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

BUILDING TECHNOLOGIES PROGRAM

Moisture and Structural Analysis for High Performance Hybrid Wall Assemblies

A. Grin and J. Lstiburek
Building Science Corporation

September 2012

Building America
U.S. Department of Energy

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

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

Moisture and Structural Analysis for High Performance Hybrid Wall Assemblies

Prepared for:

Building America

Building Technologies Program

Office of Energy Efficiency and Renewable Energy

U.S. Department of Energy

Prepared by:

A. Grin and J. Lstiburek

Building Science Corporation

30 Forest Street

Somerville, MA 02143

NREL Technical Monitor: Cheryn Engebrecht

Prepared under Subcontract No. KNDJ-0-40337-00

September 2012

[This page left blank]

Contents

List of Figures

Unless otherwise noted, all figures were created by BSC.

List of Tables

Unless otherwise noted, all tables were created by BSC.

Definitions

ASTM	American Society for Testing and Materials
BEopt	Building Energy Optimization (software)
BSC	Building Science Corporation
OSB	Oriented strand board
RH	Relative humidity
WUFI	Wärme und Feuchte instationär (software)
XPS	Extruded Polystyrene

Executive Summary

This report describes the work conducted by the Building Science Corporation (BSC) Building America Research Team's Energy Efficient Housing Research Partnerships project for Task Order No. KNDJ-1-40337-02 under Task Ordering Agreement No. KNDJ-1-40337-00.

The project title is High Performance Hybrid Assemblies and has been given Subtask 2.1 under Task 2.0 – Evaluation of Advanced Efficiency Measures for New Construction. Based on past experience in the Building America program, BSC has found that combinations of materials and approaches—in other words, systems—usually provide optimum performance. No single manufacturer typically provides all of the components for an assembly, or has the specific understanding of all the individual components necessary for optimum performance. Integration is necessary and is the reason for the teaming approach that has been taken with this research project. The hybrid walls analyzed utilize a combination of exterior insulation, diagonal metal strapping, and spray polyurethane foam and leave room for cavity-fill insulation. These systems can provide effective thermal, air, moisture, and water barrier systems in one assembly and provide structure.

The optimal wall from the Building Energy Optimization (BEopt), thermal, hygrothermal, and structural analysis is Hybrid Wall 3 (described below). Hybrid Wall 3 has the lowest associated incremental cost, lowest associated air leakage condensation risk at less than 1% of the year in Minneapolis, the best structural performance—based on American Society for Testing and Materials (ASTM) E72— as well as the second best annual energy savings at 34% in Minneapolis and 29% in New Orleans. We believe that this is one of the most promising technologies for high performance residential wall assemblies in the mass built production house arena. This wall consists of the following:

- Exterior vertical wood strapping for cladding attachment
- 1.5-in.-foil-face polyisocyanurate board insulation
- Diagonal metal strapping
- 2 × 6 advanced framed wall
- 1.5-in.-closed-cell spray polyurethane foam in each stud bay
- 3-in.-cellulose insulation
- 0.5-in.-gypsum with latex paint finish

BSC expects that the proposed hybrid wall systems will be suitable for deployment in whole house prototype demonstrations as early as 2014. Further testing will be required during the 2012 Building America program. Further testing would determine the structural capacities of various assemblies and variations on the hybrid walls analyzed in this report.

1 Problem Statement

1.1 Introduction

Based on past experience in the Building America program, Building Science Corporation (BSC) has found that combinations of materials and approaches—in other words, systems—usually provide optimum performance. No single manufacturer typically provides all of the components for an assembly, or has the specific understanding of all the individual components necessary for optimum performance. For example, most manufacturers of cavity insulation do not manufacture housewrap and sheathing, or sealant and cladding. Integration is necessary and is the reason for the teaming approach that has been taken with this research project.

1.2 Background

One of the most promising technologies for high performance residential wall assemblies in the mass built production house arena will have the following configuration:

- Advanced wood frame (24 in. 2 × 6, single plates, stack framed, single headers) (Lstiburek and Grin 2010)
- Drained cladding and window openings (rain control)
- Insulating sheathing (rigid insulation)
- Spray-foam cavity insulation (SPF as a critical seal) (Straube and Smegal 2009)
- Cellulose or spray fibrous cavity insulation (for suppression of convection)
- Gypsum board interior.

This wall provides an approximate nominal thermal resistance of R-35. It does not need a housewrap and it's believed that it will not need structural sheathing, such as oriented strand board (OSB), when the composite action of the high-density spray polyurethane foam is used to transfer the shear capacity of the insulating sheathing, the interior gypsum lining, and a diagonal metal strap to the advanced frame wood wall. Although other researchers have examined the composite effect of high density spray polyurethane foam in light wood frame wall assemblies in conjunction with structural sheathing (Parasin and Nagy 1991), BSC has completed a preliminary investigation into the option of removing the structural sheathing with the proposed walls.

1.3 Relevance to Building America's Goals

Overall, the goal of the U.S. Department of Energy's (DOE) Building America program is to "reduce home energy use by 30%-50% (compared to 2009 energy codes for new homes and pre-retrofit energy use for existing homes)." To this end, research has been conducted to "develop market-ready energy solutions that improve efficiency of new and existing homes in each U.S. climate zone, while increasing comfort, safety, and durability."[1]

The proposed hybrid wall systems have the ability to reduce the heat loss through the wall portion of the enclosure by more than 50% from 2009 code practices. The specific composition of the hybrid walls can also provide hygric buffering, significantly reduced condensation potential, and improved airtightness. These factors will reduce embodied energy through improved durability and lifespan and will greatly reduce energy use for space conditioning. The

[1] http://www1.eere.energy.gov/buildings/building_america/program_goals.html

proposed hybrid walls can be recommended for each climate zone. When implemented in conjunction with other BSC recommended high R-value systems, these hybrid wall systems can significantly reduce the space conditioning energy consumption of residential homes.

1.4 Cost Effectiveness

Each proposed hybrid wall assembly will be assigned a cost relative to standard construction. These costs will be developed in partnership with BSC's prototype and community builders and verified with construction cost databases. It is important to note that although a system may cost more initially, the more expensive wall (as specified in this project) will be more energy efficient, and this energy cost savings must be taken into account over time. It cannot be ignored that a system that is slightly more expensive initially may have to be implemented to save a significant amount of energy over the entire life of the structure, which is often much longer than a standard mortgage. Research has shown that walls exceeding an R-value of 35 can financially pay back during the life of the initial mortgage through energy savings while reducing greenhouse gas emissions (Grin 2008). Because the building enclosure is designed to use less energy, the energy and greenhouse gas emissions savings extend for the life of the building and not just for the duration of the initial mortgage.

Improving the moisture tolerance and durability of an assembly will also figure into the equation of life cost. The longer the assembly lasts, the more energy it will use over its lifetime and the more the initial energy efficiency savings could have an impact. Proper detailing of the assembly is also important to ensure that over the life of the assembly, as components such as windows and doors require replacement, the assembly easily allows these replacements without risking damage.

The additional cost for this wall system should be fairly low due to cost trading of materials (the exterior wood sheathing is replaced with insulated sheathing, etc). BSC estimates that the new wall systems will be sold at a premium of approximately $1.75–$2.25/ft^2 of wall surface. This would be for a 1.5-in.-foil-faced polyisocyanurate (FFPIC) exterior insulated advanced framed 2 × 6 wall with spray foam and cellulose insulation within the cavity. Higher R-value systems may cost more.

1.5 Tradeoffs and Other Benefits

Each proposed hybrid wall will have the following characteristics compared to a code wall:

- Higher R-value
- Increased airtightness
- Improved occupant comfort
- Enhanced durability and enclosure lifespan.

Each of these components is interlinked. The increased R-value and airtightness improves energy efficiency and occupant comfort through reducing drafts and improving surface temperatures. The added durability of the system reduces maintenance requirements, increases the lifespan of the structure, and increases its tolerance to the possible operating conditions within the home.

Energy modeling has been completed in past Building America research using EnergyGauge to show that the use of exterior insulation improves energy efficiency. As part of this project, Building Energy Optimization (BEopt) software will be used to verify the energy efficiency of the hybrid wall systems.

1.6 Integration Opportunities

The information developed from this research will help enable BSC to implement hybrid wall systems on a set of prototype homes and eventually in communities. It is anticipated that the first prototype homes could be built as early as 2012. Adoption by community builders could occur by 2015. Based on the success of these implementations, hybrid wall systems may be common place with certain builders by 2018.

1.7 Location of experiment

The experimental location for this project will be the Building Science Consulting, Inc. laboratory. The address for the laboratory is as follows:

167 Lexington Court, Units 4/5/6
Waterloo, Ontario, Canada
N2J 4R9

Industrial partner laboratory space was used in the completion of the structural testing.

1.8 Contact Information

The following BSC Industry Team members will be involved in this project:

Table 1. Industry Team Member Contact Information

Company Name	Team Member	Email	Phone
Dow	Gary Parsons	GDParsons@dow.com	(989) 636 9464
BASF	Paul Campbell	paul.w.campbell@basf.com	(704) 587 8283
GreenFiber	Bohdan Boyko	Bohdan.Boyko@greenfiber.com	(704) 379 0640
Johns Manville	John Brooks Smith	John.Smith@jm.com	(303) 978 2686
Honeywell	Xuaco Pascual	Xuaco.Pascual@honeywell.com	(804) 739 3402
Icynene	Paul Duffy	pduffy@icynene.com	(905) 363 4040

2 Experiment

2.1 Research Questions

The following research questions were answered by this project and are discussed throughout the Results and Analysis section of this report.

- What are the likely hybrid assemblies that use currently available materials?
- What are the expected energy saving and other benefits of hybrid wall assemblies?
- What is the required thickness of high-density spray polyurethane foam to achieve structural performance?
- What are the likely solutions for cladding attachment over insulating sheathing in hybrid wall assemblies?

2.2 Technical Approach

This research project evaluated the thermal, hygrothermal, and structural properties of the proposed assemblies using computer modeling and laboratory testing. BEopt was used to calculate the associated energy savings of implementing the hybrid assemblies on an average home. Therm5 was used to determine the thermal properties of each assembly. Wärme und Feuchte instationär (WUFI) was used to measure the hygrothermal properties. Dow, as an industry partner, provided the equipment, laboratory space, laboratory technicians, and materials to complete the structural testing of the hybrid assemblies.

3 Results and Analysis

A number of hybrid wall systems were proposed and compared to a common standard wall. The hybrid walls do not need a housewrap and they do not need structural sheathing (such as OSB) when the composite action of the high-density spray polyurethane foam is used to transfer the shear capacity of the insulating sheathing and a diagonal metal strap to the advanced frame wood wall. This is believed to be one of the most promising technologies for high performance residential wall assemblies in the mass built production house arena. Table 2 summarizes the walls that were investigated. The main variables for this analysis were the use of two different exterior sheathing products and two different fibrous insulations to fill the gap remaining after the installation of 1.5 in. of closed-cell spray polyurethane foam (ccSPF). The thickness of the ccSPF was not varied. It was chosen as 1.5 in. because it was determined that this is likely the thinnest it can be reliably installed in a single pass to create both an air barrier and to transfer the structural loads from the wood frame to the insulating sheathing.

Table 2. Wall Assembly List

		Standard Wall	Exterior Insulated Wall	Hybrid Wall 1	Hybrid Wall 2	Hybrid Wall 3	Hybrid Wall 5	Hybrid Wall 5
Exterior Finish	Any	✓	✓	✓	✓	✓	✓	✓
Drainage	Housewrap	✓	✓					
	Exterior face of exterior insulation, joints sealed with liquid applied membrane			✓	✓	✓	✓	✓
Exterior Insulation	1.5-in. XPS		✓	✓	✓			
	1.5-in. FF PIC					✓	✓	
	3-in. FF PIC							✓
Structural	7/16-in. OSB sheathing	✓	✓					
	Diagonal metal strapping + ccSPF			✓	✓	✓	✓	✓
Framing	Advanced framed	✓	✓	✓	✓	✓	✓	✓
Cavity Insulation 1	1.5-in. ccSPF			✓	✓	✓	✓	✓
Cavity Insulation 2	Cellulose (damp spray)			✓		✓		✓
	Spray fiberglass				✓		✓	
	R-21 fiberglass batt	✓	✓					
Interior Finish	Painted gypsum	✓	✓	✓	✓	✓	✓	✓

3.1 Energy and Cost Analysis

The BEopt analysis consists of an average American home with standard layout and form, average mechanical equipment, ENERGY STAR® appliances, and average airtightness modeled in both New Orleans and Minneapolis. The only variable within the modeling was the replacement of the wall assemblies starting with the standard 2 × 6 advanced framed wall and working through to the 3-in.-exterior insulated hybrid wall. Table 3 contains the BEopt modeling parameters for the sample house. Figure 1 shows the massing of the modeled house.

Table 3. BEopt Modeling Parameters

Building Enclosure	Roof cladding	Medium-colored asphalt shingles
	Roof insulation	R-38 blown-in fiberglass, vented attic
	Walls	Varying
	Insulating sheathing	Varying
	Windows	Vinyl I double glazed with spectrally selective glass (U = 35, solar heat gain coefficient = 0.32)
	Infiltration	
Mechanical Systems	Heat	92.5% Annual Fuel Utilization Efficiency gas furnace in conditioned space
	Cooling	13 Seasonal Energy Efficiency Ratio air conditioner in conditioned space
	Domestic Hot Water	Gas tank water heater (EF = 0.62)
	Ducts	R-6 flex runouts in conditioned space
	Ventilation	Central fan integrated supply ventilation
Appliances, Lighting, MELS	Lighting	100% ENERGY STAR compact fluorescent lamp package
	Appliances	ENERGY STAR refrigerator, dishwasher, and clothes washer

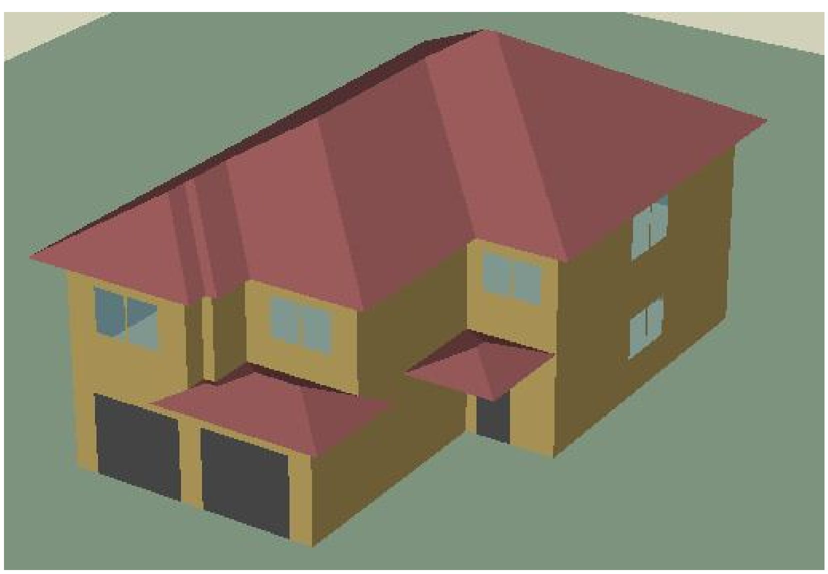


Figure 1. BEopt model home massing

It is likely that the airtightness will improve with the proper installation of spray foams and sealing of associated details, but in order to ensure the energy savings reported are a result of the improved thermal performance of the hybrid wall assembly, the airtightness of the house was not varied. Further energy savings may be found if the assembly's airtightness is improved with the installation of spray-foam cavity insulation.

The costs for each assembly were derived from RSMeans CostWorks 2011. The reported costs in Table 4 include both materials and labor for the installation of the materials. The standard wall for the purpose of comparison was assigned a value of zero dollars. The costs shown in Table 4 are incremental above the cost of the standard wall and are in dollars per square foot of wall assembly.

The initial step to 1-in.-extruded polystyrene (XPS) exterior insulating sheathing is shown as $1.66/ft^2. The incremental cost of $2.30/ft^2 for hybrid wall 1 includes 1.5-in.-ccSPF insulation, cellulose insulation, and 1.5-in.-XPS exterior insulating sheathing. hybrid wall 2 at $2.39/ft^2 uses 1.5-in.-ccSPF insulation, blown fiberglass insulation, and 1.5-in.-XPS exterior insulating sheathing. hybrid walls 3 and 4 are the same as 1 and 2 but use 1.5-in.-FFPIC in place of the 1.5-in.-XPS insulating sheathing. The significant increase in cost for hybrid wall 5 at $5.17/ft^2 is related to the additional insulating sheathing, but also includes longer fasteners, window box-outs, and vertical wood strapping for cladding attachment. The hybrid wall with the least incremental cost is hybrid wall 3 at $2.20/ft^2.

Table 4. Assembly Incremental Costs

	Incremental Cost ($/ft^2)
Standard Wall	$0.00
Exterior Insulated Wall	$1.66
Hybrid Wall 1 (1.5-in. XPS/ccSPF/Cellulose	$2.30
Hybrid Wall 2 (1.5-in. XPS/ccSPF/Fiberglass	$2.39
Hybrid Wall 3 (1.5-in. FFPIC/ccSPF/Cellulose	$2.20
Hybrid Wall 4 (1.5-in. FFPIC/ccSPF/Fiberglass	$2.29
Hybrid Wall 5 (3-in. FFPIC/ccSPF/Cellulose	$5.17

The BEopt modeling showed a 29.1%-35.4% annual source energy savings for the hybrid walls. Table 5 lists the energy savings for each hybrid wall in both New Orleans and Minneapolis. A significant portion of the energy savings can be associated with the thicker 2 × 6 framing (Standard Wall) and 2 × 6 framing with exterior insulation (exterior insulated wall). The increases in insulating value for the assembly effectively save more incremental energy in a climate where more energy is associated with space conditioning, such as Minneapolis. This is primarily due to the increased temperature differential over the enclosure. In a heating dominated climate the winter outdoor temperature is further from the interior set point than in most cooling dominated climates resulting in more energy use for space conditioning. The increase to 3-in.- exterior insulation showed little energy improvement as the thermal bridges created by the studs have been effectively eliminated by the first 1.5 in. of exterior insulation. Again, the energy savings for the hybrid walls does not account for the possibility of significantly improved airtightness.

Table 5. Source Energy Savings

	Adjusted Source Energy Savings (%/yr)	
	New Orleans	**Minneapolis**
Standard Wall	26.8	29.4
Exterior Insulated Wall	28.8	32.9
Hybrid Wall 1 (1.5-in. XPS/ccSPF/Cellulose	29.1	33.3
Hybrid Wall 2 (1.5-in. XPS/ccSPF/Fiberglass	29.1	33.4
Hybrid Wall 3 (1.5-in. FFPIC/ccSPF/Cellulose	29.4	33.9
Hybrid Wall 4 (1.5-in. FFPIC/ccSPF/Fiberglass	29.5	33.9
Hybrid Wall 5 (3-in. FFPIC/ccSPF/Cellulose	30.2	35.4

The annualized energy related costs associated with the hybrid walls in Minneapolis are shown in Figure 2. These costs account for mortgage costs, utility costs, as well as replacement or repair costs over the life of the mortgage (which in this case is 30 years) and residual value. The wall with the lowest annualized energy related costs would be optimal using this analysis. Figure 2 shows that the lowest cost wall is the standard wall while the highest cost wall is hybrid wall 5. hybrid walls 1 through 4 exhibit approximately the same energy savings and the same annualized energy costs. Further analysis is required to determine an optimal hybrid wall.

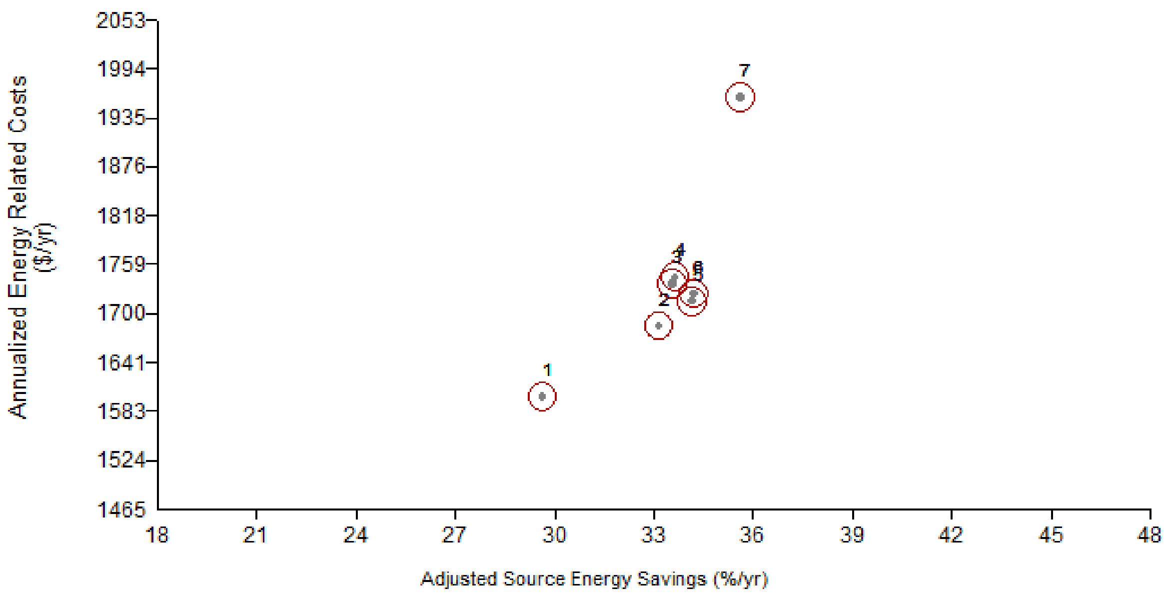


Figure 2. Annualized energy-related costs

Figure 3 and Figure 4 show the source energy use and the annual utility bills as modeled for Minneapolis. From these graphs it can again be seen that there is little difference between hybrid walls 1 through 4 in terms of energy use or utility cost. These figures both reiterate the approximate 30% energy savings over the Building America Benchmark.

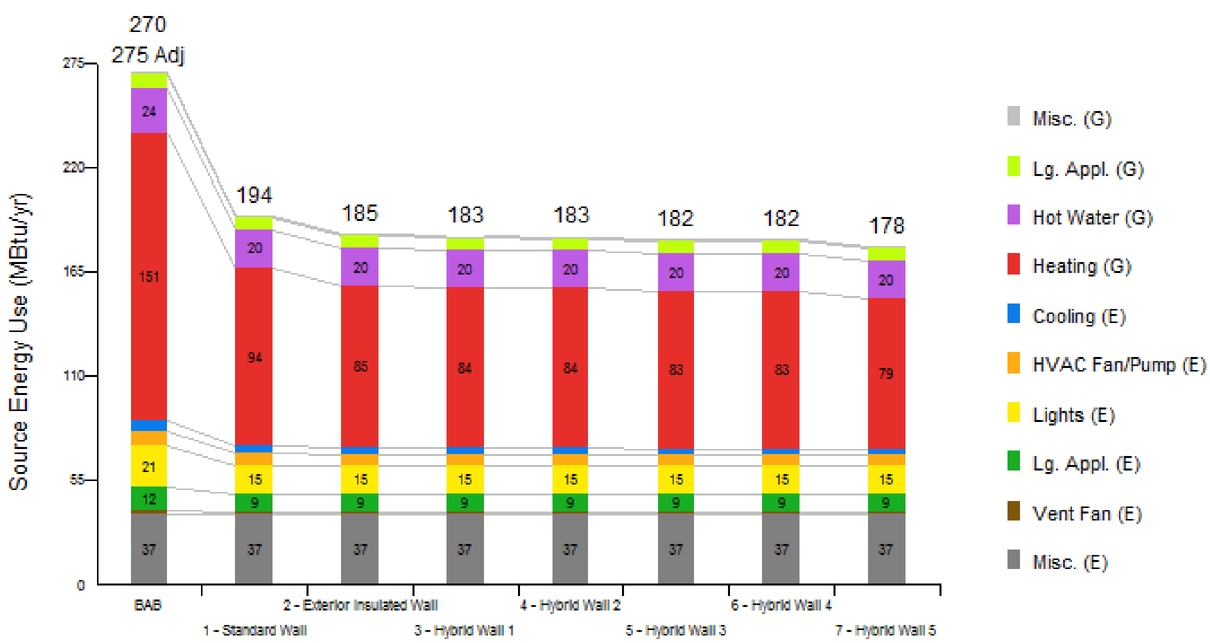


Figure 3. Source energy use

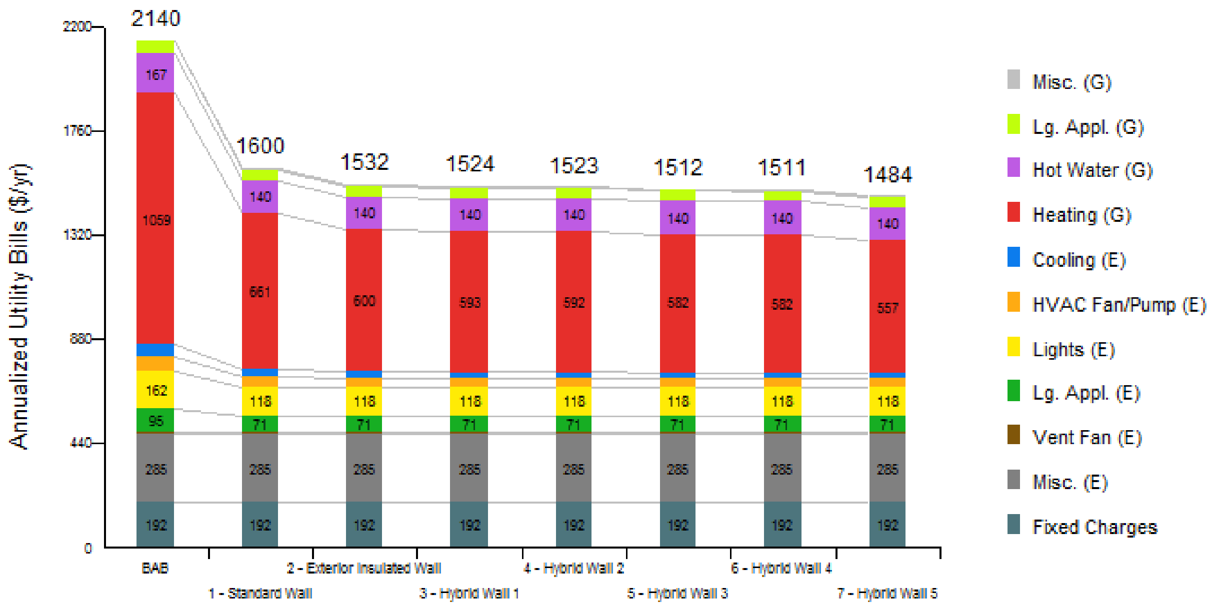


Figure 4. Annual utility costs

The full set of BEopt results for New Orleans and Minneapolis can be found in Appendix A and Appendix B, respectively.

3.2 Thermal Analysis

Therm5 was used to calculate the clear wall R-values of each hybrid assembly. Clear wall refers to the R-value of an assembly containing only insulation and minimum necessary framing materials at a clear section with no windows, corners, columns, or architectural details, and no interfaces with roofs, foundations, or other walls. Advanced framing with 2 × 6 studs at 24 in. on center, a single top plate and bottom plate, two stud corners, and simplified framing around openings has been shown to result in assemblies with a 16% framing factor. An 8 ft. section of wall with a 16% framing factor was used to simulate advanced framing. The Therm5 modeling of a clear wall R-value simply represents a point of comparison using each assembly's relative R-value. The conductivities listed in Table 6 were used in conjunction with Therm.

Comparing installed R-values can be misleading as it does not account for thermal bridging or where the insulation is installed. The clear system R-value provides a more accurate value for comparison. Table 7 provides a comparison between the installed R-value and the clear system modeled R-value. As a point of comparison, Hybrid Wall 1 has an apparent installed R-value that exceeds the Standard Wall by R-8.6, but performs R-9.2 better as a clear system primarily because of the reduction in thermal bridging.

Table 6. Material Conductivities

Enclosure Component	Thermal Conductivity k (W/mK)	R-Value per Inch (h·°F·ft^2/Btu
Drywall	0.160	0.9
SPF Framing	0.100	1.4
OSB	0.110	1.3
XPS	0.029	5.0
FFPIC	0.022	6.5
2.0 PCF CC SPF	0.024	6.0
Fiberglass Batt R-21	0.038	3.8
Damp Spray Cellulose	0.037	3.9
Spray Fiberglass	0.034	4.2

Table 7. R-Value Comparison

	Standard Wall	Exterior Insulated Wall	Hybrid Wall 1	Hybrid Wall 2	Hybrid Wall 3	Hybrid Wall 4	Hybrid Wall 5
Installed R-Value	21.0	26.0	29.6	30.8	33.6	34.8	42.6
Clear System Modeled U-Value	0.320	0.229	0.211	0.206	0.193	0.189	0.145
Clear System Modeled R-Value	17.7	2.48	2.69	27.6	29.4	30.1	39.3

3.3 Hygrothermal Analysis

Hygrothermal modeling predicts the moisture related risk associated with each hybrid wall. During hygrothermal modeling, a key value monitored will be the dew point potential of various surfaces of the assembly based on an assumed indoor and outdoor temperature and relative humidity. These measurements will determine the susceptibility of the assembly to moisture damage in each environment.

WUFI 4 was used and it is one of the most advanced commercially available hygrothermal moisture programs in use today. Its accuracy has been verified (by the Fraunhofer-Institut für Bauphysik in Holzkirchen, Germany – www.wufi.de) against numerous full-scale field studies of enclosure performance (roofs, walls, foundations, parking garage decks, etc.) over a number of years. It is one of the few models in the public domain that can properly account for adsorption of water vapor, absorption/redistribution of liquid water, and night sky radiation. Given the appropriate inputs, WUFI calculates heat and moisture flow every hour under the influence of sun, rain, temperature, and humidity. The material properties from WUFI's Generic North American Materials database were utilized for the simulation of the proposed hybrid walls. The testing will not include extreme values usually associated with major disasters, such as earthquakes or flooding.

The outdoor climatic data files provided with WUFI for New Orleans as well as Minneapolis were left unaltered. The indoor conditions varied on a sinusoidal curve with a period of one year. The temperature ranged from 68°F (20°C) in the winter to 75°F (24°C) in the summer. The relative humidity (RH) ranged from 30% in the winter to 60% in the summer. For the high humidity case in Minneapolis the RH ranged from 40% in the winter to 70% in the summer. The 40% RH wintertime condition is generally considered beyond the upper level of recommended wintertime RH for cold climates and creates a high-stress environment for the wall assembly.

In above grade walls, winter time outward air leakage and vapor condensation are concerns in cold climates. Condensation happens on surfaces with temperatures below the dew point of the air in contact with them. To determine if the assembly has the possibility for air leakage condensation, the dew point of the interior air, as well as the surface temperatures within the wall assembly, must be calculated. Since WUFI outputs data in an hourly format, it is possible to calculate the number of hours there is condensation potential on surfaces within the wall. The number of hours the wall is at risk for condensation then becomes the metric to compare the expected durability of the assembly in regard to air leakage condensation. If the interior RH is high, this risk is higher as the dew point of the interior air is higher. Based on this information, it can be shown which walls could be less durable if the air leakage condensation is able to cause moisture related deterioration.

Figure 5 through Figure 11 show the dew point of the interior air graphed in conjunction with the surface temperature of the surface within the wall where condensation could occur. For Standard Wall 1 (Figure 5), the possible condensation plane is the inside face of the OSB. Each hour the temperature of the inside face of the OSB (orange line) is below the dew point of the interior air (sinusoidal blue line), a bar is added in blue. The annual total of the bars in blue indicates the total annual risk of condensation. A summary of the hours of condensation for each modeled wall can be found in Table 8. For the exterior insulated wall, the condensation surface monitored was the inside face of the exterior insulation. In the case of the hybrid walls, the inside face of the ccSPF was monitored.

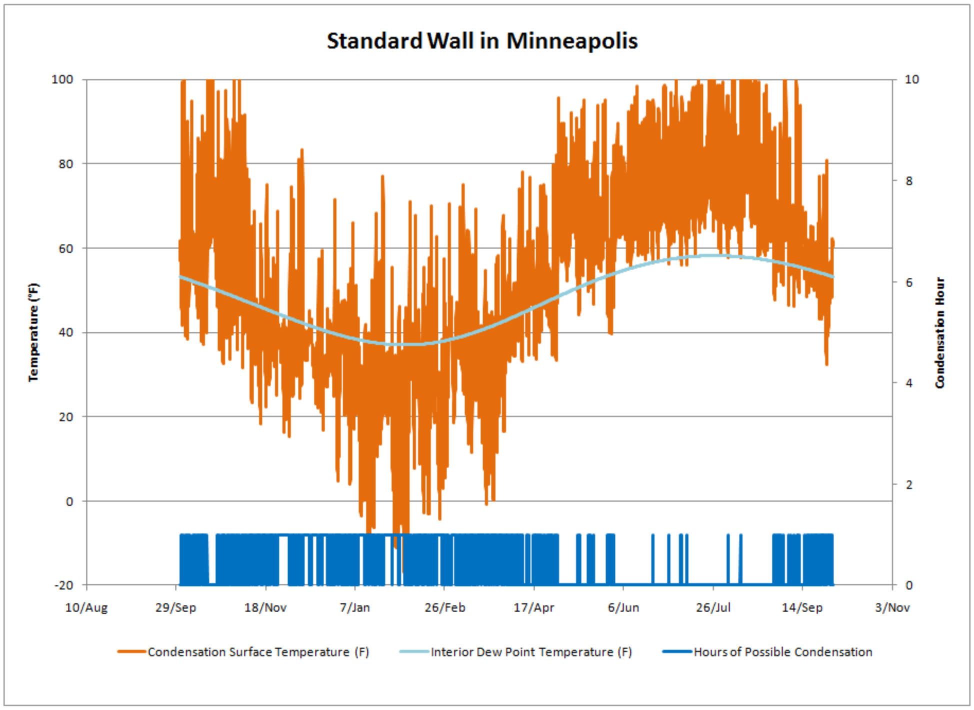


Figure 5. Standard wall in Minneapolis

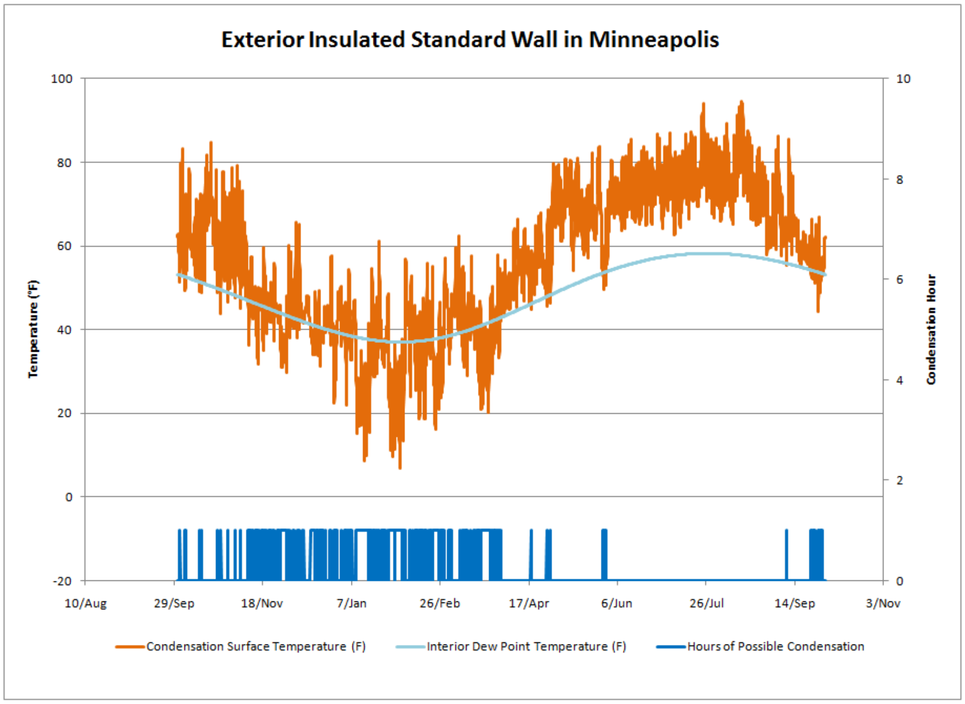


Figure 6 - Exterior insulated standard wall in Minneapolis

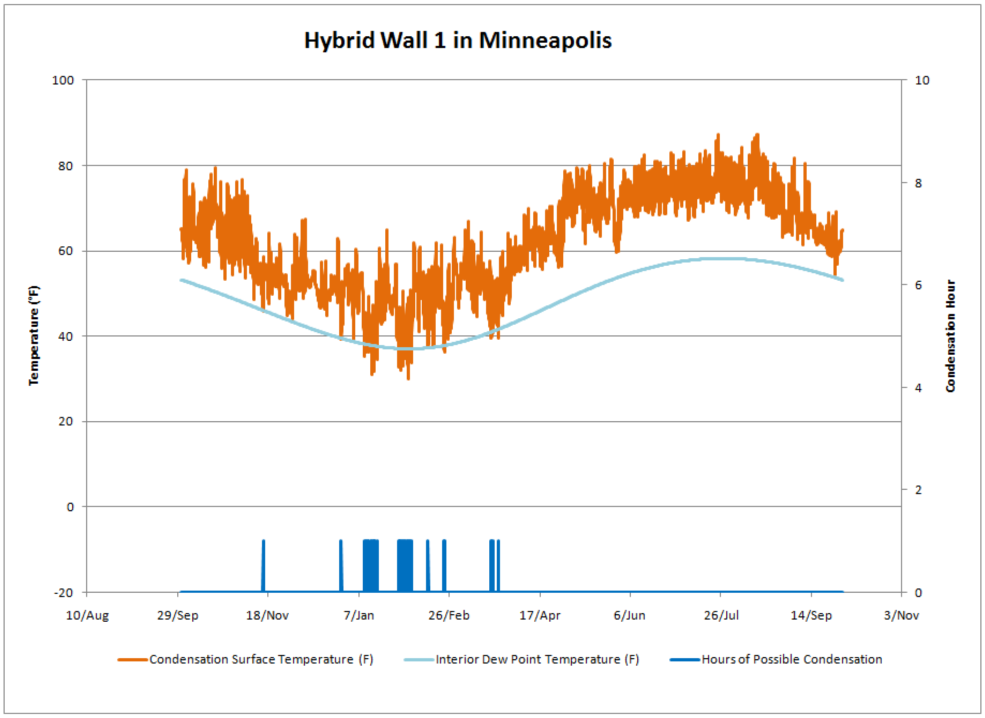


Figure 7. Hybrid wall 1 in Minneapolis

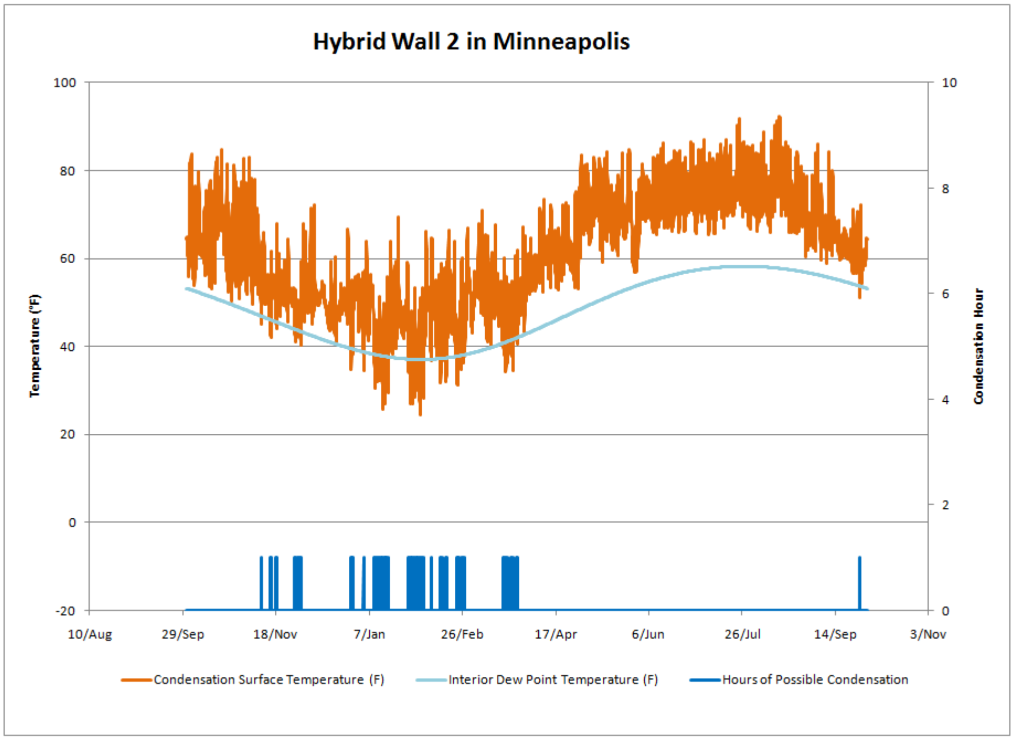


Figure 8. Hybrid wall 2 in Minneapolis

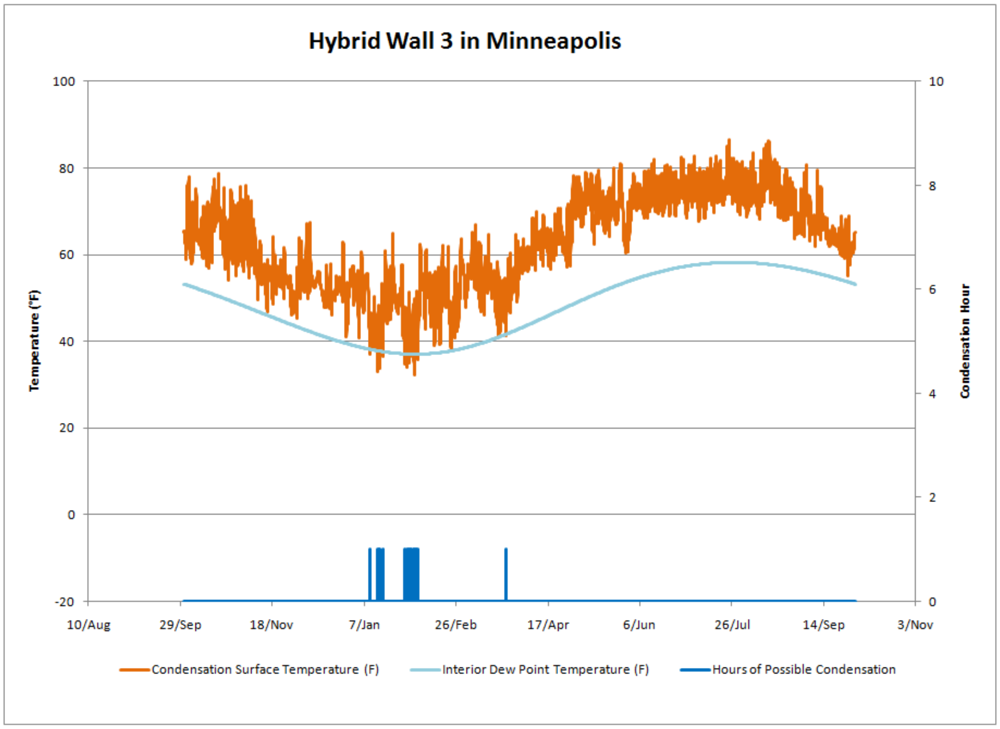


Figure 9. Hybrid wall 3 in Minneapolis

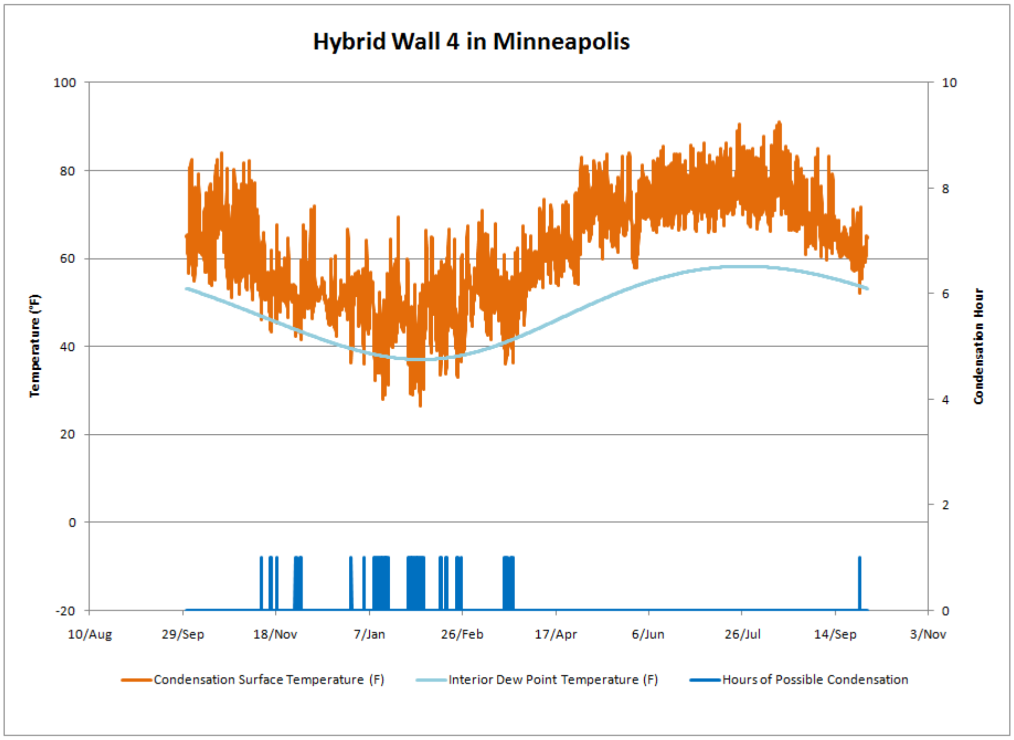


Figure 10. Hybrid wall 4 in Minneapolis

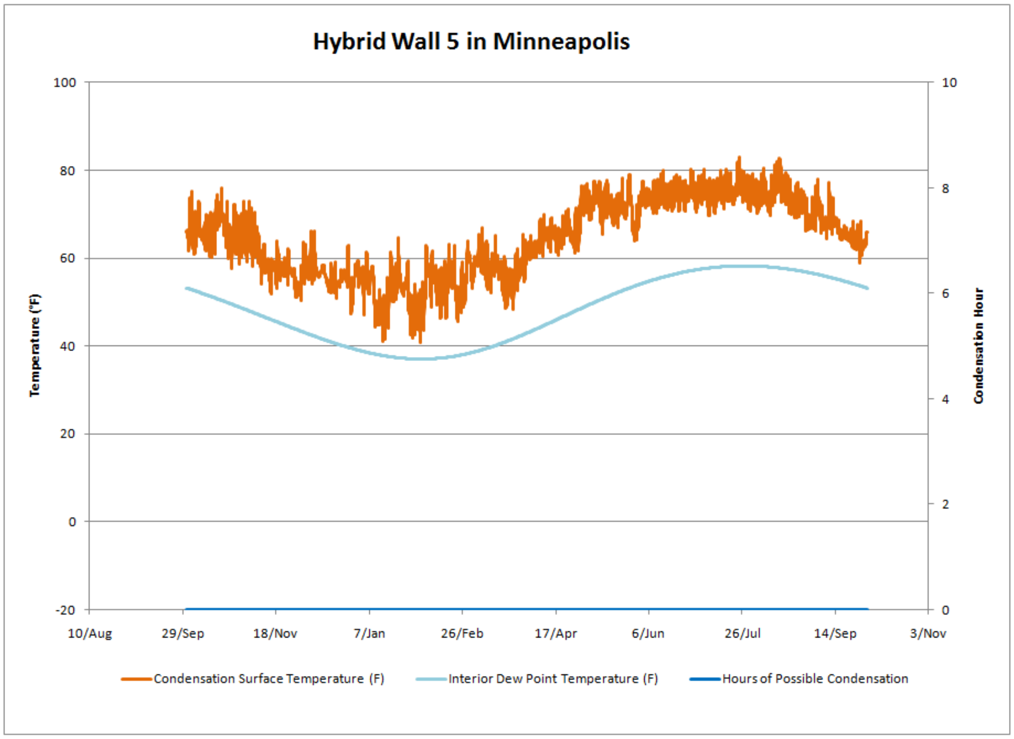


Figure 11. Hybrid wall 5 in Minneapolis

As the amount of insulation present outside of the possible condensation plane increases, the associated risk decreases. This is most significant when comparing any one of the hybrid walls to the standard case.

Table 8 shows a summary of the reductions in condensation potential. In the initial Minneapolis modeling, hybrid wall 1 showed a 95% decrease in risk compared to the standard wall. hybrid wall 3 showed a 98% reduction and hybrid wall 5 showed a 100% decrease and no condensation potential risk. In the hybrid cases, the condensation plane is a material that is not affected by moisture whereas the OSB wall will deteriorate eventually if the wetting is significant and is not balanced with drying. Since drying is minimal during periods of condensation, the severity of condensation increases the further below the dew point line the sheathing temperature falls and the length of time the sheathing temperature is below the interior air dew point line. For condensation to occur on this surface and if the enclosure is air sealed very well, there must also be air leakage to the surface from the interior. However, there is a risk that no moisture will be deposited.

Table 8. Condensation Potential Reduction

	Hours of Possible Condensation	Reduction in Condensation Potential
Standard Wall	3878	0%
Exterior Insulated Wall	2049	47%
Hybrid Wall 1	176	95%
Hybrid Wall 2	514	87%
Hybrid Wall 3	85	98%
Hybrid Wall 4	370	90%
Hybrid Wall 5	0	100%

Figure 12 shows both the standard Minneapolis modeling condensation risk as well as a high humidity case where the wintertime interior RH only fell to 40%. The condensation potential for each assembly increased. The difference in air leakage condensation risk potential is shown in Figure 12 hybrid wall 3 and 5 have the lowest condensation risk potentials.

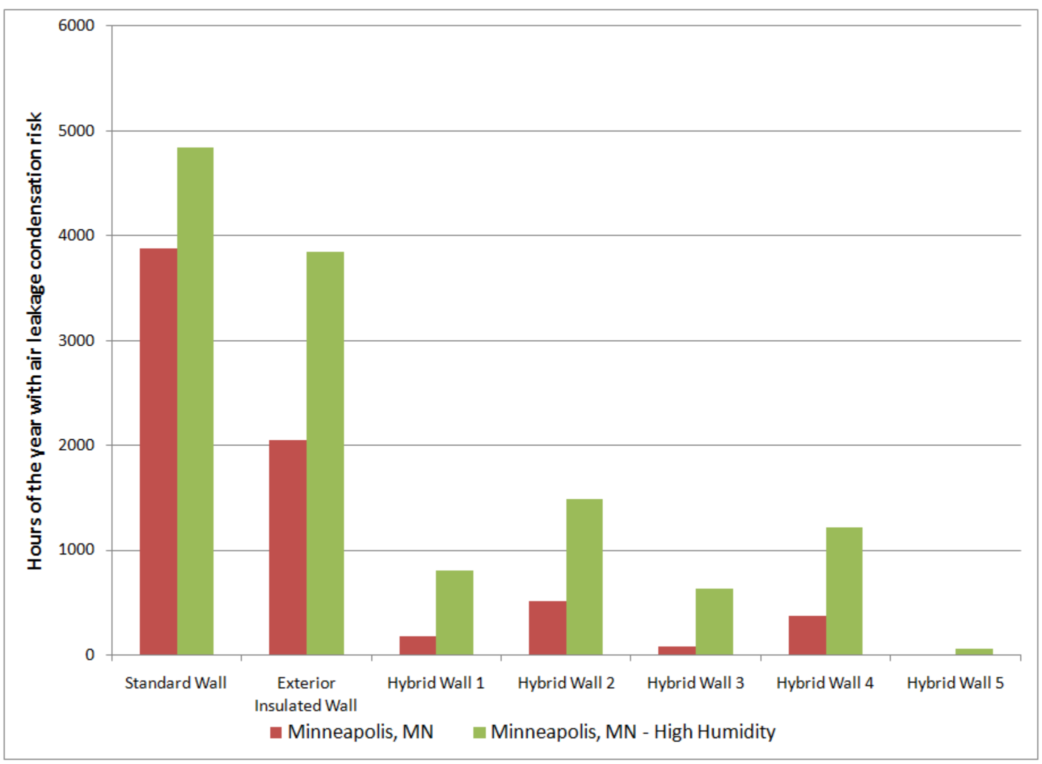


Figure 12. Minneapolis condensation risk

The hygrothermal analysis for New Orleans did not show any significant air leakage condensation risks. A full set of hygrothermal graphs for New Orleans, Minneapolis, and Minneapolis with high humidity can be found in Appendices C, D, and E, respectively.

3.4 Structural Analysis

A number of hybrid wall systems were proposed and compared to a common standard wall. The hybrid walls do not need a housewrap and likely do not need structural sheathing (such as OSB) when the composite action of the high-density spray polyurethane foam is used to transfer the shear capacity of the insulating sheathing and a diagonal metal strap to the advanced frame wood wall. American Society for Testing and Materials (ASTM) E72 (Standard Test Methods of Conducting Strength Tests of Panels for Building Construction) structural testing was completed to compare the proposed hybrid walls to a known code accepted and frequently built wall.

To help determine the level of interaction provided by the ccSPF and insulating sheathing, three variations of the hybrid wall were tested. The main variables for this analysis were the use of two different exterior insulating sheathing products. Two different fibrous insulations used to fill the gap remaining after the installation of 1.5 in. of ccSPF are discussed in the hygrothermal section. However, the fibrous insulation was not included in the structural testing because it does not add any structural strength. The thickness of the ccSPF was not varied. It was chosen as 1.5 in. because it was determined that this is likely the thinnest it can be reliably installed in a single pass to create an air barrier and transfer the structural loads from the wood frame to the insulating sheathing. Dow, as an industry partner, provided the equipment, laboratory space, laboratory technicians, and materials to complete the structural testing of the hybrid assemblies.

3.4.1 Specimen Construction

Three samples of each test wall were built in order to increase the certainty of the findings. The following are brief descriptions of each test wall. Full details can be found in Appendix F.

- Base case OSB wall
- Standard 2 × 6 advanced framing
- 7/16-in.-OSB sheathing
- Structural test wall 1 – three (3) samples
- Standard 2 × 6 advanced framing
- Diagonal metal strapping
- 1.5-in.-XPS insulating sheathing
- Stud bays remain empty for this test
- Structural test wall 2 – three (3) samples
- Same as wall 0 with 1.5-in.-ccSPF in all bays
- Structural test wall 3 – three (3) samples
- Same as wall 0 but replace XPS with 1.5-in.-foil-faced polyisocyanurate as exterior insulation and 1.5-in.-ccSPF in all bays.

To ensure each wall assembly was constructed as identically as possible, diagrams and instructions were developed and delivered to the Dow technicians. Specifics, such as fastener types, fastener diameter, and fastener locations were provided. A step-by-step construction method was developed and discussed with the Dow technicians. Both the construction of the walls and the attachment to the testing apparatus were detailed. Figure 13 shows the screw placement locations for the bottom plate. In order to ensure this testing closely relates to real world construction, a wood spacer was attached to the steel testing apparatus. The bottom plate was then affixed to the wood spacer. This ensured the bottom plate would be attached to wood as in the field in lieu of being bolted directly to steel. Figure 14 shows the locations and spacing of the advanced framed wall. Figure 15 shows the location for the flat diagonal metal strapping. Figure 16 shows the seam locations and application of the exterior insulation. Figure 17 shows a typical vertical wood strapping that is installed over most insulating sheathings (greater than 1 in. thick) for cladding attachment. Drywall and cladding were not installed for testing.

Upon completion of the testing, cores were taken through the test specimens to verify that the average ccSPF thickness was 1.5 in. The ccSPF thicknesses varied from 1.5 in. to nearly 2 in., but the areas that were thick were quite localized.

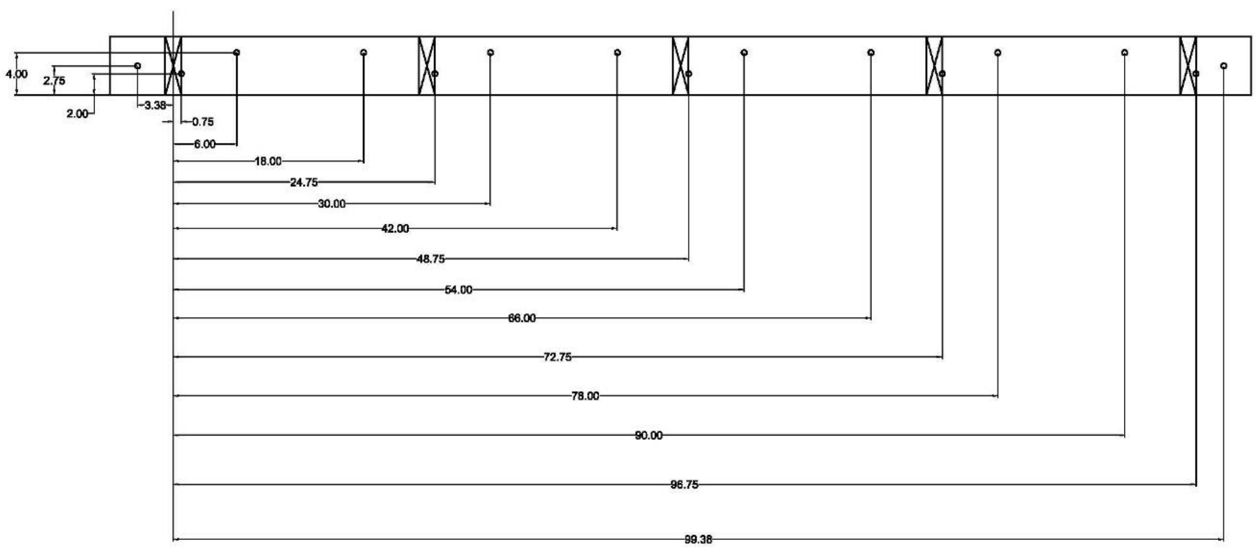


Figure 13. Bottom plate screw pattern

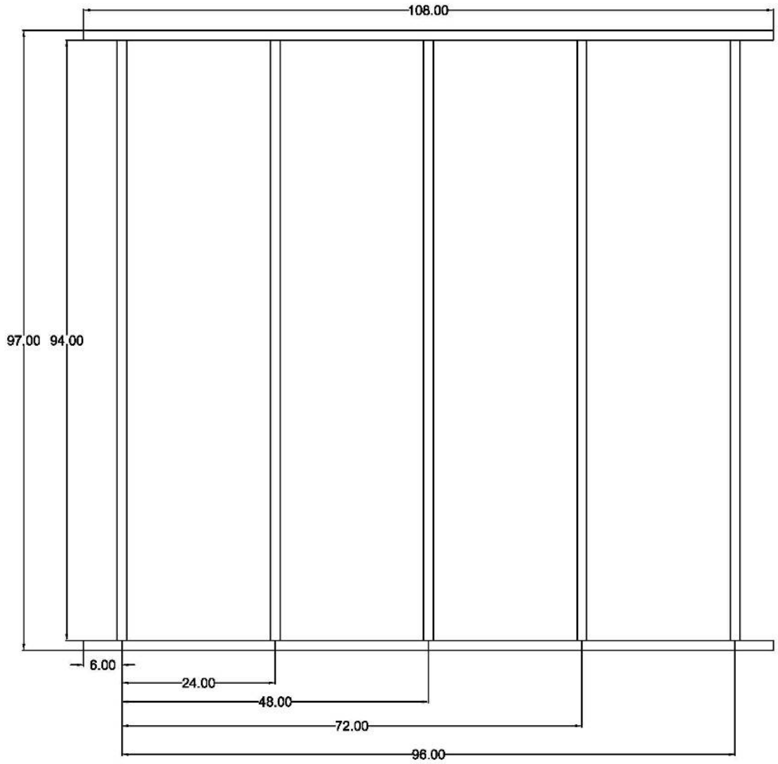


Figure 14. Advanced framed wall

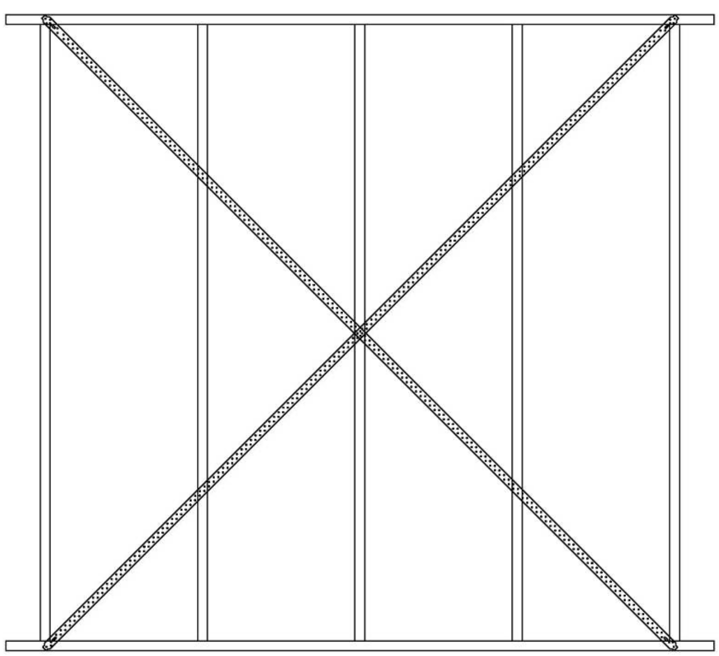


Figure 15. Diagonal strapping installed

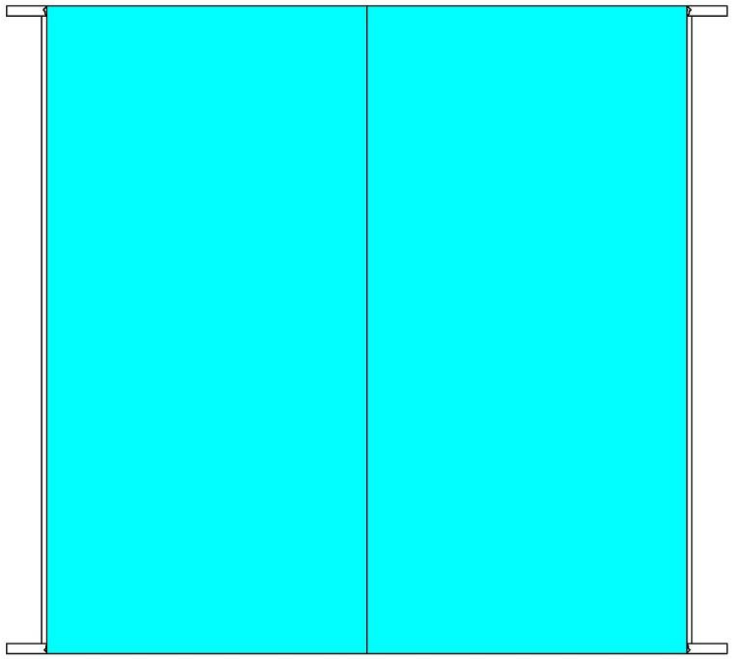


Figure 16. Exterior insulation installed

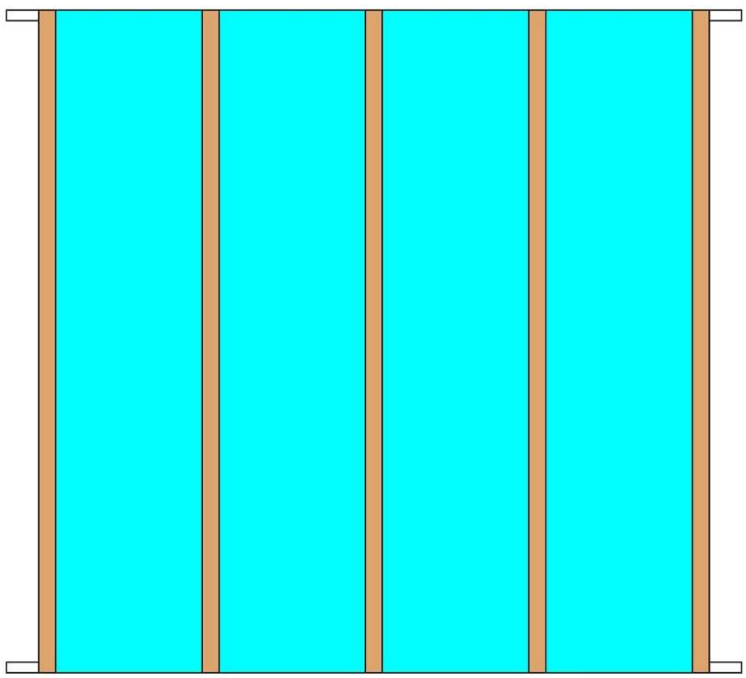


Figure 17. Vertical wood strapping installed

3.4.2 Testing Procedure

ASTM E72 (Standard Test Methods of Conducting Strength Tests of Panels for Building Construction) structural testing was completed to compare the proposed hybrid walls to a known code accepted and frequently built wall.

Walls were loaded by a hydraulic ram pushing on the top corner of the wall parallel with the top plate. The load was transferred to the full length of the top plate through an aluminum beam attached to the top plate. The bottom plate was affixed to the bottom of the structure via a pair of 6 × 6 wood spacers bolted to the assembly. The spacers allowed an 8 ft. wall specimen to be tested in an apparatus setup for 10 ft tall specimens and allowed the bottom plate to be attached with screws to a wood surface as it would be attached in the field. The horizontal displacement of the bottom plate and the top plate were measured. Bottom plate lift was also measured but was not a factor in this testing. Subtracting the bottom plate displacement from the top plate displacement calculates the horizontal displacement of the top plate in relation to the bottom plate. These values, as well as the corresponding hydraulic ram loads, were digitally recorded.

The ASTM E72 test measures deflection as a result of a set of loadings. The loading was applied at a rate of 395 lbs. per minute. Data (force and deflections) were recorded at 10 readings per second. The loading process completed during this testing was as follows:

- Ram locates wall and zeros its displacement measurement
- Loading to 790 lb
- Release loading
- Loading to 1,570 lb
- Release loading
- Loading to 2,360 lb
- Release loading
- Load to failure (4-in. deflection or 30,000 lb).

3.4.3 Structural Results Analysis

3.4.3.1 Base Case 2 × 6 With OSB Wall

The base case 2 × 6 wall was framed identically to all of the other test walls, but was sheathed with OSB, as a standard wall would be. Figure 18 contains the load versus deflection graph for the base case wall. Note that the 1,570 lb and 2,360 lb loadings produced displacement that did not return to zero upon returning to the unloaded state. The primary failure mode for this wall was the loosening of the screws through the OSB sheathing followed by the screws tearing out of the OSB. The sheets of OSB were intact except for the screw locations. Figure 19 shows the OSB failure at the fasteners. This failure mode was typical of all three walls tested.

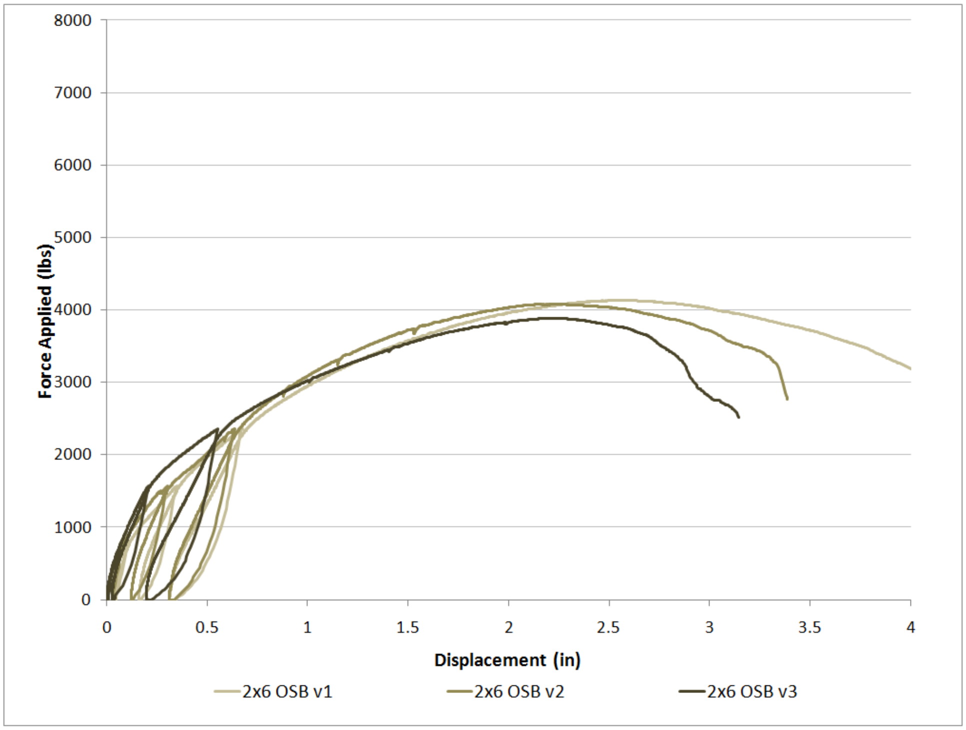


Figure 18. Standard OSB wall results

Figure 19. OSB failure at fastener

Appendix G contains a set of additional photos taken during the structural testing.

3.4.3.2 Structural Test Wall 1

The purpose of testing structural test wall 1 was to obtain a basic understanding of the strength of a diagonally strapped, 1.5-in.-XPS sheathed wall. This shows the baseline for the hybrid wall testing and allows calculations of the added strength provided by the ccSPF insulation and its interaction effect with the exterior sheathing. A photo before testing began is shown in Figure 20. Results are shown in Figure 21. The wall was unable to obtain the 2,360 lb. loading without failing by exceeding a 4 in. displacement. The diagonal metal strap took much of the loading and pulled out its nails (Figure 22) while the sheathing took minimal load with the nails easily pulling through the XPS (Figure 23). The XPS sheets twisted in plane (Figure 24) and the screws tore out the edges of the sheets. This failure mode was typical of all three walls tested.

Figure 20. Structural test wall 1 installed in apparatus

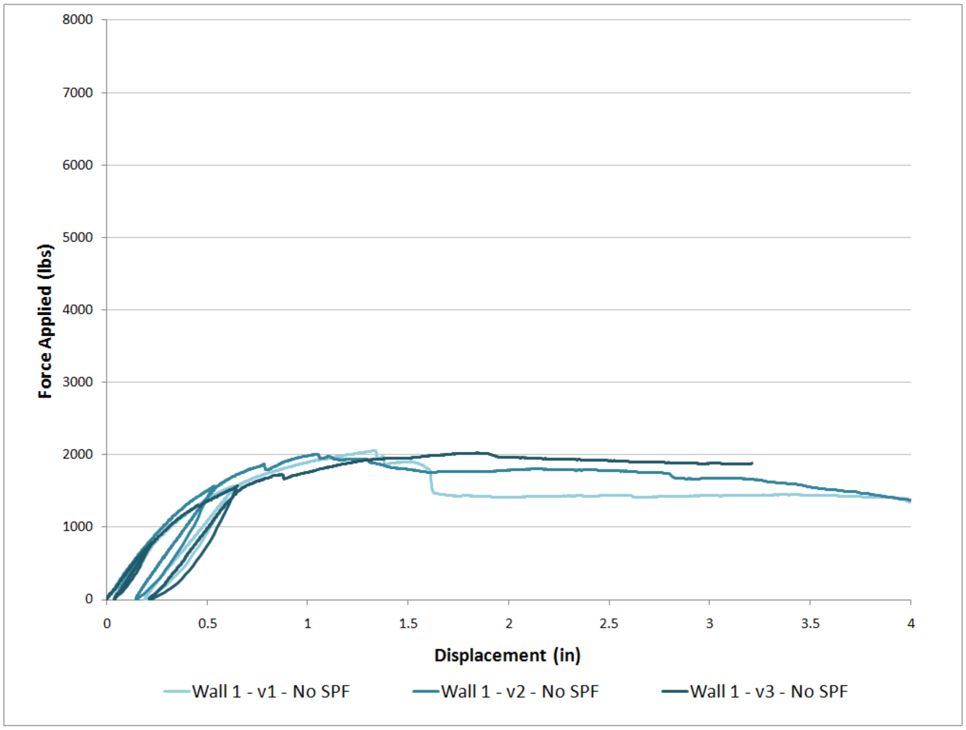


Figure 21. Structural test wall 1 results

Figure 22. Metal strap nail pullout

Figure 23. Nail pulling through XPS

Figure 24. XPS sheets twisted in-plane

Appendix G contains a set of additional photos taken during the structural testing.

3.4.3.3 Structural Test Wall 2

Structural test wall 2 contained approximately 1.5 in. of ccSPF in all stud bays and depicts Hybrid Wall 1 and Hybrid Wall 2. A photo of the wall before testing is shown in Figure 25.

Results are shown in Figure 26. The installation of ccSPF tripled the ultimate load capacity of the assembly and greatly reduced the associated displacement at each load. The load was transferred from the wood framing to the ccSPF and into the XPS sheathing as well. The sheets did not twist in plane as they did in the case of Wall 1. During final failure, loading the top approximately 2 ft. of each stud bent while the load was transferred from the top plate to the stud and to the ccSPF and sheathing. Failure occurred when the left stud began tearing free from the ccSPF (Figure 27). The tear then propagated along the underside of the top plate. Finally, the top plate shifted along the top of the studs shearing the nails out of the studs (Figure 28) and was ultimately followed by shear tearing along the full length of the underside of the top plate as it released from the ccSPF. This failure mode was typical of all three walls tested.

Figure 25. Structural testing wall 2 installed in apparatus

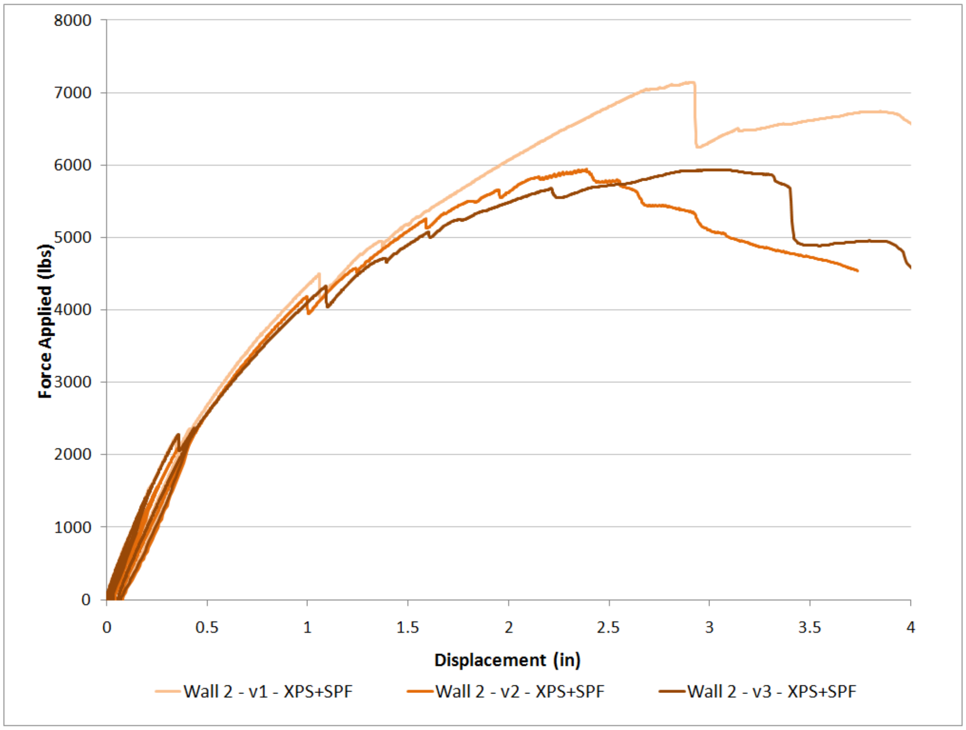


Figure 26. Structural test wall 2 results

Figure 27. Stud flexure and ccSPF tearing

Figure 28. ccSPF tear propagation

Appendix G contains a set of additional photos taken during the structural testing.

3.4.3.4 Structural Test Wall 3

Structural test wall 3 used FFPIC exterior insulation and depicts Hybrid Wall 3 and Hybrid Wall 4. Structural test wall 3 performed the best of all walls tested. Results are shown in Figure 29. Test wall 3 maintained very little residual displacements through loadings up to 2,360 lbs. while the FFPIC displaced the least of any of the walls. Each loading began at nearly zero displacement. The ultimate strength of the FFPIC sheathed walls was very similar to that of the XPS sheathed walls and exceeded 6,000 lbs. of force. The failure mode of the FFPIC insulated walls is very similar to that of the XPS walls. The left-most stud tore free from the ccSPF and was followed by the shearing of the top plate along the top of the studs (Figure 30). This failure mode was typical of all three walls tested.

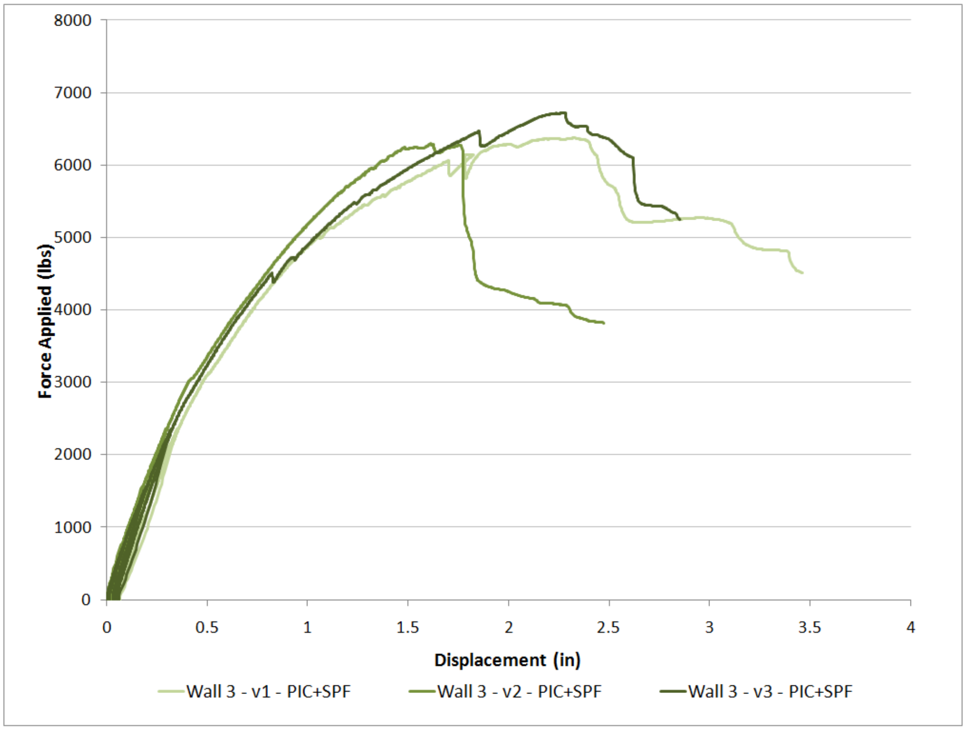


Figure 29. Structural test wall 3 results

Figure 30. ccSPF tear propagation

Appendix G contains a set of additional photos taken during the structural testing.

3.4.3.5 Summary Comparison

The information developed from the ASTM E72 structural testing performed at the Dow facilities shows that the ultimate strength of a diagonally strapped XPS sheathed wall is tripled with the addition of 1.5 in. of ccSPF to each stud bay.

When compared to a standard 2 × 6 advanced framed wall with OSB, a hybrid wall with diagonal metal strapping, XPS (or FFPIC) exterior insulation, and 1.5 in. of ccSPF within the stud bays has a 50% higher ultimate strength while displacing less (Figure 31).

Each of the proposed hybrid walls exceeds the structural capacity of a standard 2 × 6 advanced framed wall with OSB sheathing. Specifically, hybrid walls 3 and 4, which used FFPIC exterior insulation, provide the highest ultimate strength while displacing the least and, more importantly, can be loaded and unloaded with up to 2,360 lb without residual displacement.

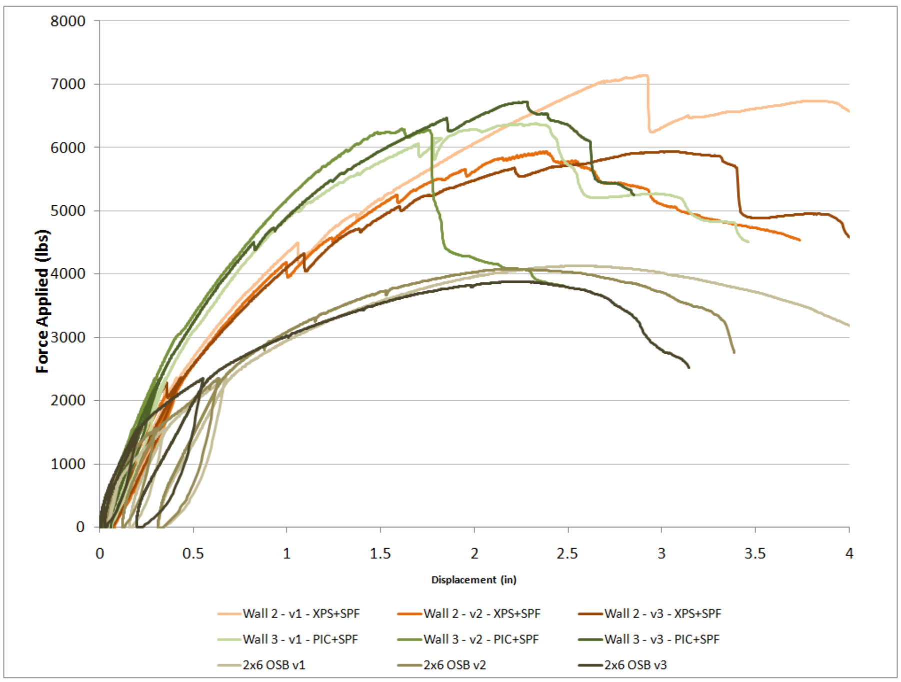


Figure 31. Summary comparison

3.5 Continued Research

Through this research, BSC expects to collect detailed information about the structural and hygrothermal performance of hybrid wall systems that will be suitable for deployment in whole house demonstrations. Further testing would determine the structural capacities of various assemblies and variations on the hybrid walls analyzed in this report. Areas of interest include:

- Structural capacity of hybrid walls without diagonal strapping
- Structural capacity of hybrid walls with full cavity closed-cell spray foam
- Structural capacity of hybrid walls with various stud fasteners
- Cyclic seismic structural capacities of hybrid assemblies.
- Flood repair options for hybrid assemblies
- Full scale wind testing of homes with hybrid walls

4 Summary

Based on BSC's past experience in the Building America program it's been found that combinations of materials and approaches—in other words, systems—usually provide optimum performance. The hybrid walls analyzed utilize a combination of exterior insulation, diagonal metal strapping, and closed-cell spray polyurethane foam, while leaving room for a cavity-fill insulation. These systems can provide effective thermal, air, moisture, and water barrier systems in one assembly while also providing structure.

The energy analysis using BEopt showed that the proposed hybrid walls save on average more than 30% source energy compared to the Building America Benchmark. Specifically, hybrid wall 3 showed a 34% source energy savings in Minneapolis. The cost analysis using RSMeans CostWorks 2011 showed that hybrid wall 3 had the lowest incremental cost at $\$2.20/ft^2$ of enclosure wall.

Thermal modeling using Therm5 showed the importance of insulation placement to reduce thermal bridging and that hybrid wall 3 and 4 had higher clear wall R-values than either of the standard walls or hybrid walls 1 and 2. hybrid wall 5 with 3 in. of exterior insulation had the highest clear wall R-value.

Hygrothermal modeling using WUFI showed that the proposed hybrid walls reduced air leakage condensation risk in Minneapolis by between 95% and 100% compared to a standard 2 × 6 wall with OSB sheathing.

The information developed from the ASTM E72 structural testing performed at the Dow facilities shows that the ultimate strength of a diagonally strapped XPS sheathed wall is tripled with the addition of 1.5 in. of ccSPF to each stud bay. When compared to a standard 2 × 6 advanced framed wall with OSB, the hybrid walls showed 50% higher ultimate strength while displacing less. Specifically, hybrid walls 3 and 4, using FFPIC exterior insulation, provide the highest ultimate strength while displacing the least, and more importantly, could be loaded and unloaded with up to 2,360 lbs. without residual displacement.

The optimal wall from the BEopt, thermal, hygrothermal, and structural analysis is Hybrid Wall 3. Hybrid Wall 3 has the lowest associated incremental cost, the lowest air leakage condensation risk (less than 1% of the year in Minneapolis), the best structural performance, and the second best annual energy savings at 34% in Minneapolis and 29% in New Orleans. It is believed that this is one of the most promising technologies for high performance residential wall assemblies in the mass built production house arena. Hybrid wall 3 consists of the following:

- Exterior vertical wood strapping for cladding attachment
- 1.5-in. foil-faced polyisocyanurate board insulation
- Diagonal metal strapping
- 2 × 6 advanced framed wall
- 1.5-in. closed-cell spray polyurethane foam in each stud bay
- 3-in.-cellulose insulation
- 0.5-in.-gypsum with latex paint finish.

BSC expects the proposed hybrid wall systems will be suitable for deployment in whole house prototype demonstrations as early as 2014. Further testing will be required during the 2012 Building America program. Further testing would determine the structural capacities of various assemblies and variations on the hybrid walls analyzed in this report.

References

Grin, A. (2008). *Evaluation of High Performance Residential Housing Technology*. University of Waterloo, Canada. Ch.r 5 pp. 77 – 89.

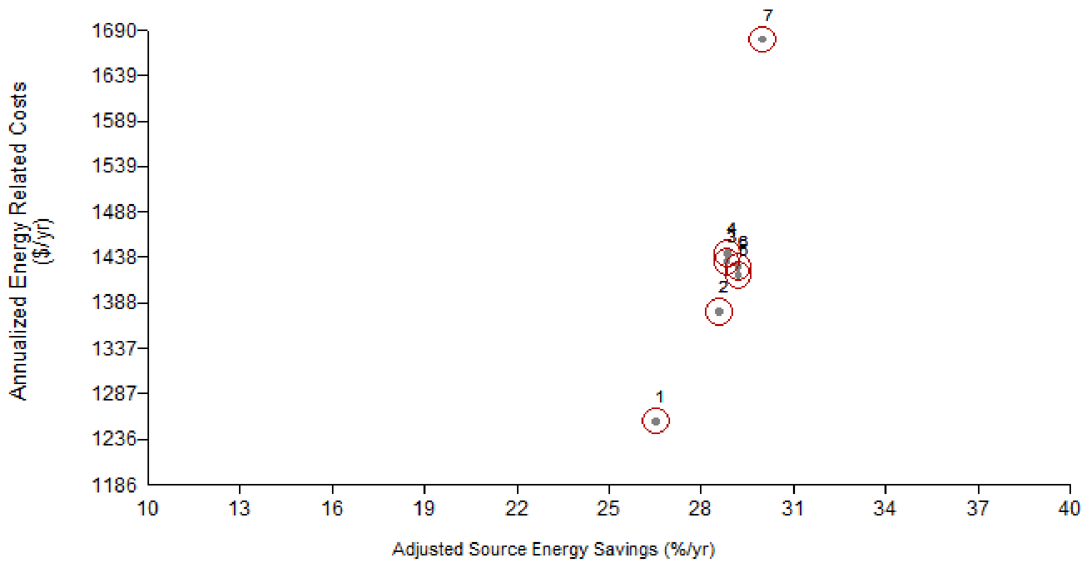
Lstiburek. J.; Grin, A. (2010). *Building America Special Research Project: Advanced Framing Deployment*, RR-1004. Buildingscience.com, September 2011.

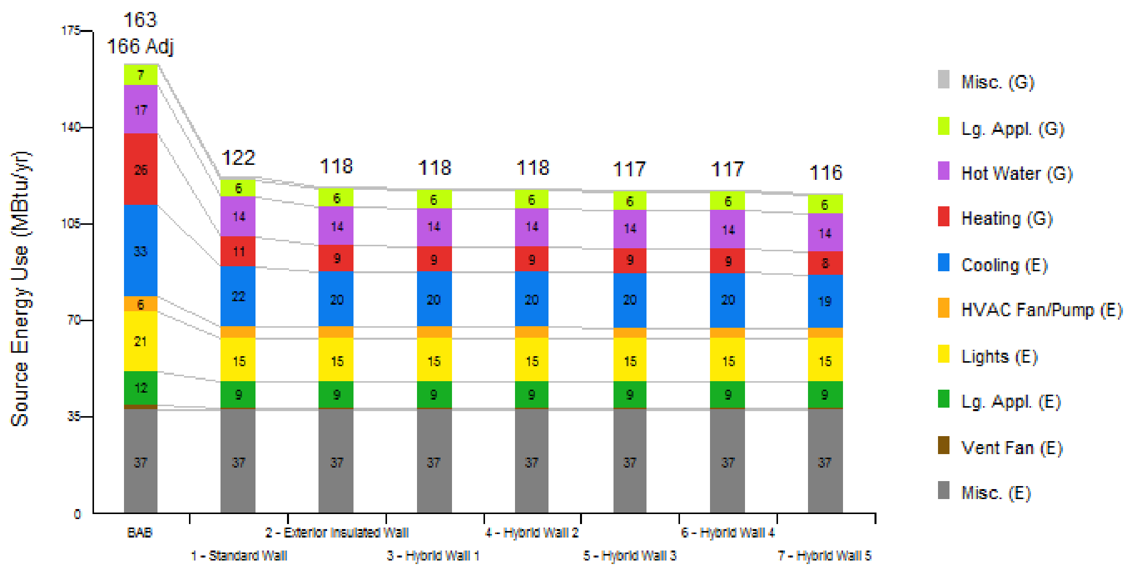
Parasin, A.V.; Nagy, N.J. (March 1991). *Effect of Spray-Applied Polyurethane Foam Insulation on the Racking Load of a Plywood Sheathed Wood Framed Wall*. Council of Forest Industries of B.C., Canada, Technical Note 91.1.

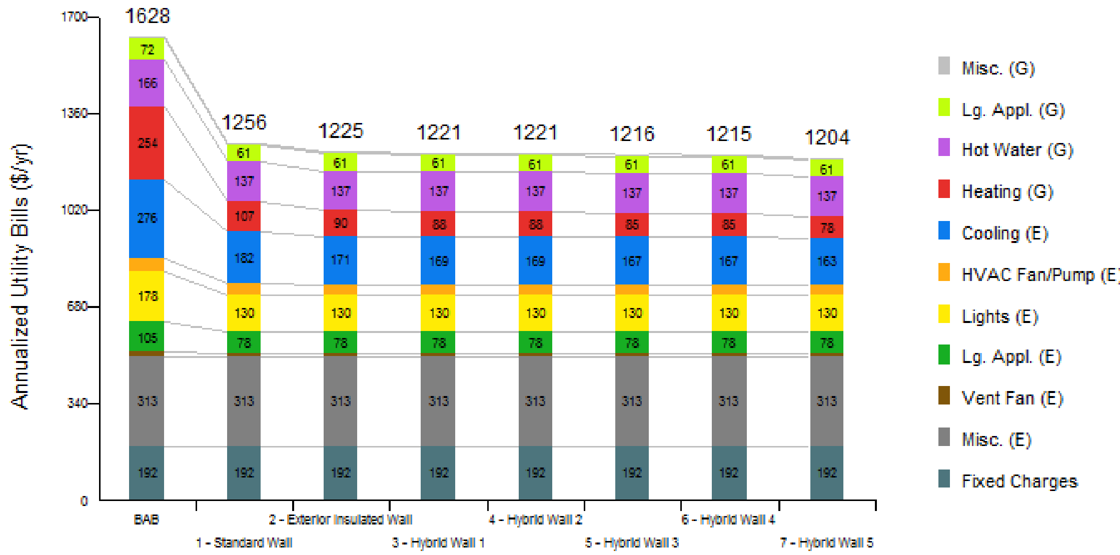
Reed Construction Data (2011). *RSMeans CostWorks 2011, 15th Annual Edition*. Norwell, MA. Retrieved May 17, 2011.

Straube, J.F.; Smegal, J. (2009). *Building America Special Research Project – High-R Walls Case Study Analysis*. RR-0903. Buildingscience.com, September 2011.

Appendix A. BEopt Results: New Orleans

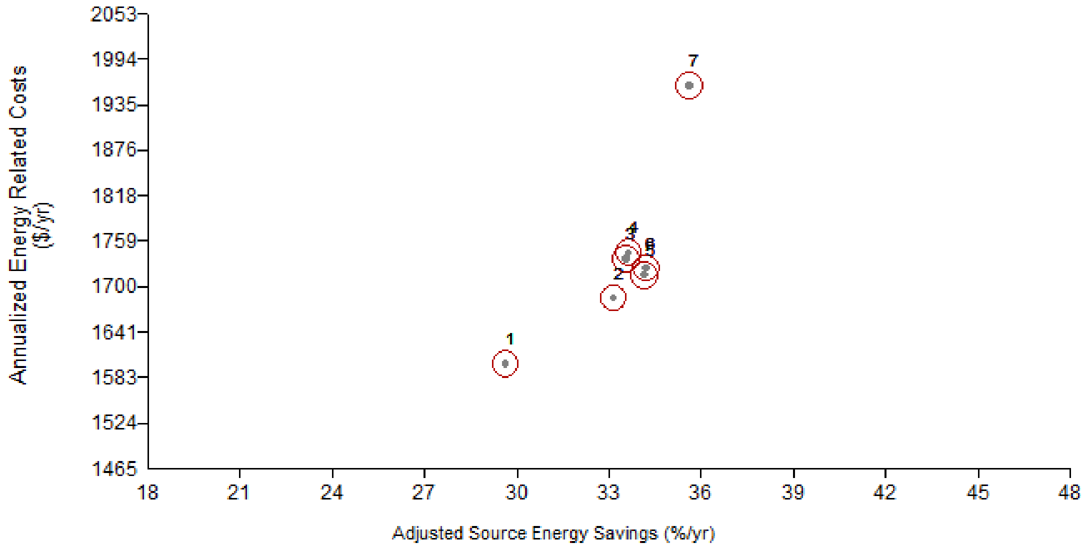




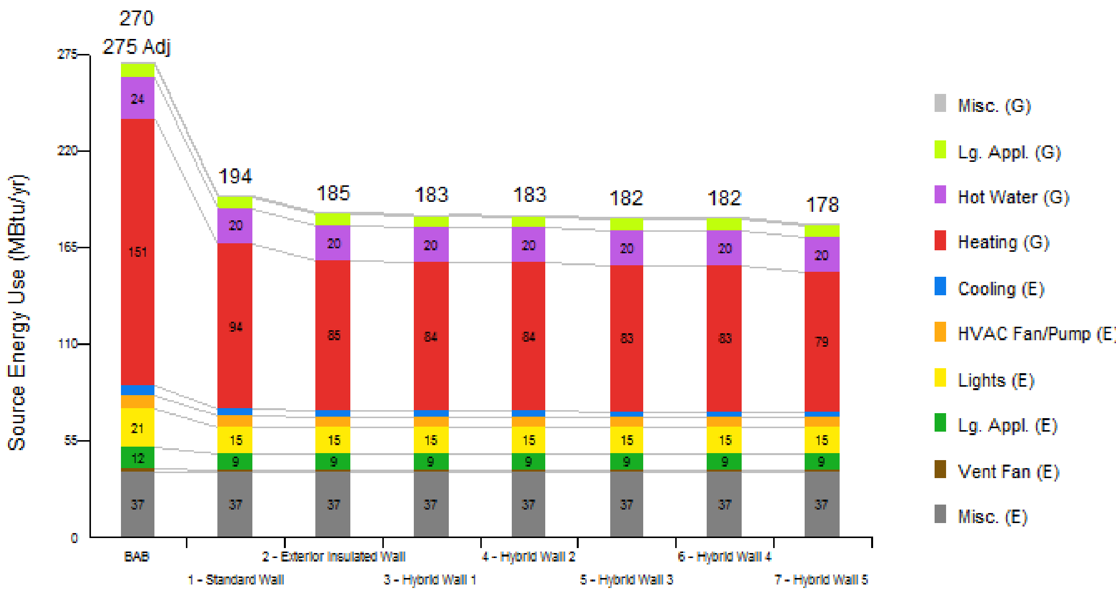

Annualized Utility Bills ($/yr)
1700
1360
1020
680
340
0
1628
1256
1225
1221
1221
1216
1215
1204
BAB
1 - Standard Wall
2 - Exterior Insulated Wall
3 - Hybrid Wall 1
4 - Hybrid Wall 2
5 - Hybrid Wall 3
6 - Hybrid Wall 4
7 - Hybrid Wall 5
Misc. (G)
Lg. Appl. (G)
Hot Water (G)
Heating (G)
Cooling (E)
HVAC Fan/Pump (E)
Lights (E)
Lg. Appl. (E)
Vent Fan (E)
Misc. (E)
Fixed Charges
72
166
254
276
178
105
313
192
61
137
107
182
130
78
90
171
88
169
85
167
78
163

Appendix B. BEopt Results: Minneapolis

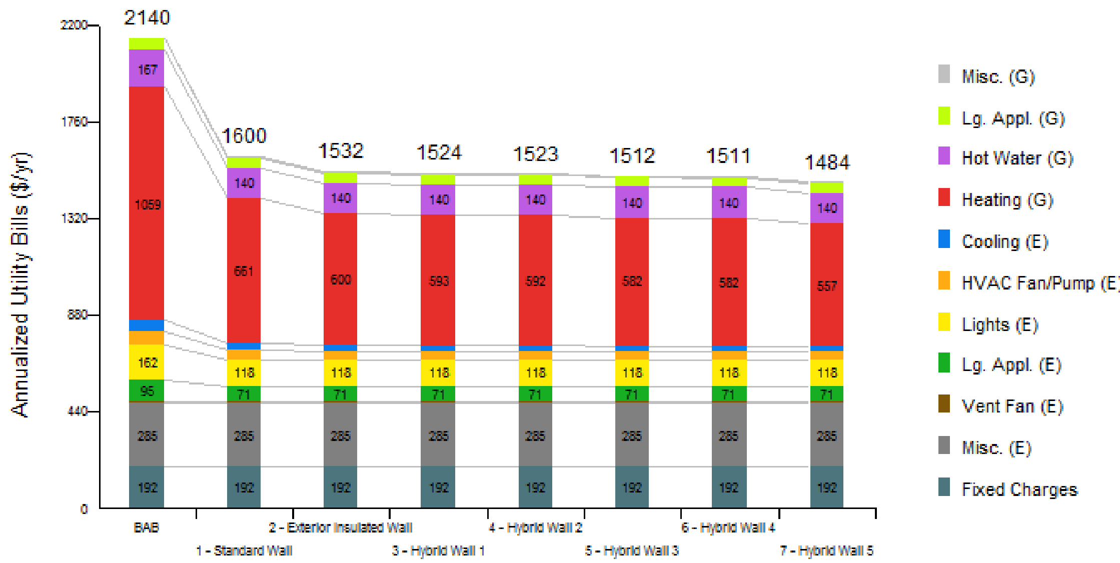
Here is the "swoosh" graph.



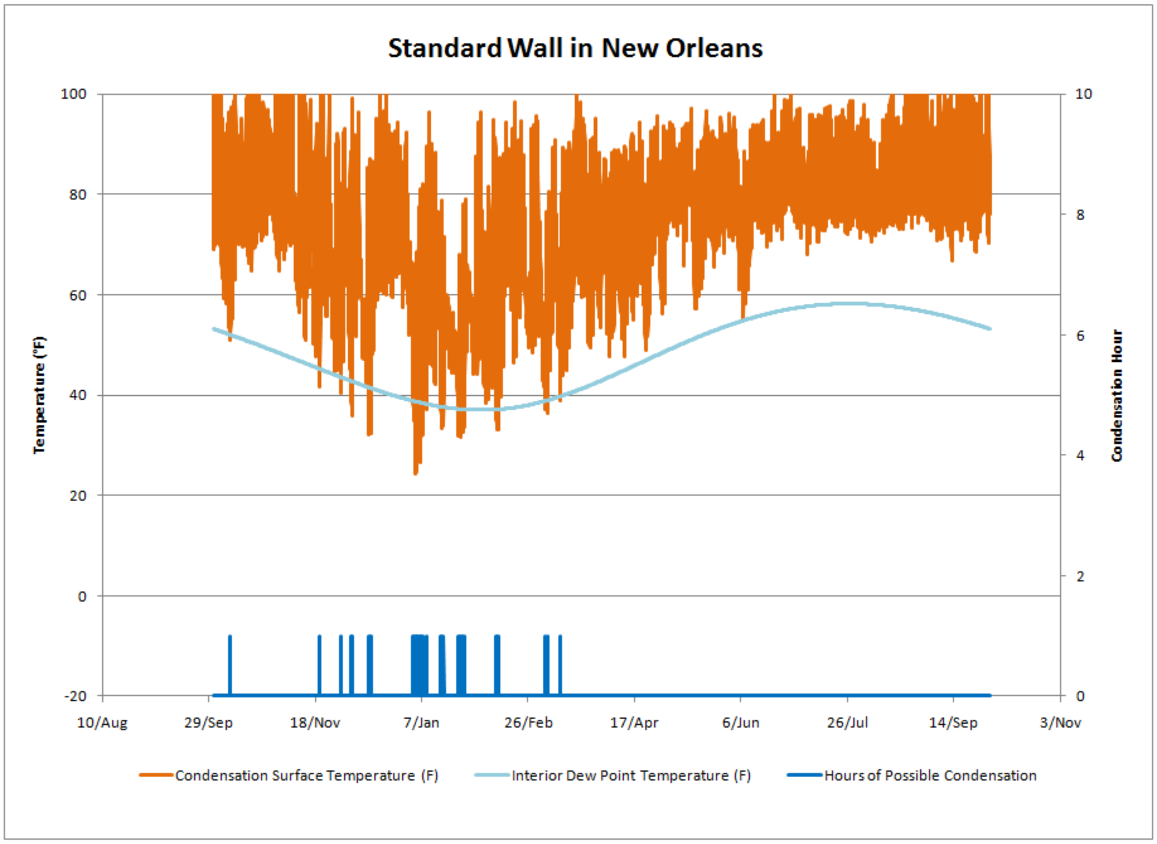
Below is the source energy savings use in components.

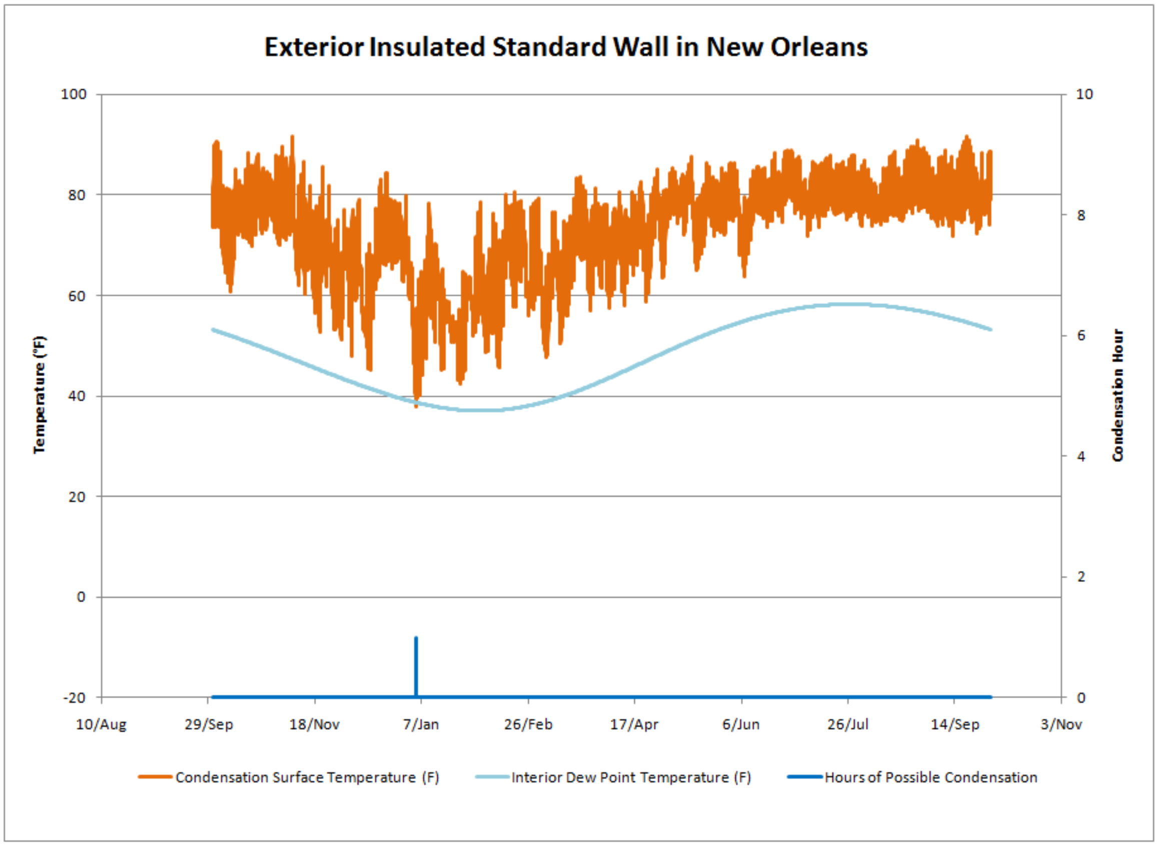


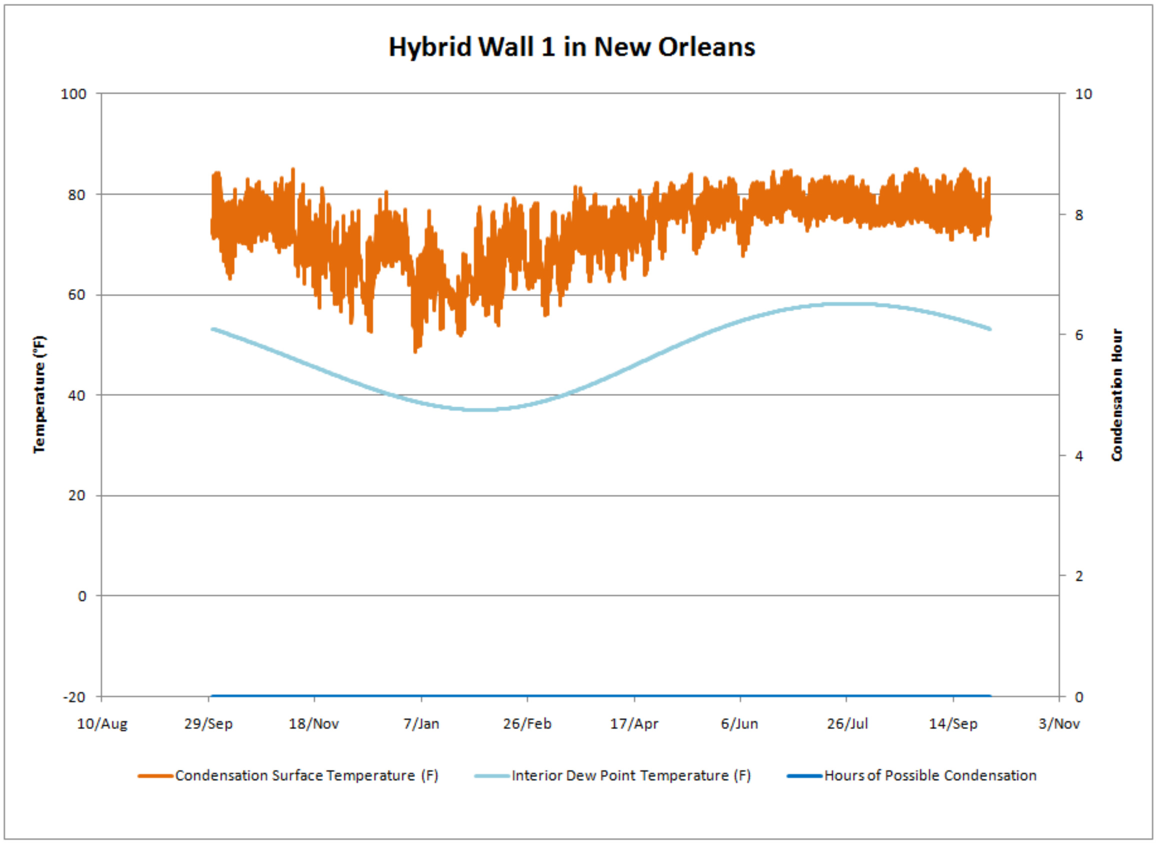
Below is the same output graph but it is in utility costs.

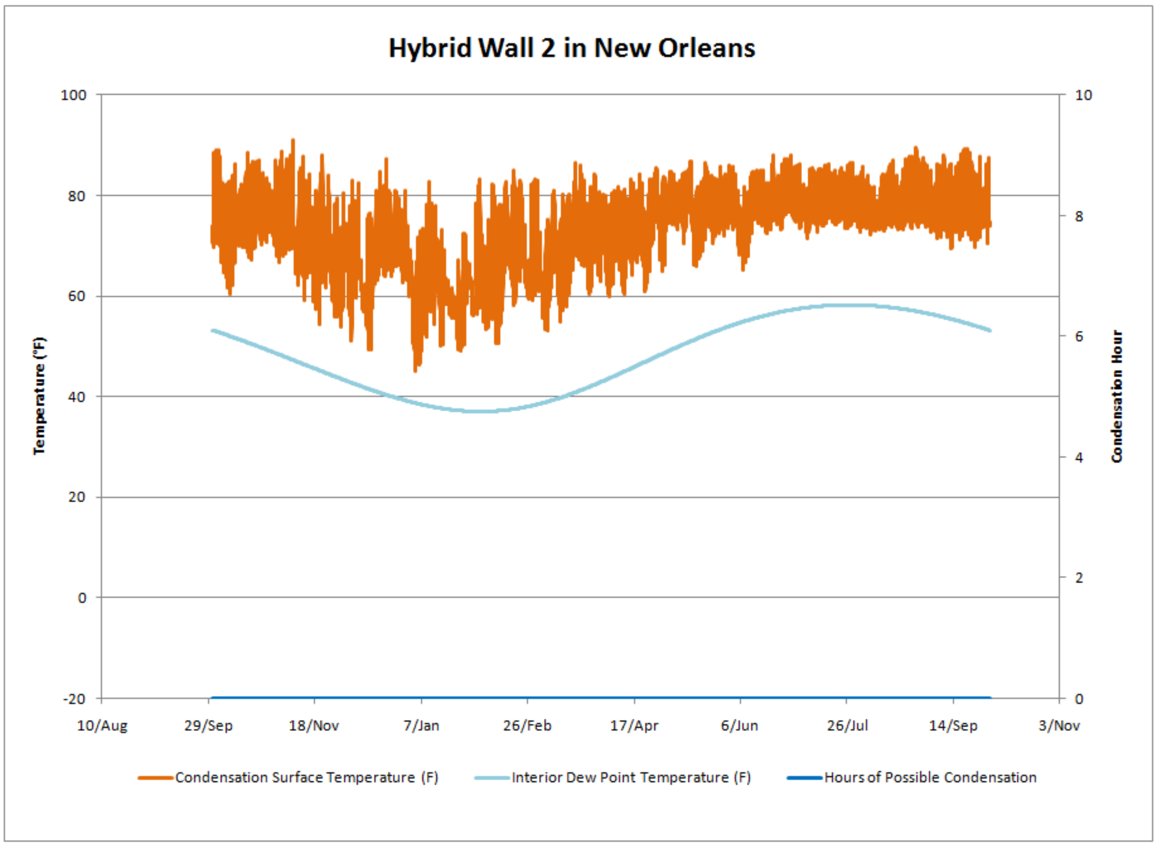


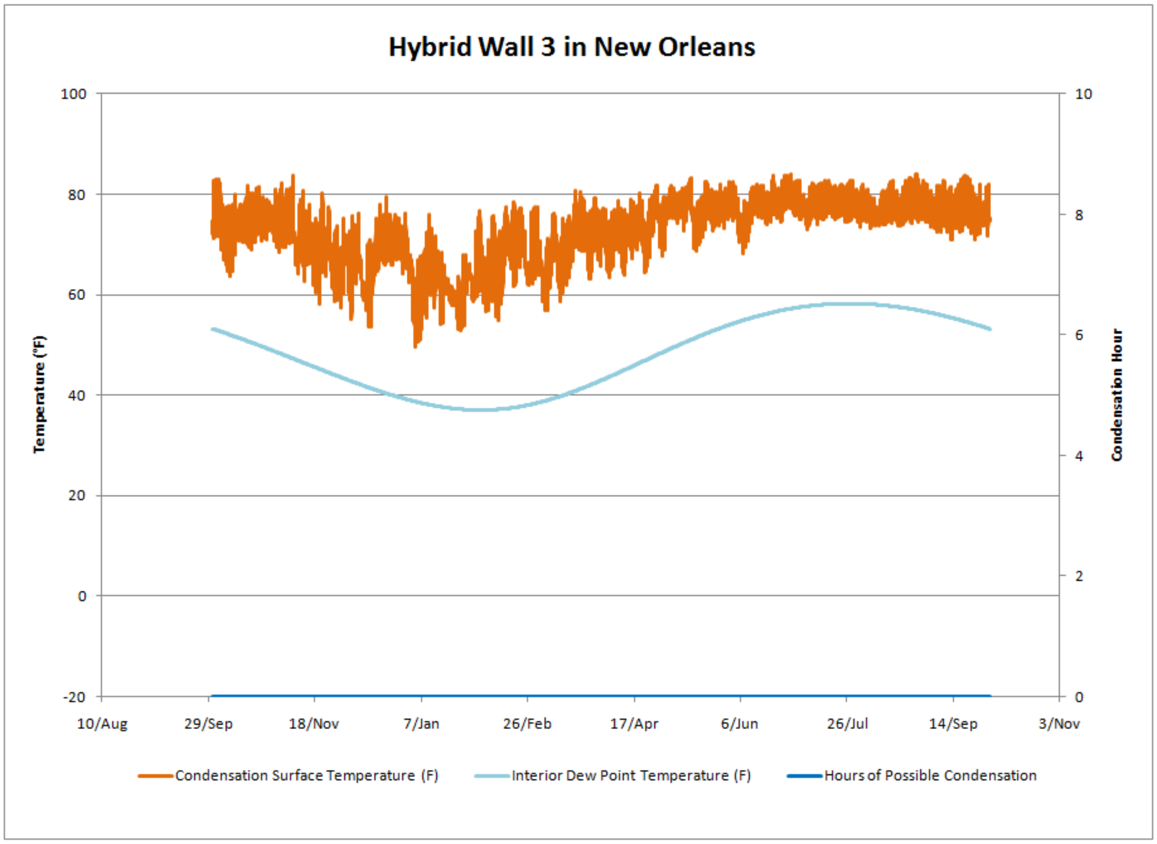
Appendix C. Hygrothermal Modeling: New Orleans

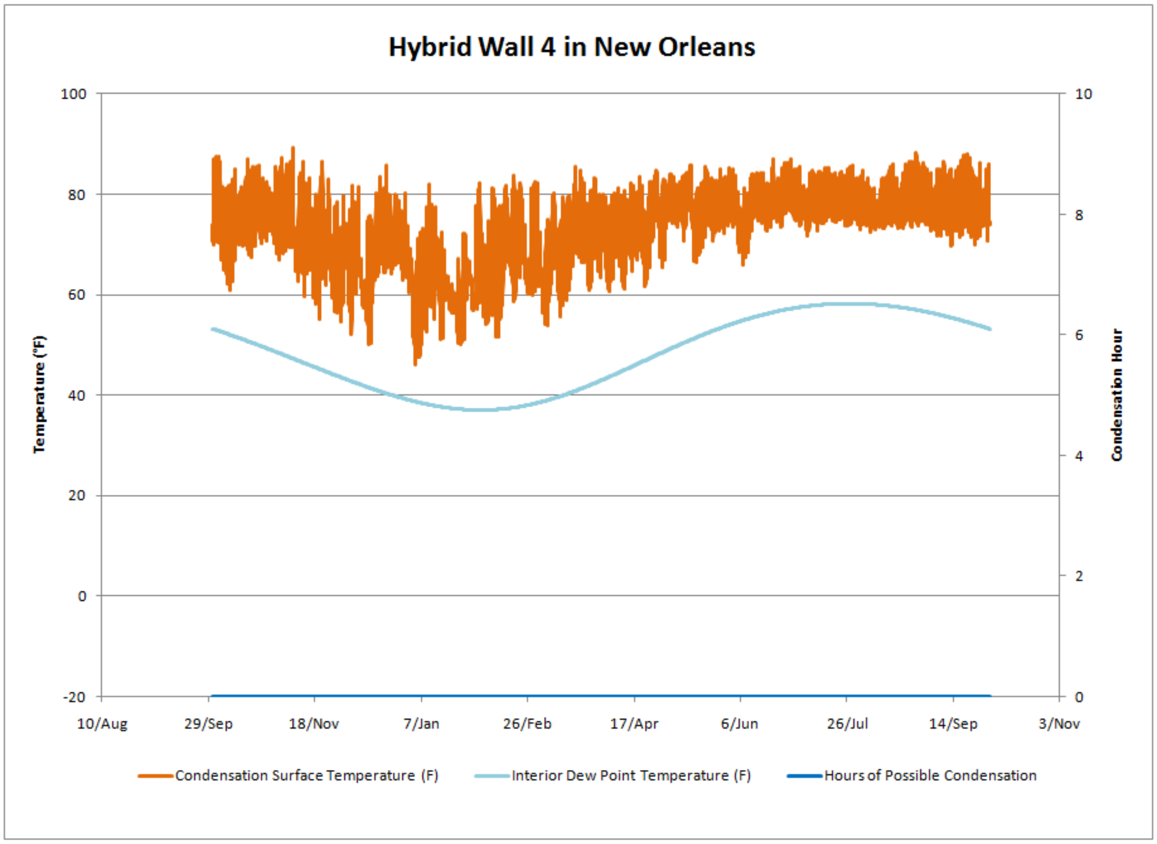


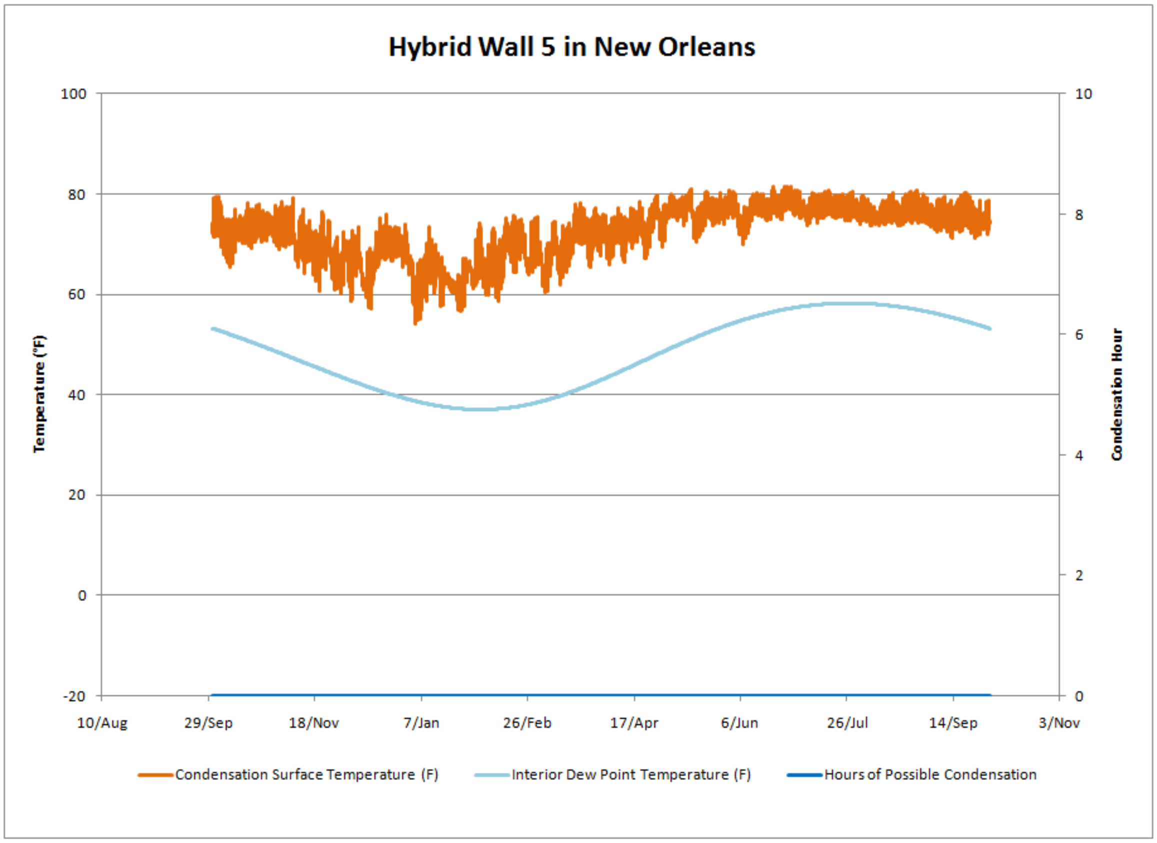

Exterior Insulated Standard Wall in New Orleans
Temperature (°F)
Condensation Hour
100
80
60
40
20
0
-20
10
8
6
4
2
0
10/Aug
29/Sep
18/Nov
7/Jan
26/Feb
17/Apr
6/Jun
26/Jul
14/Sep
3/Nov
Condensation Surface Temperature (F)
Interior Dew Point Temperature (F)
Hours of Possible Condensation


Hybrid Wall 1 in New Orleans
Temperature (°F)
Condensation Hour
100
80
60
40
20
0
-20
10
8
6
4
2
0
10/Aug
29/Sep
18/Nov
7/Jan
26/Feb
17/Apr
6/Jun
26/Jul
14/Sep
3/Nov
Condensation Surface Temperature (F)
Interior Dew Point Temperature (F)
Hours of Possible Condensation

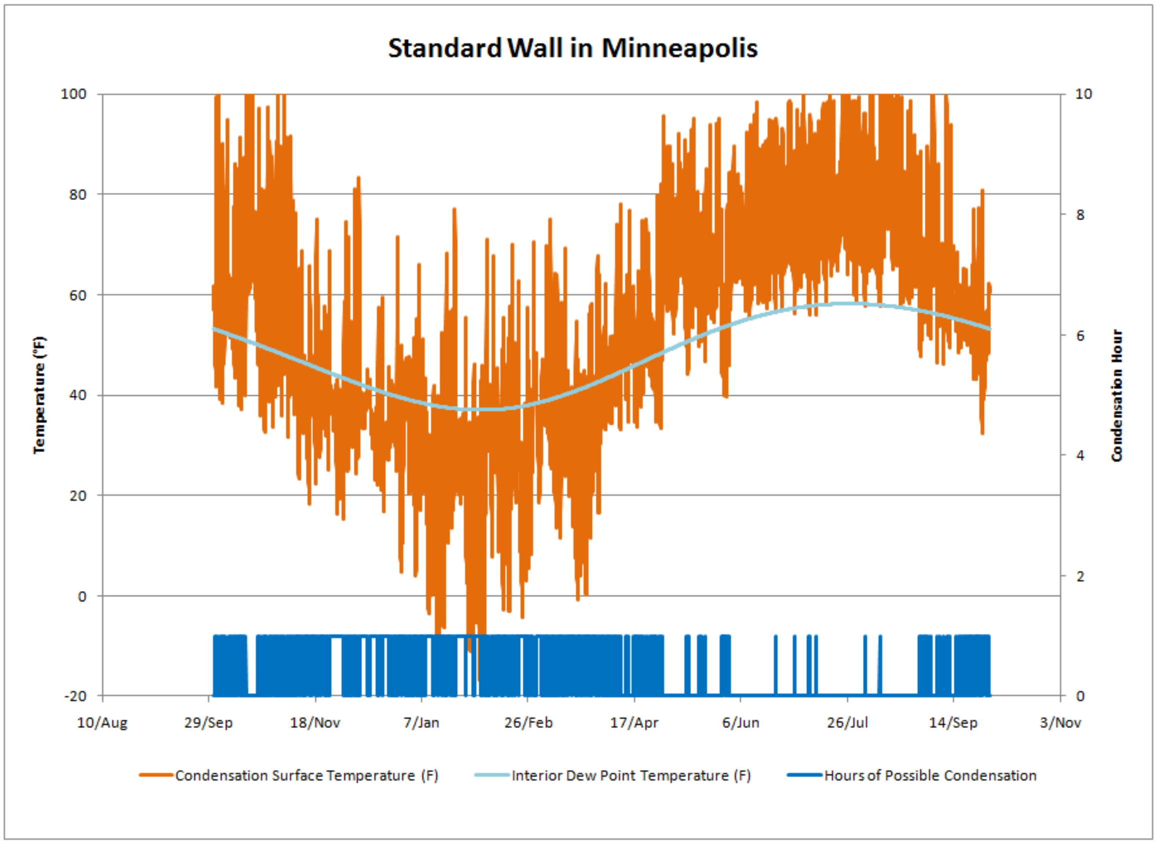

Hybrid Wall 2 in New Orleans
Temperature (°F)
Condensation Hour
100
80
60
40
20
0
-20
10
8
6
4
2
0
10/Aug
29/Sep
18/Nov
7/Jan
26/Feb
17/Apr
6/Jun
26/Jul
14/Sep
3/Nov
Condensation Surface Temperature (F)
Interior Dew Point Temperature (F)
Hours of Possible Condensation

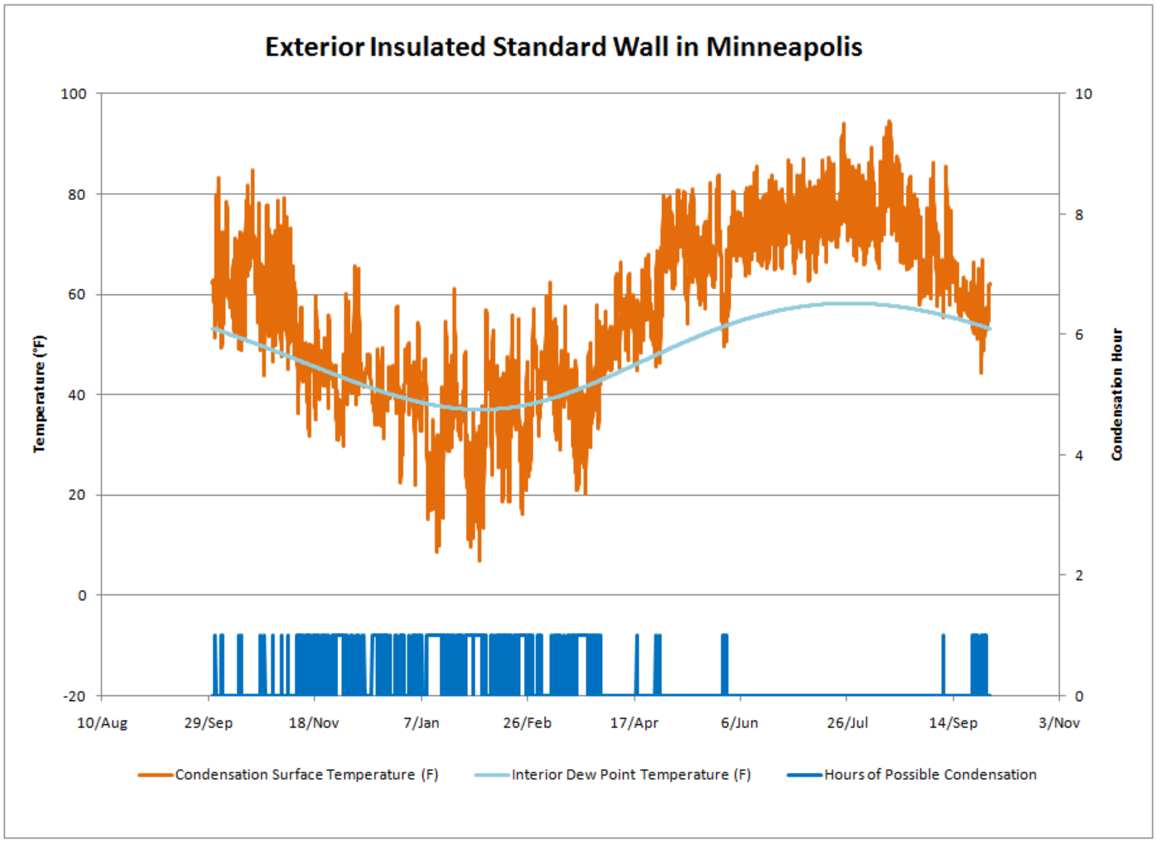

Hybrid Wall 3 in New Orleans
Temperature (°F)
Condensation Hour
100
80
60
40
20
0
-20
10
8
6
4
2
0
10/Aug
29/Sep
18/Nov
7/Jan
26/Feb
17/Apr
6/Jun
26/Jul
14/Sep
3/Nov
Condensation Surface Temperature (F)
Interior Dew Point Temperature (F)
Hours of Possible Condensation

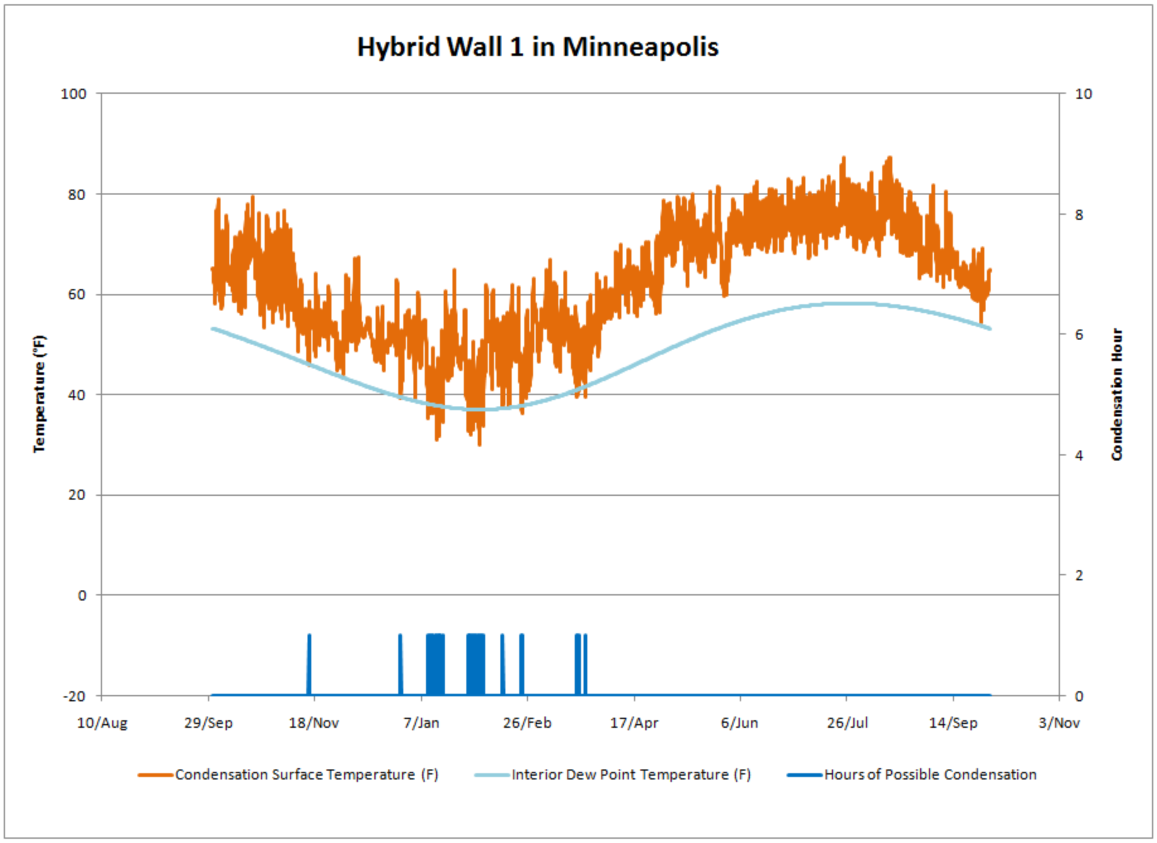

Hybrid Wall 4 in New Orleans
Temperature (°F)
Condensation Hour
100
80
60
40
20
0
-20
10
8
6
4
2
0
10/Aug
29/Sep
18/Nov
7/Jan
26/Feb
17/Apr
6/Jun
26/Jul
14/Sep
3/Nov
Condensation Surface Temperature (F)
Interior Dew Point Temperature (F)
Hours of Possible Condensation

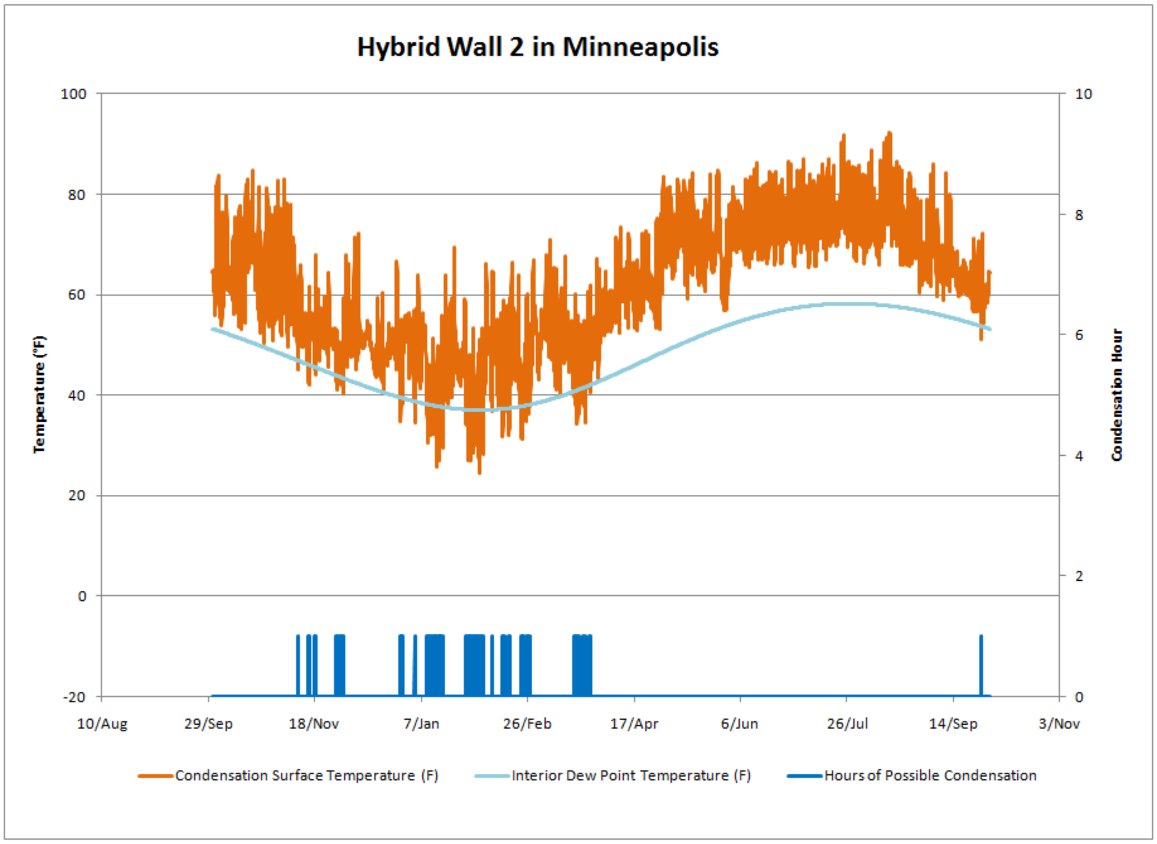

Hybrid Wall 5 in New Orleans
Temperature (°F)
Condensation Hour
100
80
60
40
20
0
-20
10
8
6
4
2
0
10/Aug
29/Sep
18/Nov
7/Jan
26/Feb
17/Apr
6/Jun
26/Jul
14/Sep
3/Nov
Condensation Surface Temperature (F)
Interior Dew Point Temperature (F)
Hours of Possible Condensation

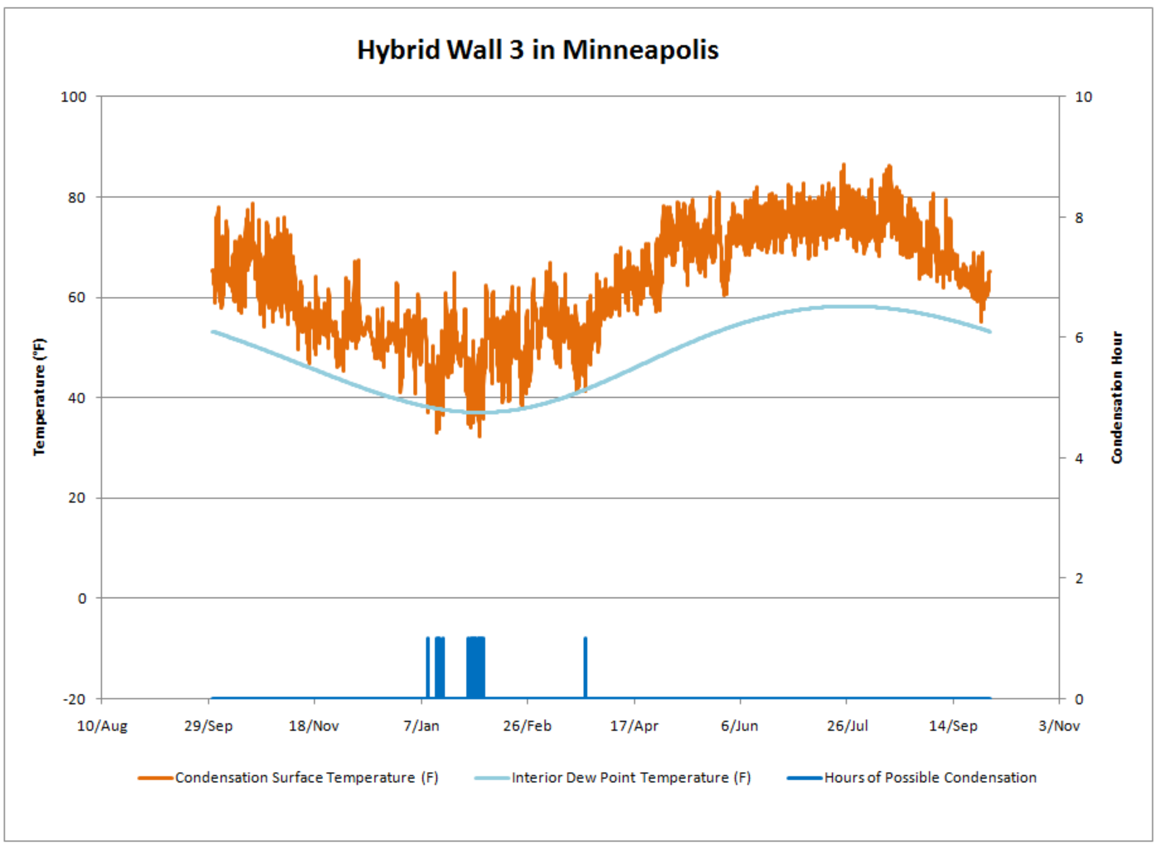
Appendix D. Hygrothermal Modeling: Minneapolis

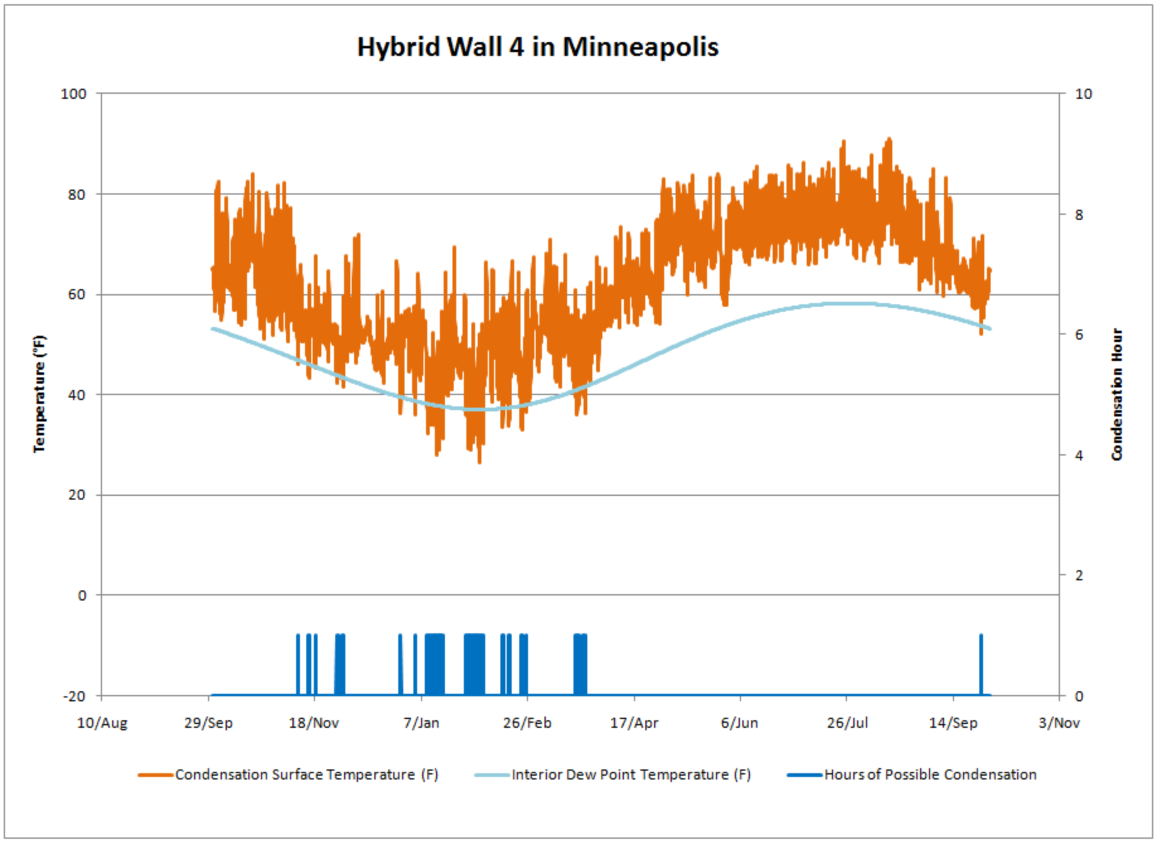


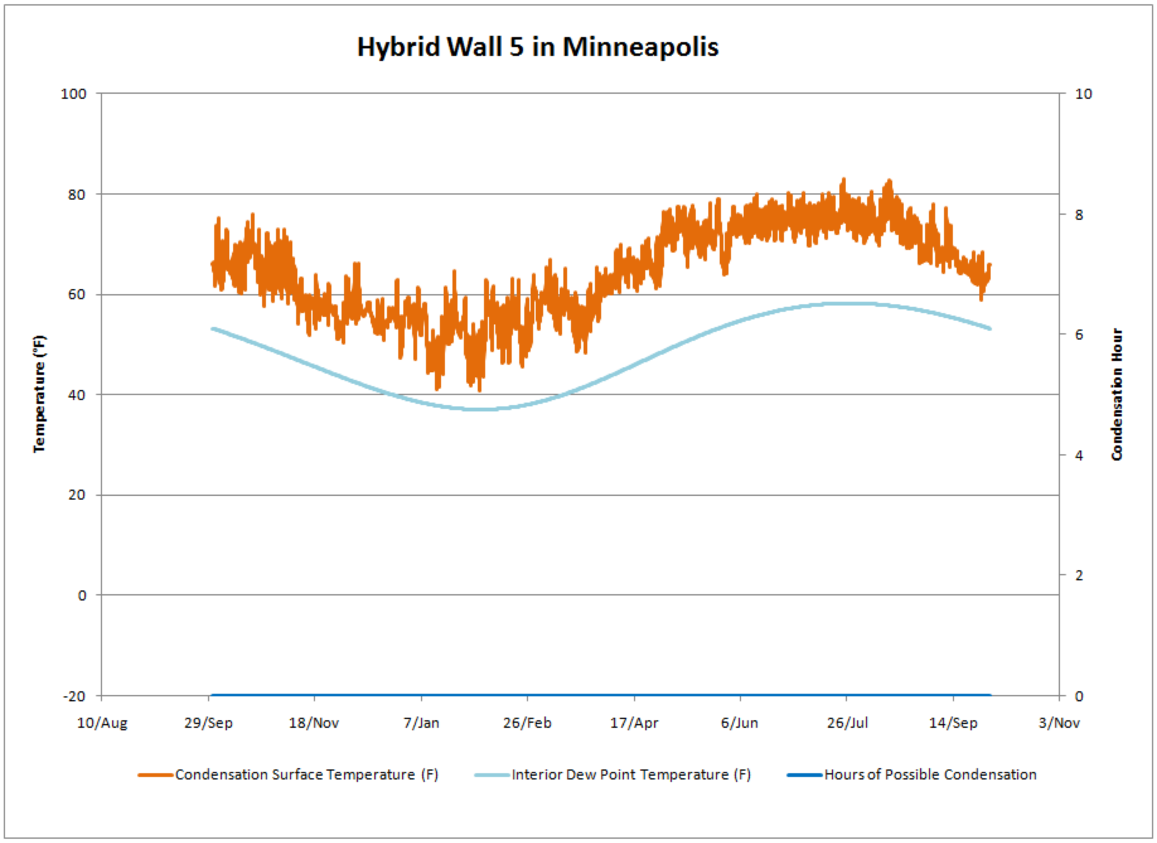

Exterior Insulated Standard Wall in Minneapolis
Temperature (°F)
Condensation Hour
100
80
60
40
20
0
-20
10
8
6
4
2
0
10/Aug
29/Sep
18/Nov
7/Jan
26/Feb
17/Apr
6/Jun
26/Jul
14/Sep
3/Nov
Condensation Surface Temperature (F)
Interior Dew Point Temperature (F)
Hours of Possible Condensation


Hybrid Wall 1 in Minneapolis
Temperature (°F)
Condensation Hour
100
80
60
40
20
0
-20
10
8
6
4
2
0
10/Aug
29/Sep
18/Nov
7/Jan
26/Feb
17/Apr
6/Jun
26/Jul
14/Sep
3/Nov
Condensation Surface Temperature (F)
Interior Dew Point Temperature (F)
Hours of Possible Condensation

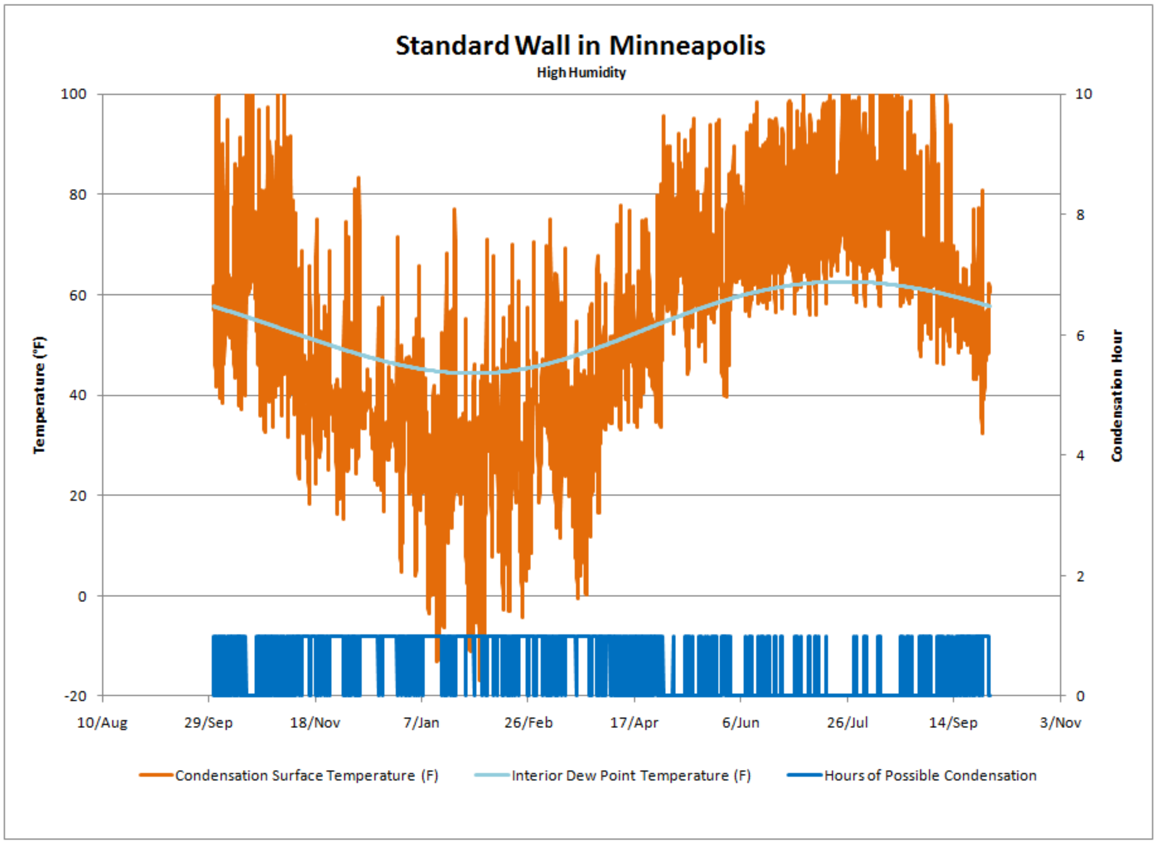

Hybrid Wall 2 in Minneapolis
Temperature (°F)
Condensation Hour
100
80
60
40
20
0
-20
10
8
6
4
2
0
10/Aug
29/Sep
18/Nov
7/Jan
26/Feb
17/Apr
6/Jun
26/Jul
14/Sep
3/Nov
Condensation Surface Temperature (F)
Interior Dew Point Temperature (F)
Hours of Possible Condensation

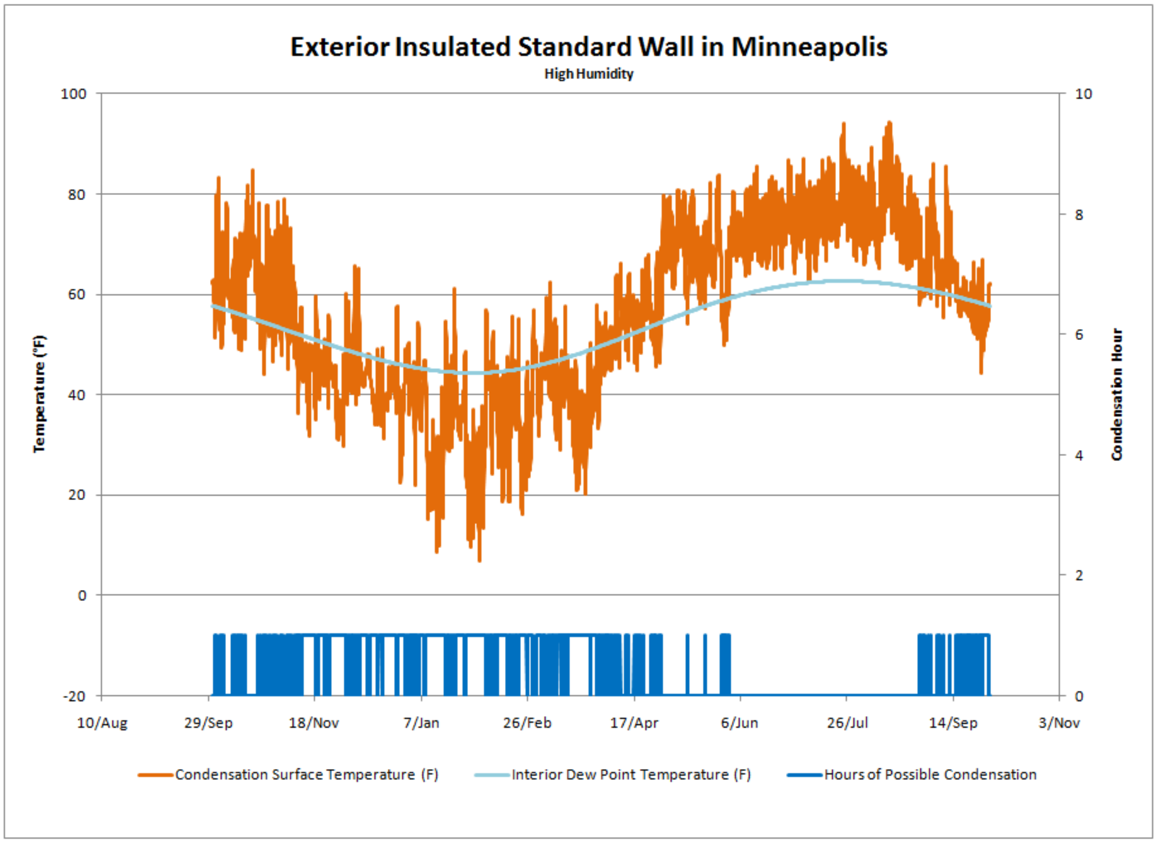

Hybrid Wall 3 in Minneapolis
Temperature (°F)
Condensation Hour
100
80
60
40
20
0
-20
10
8
6
4
2
0
10/Aug
29/Sep
18/Nov
7/Jan
26/Feb
17/Apr
6/Jun
26/Jul
14/Sep
3/Nov
Condensation Surface Temperature (F)
Interior Dew Point Temperature (F)
Hours of Possible Condensation

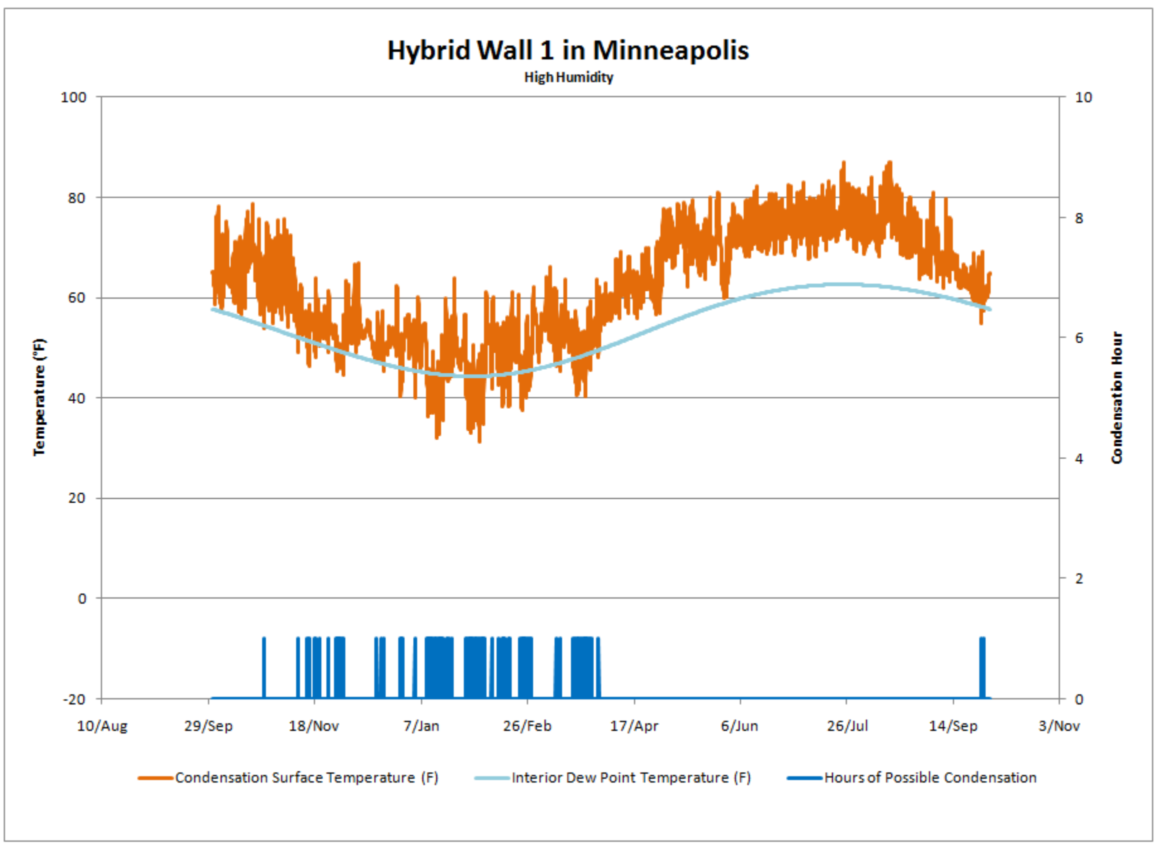

Hybrid Wall 4 in Minneapolis
Temperature (°F)
Condensation Hour
100
80
60
40
20
0
-20
10
8
6
4
2
0
10/Aug
29/Sep
18/Nov
7/Jan
26/Feb
17/Apr
6/Jun
26/Jul
14/Sep
3/Nov
Condensation Surface Temperature (F)
Interior Dew Point Temperature (F)
Hours of Possible Condensation

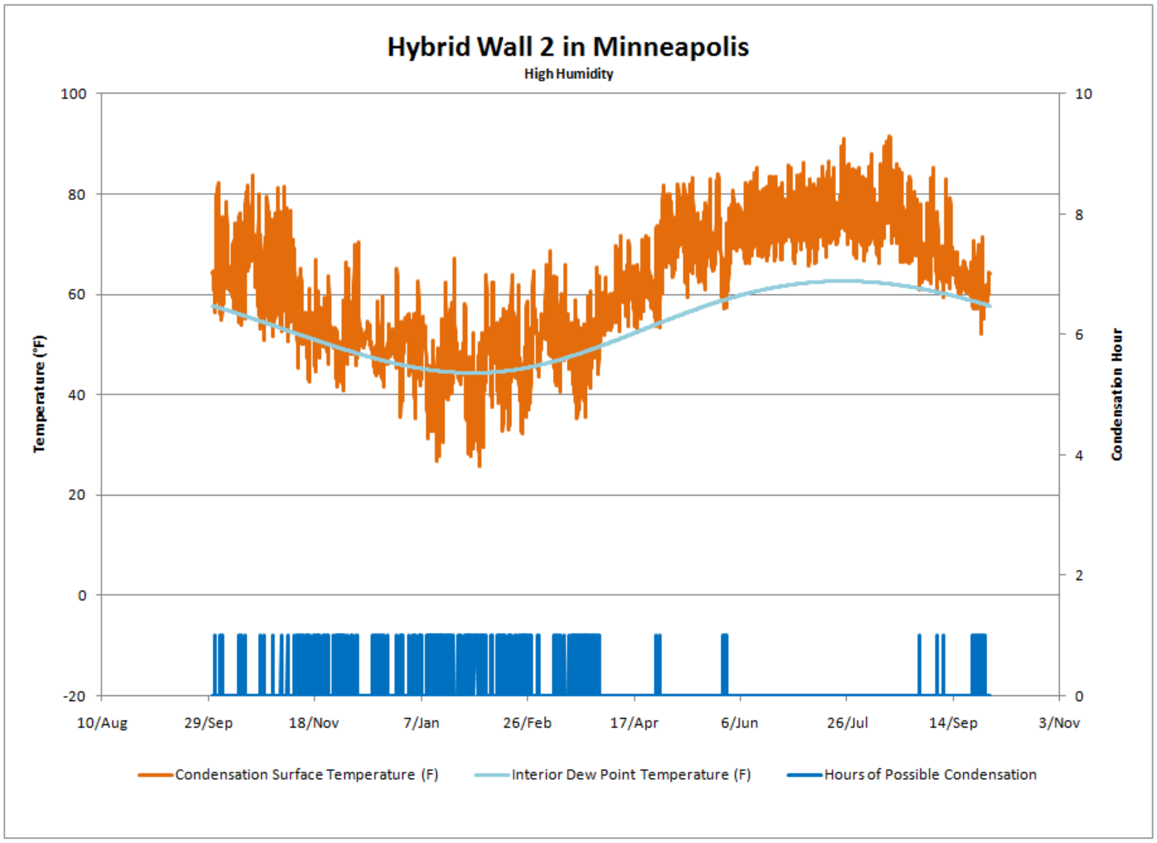

Hybrid Wall 5 in Minneapolis
Temperature (°F)
Condensation Hour
100
80
60
40
20
0
-20
10
8
6
4
2
0
10/Aug
29/Sep
18/Nov
7/Jan
26/Feb
17/Apr
6/Jun
26/Jul
14/Sep
3/Nov
Condensation Surface Temperature (F)
Interior Dew Point Temperature (F)
Hours of Possible Condensation

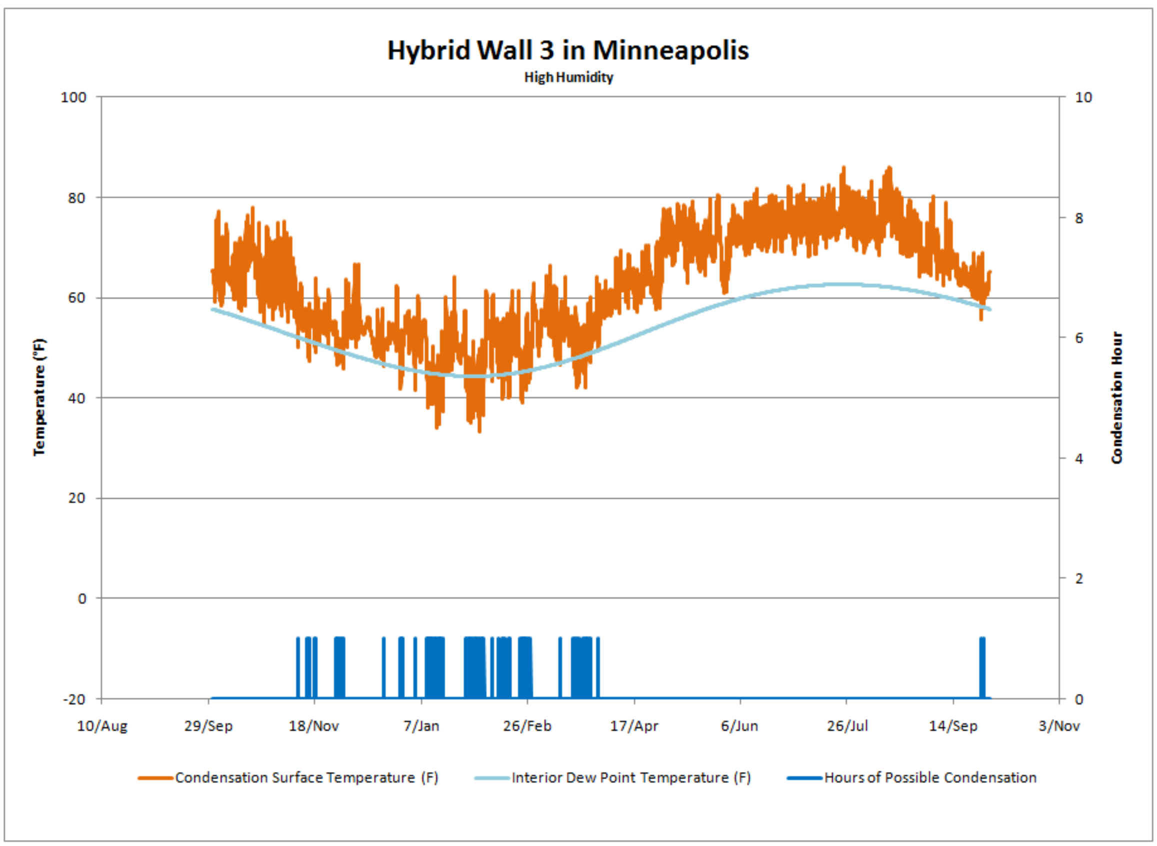
Appendix E. Hygrothermal Modeling: Minneapolis (High Humidity Case)

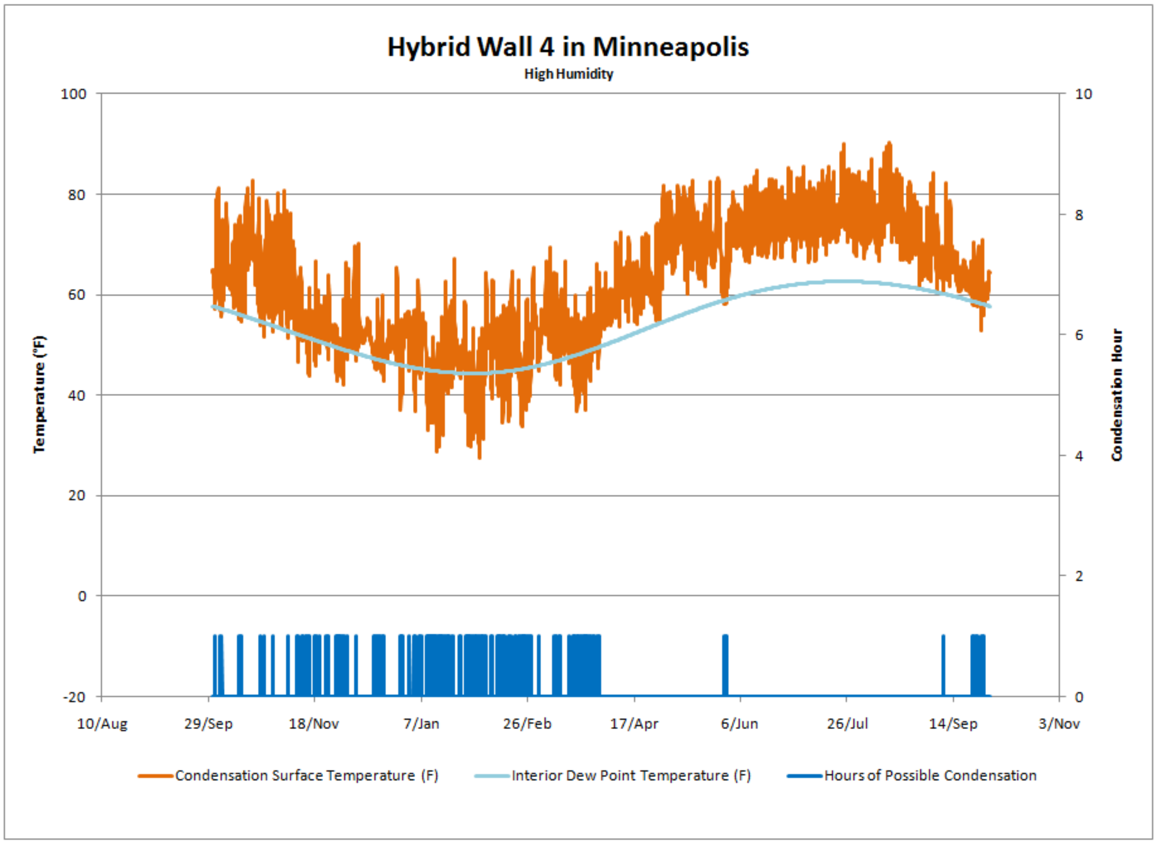


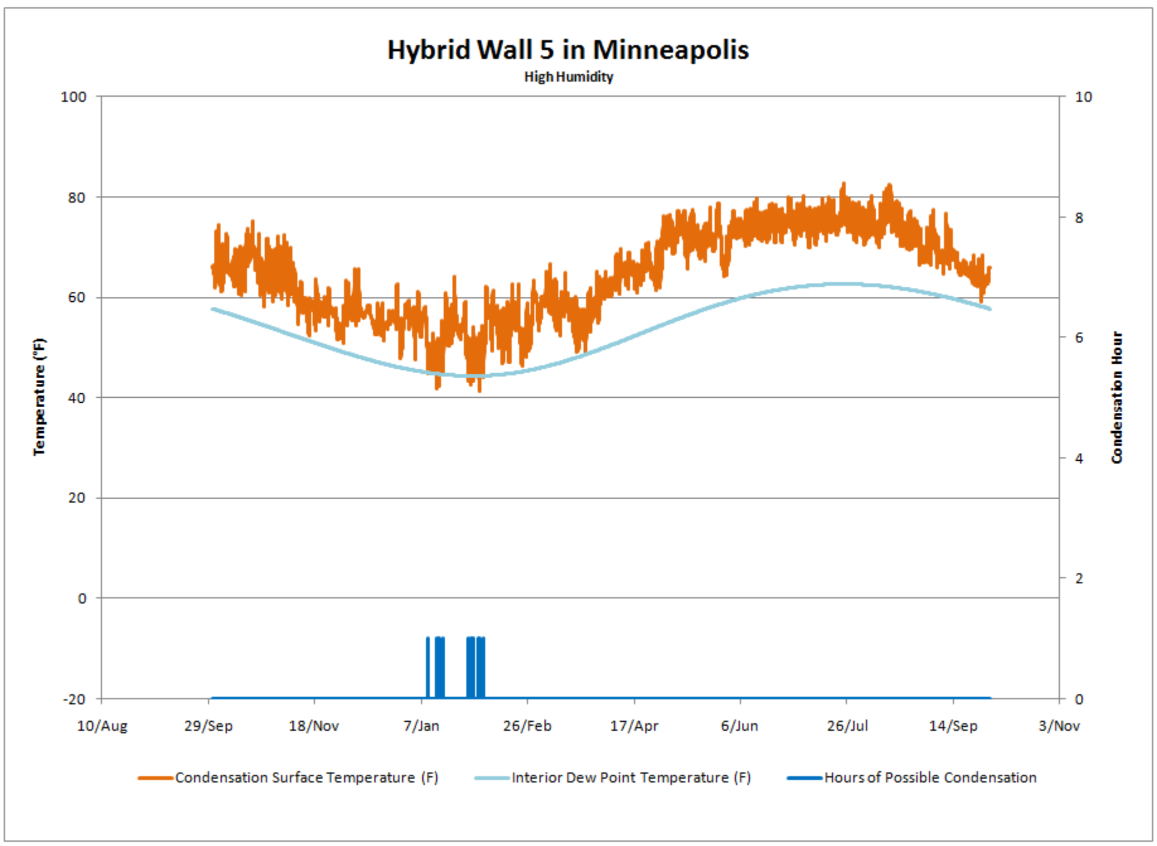

Exterior Insulated Standard Wall in Minneapolis
High Humidity
Temperature (°F)
Condensation Hour
100
80
60
40
20
0
-20
10
8
6
4
2
0
10/Aug
29/Sep
18/Nov
7/Jan
26/Feb
17/Apr
6/Jun
26/Jul
14/Sep
3/Nov
Condensation Surface Temperature (F)
Interior Dew Point Temperature (F)
Hours of Possible Condensation


Hybrid Wall 1 in Minneapolis
High Humidity
Temperature (°F)
Condensation Hour
100
80
60
40
20
0
-20
10
8
6
4
2
0
10/Aug
29/Sep
18/Nov
7/Jan
26/Feb
17/Apr
6/Jun
26/Jul
14/Sep
3/Nov
Condensation Surface Temperature (F)
Interior Dew Point Temperature (F)
Hours of Possible Condensation


Hybrid Wall 2 in Minneapolis
High Humidity
Temperature (°F)
Condensation Hour
100
80
60
40
20
0
-20
10
8
6
4
2
0
10/Aug
29/Sep
18/Nov
7/Jan
26/Feb
17/Apr
6/Jun
26/Jul
14/Sep
3/Nov
Condensation Surface Temperature (F)
Interior Dew Point Temperature (F)
Hours of Possible Condensation


Hybrid Wall 3 in Minneapolis
High Humidity
Temperature (°F)
Condensation Hour
100
80
60
40
20
0
-20
10
8
6
4
2
0
10/Aug
29/Sep
18/Nov
7/Jan
26/Feb
17/Apr
6/Jun
26/Jul
14/Sep
3/Nov
Condensation Surface Temperature (F)
Interior Dew Point Temperature (F)
Hours of Possible Condensation


Hybrid Wall 4 in Minneapolis
High Humidity
Temperature (°F)
Condensation Hour
100
80
60
40
20
0
-20
10
8
6
4
2
0
10/Aug
29/Sep
18/Nov
7/Jan
26/Feb
17/Apr
6/Jun
26/Jul
14/Sep
3/Nov
Condensation Surface Temperature (F)
Interior Dew Point Temperature (F)
Hours of Possible Condensation


Hybrid Wall 5 in Minneapolis
High Humidity
Temperature (°F)
Condensation Hour
100
80
60
40
20
0
-20
10
8
6
4
2
0
10/Aug
29/Sep
18/Nov
7/Jan
26/Feb
17/Apr
6/Jun
26/Jul
14/Sep
3/Nov
Condensation Surface Temperature (F)
Interior Dew Point Temperature (F)
Hours of Possible Condensation

Appendix F. Structural Testing Diagrams

Construction Description

Wall 1 – Three (3) Samples

8 × 8-ft Test Specimen – note – NOT actually 8 × 8 ft

Single top plates require that studs are cut to 94 in. for 8 ft, 1 in.-tall wall, which is industry standard height. Outside of stud to outside of stud horizontal measurement would be 8 ft, 1.5 in. to ensure stud bays are representative of 24in. on center framing.

2 × 6 at 24 in. on center, Single Top and Bottom Plate – Sruce Pine Fir wood lumber. Top and bottom plates are 9ft in length and overhang the 8 × 8-ft specimen 5.25 in. on either side.

Studs are nailed to top and bottom plate with two 3.5-in. nails per stud per plate spaced 1 in. in from front and rear face of plate.

4 × 6-in. lumber attached to racking frame base plate with countersunk bolts

Bottom plate of wall screwed to base system with 3-in. #8 construction screws on 12-in. spacing (two screws per bay) 4-in. from inside face of bottom plate, one at 24-in. centers 2 in. from inside face of base plate next to each stud, and one on each overhang – see drawing. Screws are used in this location for disassembly purposes.

Top plate requires bolting pattern required for top load beam attachment – unknown, what is the beam on the apparatus? Perhaps we can do the same as base? Screws could be used in this location for disassembly purposes. If screws will be used, use same pattern as Bottom Plate.

Diagonal Metal Strapping as per manufacturer's recommendations, X-pattern using WB126 Simpson Tie Strap on a 45° angle and associated nailing requirements. (Single - 2.5-in. nail at each stud intersected and two 3.5-in. nails at each top and bottom plate). Verify that the wall is square before affixing strap – see drawing

1.5 in. XPS attached with cap nails in the field as per manufacturer's recommendations, XPS would be 97in. tall and 48 in. wide leaving half studs visible on both sides as this would be the amount of XPS affixed to each stud – see drawing.

1 × 3-in. vertical wood strapping at the studs affixed with 4-in. #10 construction screws at 16 in. on center, seven screws per strap.

Stud bays remain empty for this test

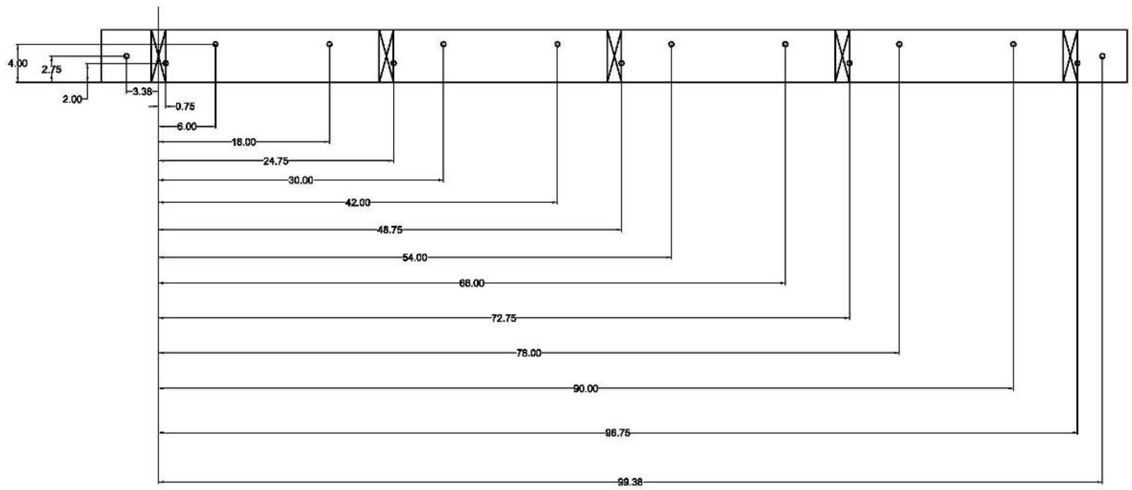
Wall 2 – three samples

Same as wall 0 + 1.5-in. ccSPF in all bays

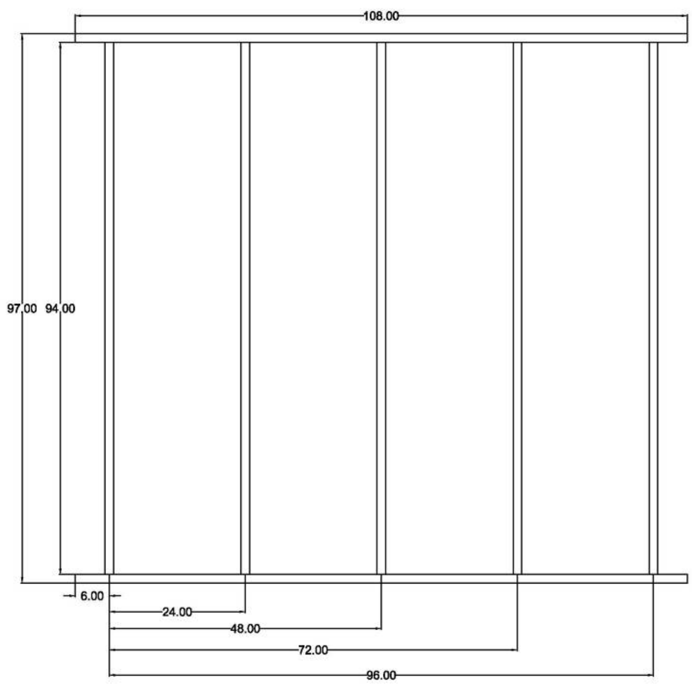
Wall 3 – three samples

Same as wall 0 + accept uses 1.5 in. foil faced polyisocyanurate as exterior insulation + 1.5 in. ccSPF in all bays

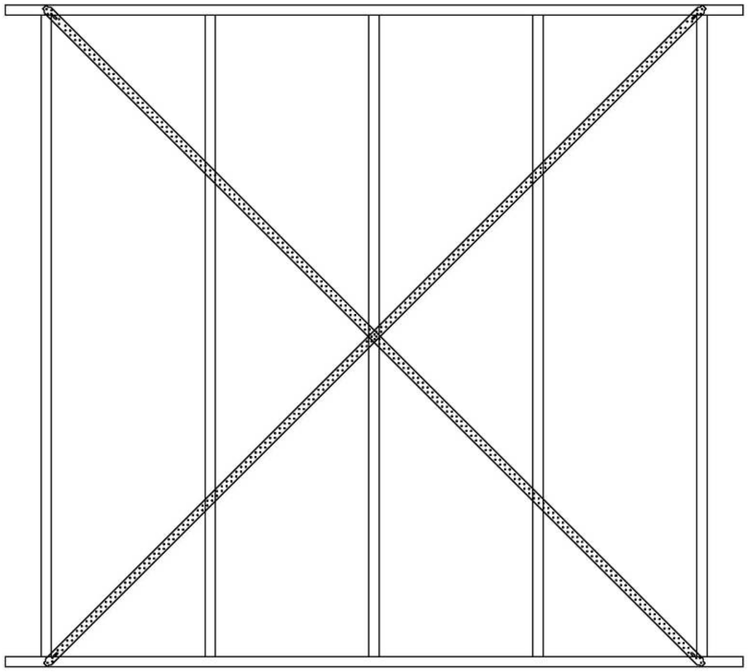
Diagrams and Details



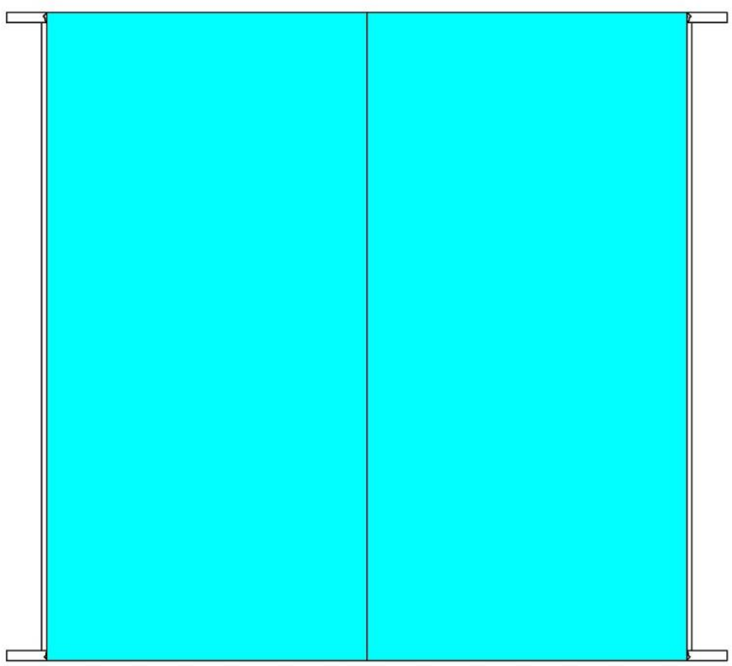
Bottom Plate Screw Pattern



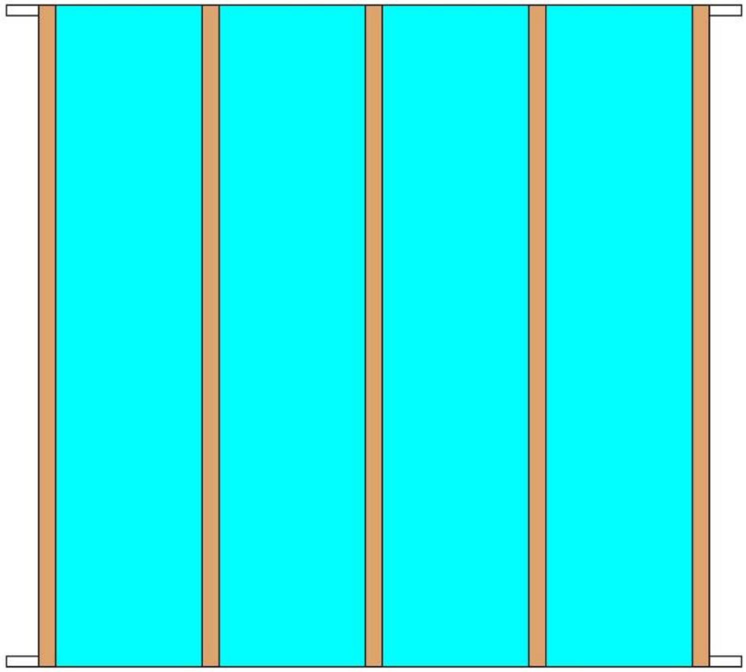
Advanced Framed Wall



Diagonal Strapping Installed



Exterior Insulation Installed



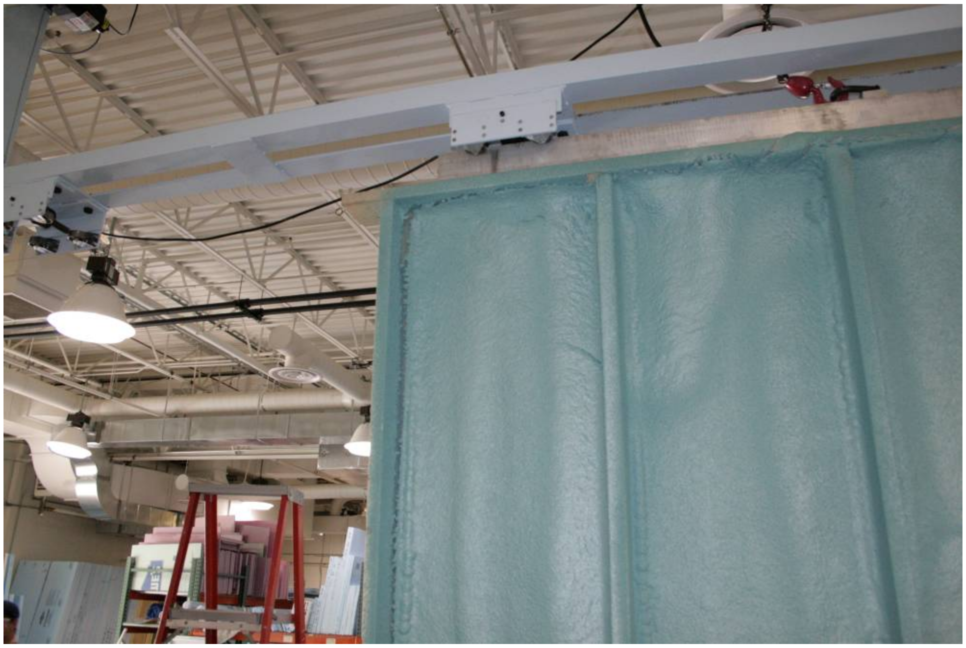
Vertical Wood Strapping Installed

Appendix G. Structural Testing Photo Documentation

Advanced framed 2 × 6 wall with OSB

Structural testing wall 1 (Photos from 3 Samples)

Structural testing wall 2 (photos from 3 samples)



Structural testing wall 3 (photos from 3 samples)


DOW
Super UFF-R
Commerci nsulation

buildingamerica.gov

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

DOE/GO-102012-3527 ▪ September 2012

Printed with a renewable-source ink on paper containing at least 50% wastepaper, including 10% post-consumer waste.