Comparative Energy and Wall Performance of Twelve Residential Houses Constructed in a Cold Climate

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ABSTRACT

Many construction options exist to build homes which comply with energy code requirements. Dow Building Solutions partnered with Cobblestone Homes to build case study, single family research houses in Midland, Michigan (climate zone 5) in 2011 to compare the performance of four building energy efficiency strategies. Energy code compliance strategies ranged from 2006 International Energy Conservation Code *(IECC), 2012 IECC, and beyond 2012 IECC high performance enclosures. A total of twelve houses were built for this case study, with three house plans replicated for each of the four energy efficient strategies. All twelve homes are in very close proximity with a similar geographic orientation and will remain occupied through the multiyear study period.*

This paper analyzes the cost and benefit of each enclosure construction method, plus a comparison of overall energy consumption. HVAC equipment energy use was separated from plug loads to understand its impact on the entire energy use of the homes.

Additionally, this paper addresses durability and moisture concerns raised about some high performance envelope strategies. Hygrothermal performance comparisons of the above grade and below grade walls was measured by relative humidity, temperature, and moisture content instruments installed in each house. This data was used to evaluate relative durability risks associated with each energy performance strategy and construction.

INTRODUCTION

Dow Building Solutions and Cobblestone Homes partnered to build single family research homes in Midland, Michigan to quantify the construction cost and energy performance benefit of residential wood frame homes built according to the 2012 *International Energy Conservation Code* (IECC) compared to the less demanding 2006 IECC code (ICC 2012, 2006). Midland, Michigan is located interface between climate zones 5 and 6 and has 6645 annual heating degree days (NCDC) and can be characterized as a cold climate. The project included twelve homes and utilized three floor plans of similar size. A base case cost was established by constructing each floor plan to comply prescriptively with the 2006 IECC. Six homes were then constructed to comply with the 2012 IECC using the performance approach. Finally three additional homes were constructed with energy performance exceeding the 2012 IECC requirements, essentially capable of net zero energy performance with the addition of renewable energy sources. The homes sizes are considered typical representatives of homes built for a family of four. Home areas are shown in Table 1. Living space includes the above grade space and additional living space in the partially finished basement. Figure 1 shows the subdivision layout and photographs of the home built.

DESCRIPTION OF HOUSES AND ENERGY EFFICIENCY FEATURES

Several strategies to control the energy performance of the test homes were investigated. For foundation walls, faced fibrous insulation was compared to both rigid extruded polystyrene foam insulation and rigid polyisocyanurate insulation. Use of continuous exterior insulation on above grade walls was compared to

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walls built with housewrap and insulation only in the cavity space, along with a comparison of 2 × 4 and 2 × 6 constructions as a component of the wall design. Additionally, fibrous insulation and closed cell spray polyurethane foams were compared as cavity insulation and rim joist insulation. Descriptions and pictures of the energy performance strategies can be found in Tables 2–3 and Figures 2–7.

80% annual fuel utilization efficiency (AFUE), 71,000 Btu natural gas furnaces were used in the 2006 IECC homes. 92% AFUE furnaces were used for both the 2012 IECC minimum and 2012 IECC premium homes with sizes ranging from 69,000—93,000 Btu. The high performance homes used 96% AFUE, 57,000 Btu furnaces. Although envelope insulation and air sealing improvements

Table 1. Description of Test Houses

	House Plan A	House Plan B	House Plan C
Conditioned floor area (ft^2)	2800	3100	3100
Conditioned space volume (ft^3)	23900	27600	27100
Floors above grade	2	1	1

Table 2. Foundation Wall and Basement Floor Design

	2006 IECC	2012 IECC—Minimum	2012 IECC—Premium	High Performance
Under Floor Slab	None	None	None	R-10 XPS
Rim Joist—Interior	R-19 Kraft Faced Fiberglass batt	R-19 Kraft Faced Fiberglass batt	R-16 cc SPF	R-16 cc SPF
Rim Joist—Exterior	None	None	R-5 XPS	R-10 XPS
Basement Wall—Interior Finished	R-13 Kraft Faced Fiberglass batt	R-19 Kraft Faced Fiberglass batt	R-5 XPS	R-10 XPS
Basement Wall—Interior Unfinished	R-10 Fiberglass vinyl faced	R-15 Fiberglass vinyl faced	R-5 PIR	R-10 PIR
Basement Wall—Exterior	None	None	R-10 XPS	R-10 XPS

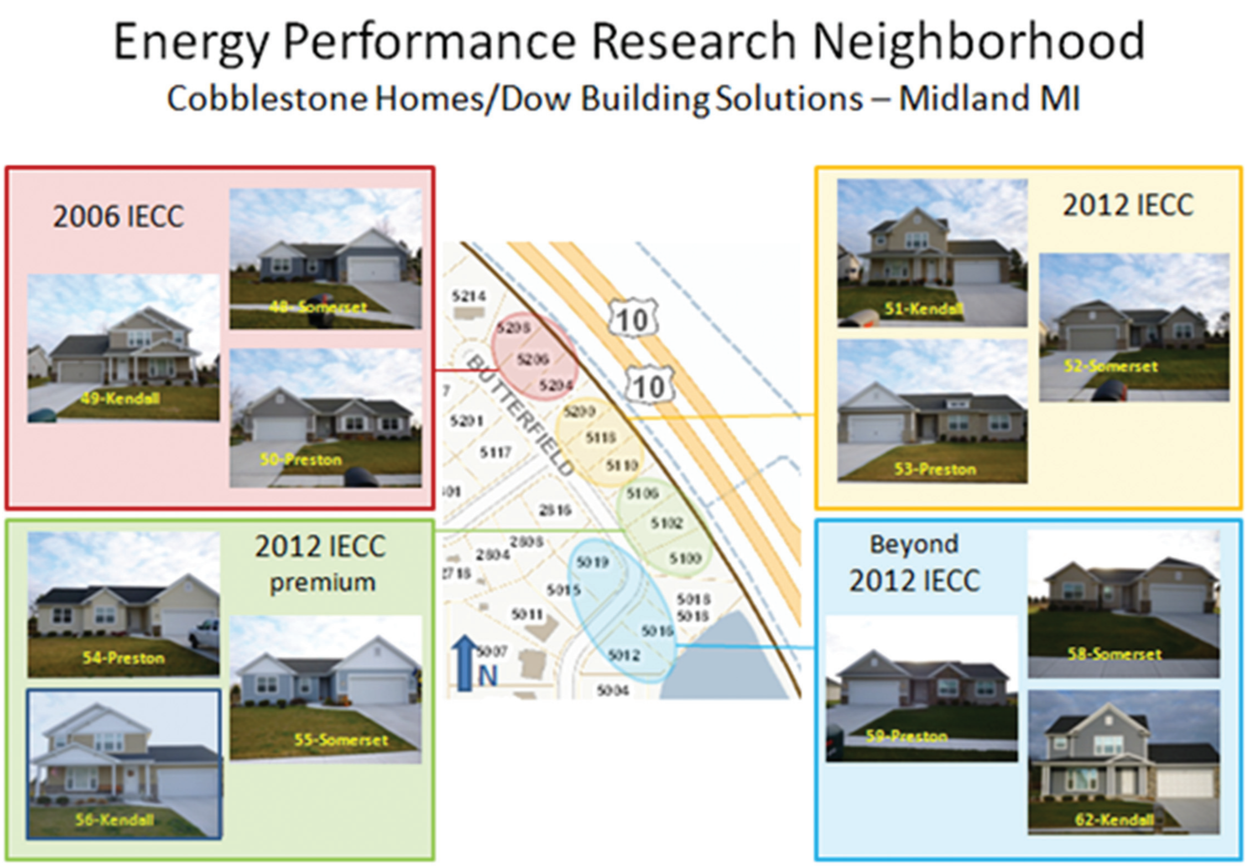


Figure 1 *Energy performance research neighborhood.*

in both 2012 IECC and high performance homes should have allowed reduced furnace sizes, HVAC contractors did not do so.

U-0.35 windows were used in the 2006 IECC homes. U-0.32 windows were used for both the 2012 IECC minimum and 2012 IECC premium homes. U-0.28 windows were used in the high performance homes.

Air Leakage Details

Above grade walls of 2006 IECC and 2012 IECC minimum homes were air sealed using minimal expanding spray foam sealant around windows and doors. Mechanical penetrations within and through the walls, rim joist, and ceilings were sealed using one-component expanding spray foam sealant. Wall plates and wall junctions were air sealed with latex caulk. The gypsum wall boards were installed using an adhesive at the top plate of the walls. Foundation air sealing in these homes was provided by taping the seams of the vinyl facing of the insulation for the unfinished area and drywall installation in the finished areas.

Table 3. Above Grade Wall and Ceiling Design

	2006 IECC	2012 IECC—Minimum	2012 IECC—Premium	High Performance
Stud Configuration	2 × 6 – 16 in. o.c.	2 × 6 – 16 in. o.c.	2 × 4 – 16 in. o.c.	2 × 6 – 24 in. o.c.
Interior	R-19 Fiberglass batt	R-19 Fiberglass batt	R-16 cc SPF	R-31 cc SPF
Exterior	Housewrap	Housewrap	R-5.5 structural insulated sheathing	R-5.5 structural insulated sheathing + R-5 XPS
Ceiling	R-38 Dry Blown Cellulose	R-49 Dry Blown Cellulose	R-49 Dry Blown Cellulose	R-12 2 in. cc SPF and R-49 Dry Blown Cellulose

Above grade walls of 2012 IECC premium and high performance homes were air sealed with continuous insulating sheathing with taped seams and closed cell spray foam in the wall cavities and rim joist. The penetrations in the ceiling of the 2012 premium homes were sealed with one-component expanding spray foam sealant while the high performance ceilings had 2 in. of closed cell spray foam applied. Windows and doors were sealed using minimal expanding spray foam sealant. Wires, pipes, and other penetrations in the wall framing were sealed using one-component expanding spray foam sealant. Wall plates and wall junctions were air sealed with latex caulk. Gypsum wall boards were installed with adhesive at the top plate of the walls. Foundation air sealing was provided by taping the seams of the rigid extruded polystyrene (XPS) or polyisocyanurate (PIR) insulating sheathing installed on the interior of the foundation wall. Closed cell spray foam in the rim joist was sprayed onto the foundation wall insulation to provide continuity.

INSTRUMENTATION

Each house was instrumented to collect hygrothermal and energy use data. Comfort data is collected using temperature and relative humidity data in above grade and below grade living spaces. Hygrothermal data including moisture content, humidity, and temperature is collected in three locations: one above grade wall cavity in a common living area such as a living room or eating area and two below grade locations in both the finished and unfinished areas of the basement. Additionally rim joist conditions are collected in both the finished and unfinished basement areas. Figures 8 and 9 show the instrumentation configuration for an example below grade measured cavity and a close up of cavity sheathing and stud moisture content and temperature measurements. Table 4 details the instrumentation used for data collection. Electrical circuit level monitoring is accomplished using a Powerhouse Dynamics eMonitor system wired to the electrical distribution box of

Figure 2 *Unfinished below grade area with vinyl faced fiberglass insulation.*

Figure 3 *Below grade finished basement area with extruded foam insulation.*

Figure 4 *Below grade unfinished area with polyisocyanurate insulation.*

Figure 5 *House 3: 2006 IECC, OSB walls prior to housewrap installation.*

Figure 6 *2012 IECC premium home with continuous insulation.*

Figure 7 *Above grade wall with spray polyurethane foam cavity and top plate insulation.*

Figure 8 *Below grade cavity instrumentation.*

Figure 9 *Upper cavity instrumentation including sheathing and stud temperature and moisture content instruments.*

each home. All energy consumption is electrical, including domestic hot water, with the exception of natural gas used for gas forced air space heating.

COMPARISON OF CONSTRUCTION COSTS

Invoices for all construction costs were compiled to calculate a total cost of construction for each of the homes. The total cost included cost variances due to site and elevation variations as well as other common construction variances such as price fluctuations, theft, damage, and weather related costs. This required a calibration process to equalize and isolate the energy performance costs. The following describes the calibration process used to eliminate cost variations not related to the energy performance strategies.

Price Variations

Construction of the twelve homes began in April of 2011 and completed in December 2011. Price changes occurred over the duration of the project. To establish a uniform price for each component, the unit price paid for all pertinent components was recorded for all the jobs. The average price of each component was used to calculate the final cost comparison.

Table 4. Instrumentation

Measurement	Device	Description
Temperature	Type T Thermocouple	
Moisture Content	Pin Resistance	Brass Screws, 1 in. apart
Relative Humidity	RH Probe	Campbell Scientific CS210/10162
	Data Logger	Campbell Scientific CR1000
	Multiplexer	Campbell Scientific AM 16/30

The installed cost for the 80% AFUE furnaces was higher than the 92% AFUE furnaces due to the increased cost for B-venting. Additionally 92% AFUE furnaces are the norm for the region, which resulted in premiums to purchase the 80%

AFUE furnaces. The HVAC cost for the 2012 IECC minimum and 2012 IECC premium homes should have been lower if smaller furnaces had been installed. Two different HVAC contractors were used on the project. An average price of the two contractors was used in the final cost comparison.

Quantity Variations

Consistent area values were used for each of the four different energy performance levels for all of the various components used on the enclosure. Area values were determined for each of the following locations on the thermal enclosure:

1. Basement floor
2. Floor over exterior (cantilever)
3. Basement wall—finished space
4. Basement wall—unfinished space
5. Rim joist
6. Above grade exterior wall between conditioned space and outside
7. Above grade exterior wall between conditioned space and garage
8. Above grade exterior wall between conditioned space and attic
9. Ceiling to attic

An analysis of the 2 × 4 and 2 × 6 materials invoiced for above grade walls revealed quantity variations between houses of the same plan type. These variations can be attributed to elevation differences, theft, and varying waste factors, among other factors. Adjustments were made to the quantity of these components to eliminate the variations using the following assumptions:

- The quantity of 2 × 6 studs (exterior walls) should be the same in 2006 IECC and 2012 minimum homes.
- The quantity of 2 × 6 studs in the high performance homes should be less than in 2006 IECC and 2012 minimum homes due to 24 o.c. spacing.
- The quantity of 2 × 4 studs (exterior and interior walls) in the 2012 IECC premium homes should equal the combined total of 2 × 6 studs (exterior walls) and 2 × 4 studs (interior walls) in the 2006 IECC homes.
- The quantity of 2 × 6 lineal material should be the same between 2006 IECC, 2012 minimum, and high performance homes.
- The quantity of 2 × 4 lineal material in the 2012 premium homes should equal the combined total of 2 × 6 and 2 × 4 lineal material in the 2006 IECC homes.

Basement framing material was tallied separately. The 2006 IECC baseline, 2012 IECC premium and high performance homes all used 2 × 4 16 in. on center interior wall framing on the inside of the foundation for the finished portion of the basement. Basement framing materials were equalized for these home types. The 2012 IECC minimum used 2 × 6 exterior and 2 × 4 partition walls. The combined 2 × 4 and 2 × 6 stud quantities were calibrated to match the baseline 2 × 4 total.

Table 5. Average Cost Premium Comparison

	2012 IECC—Minimum	2012 IECC—Premium	High Performance
Frame, Insulation, and Air Seal	$540	$4760	$12,080
Fenestration	$1380	$1380	$2330
HVAC	($410)	($410)	$890
Lighting	$100	$100	$350
Total Premium over Baseline	$1610	$5830	$15,650
Range of Premiums	$1250–$2040	$5420–$6590	$15,480–15,880

Elevation Variations

Elevation changes were made to provide variety to the neighborhood. Roof lines were altered by adding or clipping gables. Front porch styles also varied. Combinations of exterior cladding materials provided further variety. All labor and material costs related to these variations were considered and excluded from the cost comparison.

The thermal envelope, including fenestration, remained unchanged for each of the house types. The energy performance may be impacted due to minor changes in sunlight exposure and shading characteristics as a result of the elevation variations.

Lot Variations

Variations in soil conditions required different heights of foundations walls for the porches, garages, and basements. Excavation, foundation, and other lot related cost variables were excluded from the comparison. The height from the top of basement floor to the top of foundation was used to calculate the insulated area.

Job Cost Variances

Common job cost variances due to theft, damage, weather, or invoicing errors were excluded from the comparison.

COMPARISON OF PREDICTED AND ACTUAL ENERGY USE

A significant aspect of this research is to find out the impact for each of the energy performance strategies on the total amount of energy actually used. The scope of this paper covers the energy used to heat for the entire first heating season. The energy used includes natural gas only. The furnace is the only natural gas appliance in the homes, therefore 100% of the natural gas used was by the furnace. The furnace electric use was excluded to make a direct comparison to the HERS modeled Heating Btu amount.

Predicted Energy Use

Energy use was predicted using AEC REM/Rate™ Version 12.97. Specifications for 2012 minimum and 2012 premium homes were intentionally designed to have similar HERS scores. Table 6 shows both the planned and confirmed or "as built" HERS score averages for the three homes built to each energy performance strategy.

Cost Effectiveness

Table 7 compares the cost of improvements with the modeled savings over the baseline 2006 IECC homes. The baseline homes were built to common building practices in the area used to meet the 2006 IECC. These homes had an average confirmed HERS score of 77, which means their energy performance is considerably better than a home built to 2006 IECC code minimum.

Assuming a 30 year term mortgage at 4% interest, a positive cash flow can be achieved by building to the 2012 IECC minimum. Building to the 2012 IECC premium strategy is essentially cash flow neutral. We believe the 2012 IECC minimum and 2012 IECC premium represent the extremes of strategies most builders will use to comply with 2012 IECC. The optimum value strategy most likely would fall between the 2012 IECC minimum and premium and would be cash flow positive. Considering only economics, building to the high performance level does not produce a positive cash flow over a HERS Index of 77.

Actual Energy Use

Natural gas data was collected for the 2012–2013 winter. Four of the homes, one home from each of the performance strategies, were vacant for a significant portion of the winter. Data from these four homes was excluded in the comparison of actual versus modeled energy use. Figure 10 shows the total of two homes built to each energy performance strategy.

Table 6. Average Annual Modeled Energy Use

	2006 IECC	2012 IECC—Minimum	2012 IECC—Premium	High Performance
HERS Score (Planned)	82	57	57	45
HERS Score (Confirmed)	77	59	54	48
Heating (kBtu)	76	52	45	30
Heating Cost[1]	$733	$502	$434	$287
Heating Savings from Baseline	$0	$231	$299	$446

[1] Heating cost based on $.963/kBtu natural gas.

Observations

- 2006 IECC significantly outperformed the model.
- 2012 IECC minimum, 2012 IECC premium and high performance strategies all aligned well with the model.
- Three out of the four energy performance strategies outperformed the model.
- Occupants provided day and night temperature setpoints. Below are the average day and night setpoints for both homes in each performance level:
  - 2006 IECC 68.3
  - 2012 minimum 64.3
  - 2012 premium 69.5
  - high performance 73.0

The reason the 2006 IECC significantly outperformed the model is not understood. The exact impact of the thermostat setpoint on the energy use cannot be discerned. Most of the rental agreements are short term, therefore, we expect over the five year research period, the range of temperature setpoints should narrow. The high performance home used less energy

Table 7. Cash Flow Analysis of Modeled Energy Savings

	2012 IECC—Minimum	2012 IECC—Premium	High Performance
Average Cost of Improvements over Baseline	$1612	$5828	$15,644
Monthly Payment 30 Yr Term 4%	$7.70	$27.82	$74.69
Modeled Energy Savings/Month	$19.67	$25.40	$37.81
Cash Flow	$11.97	($2.42)	($36.88)

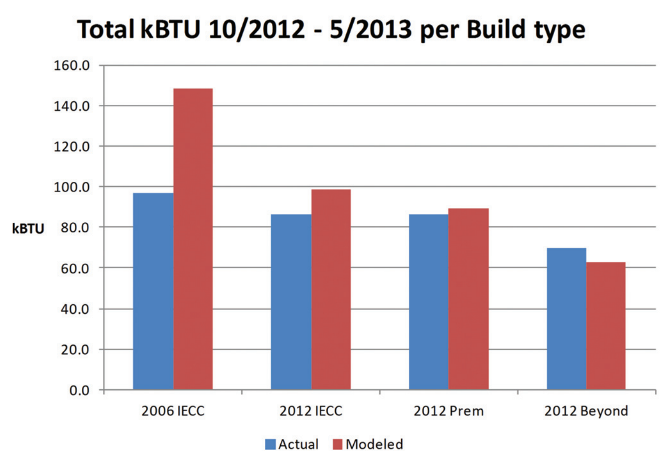


Figure 10 *Winter 2012–13 actual versus modeled natural gas use.*

than the than the 2012 minimum even though the high performance home maintained an 8.7°F higher interior temperature.

COMPARISONS OF HOME PERFORMANCE

Comparison of Air Leakage

Air leakage comparisons for all homes are shown in Table 8. Hygrothermal performance comparisons are shown for the two different 2012 strategies for above grade cavity wall, rim joist, and foundation wall.

Comparison of Air Leakage Details

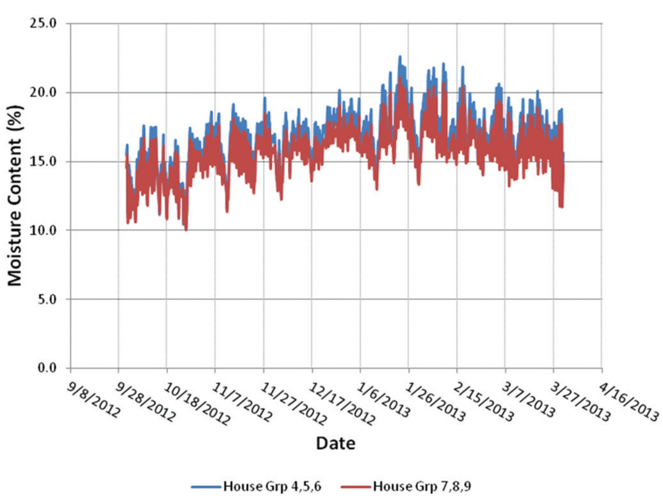
Blower door test results showed air sealing measures in all but the 2012 IECC minimum met the 2012 IECC code requirement of <3 air changes per hour (ACH) @ 50 Pa for climate zone 5. The 2006 IECC does not have a performance requirement for air leakage. The 2012 premium and high performance homes with continuous exterior sheathing and closed cell spray foam in the stud cavity produced the lowest air leakage rate.

Table 8. Whole House Air Leakage

	2006 IECC	2012 IECC—Minimum	2012 IECC—Premium	High Performance
CFM @50 Pa Average	1230	1340	960	770
CFM @50 Pa Range	1180–1270	1270–1420	880–1040	740–800
ACH @50 Pa Average	2.8	3.1	2.2	1.8

Comparison of Wall Cavity Hygrothermal Performance of Homes with Continuous Insulation and Homes with Housewrap

We chose to make the most direct hygrothermal comparison between the two strategies designed to meet the 2012 IECC as they are most directly comparable. Temperature and moisture content of both continuously insulated walls and walls with cavity insulation alone are shown in Figure 11.The continuously insulated walls are constructed with 2 × 4 framing, a sheathing layer consisting of a structural layer laminated to a R5 insulation layer, which provides the continuous thermal break, and the cavities are filled with approximately R16 closed cell spray polyurethane foam (houses 7–9). The comparison walls are constructed with 2 × 6 framing, a layer of oriented strand board (OSB) sheathing, and spun bonded polyolefin housewrap. The cavity insulation is R19 Kraft faced fiberglass batt insulation. Both wall configurations meet the requirements of the 2012 IECC. The temperature of the cavity side, interior, of the sheathing for the six homes compared is shown in Figure 11. Although the temperature movement trends for all homes is similar, the average temperature of the continuously insulated wall cavities is higher than those with cavity insulation, and, as expected, the exterior sheathing temperature of the non-continuous insulation (CI) walls approaches the exterior conditions. The average temperature of the non-CI houses was 40°F compared to the continuously insulated house group average of 45°F. The moisture content of the walls also follows the same trend but the CI walls generally have 2%–4% lower moisture content, with non-CI wall reaching a maximum moisture content of 23% in the coldest months. In comparison, the CI walls reached a lower moisture content of 21%. During the winter season, the non-CI walls had greater than 20% moisture content for 5% of the period whereas the CI walls were above 20% moisture content for 1% of the same period. It has been long noted that



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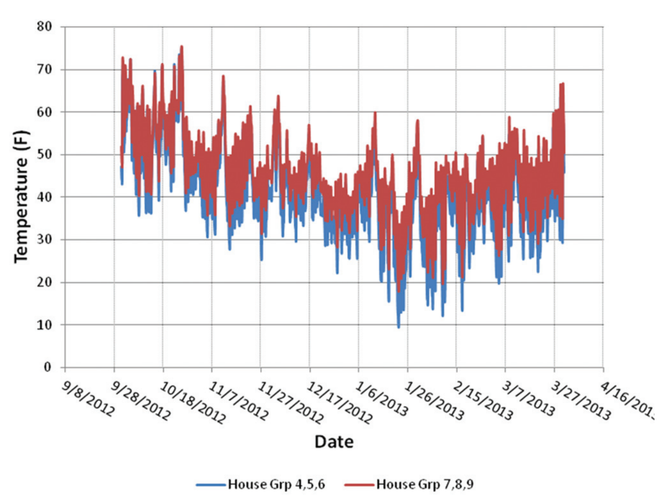


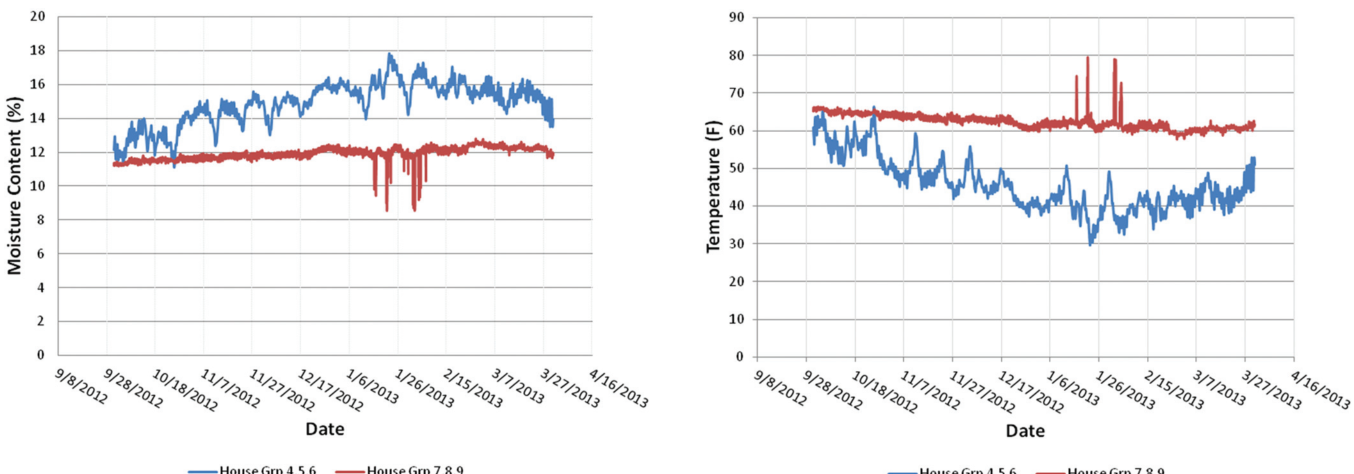
(b)

***Figure 11** (a) Moisture content and (b) temperature: above grade wall sheathing at mid-height of wall.*

wood should be protected from fungal decay by keeping the moisture content below 20%.

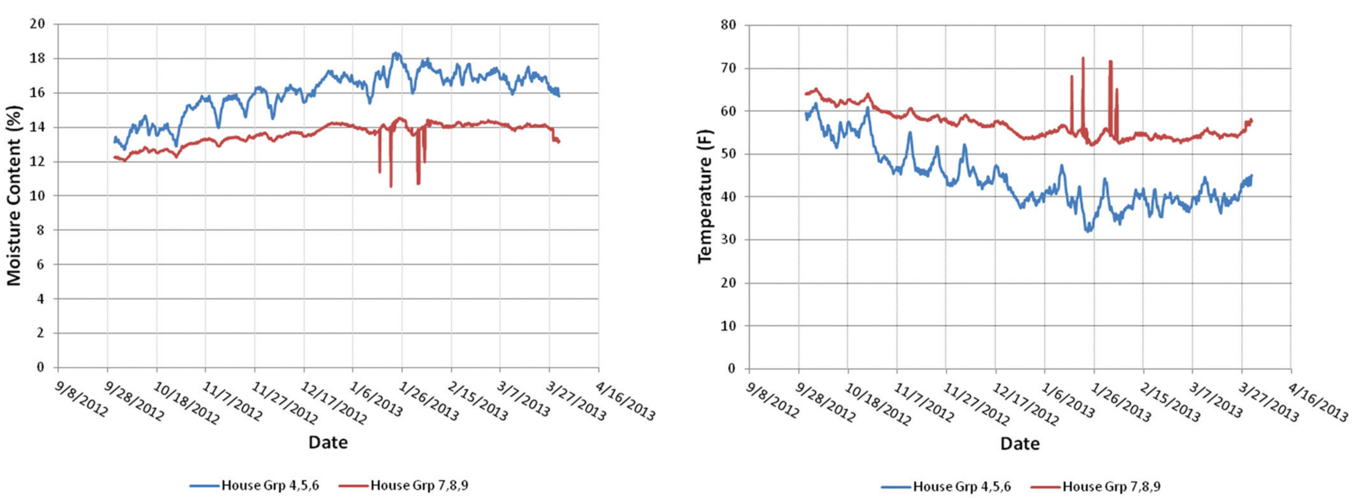
Comparison of Foundation Wall Performance

All foundations were 8 in. poured concrete with brick pattern on the interior and exterior. Foundation insulation was compared in both finished and unfinished areas of the research homes. Homes 4–6 utilize vinyl faced fiber batt insulation hung from the top of the basement wall to the basement floor in the unfinished basement area. The finished basement area of homes 4–6 is insulated by installing fiber batt insulation between 2 × 6 stud frame walls. All of the foundation insulation of homes 4–6 is installed on the interior of the basement wall. The unfinished area of homes 7–9 are insulated by adhering polyisocyanurate insulation directly to the interior of the basement wall, which does not require gypsum board or other thermal barrier for fire protection. The finished part of the basements of homes 7–9 are insulated with a layer of extruded polystyrene foam insulation applied to the basement wall prior to 2 × 4 framing and drywall. No additional insulation was installed in the framed wall cavities. In homes 7–9, a layer of continuous extruded polystyrene foam insulation was installed on the exterior of the basement wall. Instrumentation of moisture content and temperature is placed at the interface between the interior basement wall and the interior insulation system as it is of interest to measure the conditions at this location which could be prone to moisture build up. The average moisture content of the interface between the basement wall and insulation is higher for the fiber insulation compared to the rigid board insulation in both finished and unfinished basement areas. The 4, 5, 6 home group average moisture content in the unfinished basement area is 15% and reaches a maximum of 18%; in comparison, the 7, 8, 9 group average moisture is 12% and reaches a maximum of 13% (Figures 12 and 13). The temperature of the interface between



(a) (b)

Figure 13 *(a) Moisture content and (b) temperature: basement unfinished wall 1 in. from top of wall.*



(a) (b)

Figure 12 *(a) Moisture content and (b) temperature: basement finished wall 1 in. from top plate.*

the basement wall and insulation tends to more closely follow the interior basement conditions for the rigid board insulation cases whereas the temperature of the interface between the wall and fibrous insulation more closely follows the exterior temperature and in winter conditions tends to be much colder, clearly impacted by the lack of an exterior insulation layer. The location of the temperature shown is slightly below the basement sill plate as this is a worse case situation. The 4, 5, 6 group average temperature is 46°F and reaches a minimum of 30°F compared to the 7, 8, 9 group average of 62°F and minimum 58°F.

Comparison of Rim Joist Performance

Rim joists of homes 4–6 were insulated using R-19 Kraft faced batt insulation cut to fit between floor joists. Closed cell spray polyurethane foam (cc SPF) was installed in the interior band joists of homes 7–9 with additional insulation provided by the continuous insulation layer installed on the enclosure exterior, note that this would be considered a double vapor barrier situation around the OSB rim joist as both the cc SPF and XPS are low vapor permeance insulations. Figure 14 shows moisture content and temperature were measured at the interior rim joist surface under the interior insulation. Homes 7–9 demonstrate lower rim joist moisture content than homes 4–6. The average of the 4, 5, 6 group reaches moisture content above 20% for periods of time during January and February whereas the 7, 8, 9 group average remains less than 20% during the same period. It has been long noted for protection of wood and wood products from fungal decay moisture content should be kept below 20% moisture content. Temperature of the interior band of homes 7–9 is higher than the same measurement in homes 4–6.

CONCLUSION

Although this multi-year research project is in its early stages, some key conclusions can be made:

- Detailed cost analysis shows the premium Cobblestone Builders paid to build to 2012 IECC was considerably lower than many estimates.
- A comparison of HERS scores based on plan versus confirmed HERS score based on field verification and whole house air leakage testing showed a marked improvement of the 2102 CI homes over the 2012 non-CI homes.
- Actual energy used in three out of the four strategies outperformed the model.
- High performance strategy used the least amount of energy to heat the home even though it had an average thermostat set point 8.7°F higher than the 2012 minimum.
- Exterior foundation insulation significantly reduced moisture content at the interior concrete surface.
- Insulating both sides of the OSB rim joist with low vapor permeance materials (double vapor barrier) had lower moisture content than vapor open insulation strategies.
- The foam insulated walls in general had lower moisture content than those without foam insulation.

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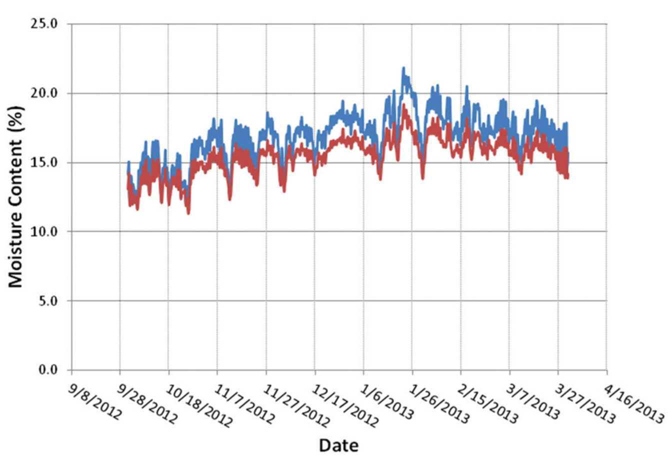

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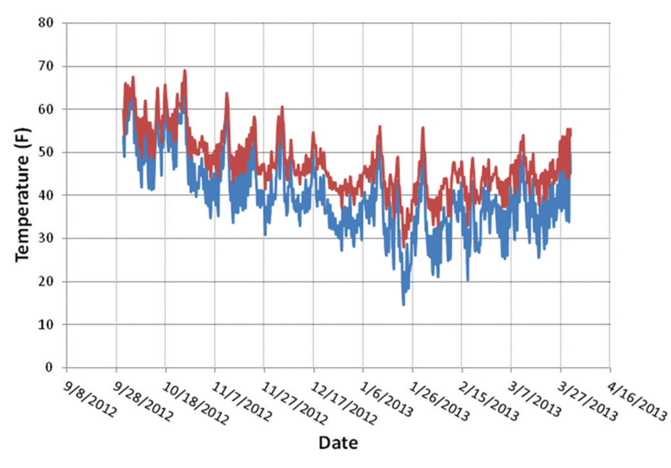

(b)

Figure 14 *(a) Moisture content and (b) temperature: rim joist at midpoint in each direction.*