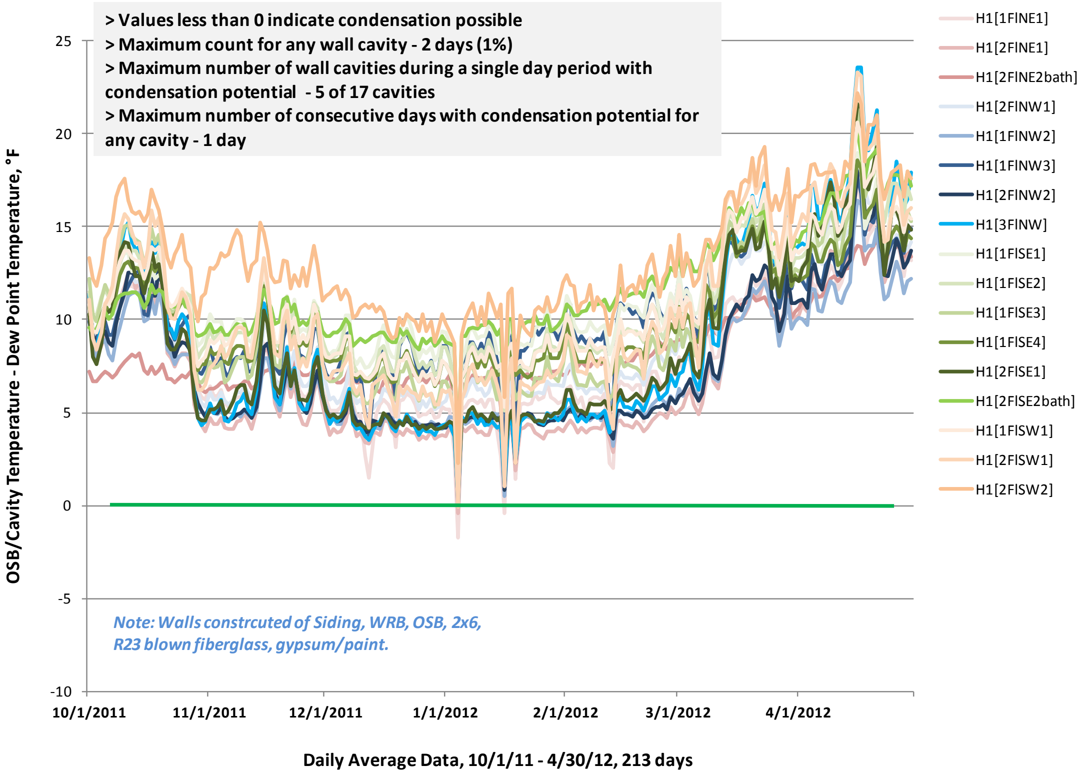

Figure 6. Heating season measured condensation potential in test home

Based on measured environmental conditions inside the wall cavities (excluding the one atypical wall section with R-46 insulation), the potential for condensation occurred for very few days in only a minor set of wall cavities during the heating season. The unoccupied home was actively humidified during the winter and the interior moisture and temperature conditions were very similar to the average conditions assumed in Figure 5. The results indicate that the theoretical calculation of condensation potential does not accurately represent the actual condensation potential across the winter heating season and therefore should be used cautiously when evaluating a particular wall design. Furthermore, the wall system design utilized in this test home in the first year following construction performs extremely well in terms of measured condensation resistance.

4.6.2 Interior Vapor Retarder

To better understand the actual moisture performance of some of the materials in the wall system and compare with assumptions, painted gypsum wall board was tested, since the layers of material in the wall system have a large effect on the amount of moisture that diffuses into the cavity. Constructed in climate zone 4, the NCTH is not required to have an interior vapor retarder per the

International Residential Code.[15] This wall design in this climate zone allows for moisture movement through the wall system to either the exterior (winter) or interior (summer). The standard paint specification is for two coats of latex paint. A section of painted drywall was removed from a test house similar to the NCTH and tested for permeability.[16] Four samples were tested using both wet and dry cup methods to determine the permeance of the painted gypsum layer. The results from both methods are summarized in Table 10.

Table 10. Summary of Gypsum/Paint Layer Permeance Tests

Test Method	Permeability, perm-in.	Permeance*, perm
Dry Cup	18.14	36.45
Wet Cup	–17.60	–35.54

* Based on the measured thickness of the gypsum/paint

The permeability of the gypsum/paint combination as tested is higher than data found in *ASHRAE Fundamentals* (2009) and other sources. However, these tests results are consistent with similar testing performed at Home Innovation on painted gypsum wallboard.

4.6.3 Preliminary Simulation Analysis

The Forest Products Lab, in collaboration with Home Innovation, is preparing a report that summarizes WUFI[17] simulations of the moisture response of sheathing in various wall systems in a climate similar to climate zone 4. The simulations predict the MC of the sheathing and the cyclic nature of the MC. The use of such simulation software can provide a general understanding of the wall system performance but is highly dependent on the assumptions made by the programmer. Such assumptions include the estimate of indoor RH in the heating season, the type of weather year selected, the physical characteristics of material layers, and the orientation of the wall element.[18] One of the wall systems investigated is configured in an identical manner to the NCTH walls. The researchers applied typical performance parameters to material layers. In some cases, for example when defining the permeance of painted gypsum, the researchers conducted parametric analyses to better understand a range of moisture performance of the OSB sheathing based on a range of drivers and material characteristics. Figure 7 shows the results of WUFI simulation of a 2 × 6 wall system with OSB sheathing, vinyl siding, R-23 fiberglass cavity insulation, and a gypsum/paint interior wall covering (with an assumed permeance of 10 perms). Results show the annual moisture response content of the sheathing following 3 years of simulation weather data.

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[15] International Residential Code, IRC 2009, by the International Code Council, Chapter 6, Section 601.3.

[16] ASTM Designation E96/E96M – 10, *Standard Test Method for Water Vapor Transmission of Materials*, was used as the test method to determine the water vapor permeance of the samples.

[17] WUFI (Wärme und Feuchte instationär) is software that allows calculation of the transient coupled one- and two dimensional heat and moisture transport in multilayer building components exposed to typical weather.

[18] A less well-known aspect of the software is the handling of air leakage and air movement through the wall system, which is known to affect the actual performance of the wall but is very difficult to simulate.

Figure 7. WUFI simulation results for an R-23 wall in climate zone 4

4.6.4 Preliminary Measured Wall Cavity Moisture Performance

The NCTH was instrumented with moisture sensors located at the interior cavity side of the OSB sheathing. Sensors were located in all wall orientations and in various rooms. Measured moisture performance data in the wall cavities are available for a period of more than 1 year, encompassing full cooling and heating seasons. Sensors measure the T/RH at the sheathing surface and the MC of the sheathing.

Although the NCTH is not occupied, it is regularly open for use by sales staff and customers. A humidifier installed on the main air handler duct adds moisture to the airstream during heating periods. The ventilation system operates as commissioned and the air handler is set to fan-run mode to maintain air movement throughout the home on a continuous basis. These equipment operational features will affect the interior moisture levels and those in the wall cavity.

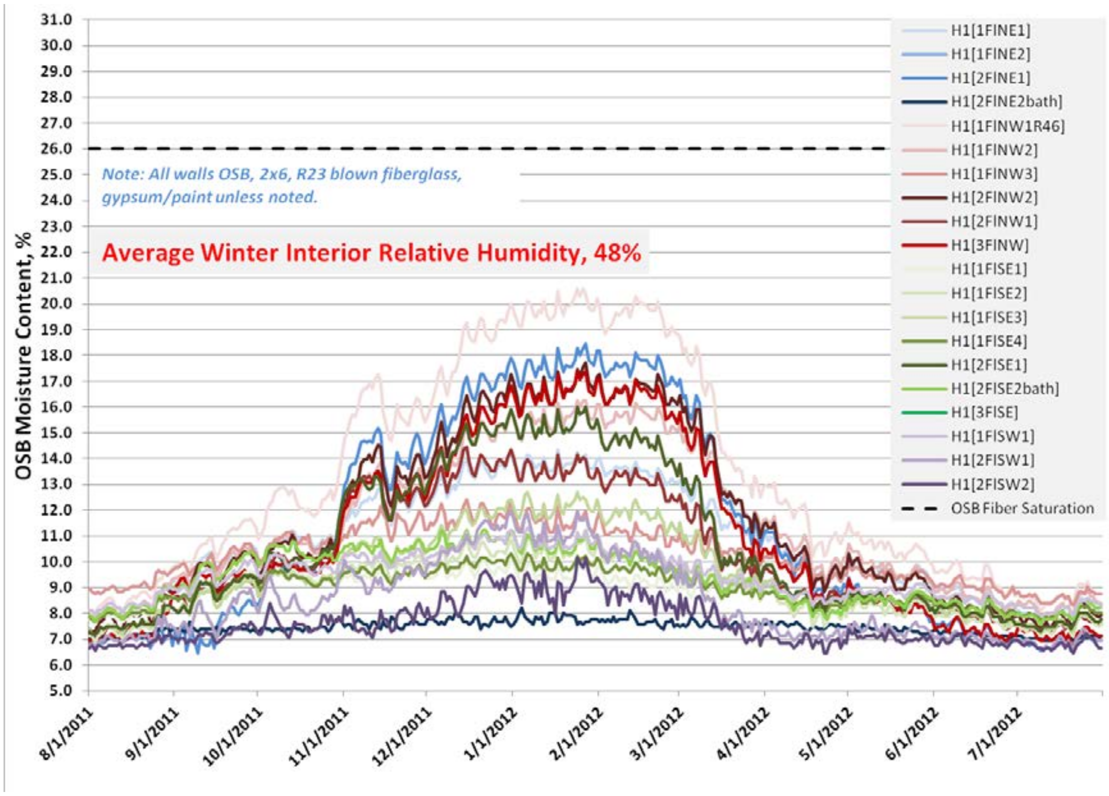

Figure 8. MC of OSB sheathing in the climate zone 4 NCTH

Figure 8 demonstrates the cyclic nature of the OSB moisture diffusion into the OSB sheathing over a full year period. Measured interior RH, an indicator of the potential for water vapor transmission into the cavity, aligned with, but is slightly higher than, typical RH used in the WUFI simulations (described above) and with estimates used in ASHRAE standards.[19] The higher the indoor moisture levels, the higher the potential for moisture movement into the wall cavity in the winter months.

Similar to the simulation results in Figure 7, the MC of the sheathing increases as the exterior temperature decreases and the vapor driver into the cavity is from the interior to the exterior. The north and east orientations generally have a more pronounced seasonal change in MC, varying by approximately 6%. All of the measured cavities dry to below 10% MC in the summer period regardless of the highest MC recorded during the winter period. The wall section with the highest recorded MC is the one wall section that is a double 2 × 6 framing completely filled with insulation (a nominal R-46). This particular wall section (which is not common in this climate zone) has the lowest sheathing temperatures in the heating season due to the much higher level of insulation in the cavity.

The MC profile measured in the wall cavities (Figure 8) resembles the results of the simulation data (Figure 7) but with lower peak measurements and a less defined rise and fall between seasons. This is likely due to the actual weather conditions, which were warmer overall compared with

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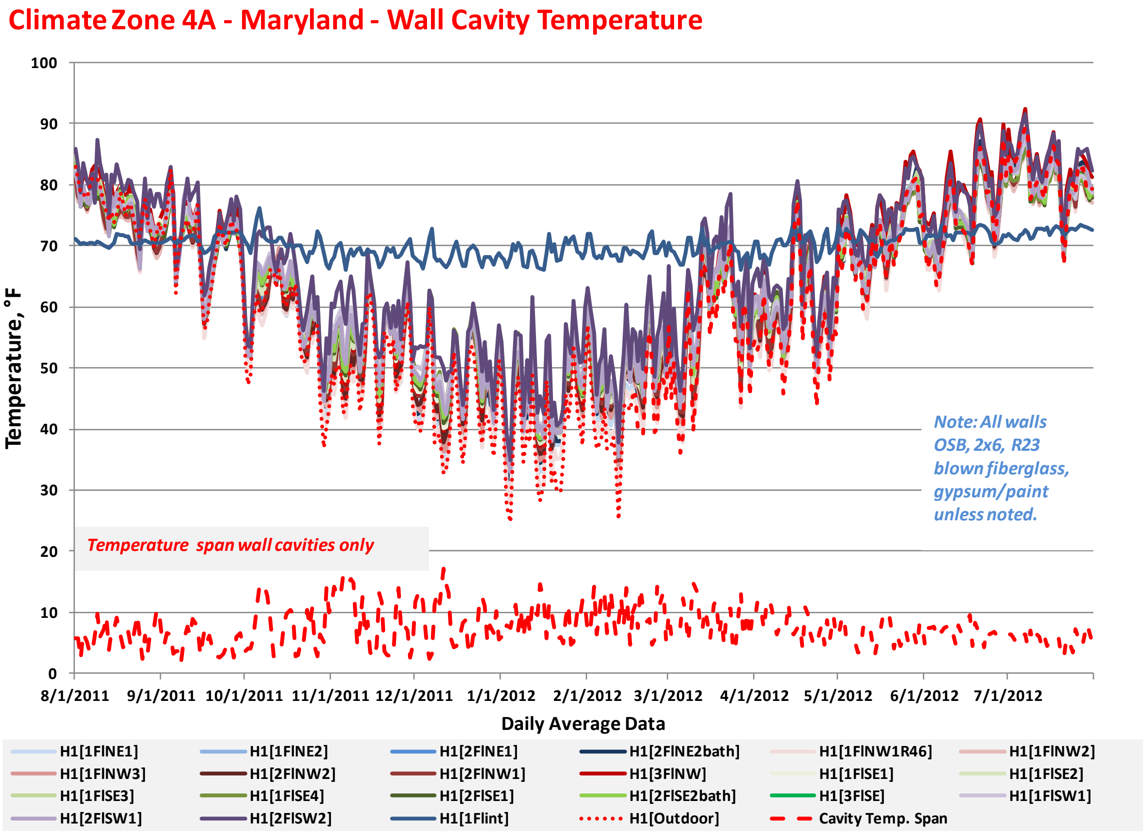
[19] ASHRAE Standard 160*, Criteria for Moisture-Control Design Analysis in Buildings*, 2009. American Society of Heating, Refrigerating and Air-Conditioning Engineers.

simulation data based on historical averages. The actual performance of the wall system demonstrates the common cyclic moisture characteristics of the sheathing.

Wall cavity temperature profiles for the same period as the MC data charted above are shown in Figure 9.



Note: All walls OSB, 2x6, R23 blown fiberglass, gypsum/paint unless noted.

Figure 9. Temperature at the OSB sheathing in the climate zone 4 NCTH

The red dotted line is the outdoor temperature and the solid dark blue line (that average near 70°F), is the indoor temperature. The red dashed line on the lower portion of the chart is the temperature difference between the maximum and the minimum for the day and provides the relative difference in cavity temperature for various wall cavities in different orientations. The range of temperatures is as much as approximately15°F in the winter period. As expected based on the configuration of the wall system, the interior cavity OSB temperature closely tracks the exterior temperature.

Similarly, the RH in the cavity at the OSB sheathing is shown in Figure 10.

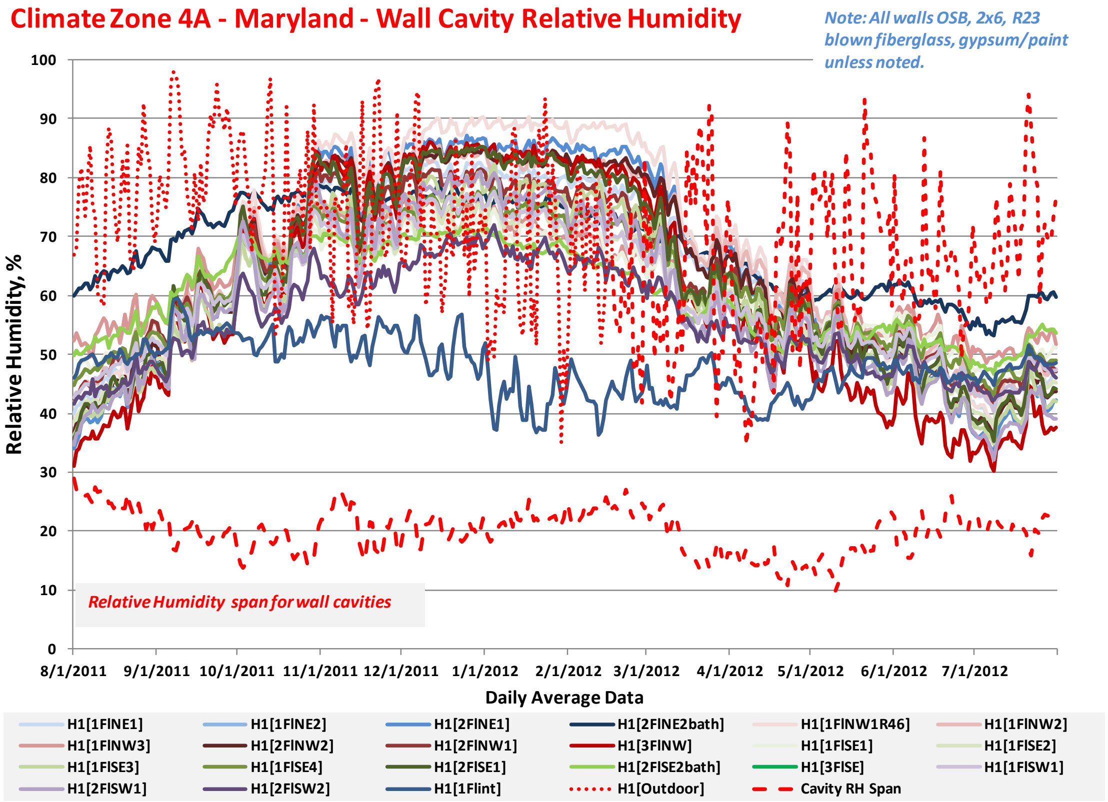


Figure 10. RH at the OSB sheathing in the NCTH (climate zone 4)

The red dotted line represents the outdoor RH and the dotted blue line is indoor RH. The red dashed line on the lower portion of the chart is the wall cavity RH difference between the maximum and the minimum for the day and provides the relative difference in cavity RH for various wall cavities in different orientations. The range of RH, about 10%–30%, is fairly constant for much of the year.

4.6.5 Model Home Measured Energy Use

Monitored energy use and utility bills were used to roughly compare the electricity and gas use of the NCTH with simulation results. Because the NCTH is operated as a sales model and therefore includes significant additional lighting, miscellaneous electric, and HVAC systems, simulations were run using standard home operating assumptions but with three times the miscellaneous use of a typical residence. A summary of the total electric and heating, cooling, and ventilation system energy use is shown in Table 11.

Although measured energy use is higher than simulated, the measured data generally confirms that the house functions as designed based on the energy efficiency features of the home. Differences between simulated and measured data can generally be explained by ambient conditions (for example, measured cooling degree day is higher than simulated cooling degree day) and by air handler operation that increased cooling loads.

Table 11. Summary of Total Electric and HVAC System Energy for a Monitoring Period

Parameter	Model Home	Model Home[a]	Model Home[b]	
	Measured	Simulation	Simulation	
Analysis Period 11/10/2011 to 10/08/2012				
Days in Period	334	334		days
Heating Degree Days	2,871	3,978		
Cooling Degree Days	2,237	1,505		
Total Electric Energy Use	34,847			kWh
Garage Office Electric Energy Use	5,866			kWh
Office Portion of Total	17%	N/A	N/A	kWh
NCTH Electric Energy Use	28,981	23,389	9,368	kWh
Compressor Energy	4,646	2,723	1,686	kWh
Heating Gas Use[c]	282	312	485	therms
Air Handler (Furnace/Air Conditioner) Energy	1,234	809	448	kWh
Site Heating and Cooling Energy, Million Btu	48.263	43.251	55.781	MBtu
Ventilation Air Handler Energy[d]	2,121	230	230	kWh

[a] Model home simulation has three times more miscellaneous electricity use than typical

[b] Typical home use in the model is based on BA Benchmark simulation protocols but with 71°F cooling to match simulated to measured performance

[c] Includes estimates for the fireplace use in the measured data

[d] Estimated fan energy for ventilation/air circulation

Due to the large electricity loads and resultant internal gains, and fewer observed heating degree days, the measured heating load on the furnace is lower than predicted. During the heating season, the furnace operated in low stage only and used approximately 162 therms of gas. The remaining 120 therms of gas usage is attributed to the gas fireplace, which was used irregularly.

The major difference in the operation of the house compared to simulation results is the furnace fan operation. In the model, the fan operates constantly to circulate air. Based on measured data, the fan-only mode operated the furnace fan (a simplified ECM), at a higher flow rate than is typical for fan-only mode. The resulting fan electricity use contributes to a higher cooling load, a reduced heating load, and contributes to slightly more outdoor ventilation air when the fresh-air damper is open. The fresh-air damper was open 61% of the time.

Other anecdotal evidence suggests the NCTH is performing well. There are two other homes in the community used as sales models in a similar manner as the NCTH (including office space in the garage and similar lighting use patterns). Although the NCTH has additional electricity use for three large flat screen TV panels, which are not typically used in the other model homes, utility bills for the NCTH are approximately 20% less per ft^2 than one model and approximately 10% less per ft^2 than the other.

5 Energy Value

5.1 Initial Cost Analysis

During the design process, WHI completed an extensive in-house cost analysis. This 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). This analysis examined energy performance, occupant comfort, and synergistic cost containment benefits such as reduced material and labor costs. High performance features were selected and designed to perform as an integrated system.

5.2 Future Cost Considerations

As with most builders, there is an ongoing evaluation of the construction costs and benefits relative to new designs and products. Balancing the house features with construction details to develop a marketable product is often driven by changes in building codes, the development of new materials, and consumer preferences.

In evaluating the energy efficiency features of the NCTH in light of ongoing product development and construction specifications, the builder made a number of observations:

- The advanced framing system can be implemented without a large increase in cost when costs and benefits are considered together. Cost increases include additional insulation and trim materials. Benefits include labor savings and wall designs that are adaptable to a wider variety of wall insulation targets without major redesign efforts.
- Converting the framing system for an existing plan can be nearly as costly as developing a new floor plan, and it may be undesirable where extensive portfolios exist in a given market. Another factor to consider is that floor area is important to consumers, and modifying interior area may be detrimental from a sales perspective.
- Drivers for switching to advanced framing can often be related more to construction and bracing preferences of the builder and considerations for durability and use of familiar products and installation methods, rather than achieving insulation goals alone. An example of this decision process is the comparison between use of wood sheathing and a weather resistant barrier layer and an exterior foam panel with taped seams.
- The cost of air sealing is of growing significance especially when much lower levels of infiltration will be required by building codes and testing will be performed to assure goals are met. The air sealing methodology selected for the NCTH appears to be capable of meeting infiltration goals consistently and reliably. However, the cost of the system versus the value remains uncertain. The builder continues to investigate other means of achieving the same performance goals at lower cost.
- The design and installation of the HVAC system remains a challenge. The cost savings, or at least a neutral cost, of installing a single system instead of two systems has been realized. The efficiency gains of installing the ducts in conditioned space, the use of bedroom transfer grilles, and minimized duct runs are all aspects of the NCTH that the builder plans to gradually incorporate based on cost savings (both for the builder and consumer) and measured performance.

- The HVAC system design includes a fresh air system, but final specifications are still under development. One consideration of the return fresh air system is the necessity of incorporating an ECM, which has wider cost implications for the HVAC equipment.

The complexity of these cost issues along with the changing building code requirements and reliable and achievable performance goals are important to ongoing cost evaluations.

6 Gaps and Lessons Learned

6.1 Overview

The level of effort invested by the builder, its trades, and the researchers during the planning stage was considered important to the successful design and implementation of the energy features for the NCTH research project. The effort expended to monitor the home, especially the wall cavity monitoring, was a critical element in assuring durability and long-term performance of the advanced designs. This investment was deemed necessary for development of specifications for future changes in other home designs. The energy efficiency features were selected for durability, practical and repeatable installation, and cost effectiveness.

6.2 Wall Framing

By incorporating the advanced wall system, the builder achieved insulation levels that will meet or exceed future code requirements. The advanced framing system can accommodate higher performance goals, for example by adding exterior insulation or using higher R-value materials in the cavity. Use of 24-in. on-center spacing can simplify installation of electrical and plumbing materials as well as reduce the time to install wall finishes. Builder framing 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.

Use of the rim headers on the first floor allowed for optimized framing around window and door openings. BA program laboratory testing supported the engineering work required to develop a standard methodology for rim header application. Specifications were required for rim header material at openings as well as nailing specifications for multiple rim elements and installation of joist hangers. While this home design was engineered, the methodology to develop prescriptive approaches to the use of rim headers was initiated through this effort. The framing contractor adapted to the design change without major complications implementing the double rim and joist hangers where needed over openings. One complication with the rim header design occurs when an opening is added in an exterior wall as occurred in this test house, in which case, standard framing techniques must be used.

Offsetting interior walls to eliminate corner breaks in the gypsum wallboard of exterior walls proved a successful design change. Both framing and sheetrock crews adapted easily to this design modification.

6.3 Floor Framing

The floor framing members were individually engineered and numbered to accommodate the floor plan. The software, developed and implemented by Weyerhaeuser Company, used for the design and layout of the floor joists incorporated main supply and branch duct runs, domestic and sprinkler plumbing pipe runs, and drain pipe runs to facilitate the incorporation of mechanical distribution in conditioned space. Floor joist elements were factory cut to align joist openings for each of these building elements. The floor framing design resulted in a rigid floor, and the numbered joists and rim boards, after a brief learning curve, made for efficient installation as reported by trade contractors.

One aspect of this design and installation method is the high level of precision needed in the layout and installation. Since the system is engineered, field modifications are less flexible and precise installation according to plans is necessary. This precision and attention to the framing layout can be a challenge.

6.4 Air Sealing

Air sealing new homes is of increasing importance due to the more stringent requirements in building codes and the requirement for testing to verify performance. The NCTH design presented a plethora of challenges for air sealing as the turret, the third floor loft, and the complicated roof framing all contributed to extensive air leakage paths where many angled framing members adjoined attic or exterior spaces. The air sealing system used in the NCTH was a spray applied elastomeric foam that allowed for a more comprehensive coverage of all interior surfaces adjoining exterior spaces. A major benefit of the system was the ability to inspect the air sealing coverage and identify locations where air sealing may be missing and, hence, problematic. Specific details on sealant coverage, for example if all bottom plates and cavity seams should be sealed, remain to be resolved. However, the general approach was found acceptable due to the excellent air leakage results and the relative straightforward installation methodology, especially for the complex framing design.

The installation of house wrap as a secondary exterior air barrier was not completely accomplished per the original design (sealing the top and bottom of house wrap was not completed). However, the test results in this NCTH and subsequent houses using the same air sealing system but with less inspection demonstrated the reliability of the system to achieve the desired outcome.

6.5 Heating, Ventilation, and Air Conditioning

The decision to install the entire heating and cooling system in conditioned space resulted in significant estimated energy savings over the BA Benchmark. HVAC system location, 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 in order to accommodate a central duct chase. This chase, which was critical for installing the entire system in conditioned space, was also utilized for plumbing piping.

The integration of the second and third floor duct layout with the floor joists required significant design stage effort and site coordination for the installation. A different approach to implement this design could be to cut an opening, at the factory, through the engineered rim board to accommodate the field installation of the duct after framing is complete. This approach may be complicated if an opening is required over a window where a rim header is used, however, a conventional header could be installed. Alternatively, the integrated duct and floor design could be eliminated if this duct were installed conventionally (below and perpendicular to the floor joist) with a bulkhead if the design can feasibly be constructed, especially from the initial development of the architectural plans. Clearly the duct design and layout remains an important issue for further design efforts and installation evaluations.

Duct leakage to outdoors was presumably through leakage points in the air barrier in areas that were physically connected to the ducts (for example at the rim areas or top of the central duct chase). Leakage to outdoors was low and therefore the energy penalty was not considered significant; however, total duct leakage remains an opportunity for further optimization of the system performance.

Bath exhaust fan airflows which measure below nominal fan ratings may be a widespread issue (not limited to this project) and may be partially due to a lack of manufacturer guidance on duct design. Testing indicated a need to investigate improved exhaust fan ducting layout and component selection. Performance may be diminished by excessive duct static pressure; performance may be improved by using different duct or fittings (for example larger diameter pipe or a less restrictive vent hood).

Lower-than-expected fresh air ventilation flow may be attributed to the return duct design, which was sized to reduce air velocity and therefore noise in accordance with Air Conditioning Contractors of America Manual D (ACCA 2009b) recommendations; this low-pressure-drop design may require a larger diameter fresh air duct to draw in adequate ventilation air. An overly restrictive fresh air intake hood may have contributed as well. The test results highlight a need for additional ducting considerations for a supply-type ventilation design to ensure sufficient ventilation.

It is expected that the additional cost of higher efficiency heating and cooling equipment is more than offset by installing a single system, instead of two, and a simplified duct system. However, final cost figures are not available.

The startup of the furnace and air conditioning system, notably the calibration adjustments to the burner gas rates and blower flow rates in various modes, highlighted how critical a thorough commissioning procedure and written report are to ensure the equipment is operating properly and efficiently.

6.6 Plumbing

While the plumbing system performance in the NCTH was not analyzed, design improvements are possible. For example, locating the kitchen and baths in closer proximity would significantly decrease the pipe lengths to the outlets and enable the use of smaller diameter pipes. This redesign would save materials, installation labor time, and energy use. For the manifold distribution system, insulating the large diameter pipe between the water heater and the manifold should be considered. Due to its large diameter, this pipe can be a source of heat loss. Low flow fixtures will also contribute to lower water heating costs for the consumer.

6.7 Quality Assurance

The builder implemented many of the design changes directly on the building plans and within scopes of work for the trade contractors. This documentation is a necessary step for reliable and repeatable satisfactory outcomes. Design reviews, site reviews, and inspections are recommended for subsequent houses to help ensure that framing, air sealing, insulation, and mechanical systems are designed and installed for optimum performance goals. Commissioning and testing were valuable for NCTH performance and are recommended for heating and cooling systems, duct air delivery, ventilation fans, and whole-house air leakage in subsequent houses.

7 Summary

7.1 Conclusions

This test home project defined construction and energy efficiency goals to achieve a high performance home design. The project goals and research questions are summarized in the following key areas.

7.1.1 Overall Constructability and Potential for Continued Use of the High Performance Design

The goal for making major wall and mechanical system design changes was to provide the necessary framework to reliably and consistently achieve high performance goals on a production home basis. Using advanced design elements such as advanced 2 × 6 framing, rim headers, offset interior walls, and an optimized floor framing system, the builder and trade contractors successfully implemented these elements into their work scopes and into the quality control practices. Although the design changes were significant for the wall panelizer, framing trade contractor, HVAC trade contractor, and builder, the transition to the new system was made without major problems. The system design was also found to be sufficiently cost-effective so that it could be incorporated in new house designs or even in conversion of existing plans. These design strategies were implemented in at least three additional houses as shown in Figure 12.

Figure 11. Three additional houses built using NCTH features

7.1.2 Wall Design To Meet Various Performance Levels

One goal of the design effort was flexibility in achieving higher energy goals. The package of solutions used in the test house design has demonstrated that additional major design changes to the wall system or the HVAC system would not be needed to achieve higher energy savings goals or for meeting modestly more stringent future energy codes or above-code programs for energy savings and environmental performance. Selection of higher energy savings choices could be made by homeowners without requiring the builder to completely redesign the structure.

7.1.3 Heating and Cooling Installation and Performance

The complete redesign of the HVAC system focused on increasing the efficiency of the overall system, reducing duct losses, providing comfort throughout all levels of the home, and limiting any cost increases. These challenging goals were met through a rigorous design process that eliminated the need for a second system (typically located in unconditioned space), reduced duct losses, moved all ducts to the interior, and balanced the supply and return air to provide minimal temperature fluctuations between floors. The newly designed system for the house size and layout showed a significant increase in performance coupled with the advanced wall system, reduced the overall installed tonnage by at least 30%. The measured duct leakage to the exterior was minimal however efforts to obtain a sealed duct system required multiple tests and is an area where improvements can be made.

The total measured heating and cooling energy for the test home fell within estimates based on simulations indicating that the envelope and equipment design functioned as intended.

7.1.4 Airtightness and Ventilation

The test house design effort also focused on developing an air sealing methodology that would result in infiltration rates of less than 3 ACH50 in a reliable, consistent, and cost-effective manner. The first two goals were met following multiple installation inspections by the builder and trade contractor and with successful implementation in three other homes in the development. However, the last goal is still being analyzed to reduce the cost of achieving the lower infiltration rate. The performance goal was deemed necessary, however, and will remain an important design element in future homes. In addition to reducing infiltration, especially in very complex framing designs, a whole-house ventilation system design was developed and implemented. The result of this development effort is an improved and standardized ventilation system that will be implemented in new home designs and may likely be used in many existing home designs.

7.1.5 Durability

In particular for the new wall system design that significantly modified the framing dimension and insulation level, the concern of moisture accumulation in the structural sheathing was addressed. The testing results showed that the sheathing will see varying moisture levels based on the changing exterior conditions and with interior moisture levels maintained by humidification. The cyclic moisture characteristics of the wall sheathing fell within acceptable ranges, from 7% to 18% in the 2 × 6 wall cavities and were well within the capability of the materials to handle moisture. The wall system was installed without vapor retarder materials enabling more complete insulation coverage while limiting cost increases.

The measured wall cavity moisture data indicated that based on actual winter outdoor and indoor T/RH, the DPT at the sheathing was rarely above the sheathing temperature and then only for brief periods of time. This measured result was significantly different when compared to standard DPT calculations that indicate an extended period of condensation in the wall configuration. When comparing the measured wall cavity moisture characteristics with simulation results from WUFI software, the cyclic pattern of MC levels was confirmed; however, the peak MC for the sheathing in theoretical estimates was higher than measured results.

7.1.6 System Testing Verification and Commissioning

All permanent features (optimized framing, insulation, windows, plumbing piping, and single HVAC system with interior ducts) were designed, implemented and successfully tested and/or commissioned. The HVAC commissioning process in particular was found to be a necessary part of the redesign effort. This necessity grew out of the higher level of complexity for house component designs (such as the wall framing or duct layout), the technical advances of the equipment (both for controls and equipment setup), and the need for verification that target performance levels were met. This test verification and commissioning effort, however, is still under development by many builders and the cost of such verification comes without direct savings and such must be incorporated using a more cost-effective methodology.

The measured energy use of the model home was much higher than would be expected from an occupied home as lighting and other loads are much higher. Similarly, the temperature setting for the indoor environment was higher than might be expected in an occupied home.

Figure 12. Completed NCTH

7.2 Next Steps

Home Innovation, working with WHI and the BA program, will continue monitoring the moisture performance of the wall system. Moisture information will be particularly valuable after the home is occupied as a residence.

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Appendix A: Energy Simulations

The NCTH as built with both the optional finished basement and third floor showed 30% whole house energy savings over the BA Benchmark,[20] excluding any size adjustment factor. The preliminary energy simulations included both a 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 13 graphically depicts the simulation results.

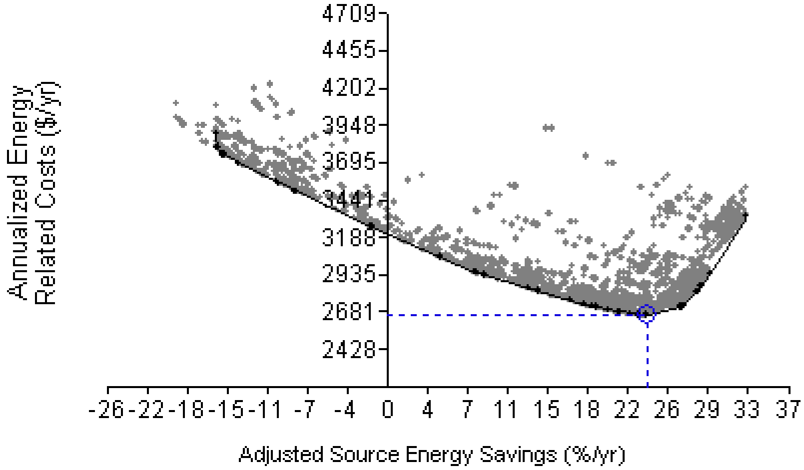

Figure 13. BEopt simulation results

The “swoosh” shape of the graph indicates that the minimum annualized energy cost occurred at source energy savings of approximately 24% (indicated by blue dotted lines). Before reaching the minimum cost point, incremental 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 are attainable, but the investment needed to attain incremental efficiency gains rises sharply. For example, meeting the project goals of 30% energy savings required an approximately 10% higher annualized energy related cost than the annualized cost of reaching 27% savings requires. 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, construction methods, and 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 BA Benchmark, the as-built design (which serves as a model home and, includes nearly 2,000 ft^2

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[20] The current BA benchmark home has insulation and air leakage minimums consistent with the 2009 International Energy Conservation Code, but is (and has always been) a whole-house analysis for both the reference house and the design house to determine energy savings.

of optional conditioned space) was subject to a size penalty that reduced overall projected savings. Because of the additional conditioned space, the BA program administers a penalty (which is manifested in a source energy reduction for the BA Benchmark design). Figure 14 shows source energy use for the BA Benchmark and the final house design. The size penalty reduced theoretical source energy savings by about 7%.

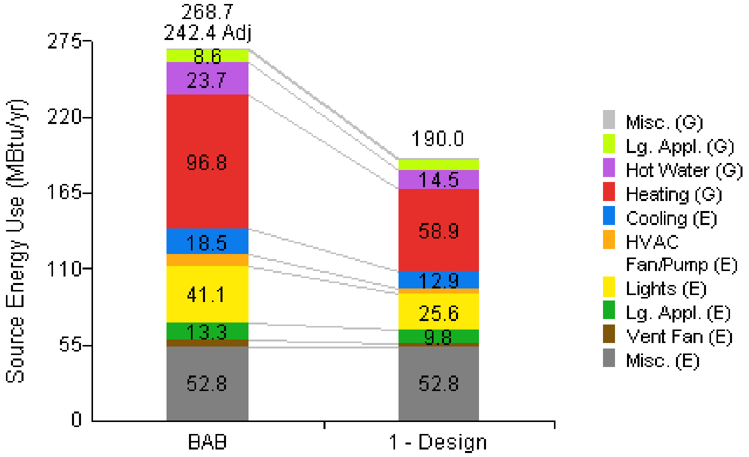

Figure 14. Source energy savings for energy efficient design compared to the BA Benchmark

(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. Components of the savings are depicted in Figure 15.

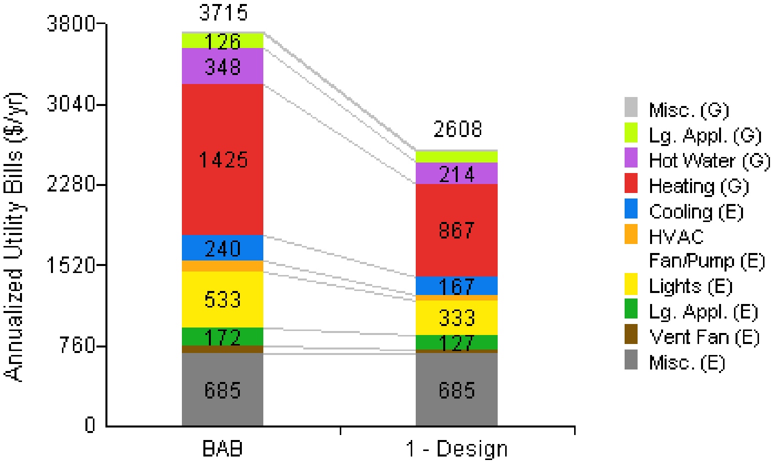

Figure 15. Annualized utility bill comparison for BA Benchmark and energy-efficient design

For a house having the same energy efficiency solution package as NCTH but that **does not** include 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 16 and Figure 17.

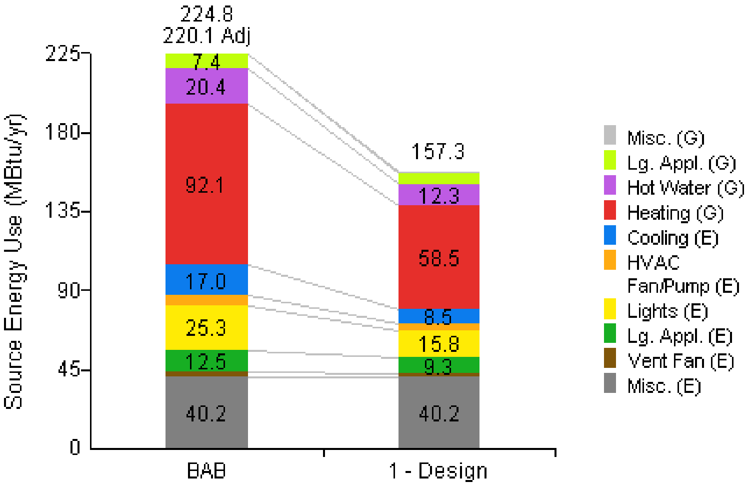

Figure 16. Source energy use for BA Benchmark and energy-efficient design

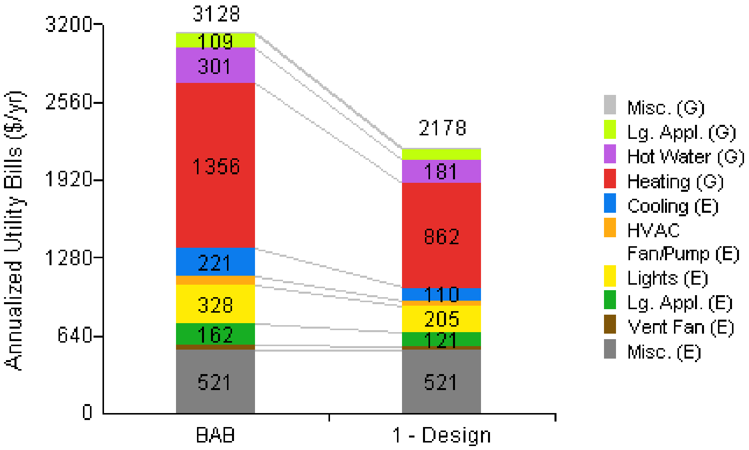

Figure 17. Annual utility bills

Appendix B: Wall Cavity Moisture Sensors

Small wireless sensors (Omnisense S-900-1 shown in Figure 18 and Figure 19, shown as modified without leg extensions) were installed in walls in the NCTH to measure the following parameters:

- Cavity temperature (-40°F–185°F)
- Cavity RH (0–100%)
- Cavity DPT
- OSB sheathing MC (7%–40%).[21]

T/RH are measured by an internal sensor located inside the plastic housing. The wood MC is determined using two screw pins driven into the sheathing and is based on the measured resistivity of the OSB material. The sensors are prepared at Home Innovation with a protective covering that inhibits moisture or other materials from entering the sensor body through the battery compartment. In this manner, the sensors have been successfully fielded in locations where expanding foam covers the sensor body.

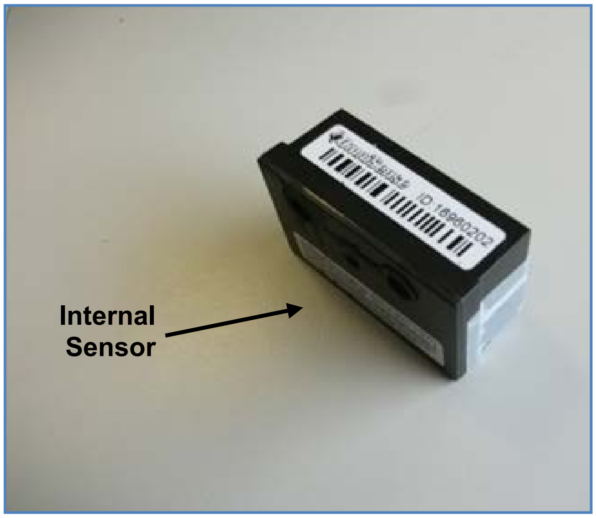

Figure 18. Omnisense S-900-1 sensor

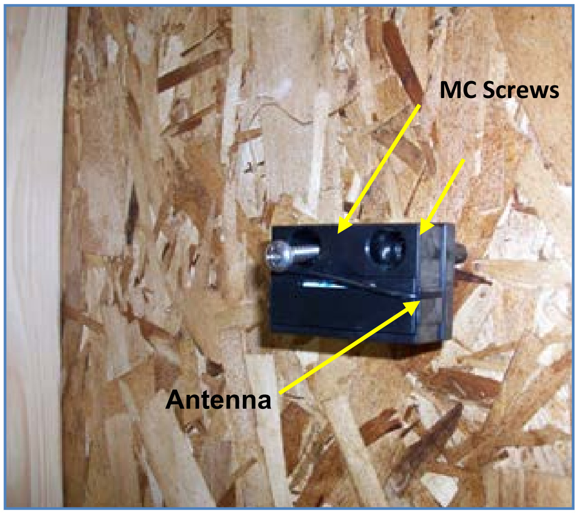

Figure 19. Installed test wall moisture sensors

The manufacturer stated accuracy for the sensor models used is ± 2.0% RH and ± 0.3°C. Home Innovation has performed numerous calibrations to verify both sensor accuracy and the correlations with MC. MC was correlated with readings on handheld electrical conductance type moisture meters as well as MC readings with wet/oven dry sample measurement calculations. The wood MC value reported through the sensor technology is a wood moisture equivalent and is the water content of wood as a percentage of dry weight. The sensor manufacturer calibrates its devices based on wood species and temperature compensation relationships outlined by the U.S. Department of Agriculture.[22] For calibration purposes, a set of sensors was installed in OSB

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[21] Calibrated from the manufacturer to USDA Douglas Fir.

[22] James, William L., *Electric Moisture Meters for Wood, Forest Products Laboratory*, General Technical Report FPL-GTR-6

samples and placed inside an environmental chamber capable of controlling T/RH. Figure 20 shows the set of sensors in the environmental chamber where T/RH were tightly controlled at various levels of humidity for calibration purposes. At various levels of humidity and when equilibrium was achieved (equilibrium MC) based on specimen weight consistency, a set of specimens were removed, weighed, oven dried, and weighed once again. The resultant ratio of the measurements provides the gravimetric MC of the specimen.

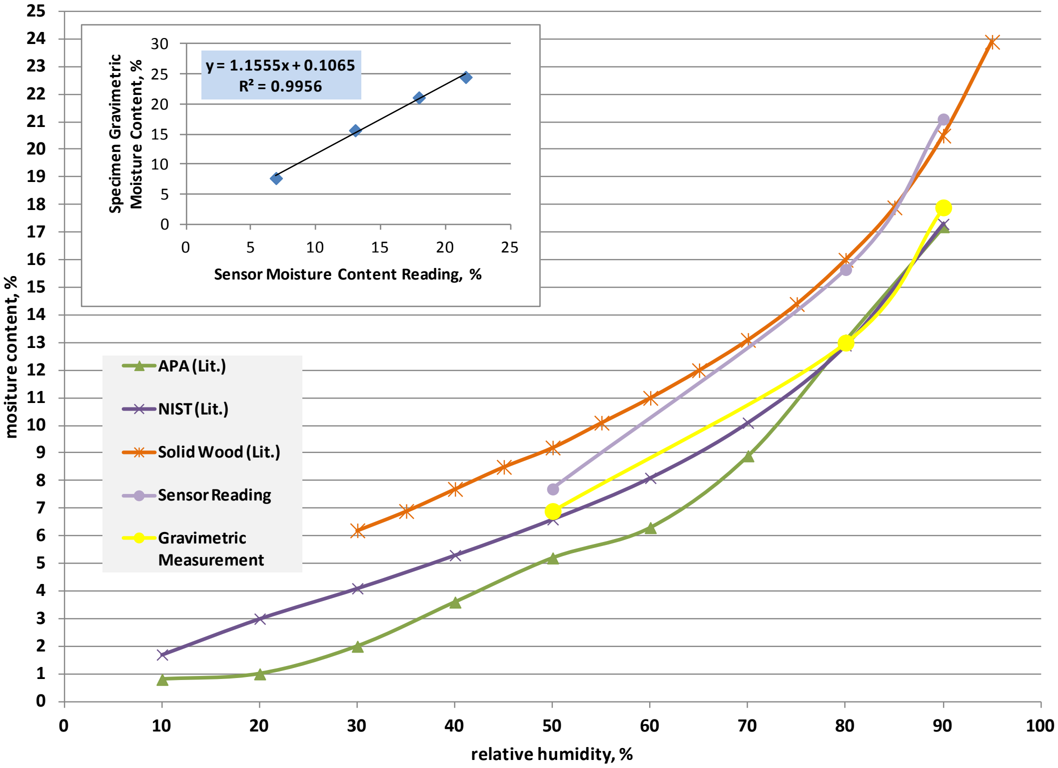

Figure 20. MC calibration curves

Figure 20 plots the sensor MC reading, the oven dry MC, and various reference curves from literature and shows the calibration relationship between the sensor reading and the measured OSB specimen MC. In all cases, the reported sensor reading is higher than the gravimetric calculation at most 2% MC. The National Institute of Standards and Technology reference curves (ASTM 2009) align well with the gravimetric measurements except at the 90% RH level where the National Institute of Standards and Technology reference is about 4% MC lower than measured calibration results. The results presented here include calibration of the sensor reading for OSB readings only, based on the gravimetric measurements as shown in Figure 20. Measurements from stud readings are left unchanged based on the sensor manufacturers' calibration to solid lumber species.

Sensors were installed in test homes in wall sections identified by orientation with more sensors being placed in the north and east orientations. For multistory homes, sensors were placed in both the first- and second-story wall sections. Interior sensors provide T/RH data in the main living space and are located as close to the thermostat as practical. A second interior sensor is located in the main bathroom and where wall cavity sensors are located. If applicable, a third interior sensor is located in the basement area to provide temperature and humidity data below grade. An exterior sensor is used to record the ambient T/RH and is shielded using a white polyvinyl chloride cap.

Sensor data are transmitted at a minimum on a 15-minute basis. All data are uploaded continuously to a website capable of data storage. The raw data are processed to calculate the dew point and grains of moisture based on the T/RH. The MC data are calibrated to a standard wood MC based on the temperature at the wood surface.

The dataset stored on the website is downloaded periodically and averaged on a daily basis for further analysis and charting. Each sensor is associated with a wall room location and orientation and ultimately with a wall configuration.

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