U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Field Evaluation of Four Novel Roof Designs for Energy-Efficient Manufactured Homes

E. Levy, J. Dentz, E. Ansanelli, G. Barker, P. Rath, and D. Dadia
ARIES Collaborative

December 2015

Building America U.S. Department of Energy

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Field Evaluation of Four Novel Roof Designs for Energy-Efficient Manufactured Homes

Prepared for:

The National Renewable Energy Laboratory

On behalf of the U.S. Department of Energy's Building America Program

Office of Energy Efficiency and Renewable Energy

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Prepared under Subcontract No. KNDJ-0-40347-05

December 2015

The work presented in this report does not represent performance of any product relative to regulated minimum efficiency requirements.

The laboratory and/or field sites used for this work are not certified rating test facilities. The conditions and methods under which products were characterized for this work differ from standard rating conditions, as described.

Because the methods and conditions differ, the reported results are not comparable to rated product performance and should only be used to estimate performance under the measured conditions.

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Unless otherwise noted, all figures were created by the ARIES team.

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Definitions

°F	Degree Fahrenheit
ARIES	Advanced Residential Integrated Energy Solutions Collaborative
Avg.	Average
DOE	U.S. Department of Energy
ft^2	Square feet
HUD	U.S. Department of Housing and Urban Development
HVAC	Heating, ventilating, and air conditioning
MC	Moisture content
MH	Manufactured home
n/a	Not applicable
RH	Relative humidity
XPS	Extruded polystyrene
ZERH	Zero Energy Ready Home

Acknowledgments

The Advanced Residential Integrated Energy Solutions Collaborative team would like to thank all those who contributed to this effort.

Bradley Meister of the California Energy Commission and Bert Kessler with the Systems Building Research Alliance represented the project sponsors.

Stacey Rothgeb, Michael Gestwick, Lieko Earle, John Winkler, and Chuck Booten of the National Renewable Energy Laboratory provided invaluable technical guidance and project oversight.

A committee composed of industry representatives provided ideas for and feedback on approaches to developing advanced building techniques that had both commercial and energy savings potential. The group included Bert Kessler of Palm Harbor Homes, Robert Garcia of Fleetwood Homes, Mark Ezzo of Clayton Homes, Manuel Santana of CAVCO, Jeff Legault of Skyline Homes, Rob Luter of Kinro, and Jess Maxcy of the California Manufactured Housing Institute.

The project team thanks the many people in the CMH family of companies that built and hosted the test unit and assisted with monitoring and maintaining it. These people include John Brean and Greg Bue of Golden West Homes and John Crass of Custom Manufactured Homes.

Staff from product suppliers provided timely technical support and donated materials and products for the tests. Those people include Francis Babineau of Johns Manville; Brian Lieburn and Brian Mallon of DOW Chemical; Craig Marden of Owens Corning; Mark Tackett of LP Corporation; and Tom Tracey and Terry Dullaghan of Senco Brands, Inc.

The ARIES team was assisted by engineer William Farish who provided timely and valuable assistance to the team.

Executive Summary

The U.S. Department of Energy Building America team Advanced Residential Integrated Energy Solutions Collaborative field-tested and analyzed four novel roof designs. The intention was to see how each design reduced space-conditioning energy use so that the knowledge gained could be applied to new manufactured homes.

A custom-built test structure sited in Jamestown, California, was used to evaluate the thermal and moisture performance of four innovative roof designs for potential use in factory-built homes. Each test bay and a conventional roof section extended from eave to eave and were isolated from adjacent bays by means of an insulated, air-sealed partition. The test designs incorporated novel insulation and ventilation strategies in several combinations including compressed batt insulation, dense-packed blown insulation, attic cavity sealing with a moisture-permeable membrane, and an unvented attic cavity with a custom diffusion vent at the roof ridge. Performance of the roof designs was monitored throughout a single heating and cooling season.

All of the designs performed well from a moisture management standpoint; moisture levels were not sufficient to support mold growth in the specific climatic conditions at the test location. The roof designs with reduced ventilation retained more heat in both the heating and cooling seasons.

The vented unsealed roof design that was augmented with dense-packed fiberglass insulation in the eaves was superior because it:

- Performed comparably to the other test designs in the heating season (all of which retained more heat than the conventional design)
- Exhibited both the lowest net heat gain and lowest peak heat fluxes in the cooling season.

1 Introduction

The U.S. Department of Energy Building America team Advanced Residential Integrated Energy Solutions Collaborative (ARIES) field-tested and analyzed four novel roof designs. The intention was to see how each design reduced space-conditioning energy use so that the knowledge gained could be applied to new manufactured homes (MHs). A windowless, single-wide, factory-built test building was fabricated and embedded with sensing equipment at a plant in southern California and transported to the test site in Jamestown, California, (International Energy Conservation Code [IECC] Climate Zone 4) to evaluate these alternative roof designs.

The tests were designed to examine how differences in roof construction impact space-conditioning loads and levels of both relative humidity (RH) and sheathing wood moisture content (MC). Roof construction is widely recognized as one of the most vulnerable areas of thermal loss and therefore may present a good opportunity for reducing energy use.

2 Background and Literature Review

Energy is one of the major contributors to homeownership costs. High energy costs create a pronounced financial burden on households with modest incomes. Manufactured homes in particular are susceptible to excessive energy costs because industry energy standards were last updated twenty years ago. These standards are nationally promulgated by the U.S. Department of Housing and Urban Development (HUD).Programs like ENERGY STAR and the U.S. Department of Energy (DOE) Zero Energy Ready Home (ZERH) showcase ways to improve home efficiency and reduce energy costs. These efforts often incur higher construction costs (associated with enhanced efficiency) to achieve lower energy bills—a combination designed to yield lower net monthly homeowner costs.

2.1 Literature Review

Considerable research has been conducted on evaluating the propensity of moisture issues in sealed and unsealed roof systems. Building America-funded research conducted by Building Science Corporation looked at the field testing of seven roof assemblies that varied by ventilation strategy and insulation type (Lstiburek and Ueno 2013). The effort included two test units in different climates: a cold climate experiment in Chicago, Illinois; and, a hot-humid climate experiment in Houston, Texas. The cold climate results revealed that under high interior moisture conditions all roofs except a vented cathedral assembly experienced wood moisture and humidity that were sufficiently high to cause failure. Importantly, monitoring indicated consistent moisture stratification and drier conditions on the west side compared to the east side. The hot-humid climate testing results were more promising; they indicated that the diffusion vented roof had a greater amount of drying and less wintertime moisture accumulation than the unvented roof. However, the moisture readings for the unvented roof were not high enough to constitute failure (Lstiburek and Ueno 2015). Both test results warrant further research with more robust assemblies and alternate specifications. Another attempt at measuring and comparing the impact of vented and sealed attics on roof thermal performance and energy use was made by the BSC team in Las Vegas, Nevada, in 1996 (Lstiburek and Rudd 2011). The experiment included three test homes, two sealed homes, and one vented control home. The researchers noted that the two sealed houses used 19% less cooling energy than the reference house.

2.2 Research Gaps and Relevance to Building America's Goals

Building America has a goal of developing cost-effective home technology solutions to reduce whole-house source energy consumption by 50% compared to the 2009 IECC. This effort aims to make this reduction in space-conditioning energy in an affordable housing segment. This work builds knowledge related to the performance of point-source space conditioning for load low homes, which is an area on which a number of Building America teams have focused. A thorough summary of the Building America literature on this subject is included in work by Building Science Corporation (Ueno and Loomis 2015). Additionally, this work examines the impact of changes in thermal performance on collateral issues—particularly moisture performance—and continues the systems approach that is deeply embedded in Building America research.

2.3 Research Questions

The alternative roof design effort addressed the following research questions:

- What is the likelihood of moisture-related deterioration of roof materials and microbial growth due to elevated RH levels with the proposed new roof designs compared to typical MH roof designs?
- What impact does roof ventilation have on the thermal and moisture performance of alternative roof systems?
- Which of the four alternative roof designs demonstrates superior performance in terms of thermal integrity and control of humidity levels in the given climate (IECC Climate Zone 4)?

3 Methods

The Advanced Residential Integrated Energy Solutions Collaborative (ARIES) team developed four alternative roof designs in partnership with home manufacturers and suppliers. All roof assemblies were built onto a single test structure to provide a uniform side-by-side assessment of thermal and moisture performance. Instrumentation was installed on the unit for long-term monitoring and remote data collection for a period of one year. The structure was built at the Golden West Homes manufacturing plant at Perris, California, and moved to a site in Jamestown, California, for long-term monitoring. A summary of the four designs is provided in Table 1.

Table 1. Summary of Test Unit Roof Designs

Design	Description
Base Design	Conventional roof construction with standard density blown insulation in the attic with baffles providing ventilation path
Design 1	Vented attic roof with dense-packed insulation at eaves
Design 2	Vented attic roof with compressed batts at eaves
Design 3	Vented, sealed attic roof with dense-packed blown insulation at the eaves
Design 4	Unvented, sealed attic roof with dense-packed blown insulation at the eaves

3.1 Attic Cavity Test Structure

The test structure was a single section MH structure measuring 14 feet wide and 34 feet long. A full-scale roof was built and placed on 7-foot-high walls; there were no interior partitions. The roof was divided into seven bays with five central bays that were each 6 feet wide. The end bays were about 2 feet wide and acted as buffer zones, which ensured there were similar thermal boundaries between the experimental design bays. The designs are representative sections of the four roof designs and the baseline case (standard construction). Each design extended from eave-to-eave and each bay was isolated (from a moisture and thermal-flow standpoint) from adjacent bays by means of an insulated and air sealed partition wall (Figure 1 and Figure 2). Details and specifications of the testing apparatus are included in Appendix A.

Figure 1. Roof test apparatus under construction

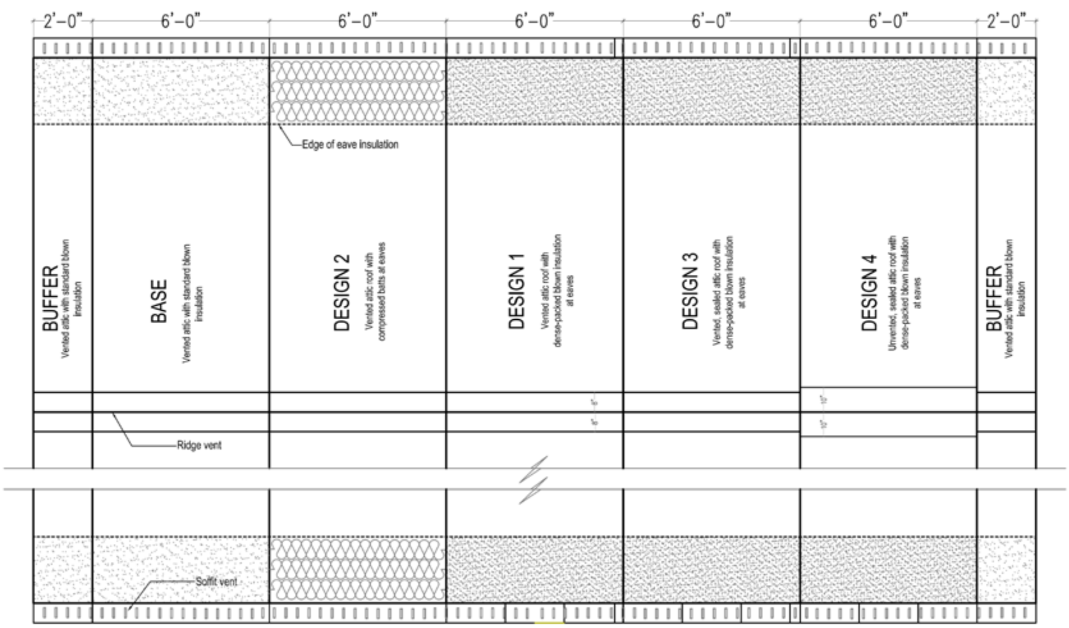

Figure 2. Roof layout

The roof design assemblies are described below:

- **Base Design:** This conventional vented roof assembly has standard density blown fiberglass insulation in the attic with baffles that provide a ventilation path (see Figure 3 and Figure 4).
- **Design 1: A** vented attic roof with dense-packed insulation at the eaves. Dense-packed/compressed blown insulation increases the thermal performance at the eaves and standard density loose fill insulation is used at the center of the attic (see Figure 3 and Figure 4).

- **Design 2:** This vented attic roof has compressed batts at the eaves. This design combines two types of insulation to achieve a more uniform U-value across the attic: blown/loose-fill insulation at the center with compressed un-faced batt insulation at the eaves (see Figure 3 and Figure 4).

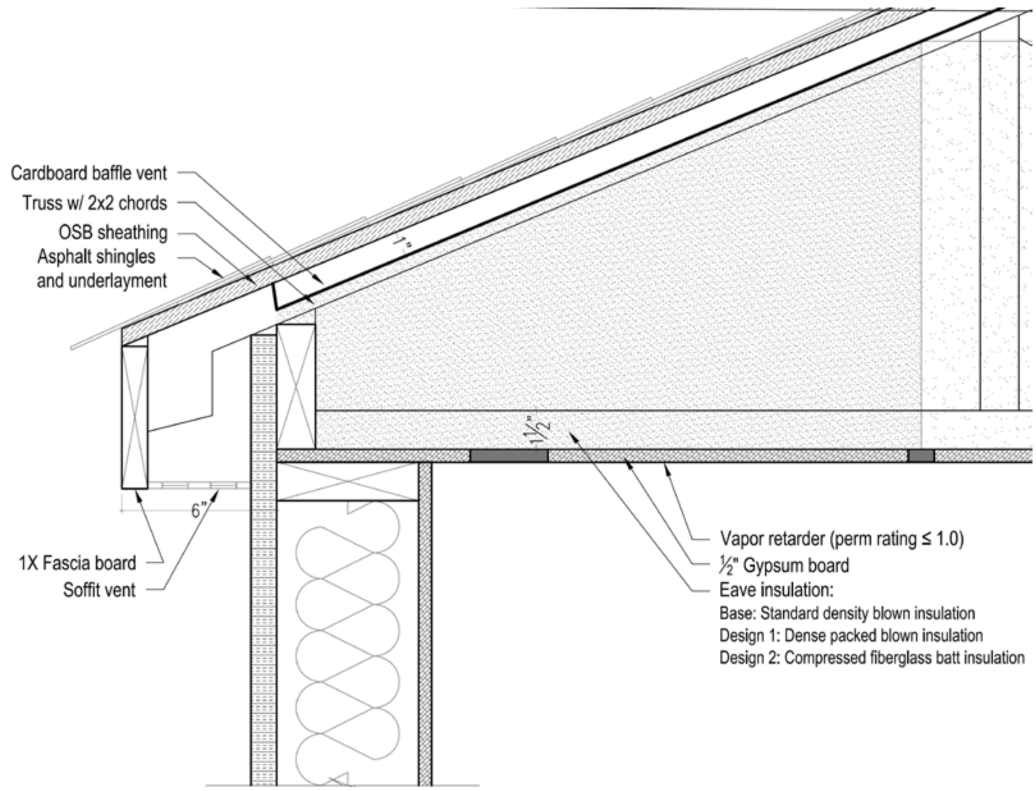

Figure 3. Typical cross section at eave—Base Design / Design 1 / Design 2

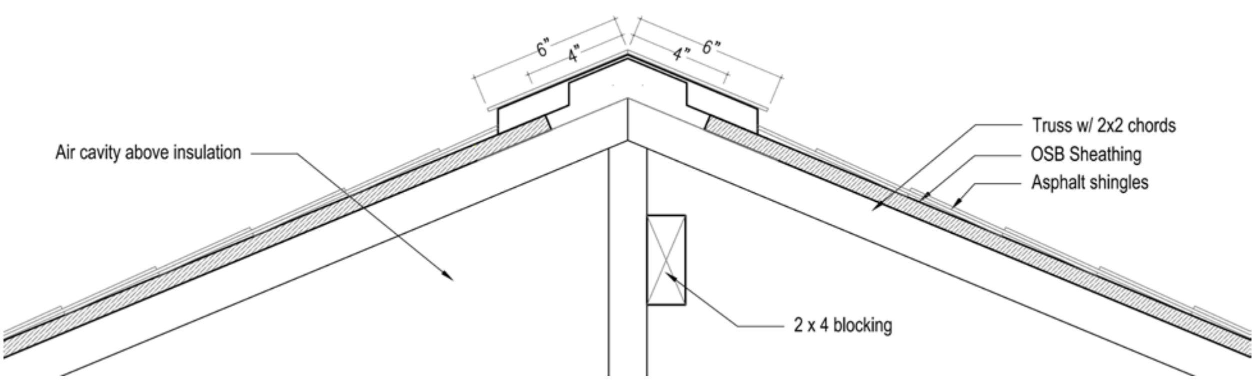

Figure 4. Typical cross section at ridge—Base Design / Design 1 / Design 2

- **Design 3:** This is a vented and sealed attic roof with dense-packed insulation at the eaves and standard density blown insulation in the field. An air barrier with a high perm rating is used to seal the attic against any air movement and communication with the vented upper roof. This roof design in particular was evaluated for impact on thermal performance because of the restriction on air movement by the air barrier.

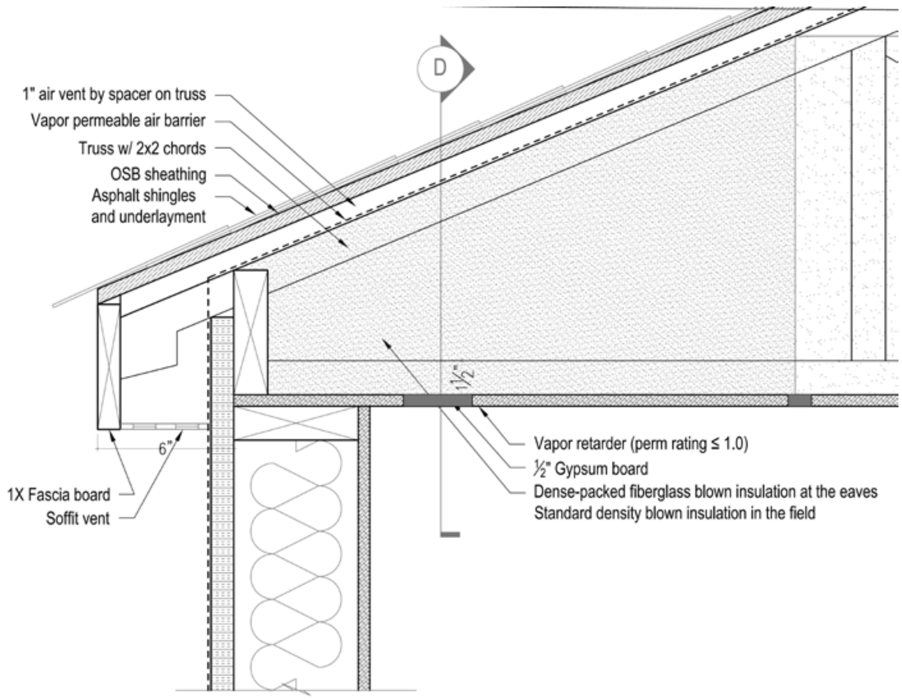

Figure 5. Cross section at eave—Design 3

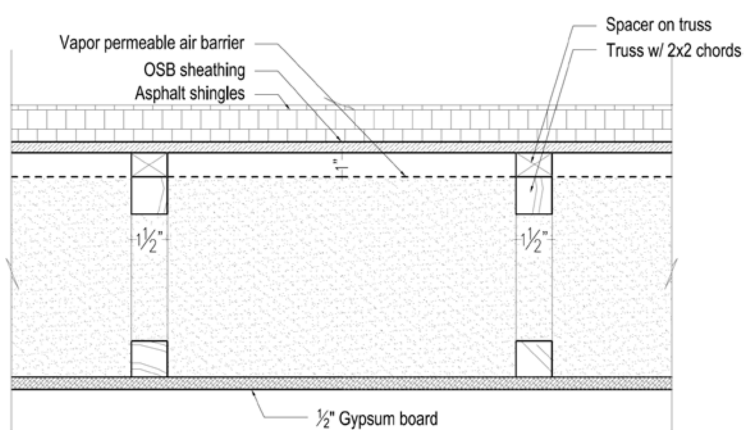

Figure 6. Section at D

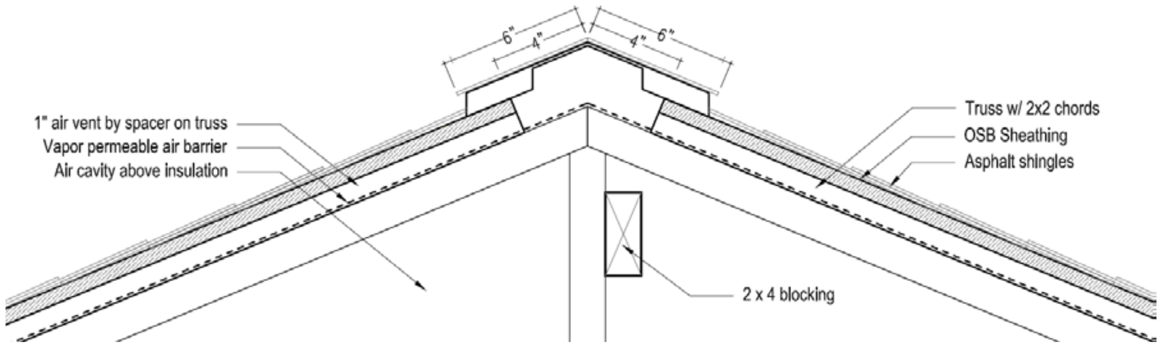

Figure 7. Cross section at ridge—Design 3

- **Design 4:** This roof option incorporates an unvented and sealed attic with dense-packed blown insulation at the eaves and standard density blown insulation in the field area. A diffusion vent (a vapor-permeable air barrier vent) is used at the ridge; this vent allows the accumulated moisture to dry out via vapor diffusion while still acting as an effective air barrier that reduces heat loss.

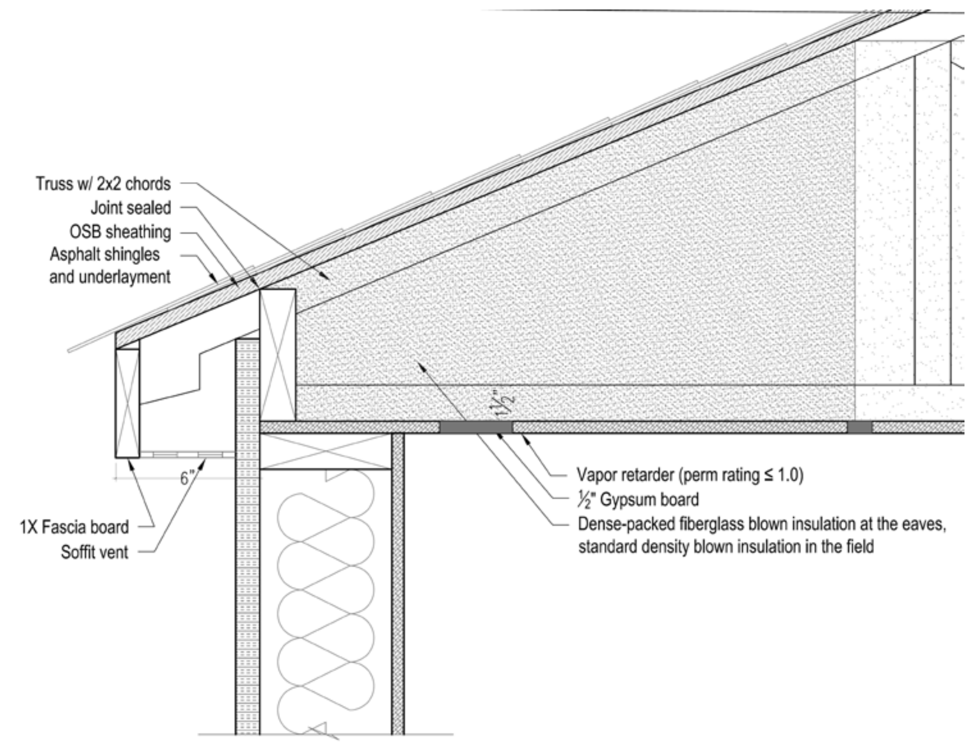

Figure 8. Cross section at eave—Design 4

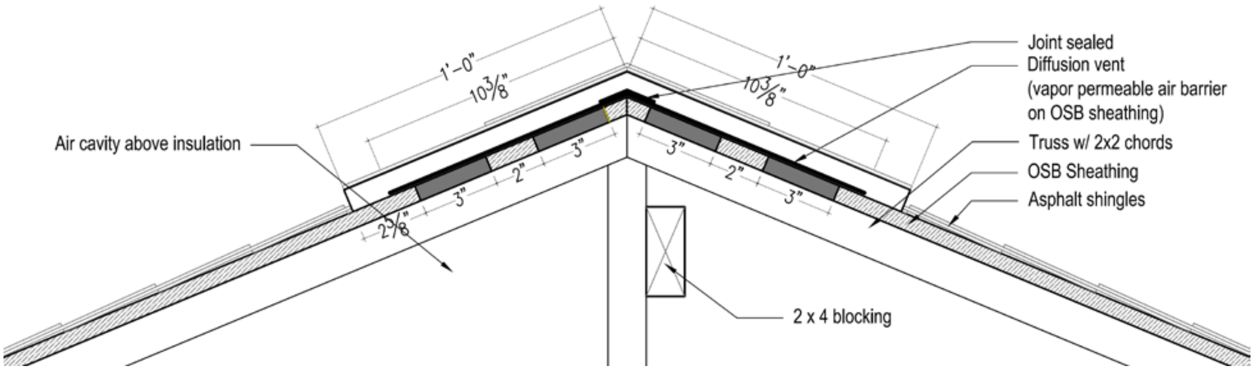

Figure 9. Cross section at ridge—Design 4

3.2 Monitoring Approach and Instrumentation

The roof was instrumented with temperature, pressure, MC, and RH sensors per requirements for moisture and thermal performance testing. Four unsealed holes (1-inch diameter) were drilled into the ceiling of each design bay to simulate air leakage. These holes approximate the numerous ceiling penetrations in a conventional ceiling. In each experimental bay there is one sealed outlet in the attic eave that routes the sensor wires to the interior of the testing unit. Each sealed outlet is connected by a single tube that passes through the exterior wall into the test house interior. The eave penetrations, wall penetrations, and each wire-carrying tube are filled and sealed with expanding foam. The end buffer bays have neither unsealed holes nor sealed outlets.

Table 2 lists the types of sensors installed in the final testing structure. Figure 10 shows the instrumentation package for the Base Design and Designs 1, 2, and 4; Figure 11 shows the sensor placement setup for Design 3. The sensor placement layout is identical for all designs. The test house is oriented along the north-south axis with the roof sides facing east and west. Where indicated in Table 2, sensors are placed in both sides of the roof. A total of 120 sensor channels are configured for the testing structure, which includes the weather station points attached to the side of the test house.

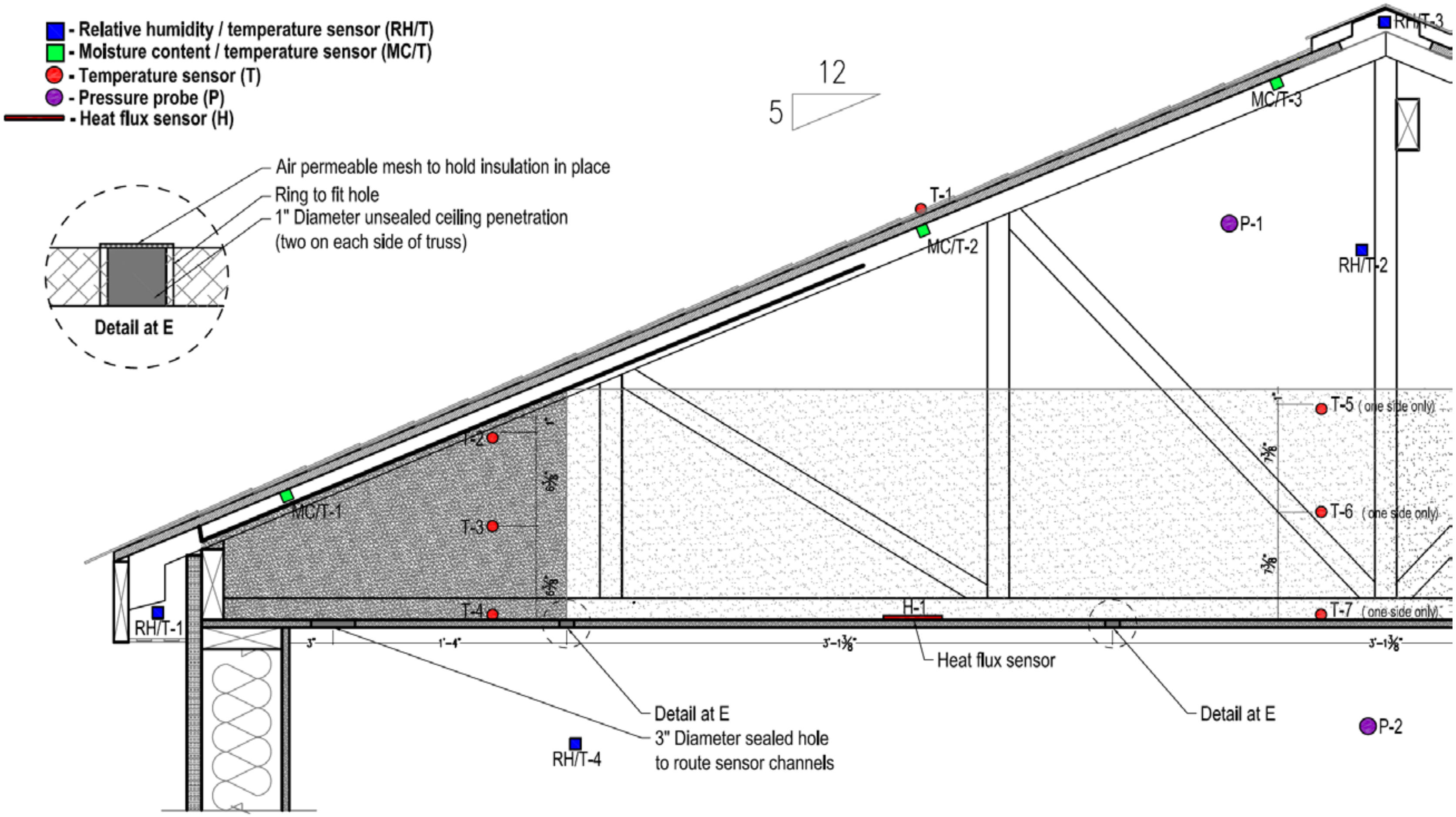

Figure 10. Instrumentation setup for Base Design / Design 1 / Design 2 / Design 4

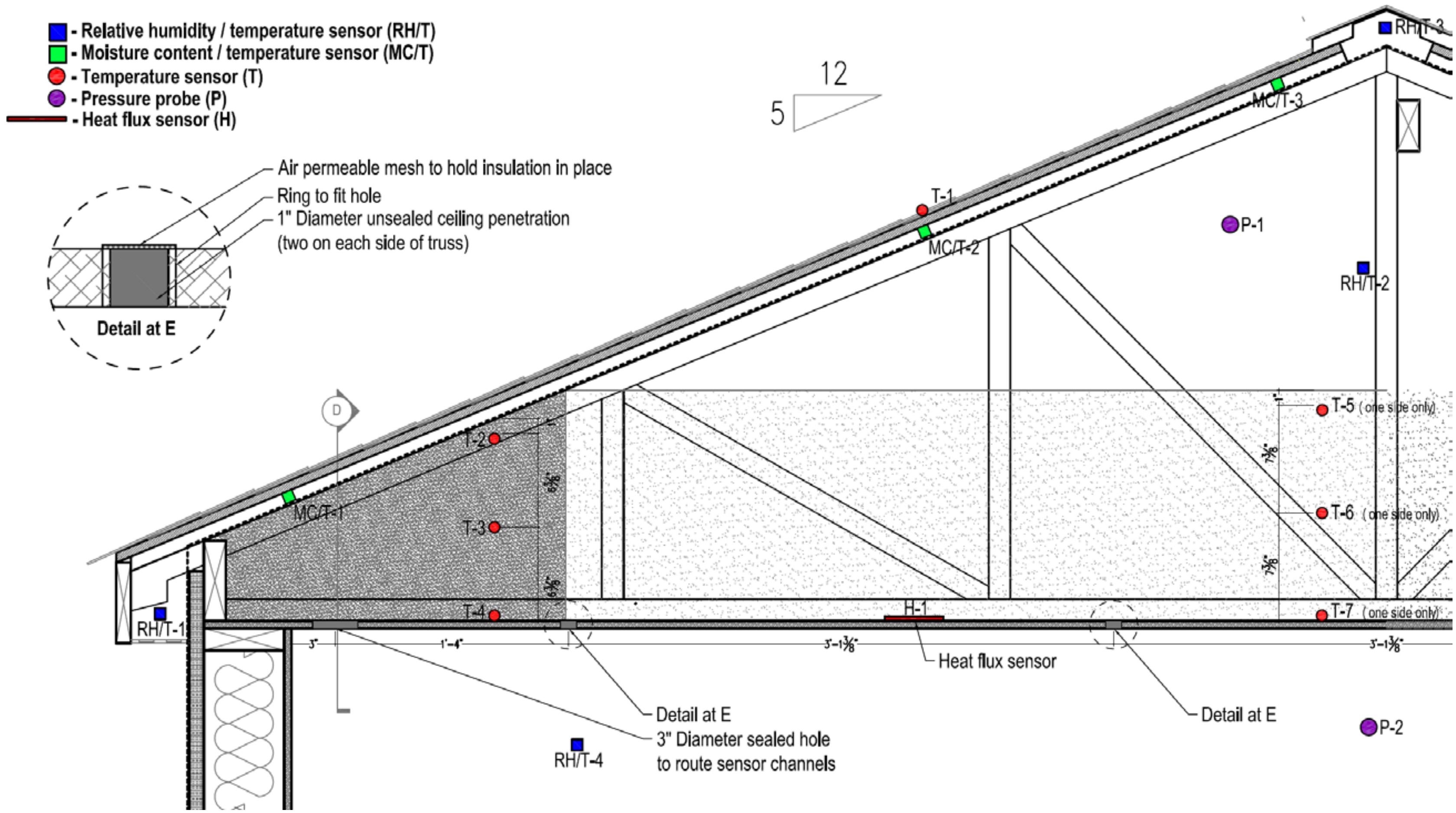

Figure 11. Instrumentation setup for Design 3

Table 2. Sensor Types

Sensor Tag	Sensor Type	Location	Purpose
T-1	Temperature sensor	Underside of the asphalt shingles in both sides of roof.	To check if the temperature under the asphalt shingles rises above the manufacturer-recommended temperature threshold.
T-2, T-3, T-4	Temperature sensor	At the lower, middle, and top ends of the insulation; eave end in both sides of roof.	Temperature sensors at the eave, placed in threes: high, low, and middle, to capture the effects of thermal gradient in the insulation. Also to compare the eave thermal performance between different roof designs.
T-5, T-6, T-7	Temperature sensor	At the lower, middle, and top ends of the insulation; in the field.	Temperature sensors in the field, placed in threes; high, low and middle to capture the effects of thermal gradient in the insulation.
RH/T-1	RH / temperature sensor	At the soffit vent in both sides of the roof.	To measure the temperature and humidity levels of the incoming air into the roof vent to compare with RH/T-2 and RH/T-3.
RH/T-2	RH / temperature sensor	In the air cavity of the attic above the blown insulation.	To evaluate the ability of the vapor-permeable air barrier in Design 3 to allow moisture to escape the attic cavity.
RH/T-3	RH / temperature sensor	At the ridge vent.	To measure the RH and temperature of the outgoing exhaust air at the ridge vent.
MC/T-1, MC/T-2, MC/T-3	MC / temperature sensor	On the underside of the sheathing at the low, middle and upper ends of the roof in both sides.	To check if the MC of the sheathing crosses the threshold conducive to microbial growth and to check if the temperature on the underside of the sheathing falls below the dew point that could potentially lead to condensation.

Sensor Tag	Sensor Type	Location	Purpose
HF	Heat-flux sensor in Base Design, Design 1, and Design 2.	On the top surface of ceiling gypsum board. Close to the eave.	To directly measure heat flow through the ceiling, comparing a vented attic with a sealed attic with identical insulation. Six sensors were used to capture every unique system combination dealing with insulation and ventilation strategies.
	Heat-flux sensor in Design 2, Design 3, and Design 4.	On the top surface of ceiling gypsum board in the center of the attic.	
RH/T-4, RH-T-5	RH / temperature sensor	At two locations in the house.	To measure interior temperature and RH for verification and control of interior conditions.
P-1, P-2	Pressure probe	In the attic cavity and in the house.	To measure the pressure difference between the attic cavity and the interior of the test unit.
T-8	Temperature sensor	Outside the structure at the weather station.	To measure ambient conditions.
RH/T-6	RH / temperature sensor		
WS	Wind speed		
SolRad	Global horizontal radiation		
P-3	Barometric pressure		

Instrumentation and data acquisition includes the following:

1. **Heat flux sensors**: These sensors provide a measure of the heat flow through the ceiling assembly that allows comparison of the thermal performance between sealed and unsealed roof cavities. Received data were analyzed to identify any patterns in heat flows and to check if trends are consistent with expectations.

   The final location of the six heat flux sensors included the eaves of the Base Design and Designs 1 and 2 and the center of ceilings in Designs 2, 3, and 4. The sensor placement allows for a comparison between all of the different insulation conditions employed in this study, which include:

   A. Eave of a conventional and vented attic under loose blown insulation

   B. Eave of a vented attic under dense-packed blown insulation

   C. Eave of a vented attic under compressed fiberglass batts

D. Center of a vented attic under loose blown insulation

E. Center of a vented and sealed attic under loose blown insulation

F. Center of an unvented and sealed attic under loose blown insulation

2. **Moisture sensors:** These sensors are used to check if the MC of the sheathing crosses the threshold that is conducive to microbial growth. Received data were checked against the standard threshold limit for wood-based products and for consistency in trends as per expectations (MC in the sheathing is expected to be higher in the winter than summer). Data across the different roof design bays were compared to identify designs more susceptible to moisture issues.

3. **RH sensors:** Along with the moisture sensors, these sensors provide data on the humidity levels at different locations in and around the roof attic. The intent is to check if the conditions inside the attic are conducive to moisture accumulation. Comparative data were captured at the soffit, inside the unit, and in the outdoor ambient air.

4. **Temperature sensors:** These sensors are strategically placed to evaluate the temperature profile at the eaves and in the attic field. Data collected indicate the heat flows and patterns in the five roof design bays and allow comparison and analysis of the differences based on the roof technologies. Sensors along the sheathing record temperatures that drop below the dew point and that may trigger moisture issues; the sensors on the underside of the asphalt shingles record elevated temperature conditions that may adversely affect the durability of the shingles.

5. **Pressure sensors:** The pressure sensors are used to monitor the pressure difference between the roof cavities, the ambient air and the interior of the house. The pressure differences between the house and attic cavities are the driving force behind air leakage into the attics and so this information is important to capture.

Data from these sensors were retrieved periodically and recorded in Excel files from which the analysis was completed.

3.3 Siting and Operations

The test structure was moved to a site in Jamestown, California. Jamestown was selected because it had significant heating and cooling degree days and was less dry compared to other sites with both substantial heating and cooling demand in California. The site had open solar access. The ridgeline of the test structure was oriented parallel to the true north-south axis (Figure 12).

Figure 12. Test unit on-site—west façade

The test apparatus was built in the first week of November 2014; then it was moved to the test site. Commissioning at the site was conducted in the last week of November 2014; after that, long-term monitoring and data collection began.

The test structure was equipped with electric resistance heating and a portable air conditioner. The portable air conditioner was provided with outside make-up air to prevent depressurization of the structure when it operated. The heating set point was 71°F; the cooling set point was 73°F. Heating season monitoring was conducted from the last week in November 2014 through the first week of April 2015. In the spring, the thermostat settings in the test unit were changed for summer-time testing. Cooling season monitoring was conducted from the beginning of May 2015 through the first week of August 2015.

4 Results

4.1 Weather Data and Interior Conditioning

The on-site weather station measured 2,749 heating degree days (65°F base) for the heating season monitoring period (11/21/2014 to 4/7/2015), and 869 cooling degree days (65°F base) for the cooling period (5/1/2015 to 8/10/2015). Typical meteorological year data are not available for the Jamestown-Sonora area; two of the nearest weather stations' typical full heating season heating degree days range from 2,300 (Modesto) to 7,700 (South Lake Tahoe) while typical cooling season cooling degree days range from 1,200 (Modesto) to less than 50 (South Lake Tahoe). Average on-site wind speed and insolation during the heating analysis period was 1.4 mph and 12.8 W/ft^2 respectively and 2.0 mph and 28.1 W/ft^2 over the cooling analysis period; precipitation was not recorded. Exterior RH typically showed wide diurnal swings of ~40% to 95% in the heating season; these were less pronounced in the summer.

The temperature and RH of the interior space of the test house were maintained between 70°–74°F and 50%–57% RH. The 2°F offset between heating and cooling equipment set points was maintained to prevent the appliances from running simultaneously.

4.2 Attic Cavity Depressurization Test

On November 21, 2015, the test unit indoor space was depressurized relative to outdoor ambient conditions to gauge the relative levels of air leakage to the outside of the test roof designs. The total leakage area across the ceiling from each attic bay to the indoor space was equal by design. A performance curve is shown in Figure 13. It was created from data generated by operating a duct blaster fan at various speeds while the data-logging equipment recorded pressure differentials between the indoor space and outdoor ambient and between the test roof cavities and the indoor space. The curve shows the degree to which attic cavity pressure is dependent on outdoor ambient pressure; because the Base Design and test Designs 1 and 2 were vented to outdoor ambient air, the pressure difference was greater for these designs than the pressure differences for Designs 3 and 4, which was expected.

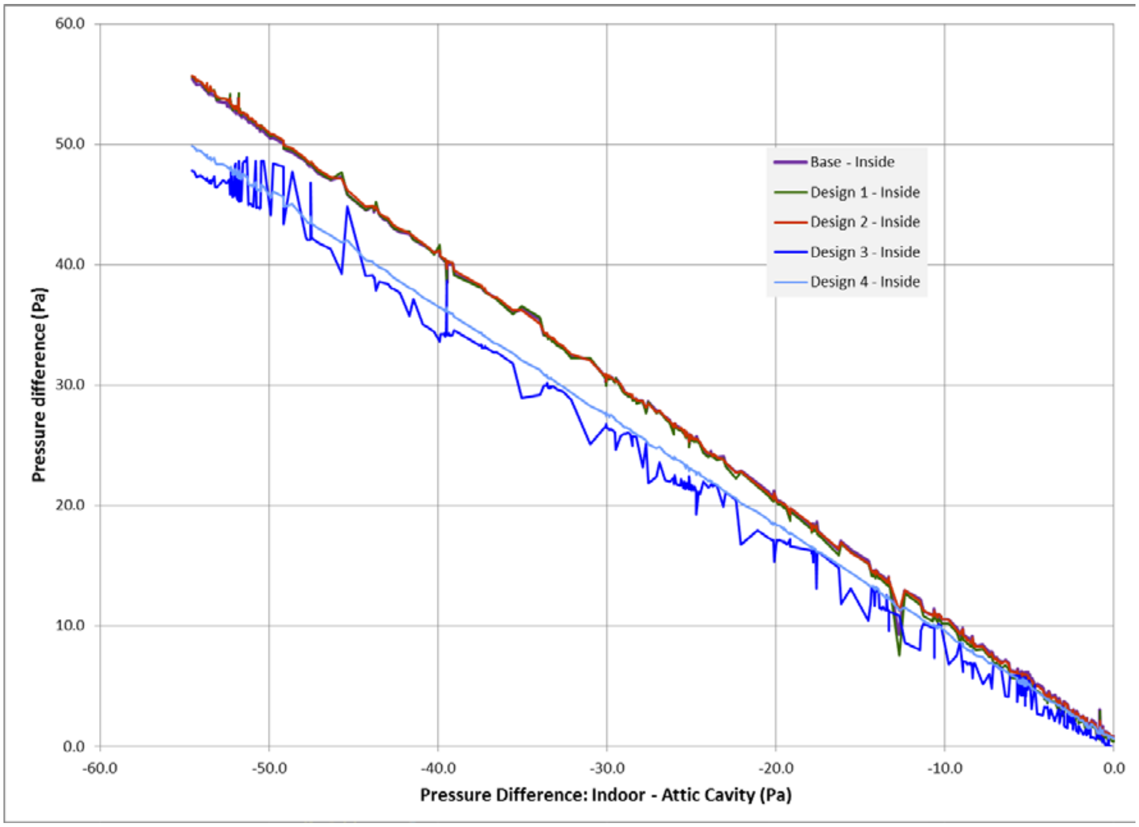

Figure 13. Depressurization performance curves for the test roof cavities

4.3 Heating Season Thermal Performance

The negative numbers in Table 3 reflect the average direction of heat flow in winter conditions—from the interior living space to the attic. Figure 14 shows typical heating season values recorded by the heat flux sensors; the conventional attic eave exhibits the highest rate of nighttime heat loss. The eave sensors in the dense-packed blown insulation and compressed fiberglass batt conditions recorded average heat transfer rates that were 30% and 40% less respectively than those of the Base Design eave sensors with only loose blown insulation. In the Base Design conditions of a vented unsealed attic with loose blown insulation in both the eaves and the center of the attic, the ceiling-center average heat transfer rate measured approximately 50% that of the corresponding eave heat transfer rate. The average ceiling-center heat flux transfer rates for the vented sealed attic and the unvented sealed attic designs were 9% and 16% less respectively than the average for the typical vented attic. A limitation of the spot measurements of heat transfer conducted here is that the heat transfer may not be totally uniform throughout the eave or ceiling center because of heterogeneity in insulation density and air sealing (e.g., compressed fiberglass batt insulation might not fully fill the corners formed between the rafters, sheathing, blocking and ceiling gypsum board).

Graphically, heat flux appears to correlate more closely with roof deck temperature than outdoor air temperature. This is most likely because the roof deck temperature incorporates solar gain as well. As expected, heat loss through the dense-packed blown insulation and compressed-batt eave designs was lower than at eaves with standard density blown insulation. On days when the outside temperature dropped below average, heat loss through the eave with compressed batts was marginally lower than heat loss through the dense-packed eave designs. At the attic-center condition, losses were smallest through the unvented sealed attic than through any of the other designs.

Table 3. Heating Season Heat Flux Sensor Measurements

	Eaves			Center-attic		
Heat Flux per Attic Design Type	Vented attic w/ standard blown eave insulation (base attic)	Vented attic w/ dense-packed blown eave insulation	Vented attic w/ compressed batt eave insulation	Vented, unsealed attic (base attic)	Vented sealed attic	Unvented sealed attic
Average W/m^2	–1.89	–1.33	–1.14	–0.91	–0.83	–0.76
Total Wh/m^2	–6,096	–4,302	–3,670	–2,955	–2,668	–2,440

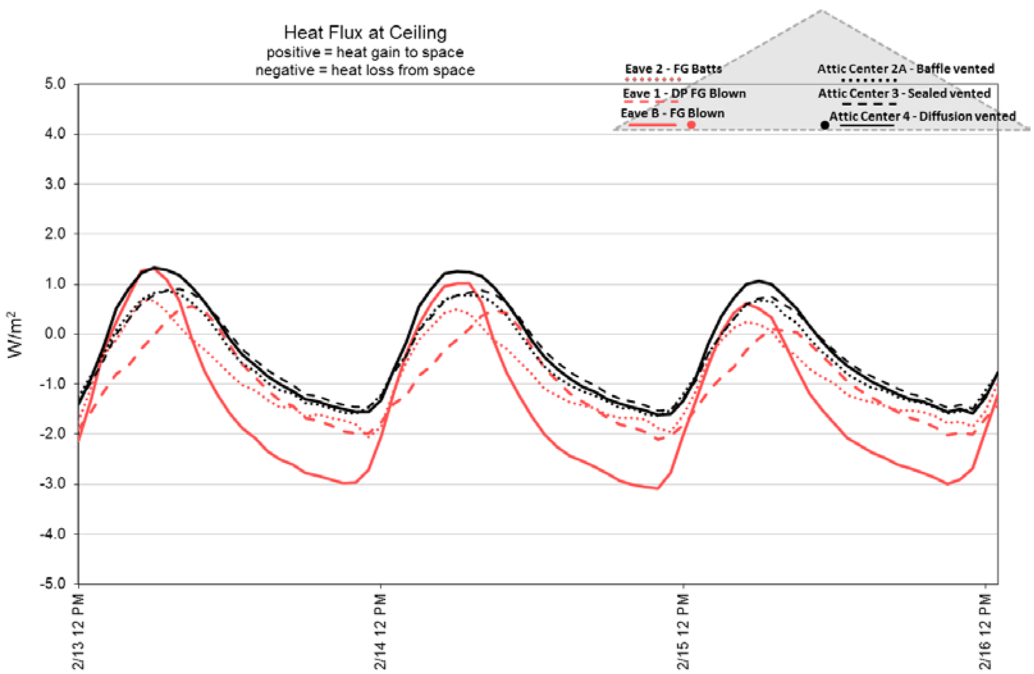

Figure 14. Typical daily range of heat transfer values at heat flux sensors in winter

4.4 Cooling Season Thermal Performance

Cooling season performance did not directly follow that of the heating season. The positive numbers in Table 4 reflect that on average the indoor space gained heat from the attic bays and the better-performing designs in the heating season tended to be the worst in the cooling season. Furthermore, the peak heat flux rates do not correlate with the average rates; it is suspected that the test conditions where airflow was reduced caused those bays to retain heat from both the outdoor ambient air and solar irradiance on the roof deck, which raised the average temperature.

In addition to the ceiling center in both sealed attics, the eave in the vented attic with compressed batt insulation exhibited a high average rate of heat flux; this condition may indicate that the compressed batts were pressing the under-deck baffles and restricting ventilation airflow there. The base condition loose-blown insulation eave and vented unsealed attic caused the least amount of heat gain to the interior living space.

Table 4. Cooling Season Heat Flux Sensor Measurements

	Eaves			Attic Center		
Heat Flux per Attic Design Type	Vented Attic w/ Standard Blown Eave Insulation (Base Attic)	Vented Attic w/ Dense-Packed Blown Eave Insulation	Vented Attic w/ Compressed Batt Eave Insulation	Vented Unsealed Attic (Base attic)	Vented Sealed Attic	Unvented Sealed Attic
Average W/m^2	0.60	0.63	1.07	0.86	1.09	1.17
Cooling season Net Wh/m^2	1,448	1,502	2,561	2,075	2,627	2,818
Maximum W/m^2	6.1	4.8	9.0	4.2	4.4	4.7
Minimum W/m^2	–3.3	–2.2	–2.4	–1.7	–1.6	–1.6
Total Gains to Interior Space Wh/m^2	2,911	2,243	3,386	2,498	2,931	3,202
Total Losses from Interior Space Wh/m^2	–1,463	–742	–825	–424	–304	–384
Standard Deviation	2.1	1.5	2.2	1.3	1.4	1.6

Figure 15 shows the highest temperatures recorded in the attic cavities on July 29, 2015. Trend lines in blue and red show temperatures at the ridge vent and center of the attic cavity respectively for each design. The sealed unvented attic (Design 4) shows the highest temperatures followed by the unsealed vented attic (Design 3) and then the three vented unsealed attic designs. The soffit temperatures in Figure 16 show higher temperatures on the east side of each attic design compared to the west soffits; while both sides of the test building were not shadowed throughout the day and received full sunlight, the east side of the building was within 10 meters of trees and other structures at greater elevation; the west side was exposed to the hillside and perhaps was cooled slightly by prevailing winds. The peak temperature of the west soffit of Design 2 is conspicuously higher than the other designs; this might be related to constriction of the baffles beneath the roof sheathing by the compressed fiberglass batts.

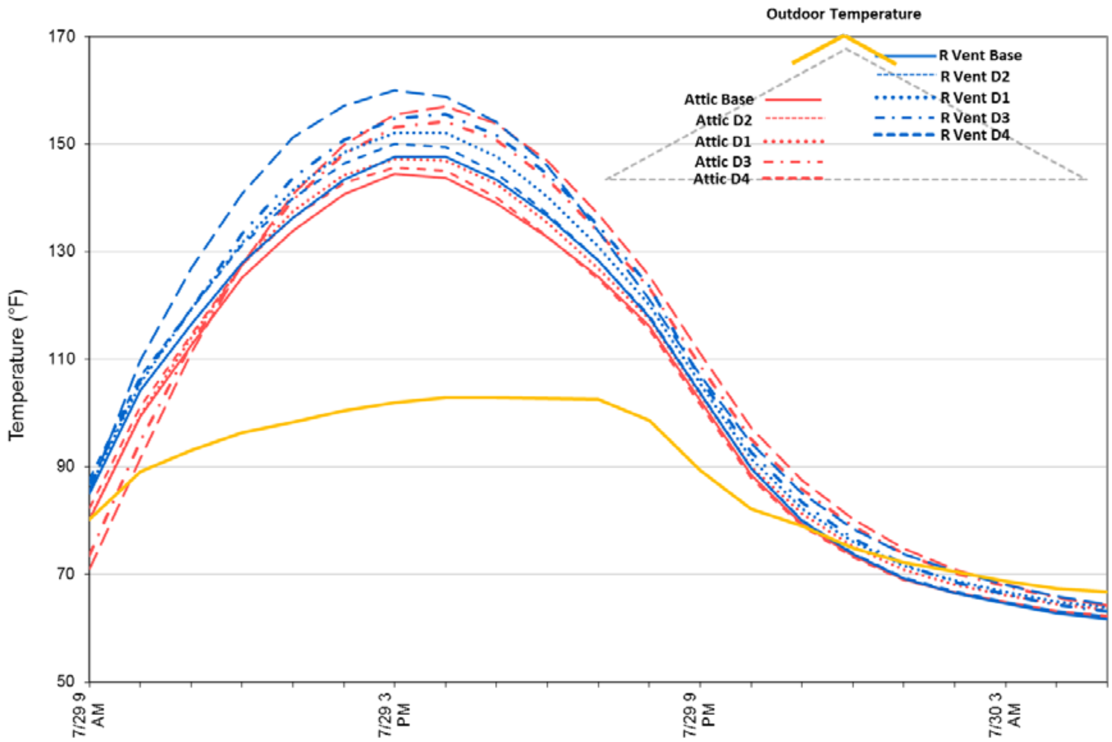

Figure 15. Attic and roof ridge temperatures on a hot summer day

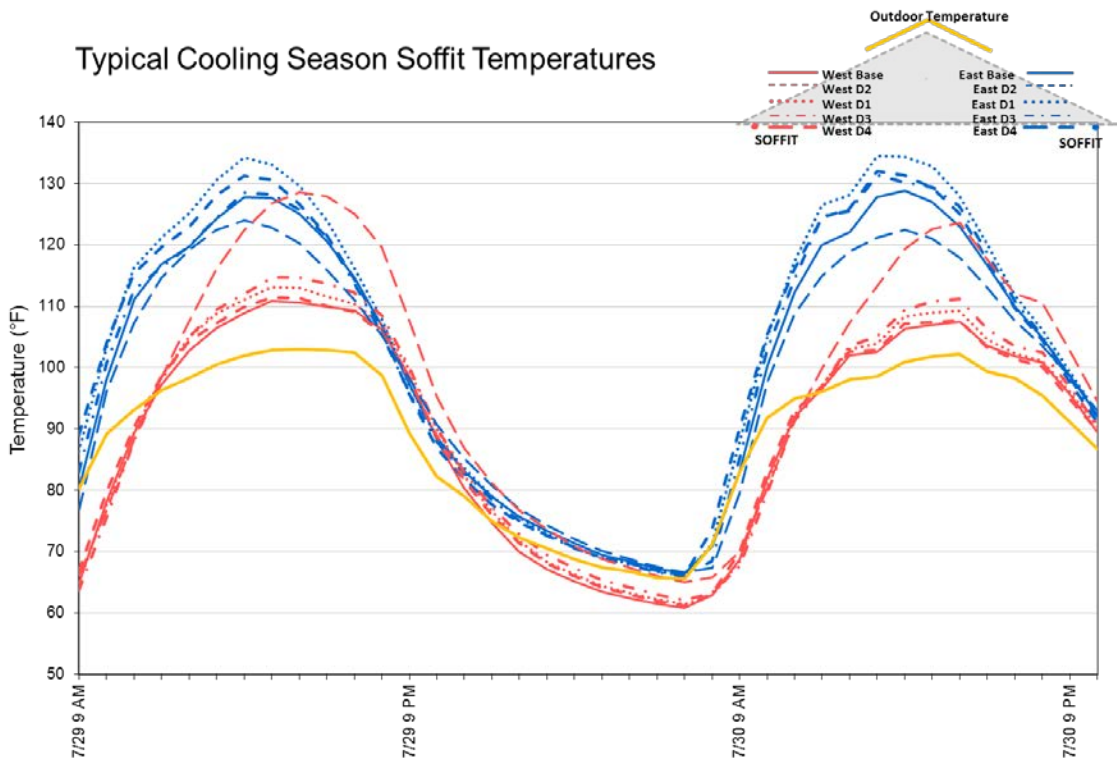

Figure 16. Soffit temperatures on July 29, 2015

The roof shingle temperatures across the five designs shown in Figure 17 are not markedly different; however, there is as much as a 5°C difference between the designs, which seems to again correlate the unsealed vented attic designs with the lowest temperatures.

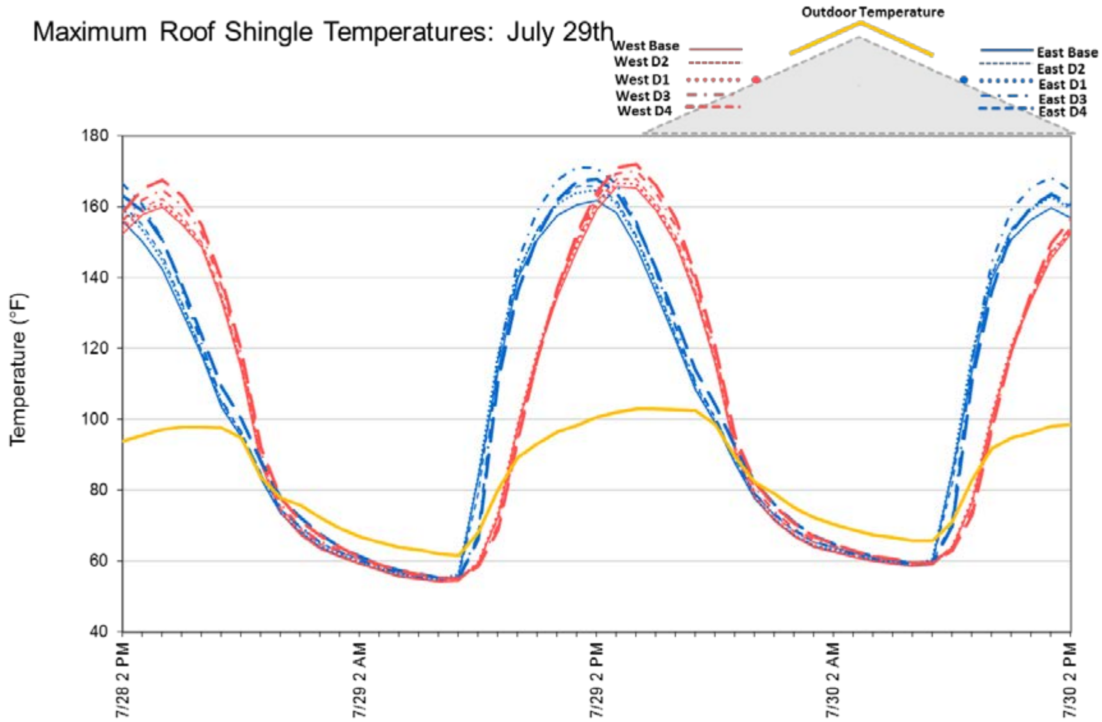

Figure 17. Peak roof shingle temperatures on July 29, 2015

4.5 Moisture Performance

The MC of the sheathing remained within reasonable limits (15% or lower) for all the roof designs (Appendix A). The standard MC range for mold occurrence and its continued growth is 19% or greater (Forest Products Laboratory 2015). However, peak heating season moisture levels were ~2% higher in Design 4 when compared to the other four. This may have implications for other climates. Interestingly, sheathing MC for three of the four designs dropped to 7% (the sensors' lower functional boundary) or lower during the cooling season. The exception was Design 1, which featured an unsealed vented attic space and dense-packed blown insulation.

RH during the height of the heating season was fairly homogenous throughout the designs in their soffits (Figure 18), attic cavities and roof ridges (Figure 19). The exception was Design 4 where soffit RH exhibited a similar average value but with a smaller deadband and where attic cavity RH was slightly above average—again with a reduced deadband. Furthermore, the attic cavity RH in Design 4 remained at or above 70% for an entire week in early January (see Figure 20), which in conjunction with high surface MC in the roof sheathing and framing could result in microbial growth (Forest Products Laboratory 2015); however, the peak MC in the sheathing in this design did not exceed 16% at any point in the heating or cooling seasons monitored.

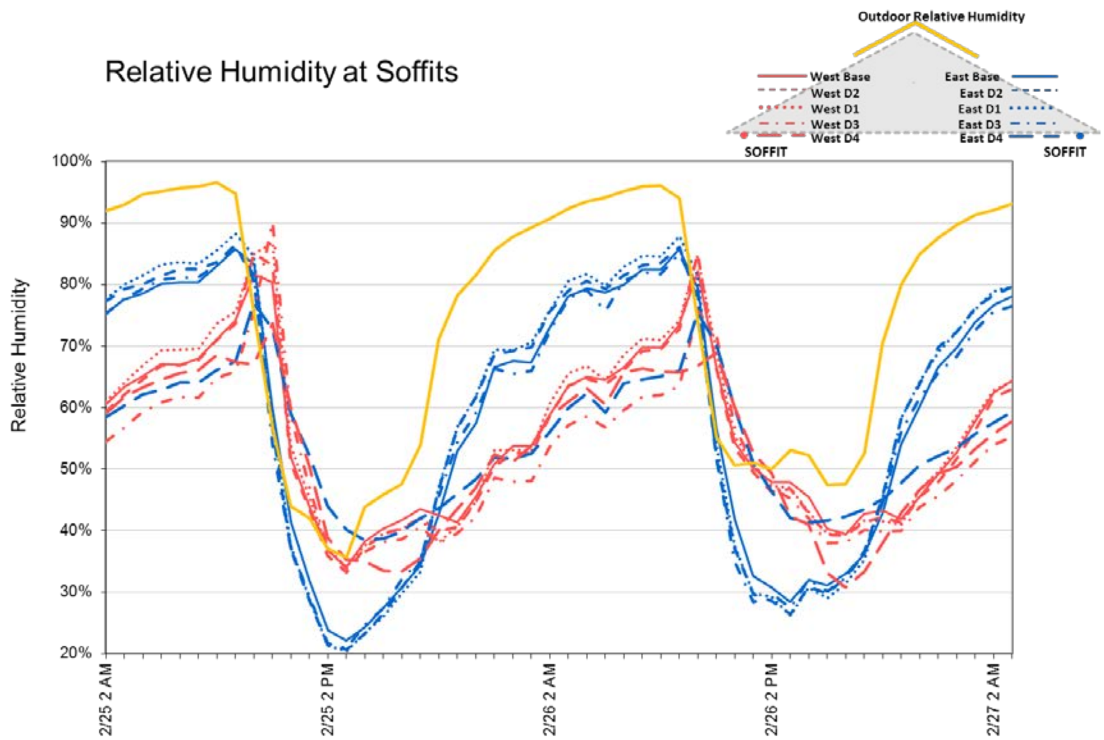

Figure 18. Typical soffit RH in heating season

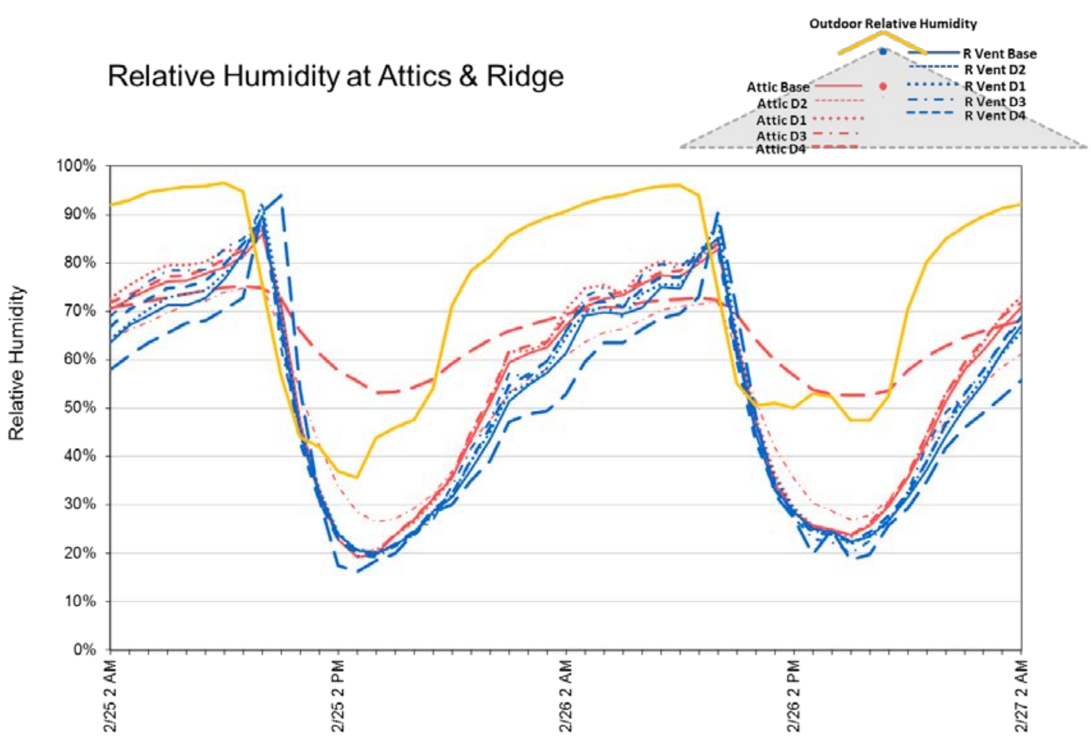

Figure 19. Typical attic and roof ridge RH in heating season

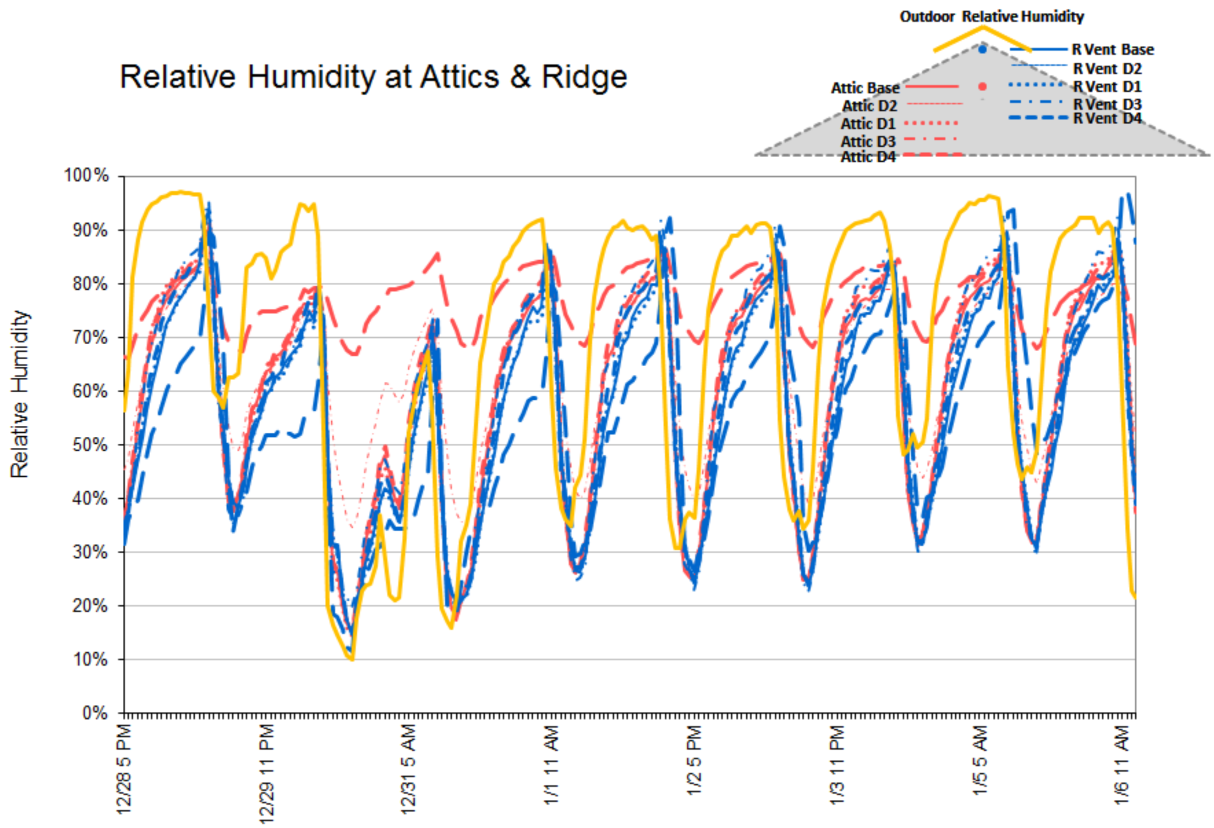

Figure 20. RH at 70% or higher in Design 4 (unvented sealed attic) for a week in midwinter

5 Conclusions

5.1 Answers to Research Questions

1. *What is the likelihood of moisture-related deterioration of roof materials and microbial growth due to elevated RH levels with the proposed new roof designs compared to typical MH roof designs?*

All of the test attic designs performed well in this regard, and the results do not indicate that moisture and mold growth would be an issue in this specific climate. The unvented sealed attic (Design 4) did sustain higher average RH and MC in the heating season than the other designs, but the recorded values fell short of critical thresholds for mold growth.

2. *What impact does roof ventilation have on the thermal and moisture performance of alternative roof systems?*

The levels of ventilation decreased from highest to lowest in this order: vented unsealed attic designs, vented and sealed attic design, and unvented sealed attic design. As the ventilation decreased, heat retention appeared to increase in both the heating and cooling season monitoring periods in this experiment; this was expected. Thus, the ventilation strategies that exhibited the best thermal performance in the heating season were the worst thermal performers in the cooling season. In terms of moisture performance, only the attic bay that was both unvented and sealed (Design 4) exhibited substantially higher average RH; at the same time this bay had slightly lower peak humidity than the other designs and a mild increase in heating season sheathing MC. The vented attic cavity in Design 3 was sealed with a membrane but still performed comparably to the unsealed vented attic bays in terms of RH and MC. Interestingly, the roof sheathing in Design 1 (unsealed vented cavity with dense-packed insulation at the eaves) showed 7.5%–8% MC during the summer cooling season, which was slightly higher than all the other designs.

3. *Which of the four alternative roof designs demonstrates superior performance in terms of thermal integrity and control of humidity levels in the given climate (IECC Climate Zone 4)?*

Moisture management during the monitoring period appeared acceptable for all four designs. Design 1 and the base design both showed the lowest net heat gain to the indoor living space in the cooling season; however, heat flux swings in both directions were lower in Design 1 than in the Base Design, which indicated more consistent performance. The heating season thermal performance of all four test designs was superior to that of the Base Design. While the attic membrane sealing and unvented strategies retained the most heat in the heating season (Designs 3 and 4), the total reduction in seasonal energy loss might not justify the added material cost and complexity of constructing these designs. Therefore, Design 1 is the best overall alternative to the conventional MH roof in this climate.

5.2 Future Research

Based on the data captured by the sensors, the U-value of the different roof designs can be derived and total seasonal heat transfer can be calculated. As part of a future research effort by the ARIES team, thermal modeling and a cost-benefit analysis will be conducted using building simulation software to evaluate the impact of the advanced roof designs on whole-house performance based on their relative cost-effectiveness.

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Appendix A

Construction Details of the Test Structure

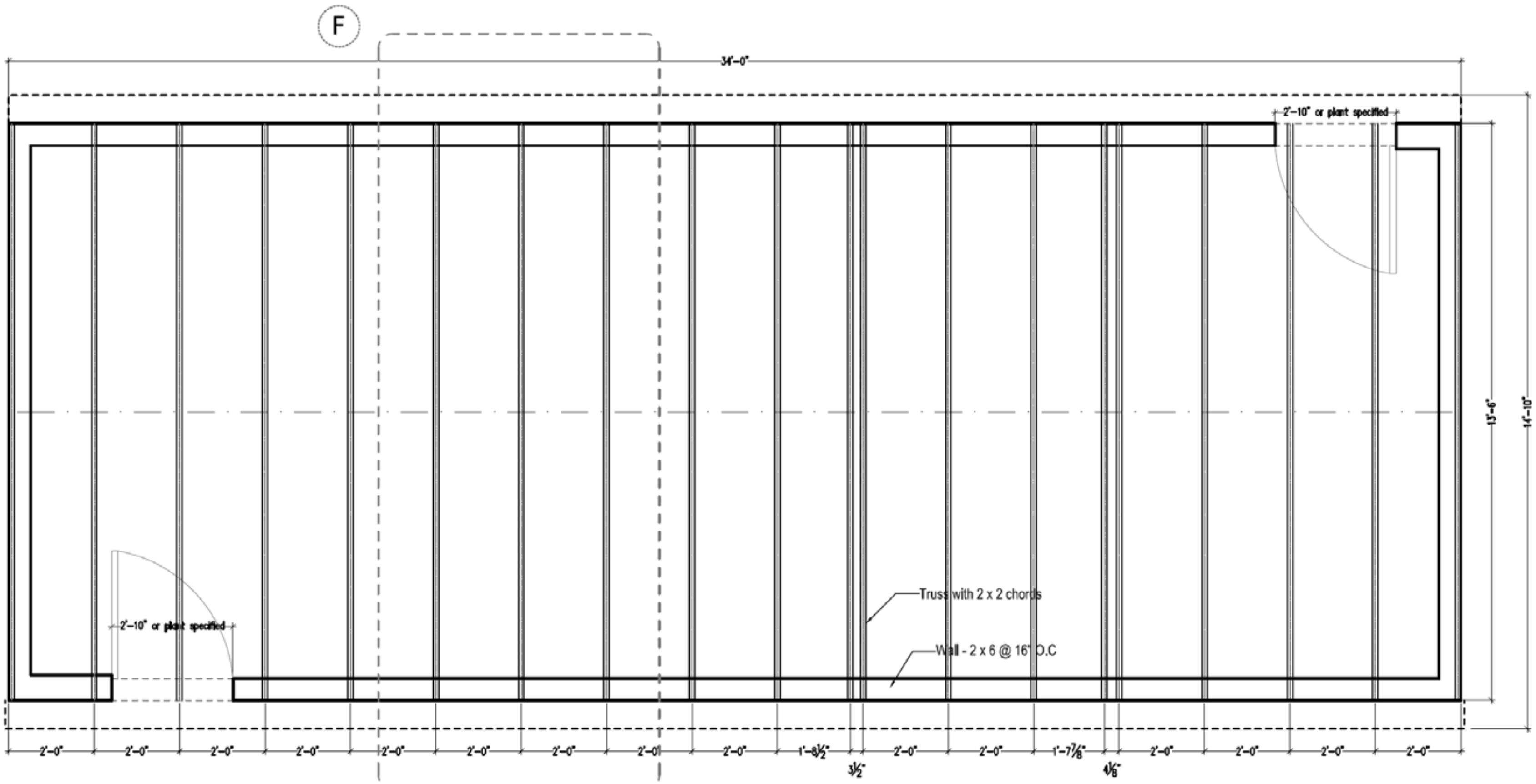

Figure 21. Prototyping and testing unit: plan

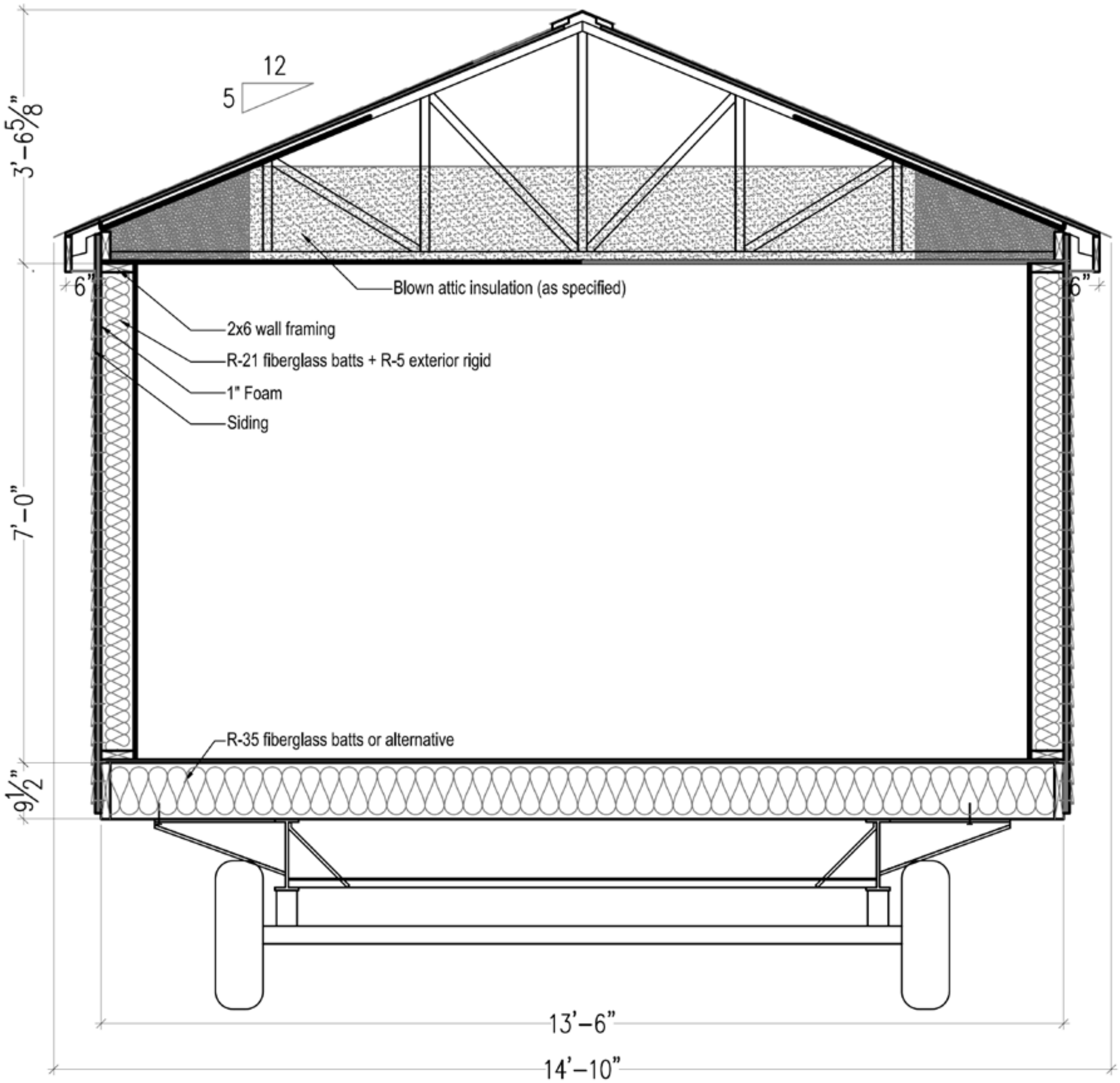

Figure 22. Prototyping and testing unit: transverse section

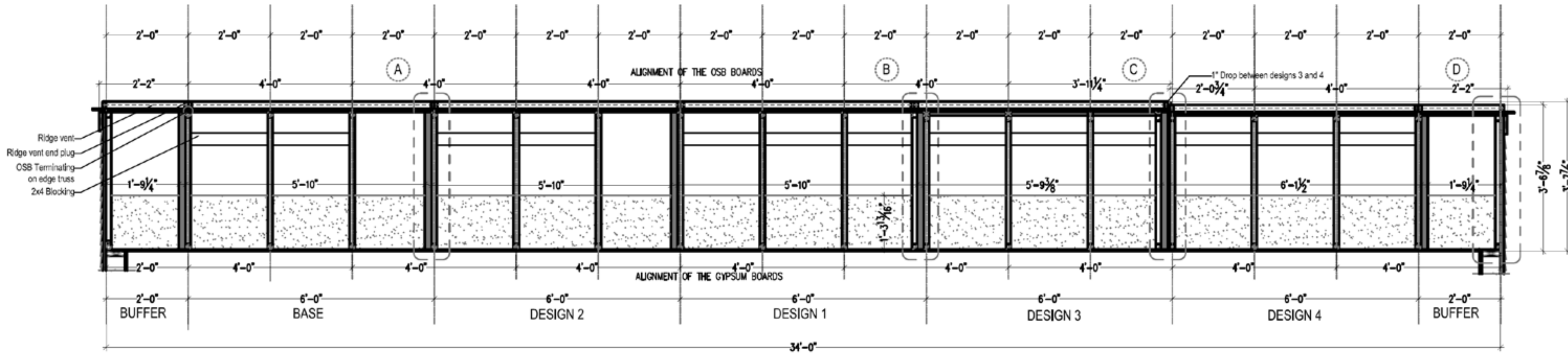

Figure 23. Prototyping and testing unit—longitudinal section

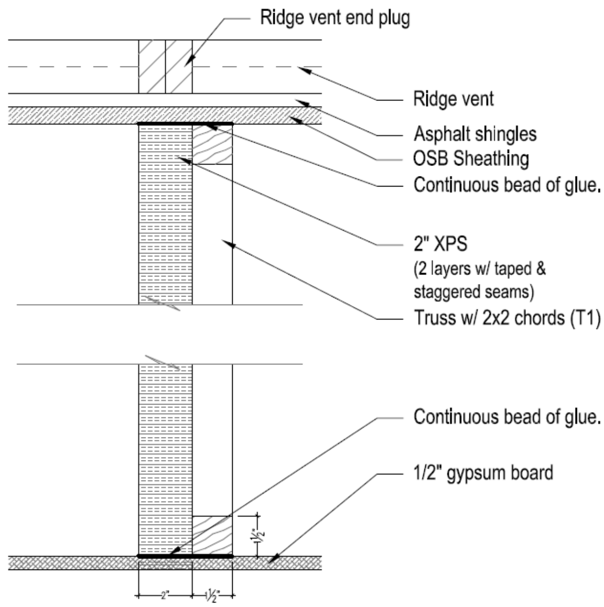

Figure 24. Detail at A (typical interior partition wall)

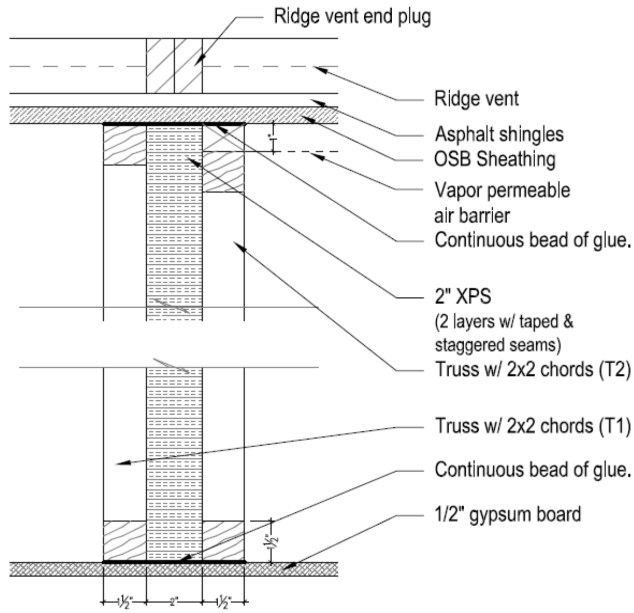

Figure 25. Detail at B (partition wall where truss types switch)

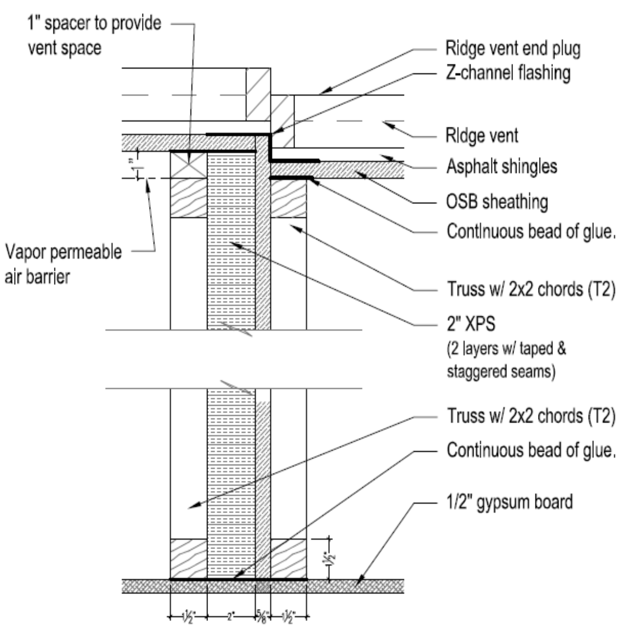

Figure 26. Detail at C (partition wall between Design 3 and Design 4)

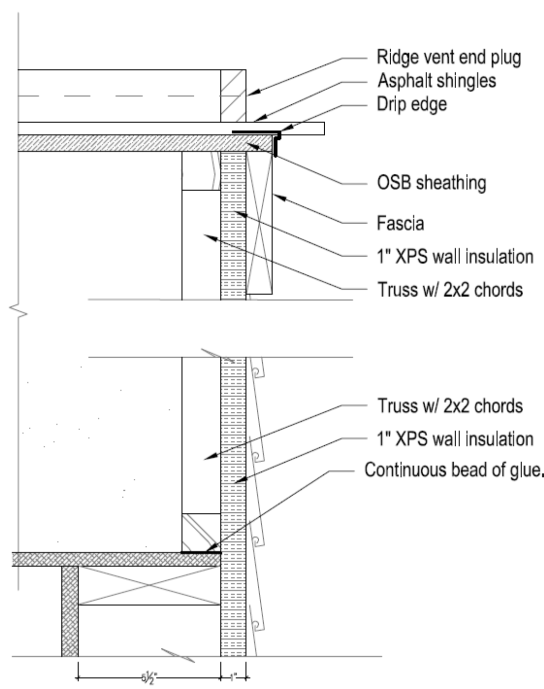

Figure 27. Detail at D (termination at gable-end)

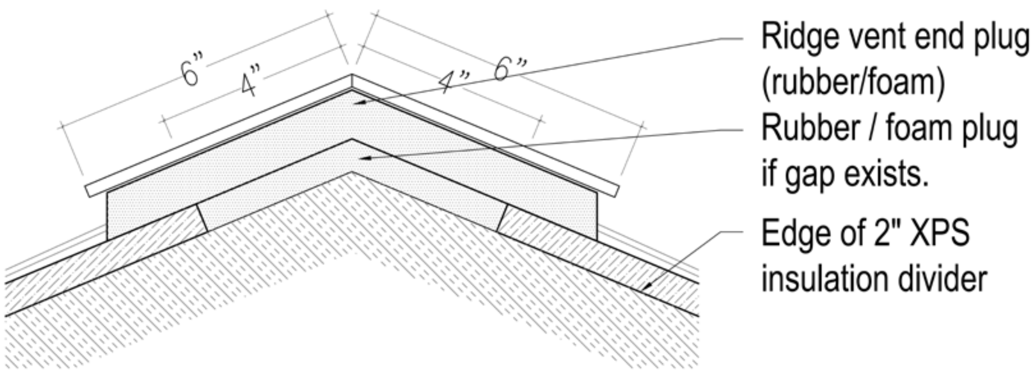

Figure 28. Typical Ridge Detail at Partition Between Bays

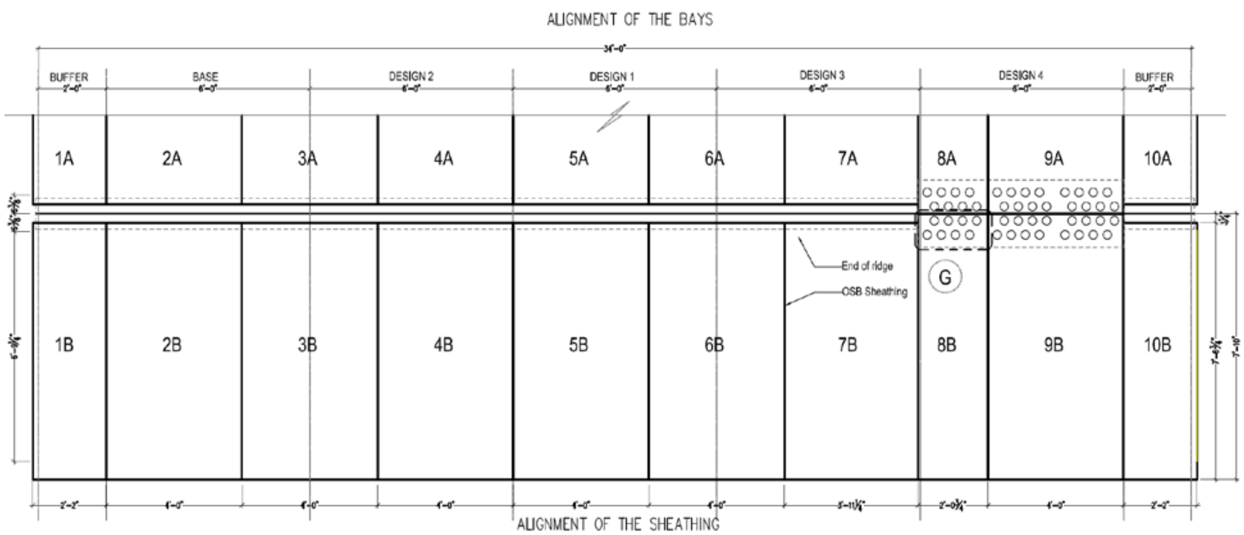

Figure 29. Oriented strand board sheathing layout on roof

Specifications and details of the manufactured housing unit planned for the prototyping and testing are listed in Table 5. The roof was subject to long-term monitoring and assessment and had sensors installed to monitor temperature, pressure, and humidity levels within the roof cavities at possible condensation surfaces and in ventilation pathways. Interior humidity conditions were artificially introduced and the temperature inside was controlled. Temperature and RH set points were controlled remotely via a data logger. At the conclusion of the experiments, the assemblies will be disassembled and checked for any evidence of condensation, moisture accumulation, or moisture-related damage.

Table 5. Prototype House Specifications

Specs	Base Design (incl. buffers)	Design 1	Design 2	Design 3	Design 4
ROOF CONSTRUCTION					
Roof Design	Conventional roof	Vented attic roof with dense-packed insulation at eaves	Vented attic roof with compressed batts at eaves	Vented sealed attic roof with dense-packed blown insulation at the eaves	Unvented sealed attic roof with dense-packed blown insulation at the eaves
Description	Conventional roof construction with standard density blown insulation.	Dense-packed blown insulation to increase the thermal performance at the eaves. Standard density loose fill insulation at the center of the attic.	Combines two types of insulation to achieve a more uniform U-value across the attic; blown/loose-fill insulation at the center with compressed unfaced batt insulation at the eaves.	Sealed attic roof with dense-packed insulation at the eaves and standard density blown insulation in the field. An air barrier with a high perm rating is used to seal the attic.	Sealed attic with dense-packed blown insulation at the eaves and standard density blown insulation in the field. Diffusion vent (a vapor-permeable air barrier vent) used at the ridge to allow accumulated moisture to dry out via vapor diffusion while still acting as an air barrier.
Roof Frame	Truss with 2x2 chords (spacing as specified in drawings).				
Attic Insulation	Field: R-49 standard density blown FG Eave: R-49 standard density blown FG	Field: R-49 standard density blown FG Eave: Dense-pack blown FG	Field: R-49 standard density blown FG Eave: R-38 compressed FG batts (or approved alternative)	Field: R-49 standard density blown FG Eave: Dense-pack blown FG	Field: R-49 standard density blown FG Eave: Dense-pack blown FG
Ventilation	Vented	Vented	Vented	Vented	Unvented

Specs	Base Design (incl. buffers)	Design 1	Design 2	Design 3	Design 4
Ventilation Type	Baffles, ridge and soffit vents, end plugs at ridge vent	Baffles, ridge and soffit vents, end plugs at ridge vent	Baffles, ridge and soffit vents, end plugs at ridge vent	1.5-in. x 1-in. spacers on truss, ridge, and soffit vents; end plugs at ridge vent	Ridge and soffit vents, end plugs at ridge vent[a]
Air barrier	n/a	n/a	n/a	Vapor-permeable air membrane[b] around the roof truss cavity	Diffusion vent at the ridge. Vapor-permeable air barrier[b]
Roof Partitions	2-in. thick XPS rigid insulation (2 layers of 1-in. thick with staggered seams)				
Roof Finish	Asphalt shingles with underlayment				
GENERAL CONSTRUCTION					
Exterior Wall (see Appendix A)	Height: 7-ft. sidewalls Framing: 2-in. X 6-in. @ 16-in. o.c. Insulation: R-21 FG batts in cavity R-5 exterior rigid foam insulation (XPS) Wall underlayment: Building paper or typical practice for weather-tight barrier Interior finish: ½-in. gypsum board with paint Exterior finish: Vinyl or hardboard siding				
Doors	Doors 1 and 2: Standard insulated MH exterior door with locks				
Floor	Framing: 2x10 floor joists @ 16-in. o.c. or approved alternative Insulation: R-38 FG batts (or approved alternative) between joists				

Specs	Base Design (incl. buffers)	Design 1	Design 2	Design 3	Design 4
	Floor finish: Linoleum on floor decking				
Air-Tightness Measures	The testing structure must be sealed against air leakage at all joints, seams, and penetrations associated with the building thermal envelope including: • Taping all joints of the exterior continuous wall insulation • Gaps and penetrations in the thermal envelope sealed with caulk, foam or gasket, or other suitable material • Rough openings around exterior doors sealed with caulk or foam • Sealing methods between dissimilar materials must allow for differential expansion and contraction • Bottom plate sealed to floor decking and top plate sealed to the ceiling gypsum board.				
OTHER EQUIPMENT AND MATERIAL					
Mechanical System	Portable heat pump				
Electrical	Portable lights Power bars and cables to provide electrical service and internet				
Furniture	Tables and surfaces for testing equipment				

[a] Design 4 is unvented but will be constructed with ridge and soffit vents.
[b] Air barrier membrane should have perm rating >10.

Additional Construction Details

Installation of the Attic Air Barrier for Design 3

The installation procedure of the air barrier is described below:

A vapor-permeable air barrier membrane is installed between the 1-in. vent spacer and the truss. The membrane spans across the three truss bays and is attached to the top chord of a truss by means of adhesive. If staples are used to tack the membrane to the truss, then the staples must be taped and sealed. The spacer is nailed to the truss through the air barrier layer.

The air barrier membrane is wrapped around the sides and the eaves to effectively seal the roof cavity. At the edge of the roof bay the membrane is wrapped over the truss and taped to the side of the top chord. In addition, the length of the membrane along the slope is attached to the rigid XPS foam layer by means of adhesive or a continuous bead of glue. At the eaves, the air barrier layer is wrapped over and the edges are taped to the rigid wall insulation. The siding is installed per typical practice.

Installation of the Diffusion Vent for Design 4

The components and installation procedure of the diffusion vent are described below:

A series of 3-in. diameter holes are drilled into the roof sheathing near the ridge of the truss bays. Holes should be drilled instead of omitting sheathing because of the large area of the diffusion ports; a large opening would compromise the structural stability of the roof during construction and provide no nailing base for the outer layers. The diffusion vent holes are covered with a layer of a vapor-permeable air barrier membrane with a high perm rating (e.g., Tyvek house wrap).

The edges of the air barrier membrane are taped to the roof oriented strand board sheathing to seal the unvented roof cavity below. The edge of the roof underlayment is also taped to the edge of the air barrier membrane. The asphalt shingles are installed on the roof per typical practice. The ridge is then covered with the typical attic ridge vent, which is in turn covered by sheathing and ridge cap shingles. See Figure 30 for an isometric view of the detail at the ridge.

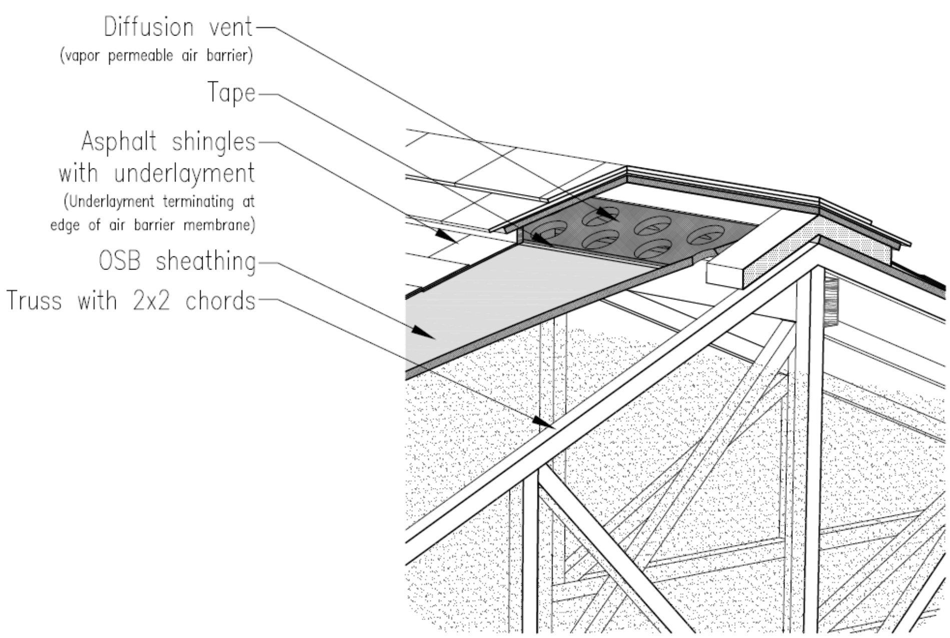

Figure 30. Isometric view of the ridge in Design 4

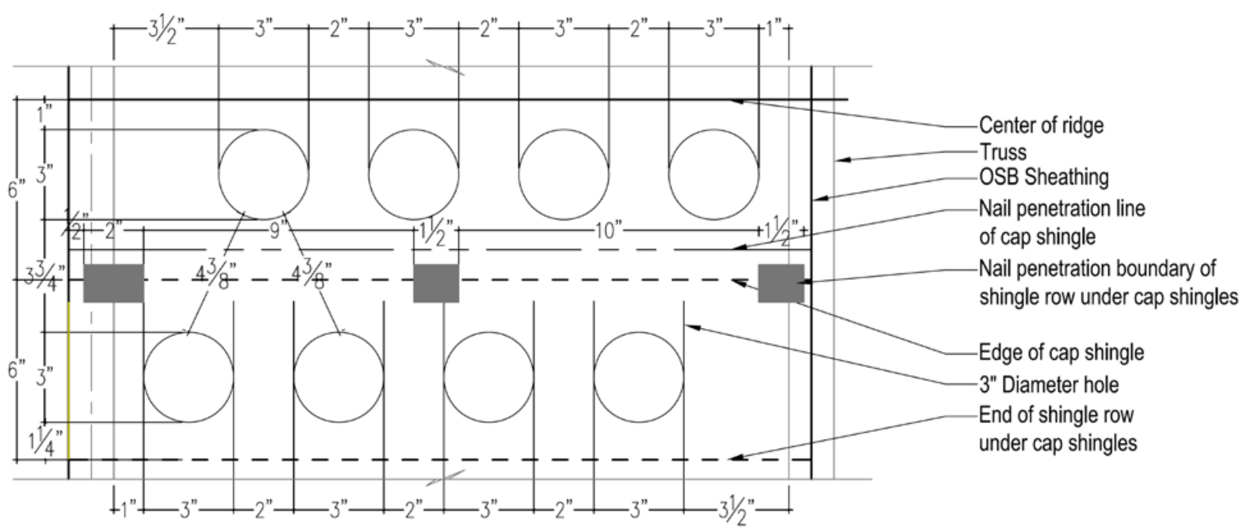

Figure 31. Detail at ridge diffusion vent

Monitoring Instrumentation

The roof was instrumented with temperature, pressure, MC, and RH sensors per requirements for moisture and thermal performance testing. Four unsealed holes (1-in. dia.) were drilled into the ceiling of each design bay to simulate leakage. These holes approximate the numerous ceiling penetrations in a conventional ceiling. There were two sealed outlets per experimental bay in the attic ceiling for the purpose of routing the sensor channels to the interior of the testing unit. These sealed outlets were drilled in the ceiling at the eave ends. The end buffer bays did not have unsealed holes or sealed outlets.

Test Unit Local Climate Data and Indoor Space Conditioning

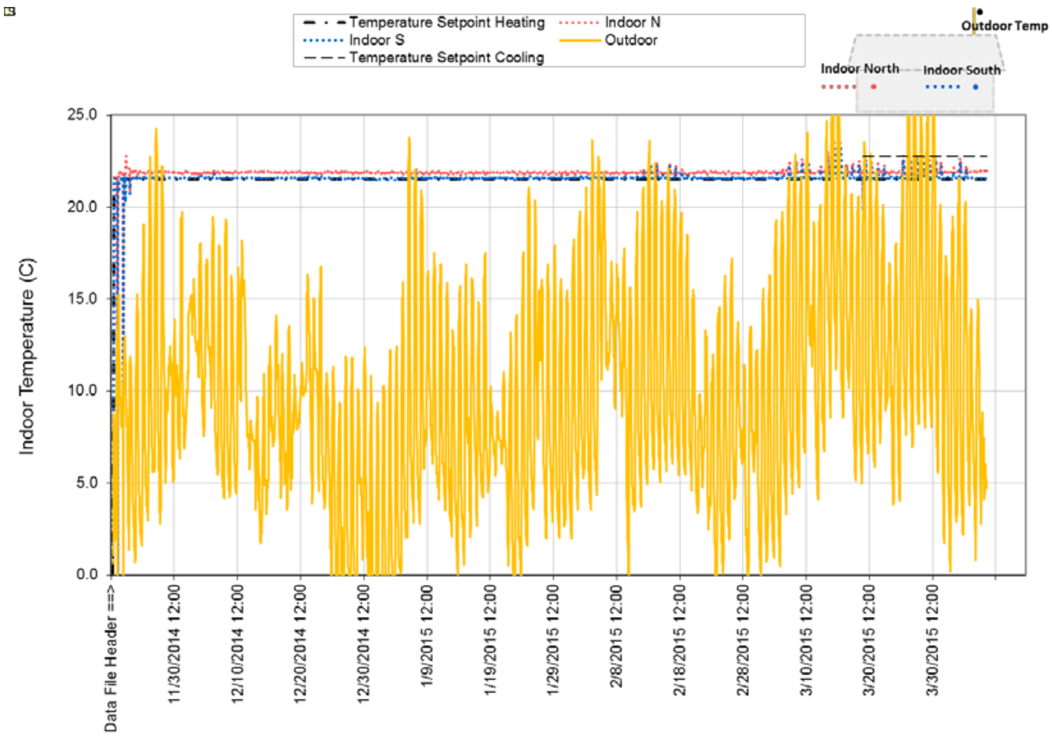

Figure 32. Heating season ambient and indoor temperatures

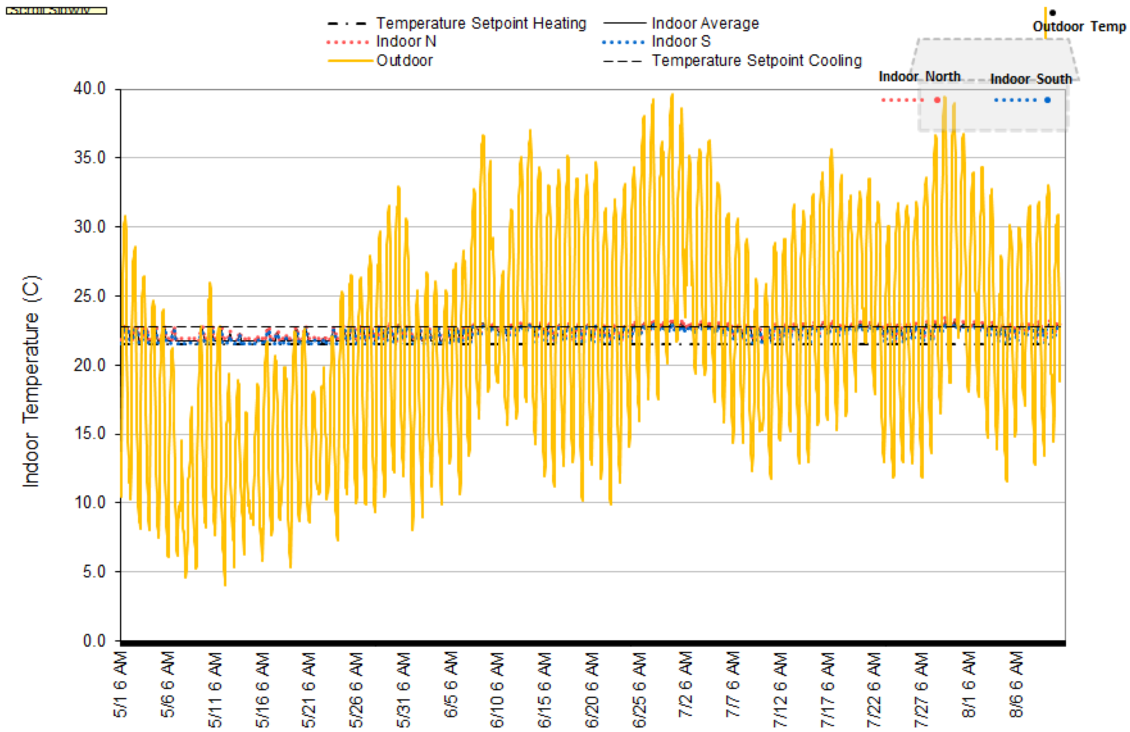

Figure 33. Cooling season ambient and indoor temperatures

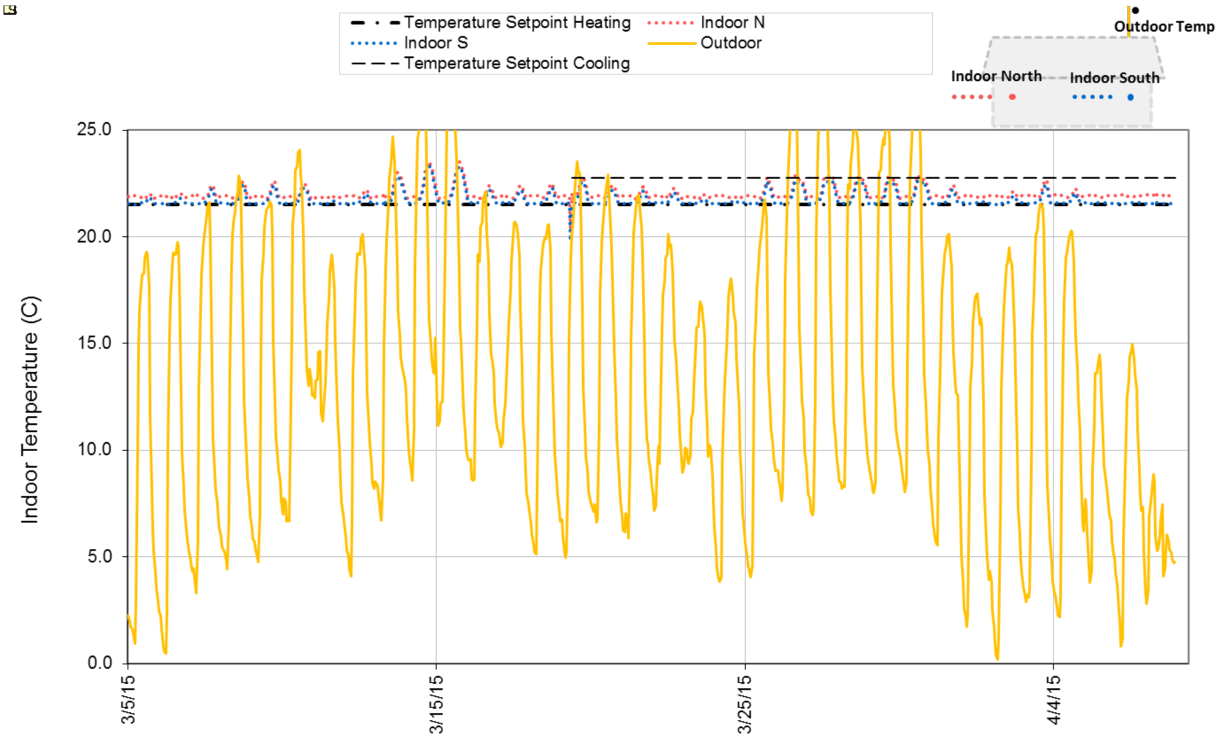

Figure 34. Space-conditioning equipment performance

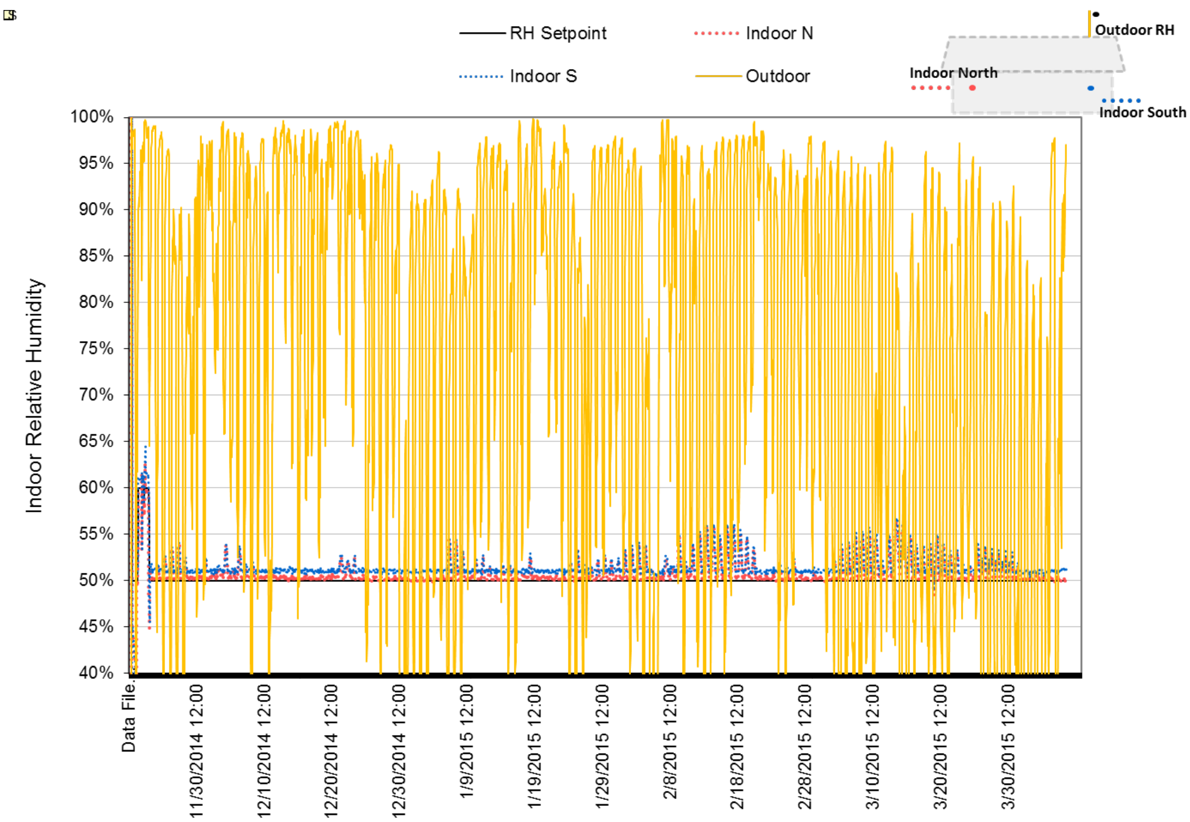

Figure 35. Heating season ambient and indoor RH

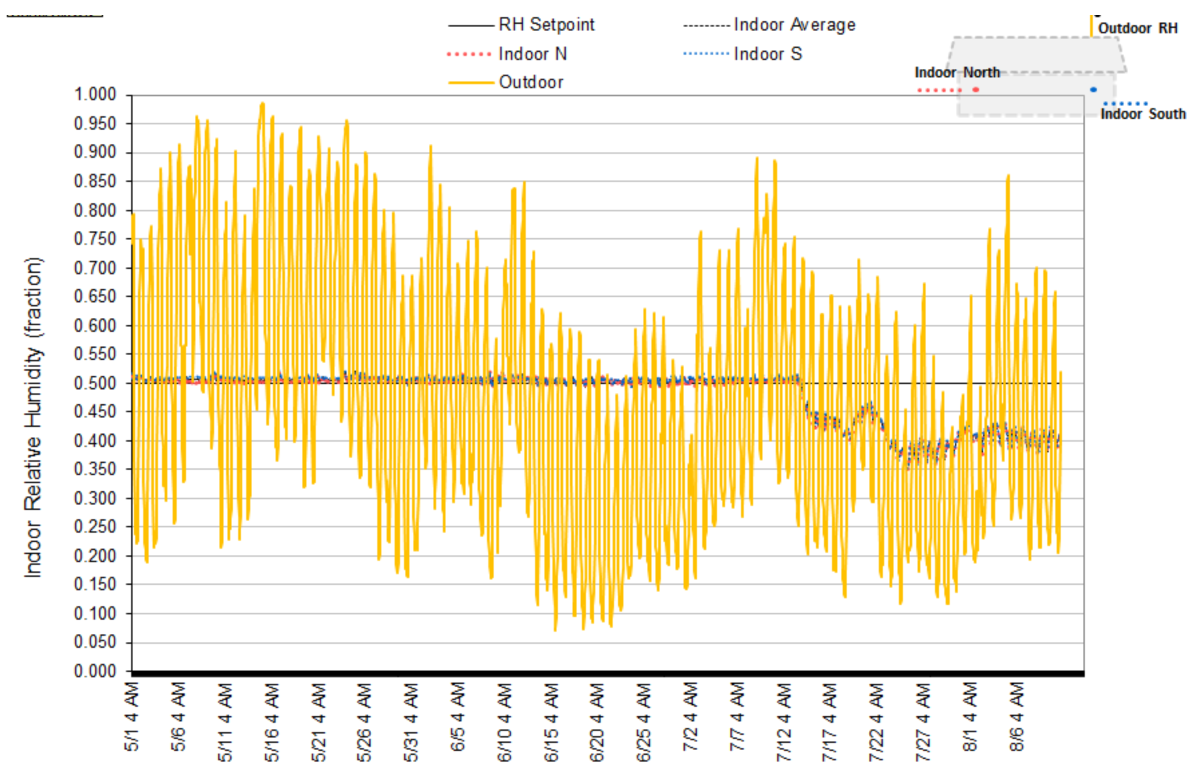

Figure 36. Cooling season ambient and indoor RH

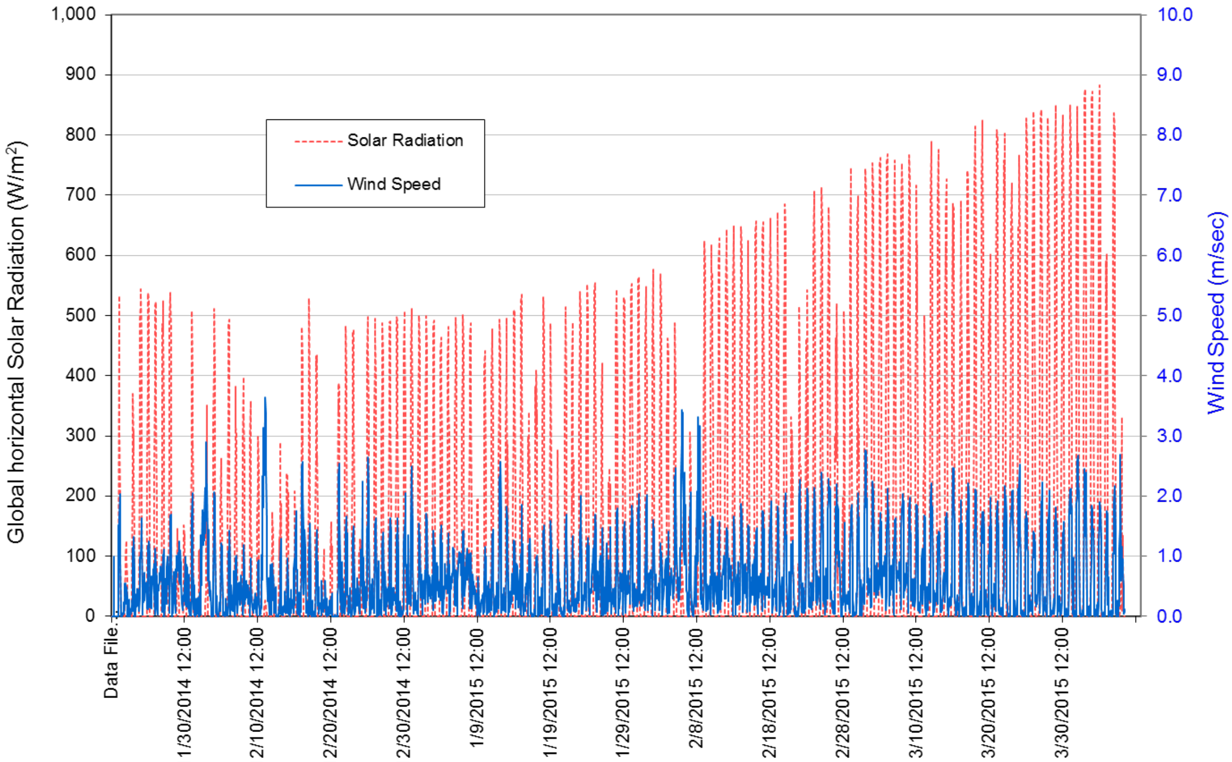

Figure 37. Heating season hourly site insolation and wind speed

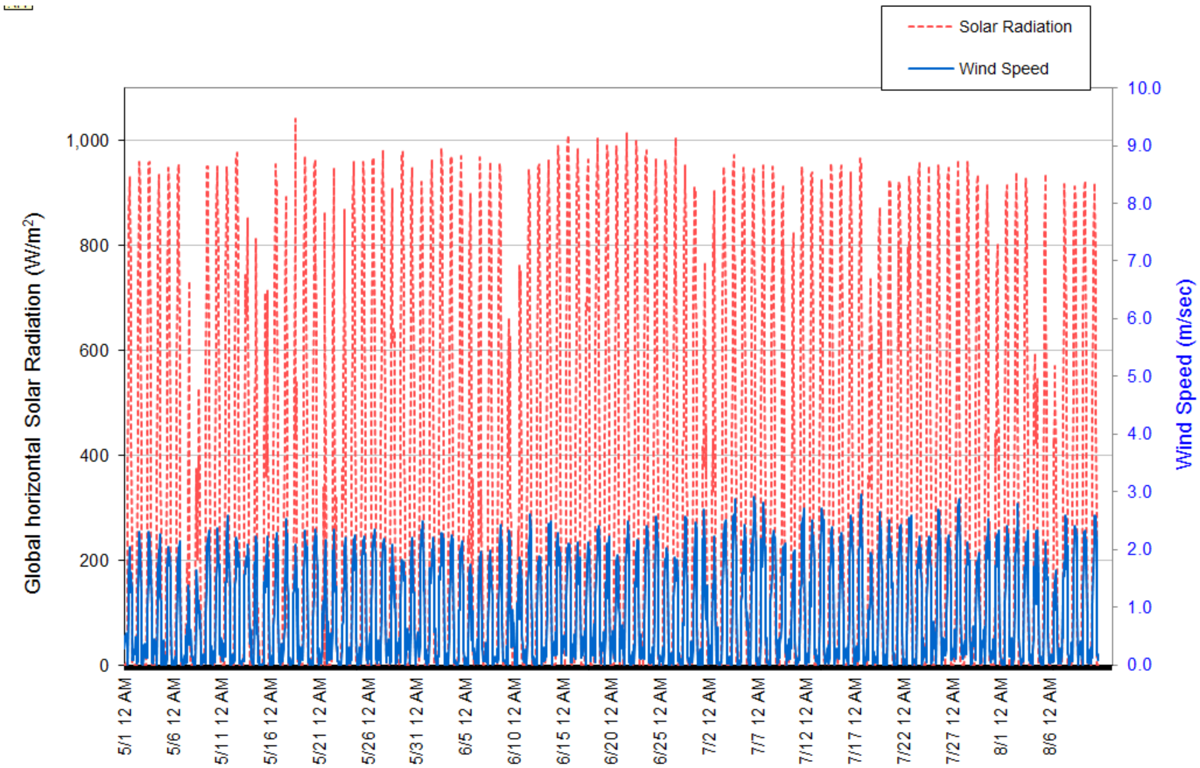

Figure 38. Cooling season hourly site insolation and wind speed

Attic Designs Moisture Data

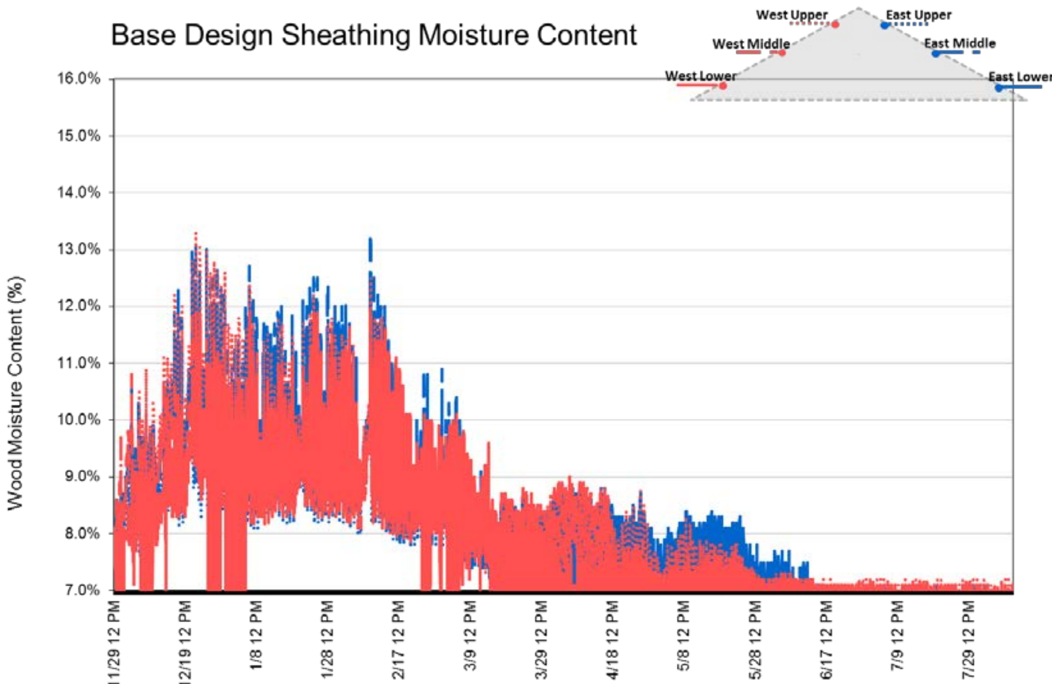

Figure 39. Base design sheathing MC

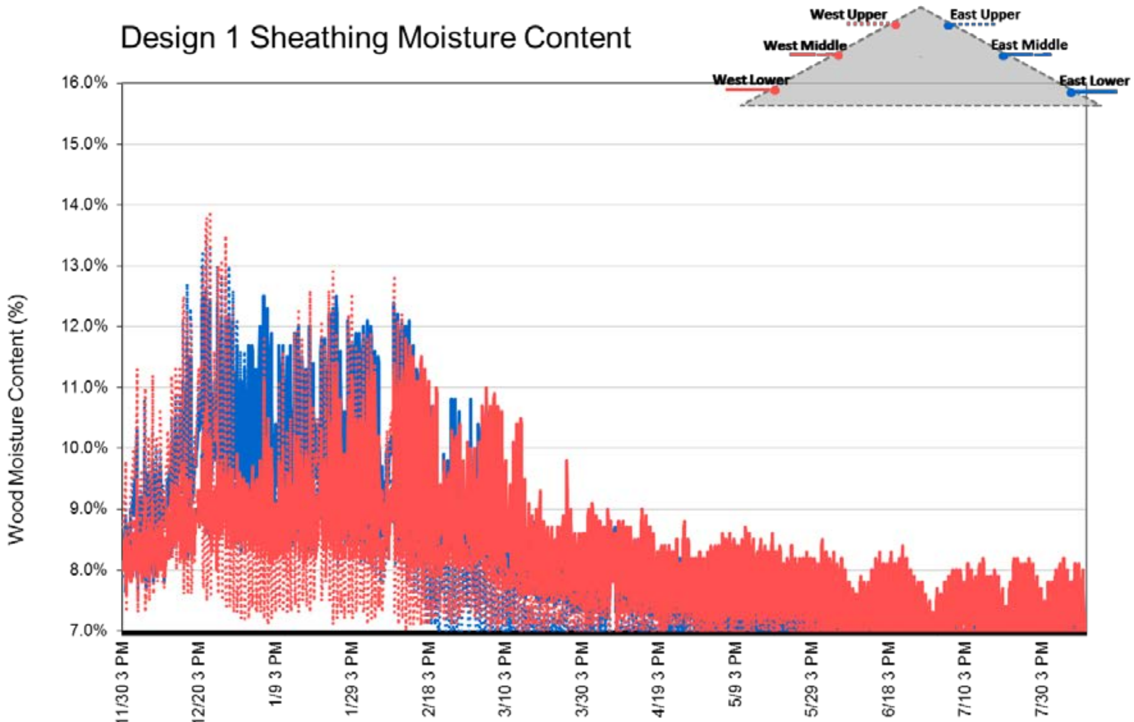

Figure 40. Design 1 sheathing MC

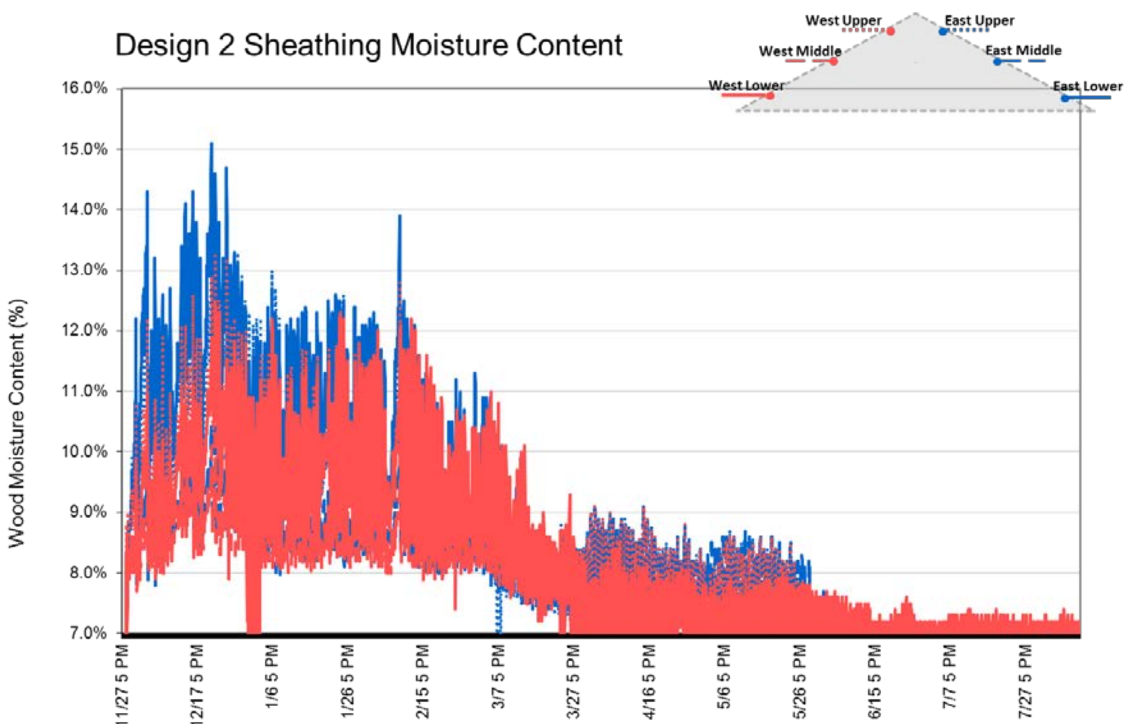

Figure 41. Design 2 sheathing MC

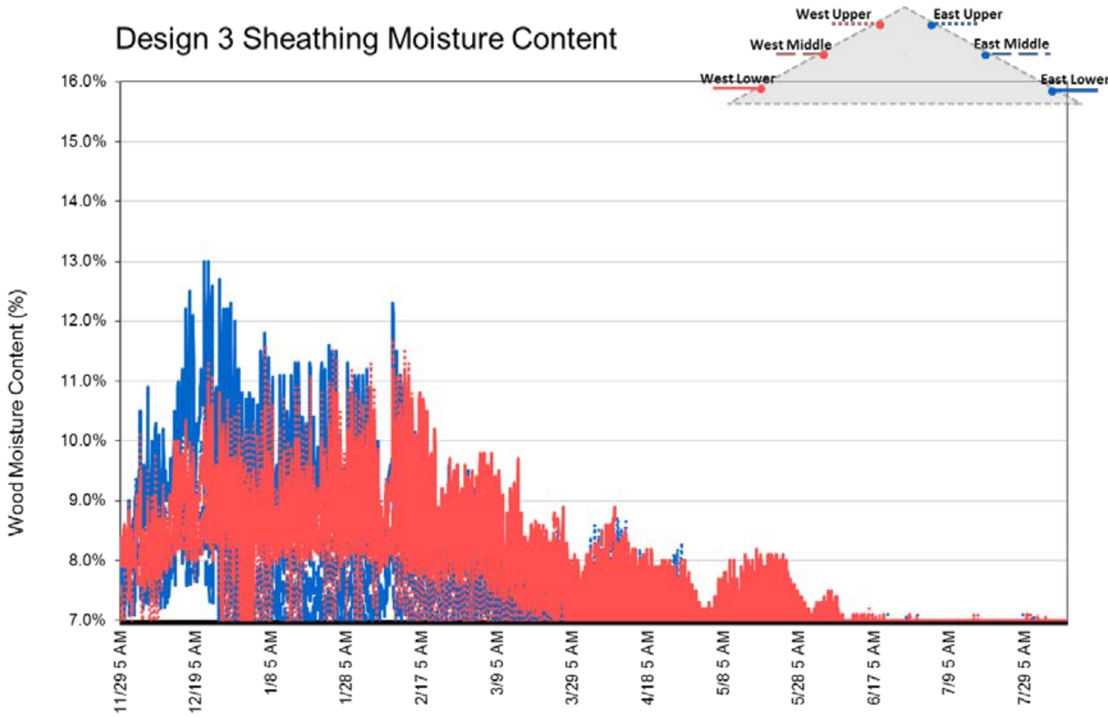

Figure 42. Design 3 sheathing MC

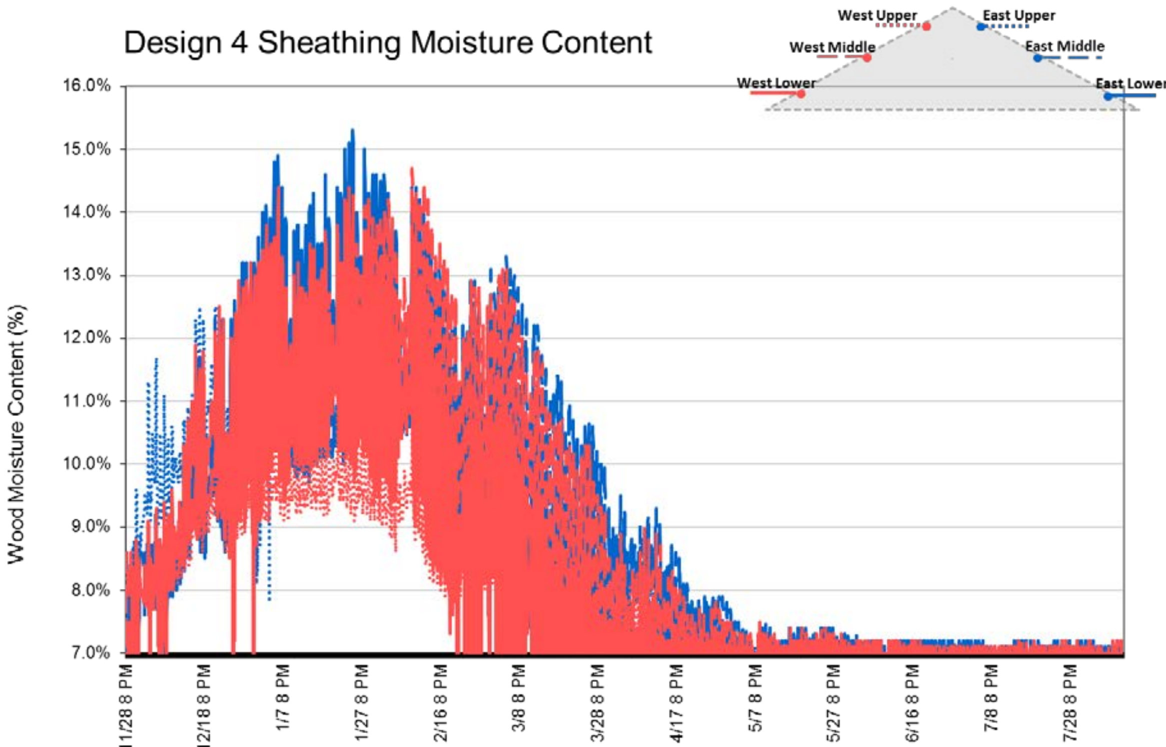

Figure 43. Design 4 sheathing MC

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