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Moisture Research—Optimizing Wall Assemblies

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Consortium for Advanced Residential Buildings

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Moisture Research—Optimization of Wall Assemblies

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Definitions

ACH	Air changes per hour
ASTM	American Society for Testing and Materials
Btu	British thermal unit
CARB	Consortium for Advanced Residential Buildings
ft^2	Square foot
ft^3	Cubic foot
h	Hour
IBP	Institute for Building Physics
in.	Inch
IRC	International Residential Code
lb	Pound
LIM	Lowest isopleth for mold
MC	Moisture content
MDSPF	Medium-density spray polyurethane foam
NRCC	National Research Council Canada
OSB	Oriented strand board
RH	Relative humidity
SPF	Spray polyurethane foam
THERM	Two-dimensional heat transfer tool
vol %	Volume percent
WUFI	Wärme- und Feuchtetransport Instationär
XPS	Extruded polystyrene

Executive Summary

The Consortium for Advanced Residential Buildings (CARB) evaluated several different configurations of wall assemblies to determine the accuracy of moisture modeling and make recommendations to ensure durable, efficient assemblies. WUFI[1] and THERM[2] were used to model the hygrothermal and heat transfer characteristics of these walls. Assemblies evaluated include the following:

- Code minimum walls using spray foam insulation and fiberglass batts
- High R-value walls at least 12 in. thick: R-40 and R-60 assemblies
- Brick walls with interior insulation.

Code minimum walls were evaluated in climate zones 4 through 7 and in the dry, moist, and marine moisture regimes. Three different classes of vapor retarder were analyzed along with varying thicknesses of exterior and cavity insulation. Three different methods of constructing high R-value (high-R) walls were analyzed—two employing hybrid insulation strategies and one double-stud cellulose assembly. Varying combinations of foam and fibrous insulation were evaluated with and without vented cladding in climate zones 4, 5, 6, and 7, all in moisture regime A. Finally, two different brick assemblies with different brick densities and insulation strategies were modeled in climate zone 4A.

All walls were analyzed against currently accepted failure criteria including condensation potential, moisture content thresholds, drying capacity of the assembly, potential for mold growth, and freeze-thaw damage with respect to brick.

While the majority of the code minimum walls analyzed fail the ASHRAE 160-2009 30-day criteria, the walls with Class III vapor retarders and the lowest levels of foam required by code fail the ASHRAE criteria by a much higher margin than the rest. In addition, condensation potential is near or above 20% for most of the walls with that configuration.

The analysis of high R-value walls indicates that assemblies constructed with the oriented strand board (OSB) on the exterior of all the insulation should employ a vented cladding to assist in drying of that layer regardless of the type of insulation in the cavity. Drying to the interior is severely limited in these walls, therefore, drying to the exterior must be enhanced.

High R-value walls constructed with the OSB sandwiched between a moisture permeable insulation on the interior and an impermeable insulation on the exterior should maximize the ratio of impermeable to permeable insulation. This keeps the OSB as warm as possible, reduces the potential for condensation, and promotes drying to the interior. Based on modeling results, a minimum of 50% of the total cavity wall R-value should be provided by the impermeable insulation in climate zones 4 through 6, and 60% is recommended in climate zone 7.

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[1] Wärme-und Feuchtetransport instationär (Transient Heat and Moisture Transport), a moisture prediction tool created by the Fraunhofer Institute for Building Physics and Oak Ridge National Laboratory

[2] Two-dimensional heat transfer tool created by Lawrence Berkeley National Laboratory

Before insulation retrofits are undertaken in buildings with structural brick walls, the hygrothermal properties of the brick should be determined. Properties vary so widely across the country that no generic recommendations for insulation strategies can be given here. Analysis shows that the insulation strategies appropriate for one type of brick are not necessarily appropriate for another. Criteria that should be analyzed include freeze-thaw cycles in conjunction with the critical saturation threshold and drying potential of the masonry. Analysis periods longer than 3 years are recommended when modeling.

Further research into the appropriateness of the ASHRAE 160-2009 interior conditions in moist climates is needed. Interior relative humidity levels generated with this method are higher than recorded in actual studies (Arena et al. 2010) and result in overly pessimistic predictions for mold growth on the interior of the assembly.

Considering that almost every wall in this study failed the ASHRAE 30-day criteria, it is recommended that this threshold be reevaluated by industry professionals.

1 Introduction

Moisture problems within the building shell can be caused by a number of factors including excess interior moisture that is transported into the wall through air leakage and vapor drive, bulk water intrusion from leaks and wind-driven rain, capillary action from concrete to wood connections, and through wetted building materials such as siding wetted from rain splash back. Depending on the temperature of the surfaces and the permeability of the materials, that moisture can get trapped inside the walls, potentially leading to mold growth, decay of the building materials, or both.

For mold to grow on the surface, the mean monthly relative humidity (RH) of the air next to the surface must be approximately 80% or greater. Decay of wooden building components, also caused by fungi, requires temperatures between 23°F and 113°F (there is little growth below 50°F), exposure to air, and a wood moisture content (MC) greater than 30% (ASTM 2001). Because most untreated wood is dryer than this, it usually takes wetting by some other means such as window or roof leaks, foundation moisture, splash back, or excessive condensation for the wood to reach this level of MC.

In an effort to provide a better understanding of the various mechanisms and interactions of moisture and heat transfer in building envelopes, transient mathematical models have been developed. There has been a rapid improvement in the capabilities of computer-based moisture analysis tools that can predict the movement and accumulation of moisture in building components and materials. One of those tools, WUFI, was created by the Fraunhofer Institute for Building Physics and Oak Ridge National Laboratory. WUFI predicts moisture transfer by diffusion and capillary flow. It allows users to assess the effectiveness of the wall materials and construction assemblies against moisture flow and indicates area where condensation can occur.

According to ASTM (2001), although WUFI is a highly validated model for hygrothermal applications, it has several limitations, which include the following:

- Because WUFI deals only with one-dimensional processes, it cannot adequately model multidimensional thermal and moisture bridges.
- Airflows in the component, uptake of groundwater, and gravity effects have been neglected.
- Some materials like wood and concrete can change their material properties as a function of their present and past MC and, as a result, do not lend themselves to simplified transport equations.

This research study is intended to analyze the hygrothermal performance of different wall assemblies that are gaining popularity in the market, but have yet to be comprehensively monitored with respect to moisture and heat transfer. In addition to the modeling results presented here, CARB will be collecting moisture data on a high-R, double-stud cellulose wall in climate zone 5 and a retrofit brick assembly using a hybrid insulation strategy in climate zone 4. Results of the data collection will be published at the end of 2012.

1.1 Background

Over the past 30 years, significant research has been conducted on moisture levels in homes and inside building components. In Chapter 13 of ASTM Manual 18, *Moisture Control in Buildings: The Key Factor in Mold Prevention* (ASTM 2009), George Tsongas reviews some of the most relevant case studies of moisture problems and research activities in residential buildings over the last several decades. But, in his summary, Tsongas states, “In mixed use climates, especially those with high humidity in the summer, best practices are often debated. Unfortunately, there are very few studies involving buildings in mixed climates.”

Viitanen and Salonvaara echo this need for field research in Chapter 4 of ASTM Manual 40, *Moisture Analysis and Condensation Control in Building Envelopes* (ASTM 2001), in their discussion of failure criteria. They argue that there are several standards for testing the resistance or durability of materials against mold and decay fungi, but that the results of the tests are often relative. In reality, conditions are often different in the field and many factors affect durability and performance. Like Tsongas, they feel that field tests in real conditions and in different climates should be performed.

With the increased use of foam insulation, various vapor barrier applications, the drastic increase in retrofit activities, and the increasing thickness of the walls (all factors that can reduce the drying potential of the walls) moisture issues could potentially become much bigger problems. High-R wall assemblies and assemblies employing a combination of insulation products are gaining popularity in the market because of programs like Passive House, net zero energy home challenges in several states, and highly incentivized retrofit programs. New insulation products, code changes, and the desire to reduce costs to achieve these new efficiency levels are also factors behind the various assemblies available today.

Although several people have performed extensive analysis on some of these assemblies using moisture modeling software, little field research has been conducted on high-R walls and masonry retrofits to validate the results. CARB intends to monitor different wall assemblies that have not been previously monitored to determine the accuracy of moisture modeling and make recommendations to ensure durable, efficient assemblies. Climate zones of the greatest interest are 4A, 5A, 6A, and 7. These zones experience both cooling and heating seasons as well as considerable humidity during the summer which will likely reduce the drying potential of the wall assemblies. Assemblies of the greatest interest include the following:

- **Brick walls plus interior insulation.** Builders are faced with the proper way to insulate brick masonry walls in both new construction and retrofit applications. Typical applications usually include an air space, framing, and batt insulation between the studs. Increasing insulation requirements and stricter air leakage targets are forcing builders to evaluate the best strategies while balancing costs and maximizing living space. Common solutions are to install foam (spray or rigid boards) between the studs and the brick, thereby increasing the R-value while maintaining the interior footprint. Several modeling studies have examined freeze-thaw cycles and condensation and moisture potential in these assemblies (Wilkinson et al. 2009; Khudaverdian 2007; Straube 2007; Tariku and Jumaran 2006; Sedlbauer and Kunzel 2000), but other than a study conducted by Said and colleagues (2003) from 1995 to 1997 on a brick wall retrofitted with interior insulation, little monitored data are available. Said's retrofit study did not involve any foam between the interior frame wall and the brick, as is being proposed here.

- **Superinsulated walls.** Walls with R-values in the R-40 to R-60 range are becoming more prevalent. Passive house and net zero energy home programs are a couple of driving forces behind the increased number of superinsulated walls. These walls can be constructed with a single insulation product or a hybrid of two or more products such as spray foam and blown-in cellulose or fiberglass. In a previous Building America special research project conducted by Straube and Smegal (2009), several different walls with R-values near 40 were evaluated in Climate Zone 6 using WUFI. The National Research Council Canada (NRCC) and the Cold Climate Housing Research Center are conducting research and performing monitoring in extreme cold climates on a variety of wall assemblies and R-values, but the research is limited to those climates, which affect a very small percentage of homeowners in the United States[3].
- **2009 International Energy Conservation Code compliant walls (spray foam insulation plus fiberglass batts).** In recent editions of the International Residential Code (IRC), minimum R-values for foam insulation have been specified when employing hybrid insulation strategies in ceilings and walls (IRC 2006). This is intended to prevent condensation from forming on the inside face of the foam. Table 601.3.1 in the 2009 IRC lists prescriptive R-values for exterior rigid insulation that must be met to eliminate an interior vapor barrier. A note under the table states that these same levels should be met if using spray foam inside the cavity. This has raised some questions in the industry. Some feel that these levels are too high; others believe that they are too low and could result in moisture problems within the wall cavities. The Spray Polyurethane Foam Alliance has teamed with CARB to analyze the condensation potential of these assemblies in climate zones 4–7 using WUFI. Field verification of these results is intended.

The goals of this study are to (1) evaluate predictions from WUFI and develop recommendations for the best combination of components for the listed wall assemblies and (2) to supplement existing guidelines for producing energy efficient, durable wall systems that meet the changing requirements of codes, new programs, and the construction industry.

1.2 Report Organization

This research report is organized into one main section and three subsequent subsections for each of the wall categories described in the previous section. The main section discusses the research methodology, basic software assumptions, limitations, and failure criteria. The main section aims to set the context for the reader before presenting a detailed explanation of wall constructions, analysis, and results.

Each subsequent section is based on a wall type: walls constructed to the minimum code requirements, superinsulated walls, and brick masonry walls. Wall construction details, relevant assumptions, results, and discussion specific to each assembly can be found in each of the respective sections.

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[3] http://www.gwscientific.com/cchrc/rtf_data/REMOTE/remote.html

2 Method

2.1 Modeling

2.1.1 Tools

Hygrothermal modeling was performed with WUFI, a computer-based moisture analysis tool that can predict the movement and accumulation of moisture in building components and materials. WUFI predicts moisture transfer by diffusion and capillary flow. It allows users to assess the effectiveness of the wall materials and constructions with respect to moisture flow and areas where condensation can occur.

To evaluate the thermal bridging effects of the framing members and the condensation potential at the intersection of the insulation and framing, CARB used THERM, which can model two-dimensional heat-transfer effects in buildings. Local temperature patterns in an assembly can be mapped in THERM, allowing the user to analyze the potential for condensation, moisture damage, and structural integrity. Using THERM, CARB evaluated the condensation potential of the framing/insulation intersections.

2.1.2 Boundary Conditions

WUFI offers several different methods for generating interior temperature and RH levels. For this study, the interior conditions for all three wall types were generated using the ASHRAE 160-2009 method. It should be noted that, in all climates, the interior RH levels predicted by this method reach 90% even though cooling was assumed. Using these interior conditions, WUFI predicts that there is the potential for mold growth on the interior surface of the drywall in all climates. Realistically, we know that this is not true. Except for bathrooms with inadequate ventilation, little mold is found on interior walls in any of these climates if no unusual circumstances are present. Because of this, several other methods of generating the interior conditions were analyzed, but all have drawbacks.

The most popular method used in other studies is to generate a sine curve where the interior conditions typically range from 68°F–72°F and 40% to 60% RH. A comparison of the results between ASHRAE 160-2009 interior conditions and the standard sine curve is provided for the code minimum walls as a point of reference. In dry climates this is probably too high an estimate of annual RH, and in moist climates it might be too low. It can be argued that in cold climates, hygrothermal analysis of these building assemblies should assume interior wintertime RH levels below 40% (Straube and Smegal 2009; Lstiburek 2004). Where this can be the case in older, leakier homes, homes built to today's code requirements or better could be seeing higher RH levels because of the tightness of the building shell, even when constructed with mechanical ventilation levels as prescribed in ASHRAE Standard 62.2 (2010). Data collected in an effort to validate the assumptions for the interior conditions in ASHRAE Standard 160-2009 (Arena et al. 2010) show a range of wintertime indoor RH levels in 20 different homes in climate zone 5 (mid-30% to mid-50% RH levels). Also, several professionals consulted recently who are actively monitoring homes built with lower than average natural air change rates have noted RH levels above 40%. Therefore, a conservative analysis has been provided in this study and sine curves with RH levels below 40% were not evaluated.

Table 1 displays the values input for the ASHRAE 160-2009 option in WUFI. Air conditioning was assumed in all climates.

Table 1. ASHRAE Standard 160-2009 Interior Boundary Conditions

Parameter	Assumption
Heating Set Point	70°F
Cooling Set Point	75°F
Floating Indoor Temperature Shift	5°F
Moisture Generation Rate (lb/h)	1.3
Air Exchange Rate (1/h)	0.2 (equivalent of standard construction)

The boundaries for the since curve were set to 68°F to 72°F and 40% to 60% RH. In addition to these boundary conditions, exterior and interior surface conditions were also defined. Table 2 displays the values used in the analysis.

Table 2. Exterior and Interior Surface Conditions Used in WUFI Analysis

Surface Condition	External Surface Conditions	Internal Surface Conditions
Heat Resistance ($h\cdot ft^2\cdot °F/Btu$)	0.334 (default)	0.71 (default)
Moisture Resistance (perm)	Zero (no coating)	10.7 (latex paint)
Radiation Absorption/ Emission	0.5/0.95 (oil paint, green, light)	n/a
Rainwater Absorption	0.7 (default)	n/a

2.1.3 Basic Assumptions

All simulations assume a 2,400-ft^2 house with three bedrooms and a volume of 19,200 ft^3. In order to maintain uniformity among the different climates and generate a worst-case scenario, all frame wall assemblies were assumed to be oriented north, eliminating the drying effects of the sun. The brick walls were oriented according to the worst-case scenario for driving rain. WUFI allows the user to select a representative warm year weather file or a representative cold year. These files are based on the years in the warmest and coldest tenth percentile of the weather data available. This analysis was based on the cold year weather files.

Table 3. Climate Zones and Representative Cities

Climate Zone	Representative City
4A	Nashville, Tennessee
4B	Albuquerque, New Mexico
4C	Seattle, Washington
5A	Detroit, Michigan
5B	Elko, Nevada
6A	Madison, Wisconsin
6B	Billings, Montana
7A	International Falls, Minnesota

The temperature and moisture content of the construction layers were assumed to be constant across the layers at the start of the simulation. Initial temperature and relative humidity within each component were assumed to be 68°F and 80% respectively (representative of building materials during the construction phase).

All the simulations were run for a period of three consecutive years beginning on October 1, 2011 (1,095 days/26,280 h). This run time allows for the wall to acclimatize and reduces the effects of the assumed initial moisture content and temperature within the wall assembly.

2.2 Failure Criteria

CARB researched and analyzed currently accepted failure criteria for moisture levels in walls. While these are the cited in research and manuals on moisture performance in building assemblies, there are concerns with many of them. These concerns are explained in the General Discussion section at the end of this report. For completeness, all walls were evaluated with respect to the following thresholds and/or considerations.

2.2.1 Moisture Content in Oriented Strand Board (Rot/Decay)

It is often quoted that that the minimum MC requirement for the growth of fungi is approximately 20% in wood corresponding to about 80%- 90% RH (Siau 1984). Decay generally occurs above 90%–95% at 68°F (ASTM 2001). The minimum, maximum and average MC of the OSB sheathing was calculated for each wall and evaluated against these thresholds.

2.2.2 Assembly Moisture Content

The initial and final moisture content for the entire assembly was evaluated for each wall over a 3-year period. The desired result was that the final moisture content was less than the initial at the end of the modeling period indicating that the walls have the potential to dry out over time.

2.2.3 Condensation Potential

2.2.3.1 WUFI

Condensation potential within the wall was evaluated by comparing the interior air dew point temperature to the surface temperature of the potential condensing layer(s). If the surface temperature of the material is lower than the dew point temperature of the air (Straube and Smegal 2009), condensation is likely to occur: the longer the period during which the surface temperature falls below the air dew point temperature, the greater the risk for damage. The critical juncture analyzed was the first condensing surface in each assembly.

Based on the indoor boundary conditions, the dew point was calculated on an hourly basis for the entire 3-year modeling period. The surface temperature of the condensing surface was then compared to that dew point. The percentage of time that the surface temperature fell below the dew point was calculated and tabulated for each wall.

2.2.3.2 THERM

THERM was used to evaluate the condensation potential at the studs. The analysis was conducted at interior temperatures of 70°F and 68°F in order to compare the results to both the ASHRAE 160-2009 and the sine curve interior conditions. Exterior boundary conditions used for this analysis were calculated by averaging the mean temperatures for each climate for the months of December, January and February. Outdoor average temperatures for each of the three months and the corresponding overall averages are shown in Table 4.

Table 4. Average Outdoor Winter Temperature for Climate Files Evaluated[a]

Climate Zone	Climate File	December (°F)	January (°F)	February (°F)	Average (°F)
4A	Nashville, Tennessee	36.3	36.5	41.4	38.1
4B	Albuquerque, New Mexico	36.7	39.7	35.8	37.4
4C	Seattle, Washington	40.1	42.4	41.7	41.4
5A	Detroit, Michigan	24.3	25.3	30.0	26.5
5B	Elko, Nevada	23.2	32.5	25.7	27.1
6A	Madison, Wisconsin	14.7	19.6	19.8	18.0
6B	Billings, Montana	23.9	27.9	28.4	26.7
7	International Falls, Minnesota	1.6	11.3	5.7	6.2

[a] See http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data2.cfm/region=4_north_and_central_america_wmo_region_4.

2.2.4 ASHRAE Criteria

In 2009, ASHRAE published ASHRAE Standard 160-2009 *Criteria for Moisture-Control Design Analysis in Buildings.* This standard sets the performance criteria to minimize problems associated with moisture in building envelope assemblies.

The standard specifies that the following conditions be met: A 30-day running average surface RH <80% when the 30-day running average surface temperature is between 41°F and 104°F.

This threshold applies to all materials and surfaces in the building envelope except the exterior surface. The first condensing surface in each assembly analyzed was chosen as the surface to be evaluated with this criterion.

Surface temperature and RH of the first condensing surface was averaged over a 30-day period and compared to the ASHRAE 160-2009 limits.

2.2.5 Isopleths

Graphs called isopleths were created for each of the walls to identify potential mold growth on the interior surface of the wall assembly and the interior face of the condensing surface. An isopleth system captures the germination time and growth rates of mold based on humidity and temperature. WUFI assigns a lowest isopleth for mold (LIM), which is the temperature-dependent, lowest RH under which no fungus activity is expected.

Figure 1 shows a graph with limiting isopleths. Each point in this graph represents the hygrothermal conditions at the interior surface of the assembly at a certain time. The color of the dots changes with time. For the isopleth in Figure 1, at the start of the calculation the dot color is red. It turns to green and finally blue at the end of the 3-year calculation period.

LIM B I and LIM B II refer to limiting isopleth for specific fungi and substrate classes. If the conditions lie above the limiting isopleths, mold growth could be possible, but additional criteria evaluation is required for a firm assessment.

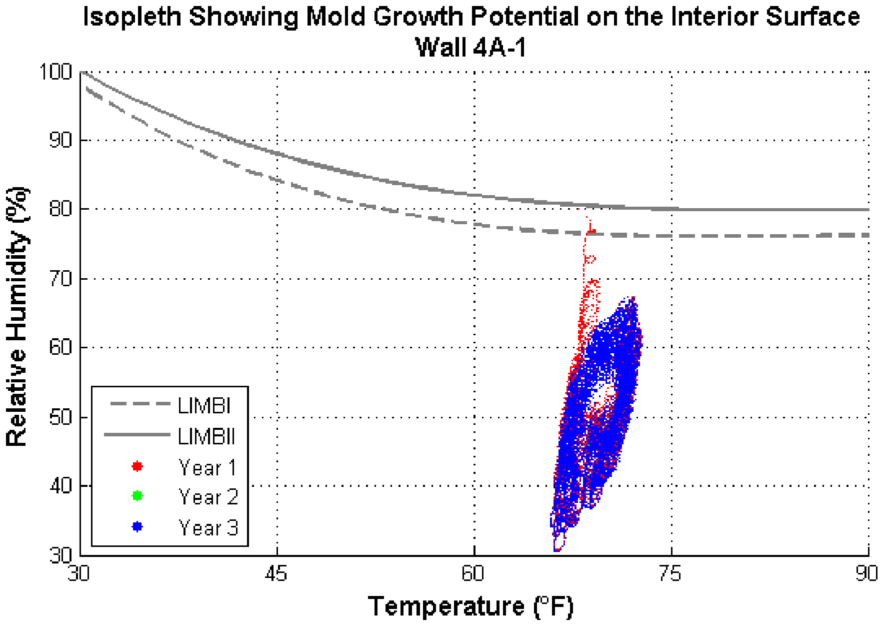

Figure 1. Isopleth graph for wall 4A1 predicting no potential for mold growth on the interior face of the drywall over a 3-year period

3 Code Minimum Walls

3.1 Introduction

In recent editions of the IRC, minimum R-values for foam insulation have been specified when employing hybrid insulation strategies in ceilings and walls. These levels are intended to prevent condensation from forming on the inside face of the foam. Table 601.3.1 in the 2009 IRC lists prescriptive R-values for exterior rigid insulation that must be met if a Class III vapor retarder is intended. A footnote under the table states that these same levels should be met if using spray foam (with a minimum density of 2 lb/ft^3) inside the cavity.

These required levels have raised some questions in the industry. Some feel that these levels are too high; others believe that they are too low and could result in moisture problems within the wall cavities. The Spray Polyurethane Foam Alliance hired Steven Winter Associates, Inc. (leader of the BA team CARB) to analyze the potential for moisture problems in hybrid wall assemblies in climate zones 4–7. Various levels of medium-density (2 lb/ft^3) spray polyurethane foam (MDSPF; installed against the inside face of the exterior sheathing) in combination with blown fiberglass cavity insulation were analyzed. All analysis methods and results of this study are explained in detail in this report.

3.2 Wall Construction Details

Figure 2 shows the typical detail for the walls analyzed in this section. The stud size and minimum level of MDSPF vary depending on the climate zone being analyzed.

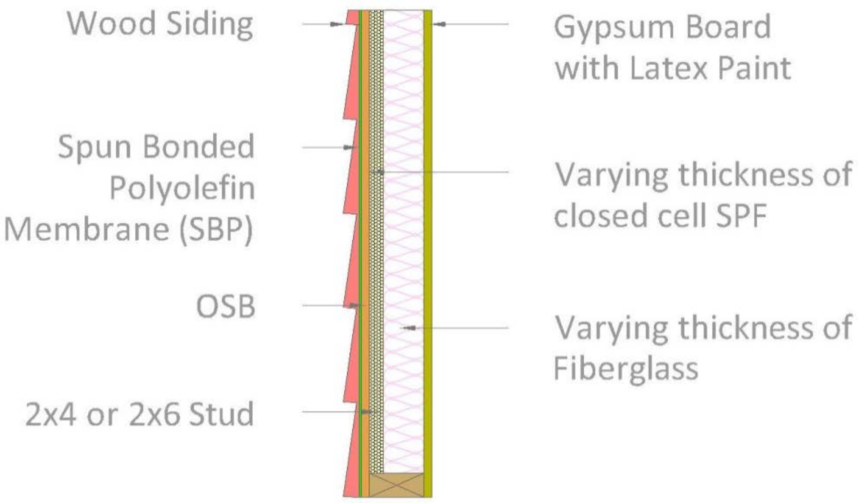

Figure 2 Typical wall construction for the walls built to code; cavity depth and foam levels vary depending on the climate

Table 5 lists each wall analyzed in WUFI and shows the specific climate and weather file used. The R-values of the MDSPF, fiberglass, and the total cavity R-value are also provided along with the percentage of the total R-value that the MDSPF contributes. The MDSPF R-value was based on 2 lb foam with an R-value of 6.5/in. The minimum level of foam was determined from Table 601.3.1 in the IRC. Fiberglass insulation with an R-value of 4/in. was then assumed to fill the remainder of the cavity. Each of the three vapor retarder classes was analyzed. Values assumed for modeling were as follows:

- Class III: 10.7 perm (latex paint)
- Class II: 1.0 perm (kraft-faced batt)
- Class I: 0.1 perm (sheet polyethylene).

Table 5. Code Built Wall Assemblies Evaluated

Wall ID	Vapor Retarder Perm Rating	MDSPF R-Value	Fiberglass R-Value	Total R-Value	MDSPF % of Total R-Value
	(perm-in)	(h·ft^2·°F/Btu)	(h·ft^2·°F/Btu)	(h·ft^2·°F/Btu)	
4A: Nashville, Tennessee					
4A-1	10.7	2.50	12.46	15.0	17
4A-2	10.7	4.13	11.46	15.6	26
4A-3	10.7	5.75	10.46	16.2	35
4A-4	10.7	7.38	9.46	16.8	44
4A-5	1.0	2.50	12.46	15.0	17
4A-6	1.0	4.13	11.46	15.6	26
4A-7	1.0	5.75	10.46	16.2	35
4A-8	1.0	7.38	9.46	16.8	44
4A-9	0.1	2.50	12.46	15.0	17
4A-10	0.1	4.13	11.46	15.6	26
4A-11	0.1	5.75	10.46	16.2	35
4A-12	0.1	7.38	9.46	16.8	44
4B: Albuquerque, New Mexico					
4B-1	10.7	2.50	12.46	15.0	17
4B-2	10.7	4.13	11.46	15.6	26
4B-3	10.7	5.75	10.46	16.2	35
4B-4	10.7	7.38	9.46	16.8	44
4B-5	1.0	2.50	12.46	15.0	17
4B-6	1.0	4.13	11.46	15.6	26
4B-7	1.0	5.75	10.46	16.2	35
4B-8	1.0	7.38	9.46	16.8	44
4B-9	0.1	2.50	12.46	15.0	17
4B-10	0.1	4.13	11.46	15.6	26
4B-11	0.1	5.75	10.46	16.2	35
4B-12	0.1	7.38	9.46	16.8	44

Wall ID	Vapor Retarder Perm Rating	MDSPF R-Value	Fiberglass R-Value	Total R-Value	MDSPF % of Total R-value
	(perm-in)	(h·ft^2·°F/Btu)	(h·ft^2·°F/Btu)	(h·ft^2·°F/Btu)	
4C: Seattle, Washington[3]					
4C-1	10.7	3.75	19.69	23.4	16
4C-2	10.7	5.38	18.69	24.1	22
4C-3	10.7	7.00	17.69	24.7	28
4C-4	10.7	8.63	16.69	25.3	34
4C-5	1.0	3.75	19.69	23.4	16
4C-6	1.0	5.38	18.69	24.1	22
4C-7	1.0	7.00	17.69	24.7	28
4C-8	1.0	8.63	16.69	25.3	34
4C-9	0.1	3.75	19.69	23.4	16
4C-10	0.1	5.38	18.69	24.1	22
4C-11	0.1	7.00	17.69	24.7	28
4C-12	0.1	8.63	16.69	25.3	34
5A: Detroit, Michigan					
5A-1	10.7	7.50	17.38	24.9	30
5A-2	10.7	9.13	16.38	25.5	36
5A-3	10.7	10.75	15.38	26.1	41
5A-4	10.7	12.38	14.38	26.8	46
5A-5	1.0	7.50	17.38	24.9	30
5A-6	1.0	9.13	16.38	25.5	36
5A-7	1.0	10.75	15.38	26.1	41
5A-8	1.0	12.38	14.38	26.8	46
5A-9	0.1	7.50	17.38	24.9	30
5A-10	0.1	9.13	16.38	25.5	36
5A-11	0.1	10.75	15.38	26.1	41
5A-12	0.1	12.38	14.38	26.8	46
5B: Elko, Nevada					
5B-1	10.7	7.50	17.38	24.9	30
5B-2	10.7	9.13	16.38	25.5	36
5B-3	10.7	10.75	15.38	26.1	41
5B-4	10.7	12.38	14.38	26.8	46
5B-5	1.0	7.50	17.38	24.9	30
5B-6	1.0	9.13	16.38	25.5	36
5B-7	1.0	10.75	15.38	26.1	41
5B-8	1.0	12.38	14.38	26.8	46
5B-9	0.1	7.50	17.38	24.9	30
5B-10	0.1	9.13	16.38	25.5	36
5B-11	0.1	10.75	15.38	26.1	41
5B-12	0.1	12.38	14.38	26.8	46

Wall ID	Vapor Retarder Perm Rating	MDSPF R-Value	Fiberglass R-Value	Total R-Value	MDSPF % of Total R-Value
	(perm-in)	(h·ft²·°F/Btu)	(h·ft²·°F/Btu)	(h·ft²·°F/Btu)	
6A: Madison, Wisconsin					
6A-1	10.7	11.25	15.08	26.3	43
6A-2	10.7	12.88	14.08	27.0	48
6A-3	10.7	14.50	13.08	27.6	53
6A-4	1.0	11.25	15.08	26.3	43
6A-5	1.0	12.88	14.08	27.0	48
6A-6	1.0	14.50	13.08	27.6	53
6A-7	0.1	11.25	15.08	26.3	43
6A-8	0.1	12.88	14.08	27.0	48
6A-9	0.1	14.50	13.08	27.6	53
6B: Billings, Montana					
6B-1	10.7	11.25	15.08	26.3	43
6B-2	10.7	12.88	14.08	27.0	48
6B-3	10.7	14.50	13.08	27.6	53
6B-4	1.0	11.25	15.08	26.3	43
6B-5	1.0	12.88	14.08	27.0	48
6B-6	1.0	14.50	13.08	27.6	53
6B-7	0.1	11.25	15.08	26.3	43
6B-8	0.1	12.88	14.08	27.0	48
6B-9	0.1	14.50	13.08	27.6	53
7: International Falls, Minnesota					
7-1	10.7	15.00	12.77	27.8	54
7-2	10.7	16.63	11.77	28.4	59
7-3	10.7	18.25	10.77	29.0	63
7-4	1.0	15.00	12.77	27.8	54
7-5	1.0	16.63	11.77	28.4	59
7-6	1.0	18.25	10.77	29.0	63
7-7	0.1	15.00	12.77	27.8	54
7-8	0.1	16.63	11.77	28.4	59
7-9	0.1	18.25	10.77	29.0	63

3.3 Results

3.3.1 Moisture Content in Oriented Strand Board (Rot/Decay)

Based on the construction and conditions outlined in the previous section, the maximum MC of the OSB in most of the cases modeled did not exceed 20%. Drying was seen over the 3-year period as shown in Figure 3 and Figure 4. Failures only occurred in climate zone 4C in the wall with the lowest level of foam and Class III vapor retarders (4C-1) when using the ASHRAE 160-2009 interior conditions. The OSB in this wall also increased in MC over the 3-year period.

The highest MCs were recorded in the marine C and moist A zones with only 4C exceeding 20% during the 3-year period (Figure 3). The highest MC levels occurred during the first year of the simulation, in the assemblies with the lowest levels of foam, and in the walls with the Class III vapor retarder.

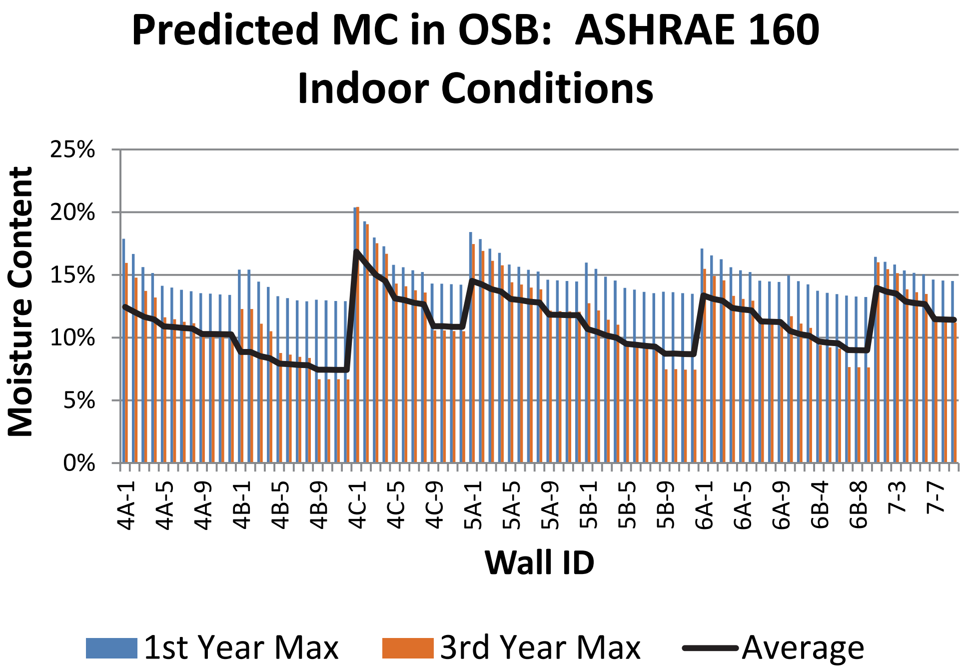

Figure 3. Predicted moisture content in OSB: ASHRAE 160-2009 interior conditions

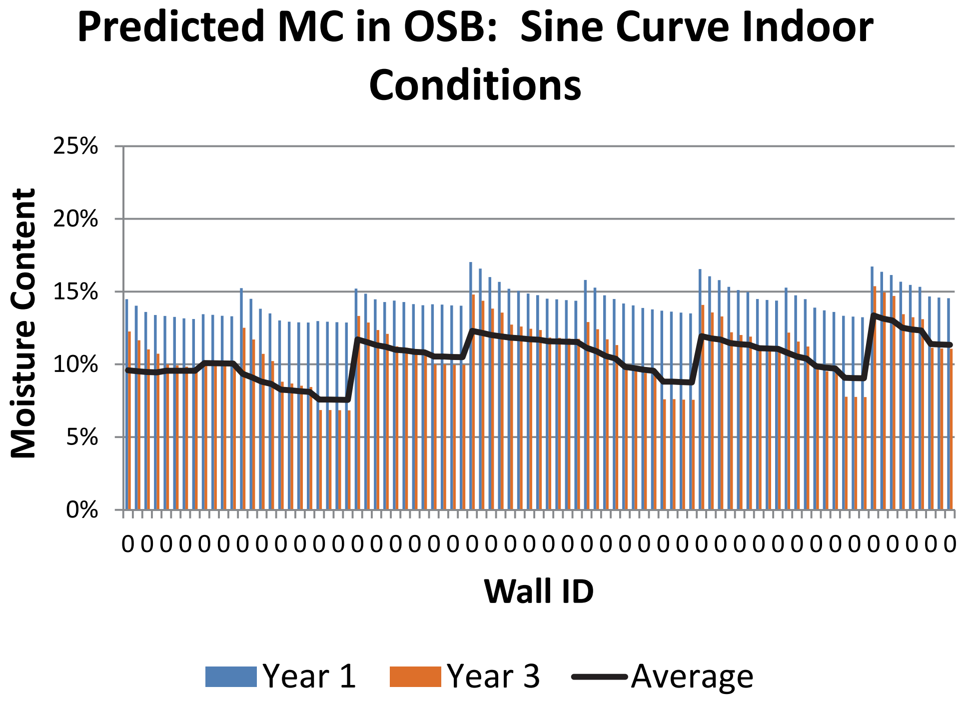

Figure 4. Predicted moisture content in OSB: sine curve interior conditions

Figure 5 shows a direct comparison of the results for the ASHRAE 160-2009 and the sine curve interior conditions. Although there is fairly good agreement between the two methods for the dry B zones, there is a significant difference in predictions in the moist A and marine C zones. The largest disparity is in the marine climate. In general, using the ASHRAE 160-2009 interior conditions results in MC predictions that are significantly higher in the A zones and slightly lower in the dry climates than the MC predictions using the typical sine curve. This difference becomes less significant as the climates get colder.

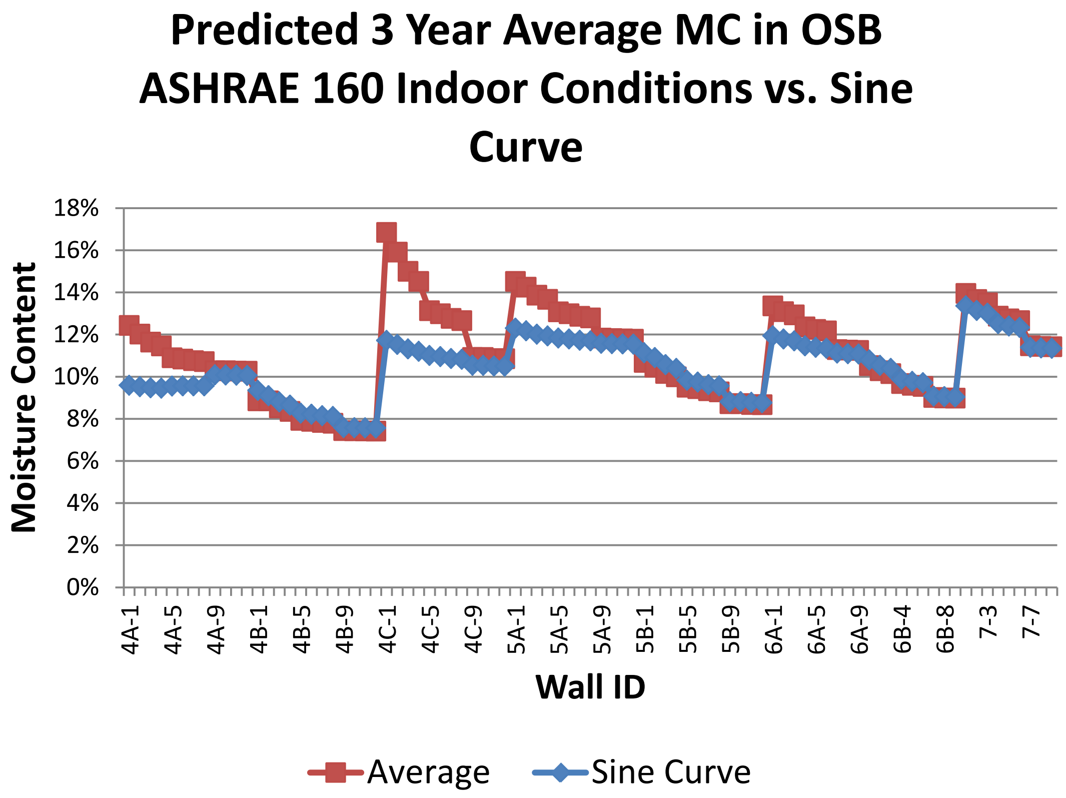

Figure 5. Comparison of OSB MC using ASHRAE 160-2009 and sine curve interior conditions

3.3.2 Assembly Moisture Content

The initial and final MCs for the entire assembly were evaluated for each case. Using both methods for generating the interior conditions, the final MC was lower than the initial for all the walls evaluated, indicating that the assemblies dried out over the 3-year period.

Figure 6 shows the difference in predicted assembly MC over the 3-year modeling period for both the ASHRAE 160-2009 and the sine curve interior conditions. Results are consistent with those of the OSB MC predictions. Using the ASHRAE 160-2009 method, less drying is predicted over the 3-year period for the moist A regimes than when using the sine curve. Inversely, more drying is predicted for the dry regimes when using ASHRAE 160-2009 than when using the sine curve. Again, the differences in predictions between the two methods are more severe in the moist climates. The differences in the marine C zone are by far the most drastic.

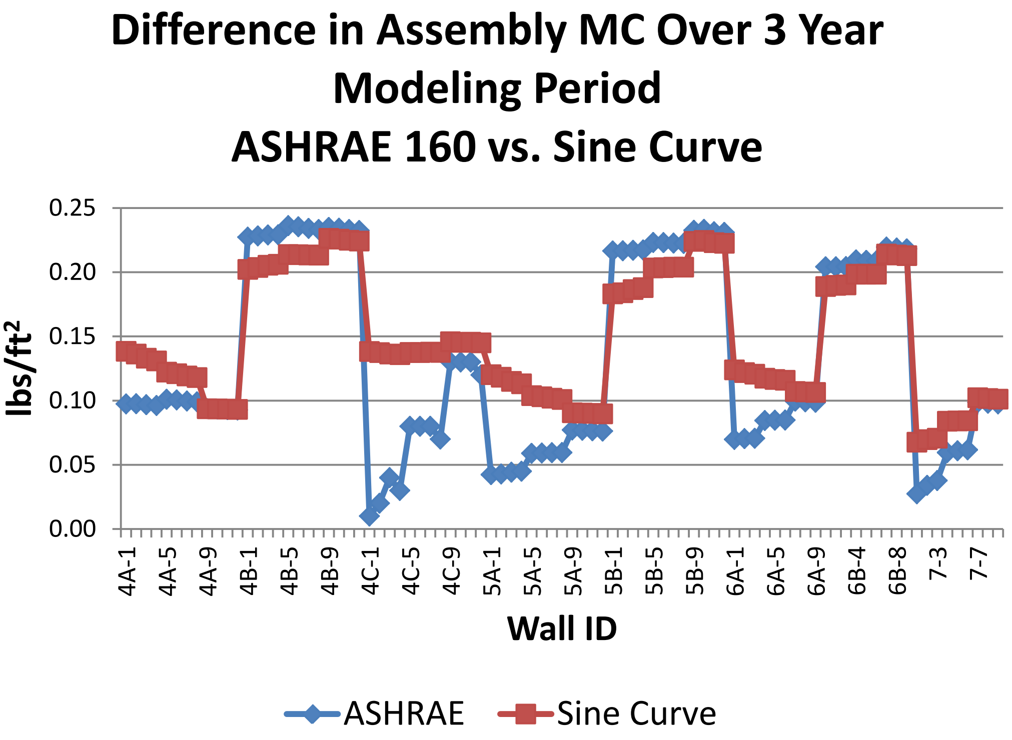

Figure 6. Difference in predicted assembly MC from beginning to end of modeling period: ASHRAE 160-2009 versus sine curve interior conditions

3.3.3 Condensation Potential

Using the hourly results from WUFI and isotherms from THERM, CARB analyzed the condensation potential for each wall. The MDSPF/fiberglass interface was the critical juncture analyzed. Results from WUFI indicate that all walls in the study show some potential for condensation at the interior face of the MDSPF. Figure 7 illustrates the condensation potential for each case as predicted by WUFI when the sine curves are used to predict indoor conditions versus the ASHRAE 160-2009 indoor conditions.

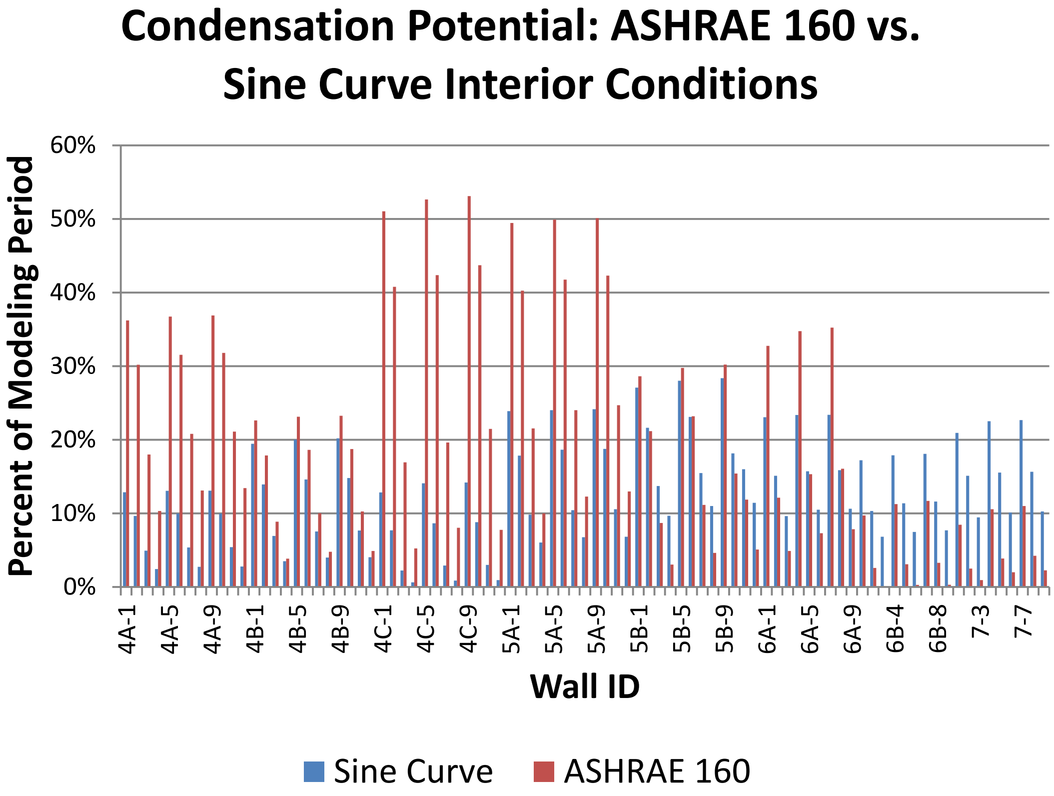

Figure 7. Condensation potential for the different levels of MDSPF for two different sets of indoor conditions: sine curve and the ASHRAE 160-2009 method

Perm rating of the vapor retarder had little effect on the condensation potential because this analysis assumes that interior air is the vehicle for supplying moisture to the condensing surface, not diffusion. Interior moisture conditions and R-value of the spray foam were the driving factors.

Again, agreement in the dry climates is fairly good. Unlike all the other zones, however, the ASHRAE 160-2009 conditions result in a lower predicted condensation potential than the sine curve in climate zones 6B and 7. Interior RH levels in those two zones dip into the upper 20% range using ASHRAE 160-2009, but are held to a minimum of 40% with the sine curve. Disparity between the two methods of generating the interior conditions is quite high in the moist climates, especially the warmer climates and the marine climate.

Although little guidance is available on what level of condensation is acceptable, walls in climate zones 4A, 4C, 5A, and 6A appear to be at the highest risk.

Table 6 summarizes the temperatures used in THERM and the resulting temperatures of the condensing surfaces: the interior face of the MDSPF in the center of the cavity and at the stud. Using the hourly results from the WUFI files with the ASHRAE 160-2009 interior conditions, the average dew point temperature for each climate was calculated for the 3 coldest months.

Climate zones 4A, 4C, 5A, 5B, and 6A show risks of condensation potential with these boundary conditions because the interior face of the MDSPF and the stud are predicted to be below the dew point temperatures. The interior air dew point from the sine curve analysis is approximately 45°F. Based on that temperature, walls in 4A and 4C see a reduced risk for condensation, but the walls in 6A, 6B, and 7 would be at greater risk.

Table 6. THERM Analysis of Temperatures at the Interior Face of the MDSPF at the Center of the Cavity and at the Stud

Climate Zone	Climate File	Average Outdoor Temperature (°F)	Average Dew Point Temperature (December, January, February) (°F)	Interior Surface of MDSPF (°F)	Stud Temperature at Interior Surface of MDSFP (°F)
4A	Nashville, Tennessee	38	51	**46**	**46**
4B	Albuquerque, New Mexico	37	45	46	46
4C	Seattle, Washington	41	52	**48**	**48**
5A	Detroit, Michigan	27	45	**42**	**40**
5B	Elko, Nevada	27	45	**42**	**41**
6A	Madison, Wisconsin	18	42	**41**	**39**
6B	Billings, Montana	27	43	46	44
7	International Falls, Minnesota	6	39	41	38

Considering that these results are based on average values for the 3 coldest months, it can be concluded that 50% of the time, the outdoor temperatures will fall below the averages listed, resulting in lower interior wall surface temperatures than those listed. These values support the WUFI results that all the walls have some potential for condensation based on the lowest levels of foam required by the code.

According to both WUFI and THERM, walls of particular concern are 4A, 4C, 5A, 5B, and 6A. For these five sites, the interior surface of the MDSPF in the walls with the lowest levels of MDSPF is predicted to condense close to or above 30% of the year when the dew point is calculated based on the interior air temperature and RH.

3.3.4 ASHRAE Criteria

Based on the raw data, only 7 of the 87 walls pass the ASHRAE conditions using the customized sine curves and only 3 pass using ASHRAE 160-2009 conditions when cooling is assumed.

After looking at the results in more detail, it was determined that a significant percentage of the failures occurred in the first year at the very beginning of the modeling period. This is partly because the initial MC of the walls is assumed to be high at the time of construction. In addition to that, the modeling period begins in October, a cool month, reducing drying potential. Many of the walls dry out enough to pass the criteria in the first month or so. It should be noted that almost all the walls with the Class III vapor retarder fail the 30-day criteria using both methods to generate the interior conditions. Figure 8 shows which walls fail the ASHRAE 160-2009 criteria and to what extent.

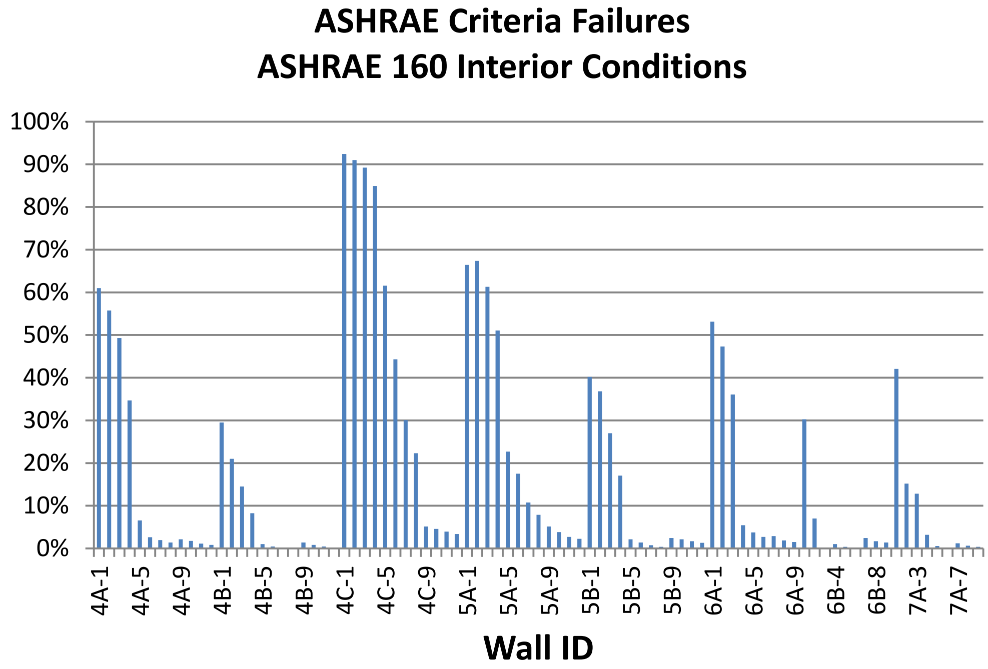

Figure 8. Percentage of the total number of averages that each wall failed the ASHRAE 160-2009 criteria: ASHRAE 160-2009 interior conditions

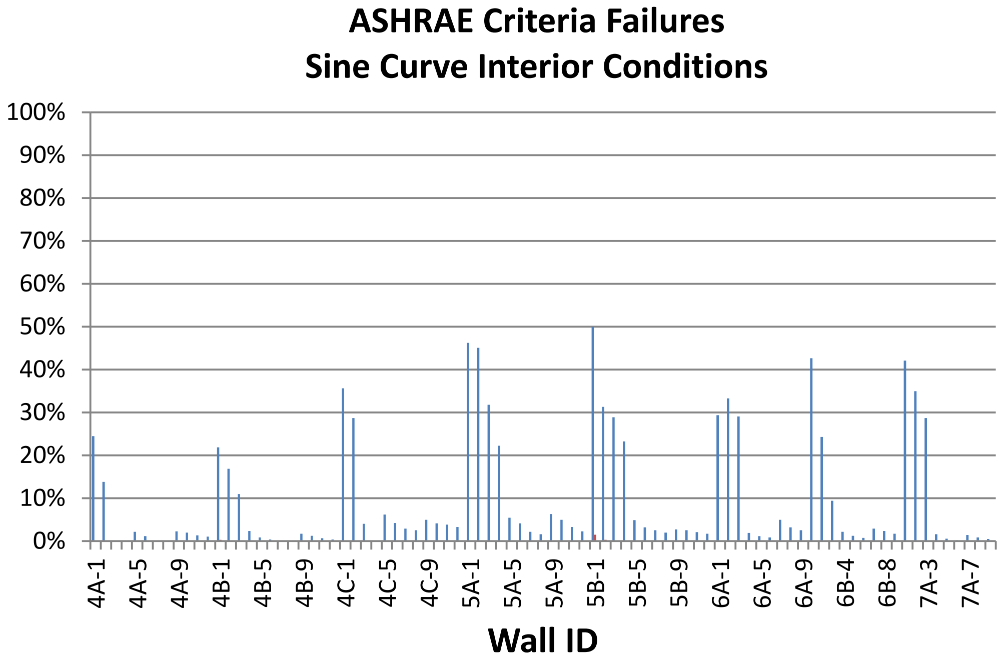

Figure 9. Percentage of the total number of averages that each wall failed the ASHRAE 160-2009 criteria: sine curve interior conditions

3.3.5 Isopleths

For all walls in climate zones 4A, 4C, 5A, 6A, and 7, the ASHRAE 160-2009 indoor conditions result in isopleths that indicate the potential for mold on both the interior surface of the drywall and the interior face of the MDSPF. For climates 4B, 5B, and 6B no mold growth is predicted for the interior of the drywall. Mold growth is predicted on the interior face of the MDSPF for all walls with a Class III vapor retarder.

3.3.6 Results Summary for Code Built Walls

Table 7 summarizes all the results of the analysis performed on the walls described in this section. Entries located in white rows were modeled with a Class III vapor retarder, light blue indicates a Class II vapor retarder, and dark blue represents a Class I vapor retarder. A red “X” denotes a failure in that category. As noted earlier, when evaluating the hygrothermal performance of these walls in the dry B climate zones, there is fairly good agreement between the predictions from the two methods of generating the interior boundary conditions. The difference between the two methods in the moist A and marine C zones, however, is fairly drastic.

Table 7. Results Summary for Code Built Walls

	Sine Wave (69.8°F ± 1.8°F, 50% RH ± 10%)						ASHRAE 160-2009, Cooling Assumed					
	ASHRAE Criteria	OSB MC	Assembly MC	Isopleths, Interior	Isopleths, MDSPF	Condensation Potential (%)	ASHRAE Criteria	OSB MC	Assembly MC	Isopleths, Interior	Isopleths, MDSPF	Condensation Potential (%)
4A-1	X	√	√	√	X	13	X	√	√	X	X	36
4A-2	X	√	√	√	X	10	X	√	√	X	X	30
4A-3	√	√	√	√	X	5	X	√	√	X	X	18
4A-4	√	√	√	√	X	2	X	√	√	X	X	10
4A-5	√	√	√	√	X	13	X	√	√	X	X	37
4A-6	√	√	√	√	X	10	√	√	√	X	X	32
4A-7	√	√	√	√	√	5	√	√	√	X	X	21
4A-8	√	√	√	√	√	3	√	√	√	X	X	13
4A-9	√	√	√	√	X	13	√	√	√	X	X	37
4A-10	√	√	√	√	X	10	√	√	√	X	X	32
4A-11	√	√	√	√	X	5	√	√	√	X	X	21
4A-12	√	√	√	√	X	3	√	√	√	X	X	13
4B-1	X	√	√	√	X	19	X	√	√	√	X	23
4B-2	X	√	√	√	X	14	X	√	√	√	X	18
4B-3	X	√	√	√	X	7	X	√	√	√	X	9
4B-4	√	√	√	√	X	3	X	√	√	√	X	4
4B-5	√	√	√	√	√	20	√	√	√	√	√	23
4B-6	√	√	√	√	√	15	√	√	√	√	√	19
4B-7	√	√	√	√	√	8	√	√	√	√	√	10
4B-8	√	√	√	√	√	4	√	√	√	√	√	5
4B-9	√	√	√	√	X	20	√	√	√	√	X	23
4B-10	√	√	√	√	√	15	√	√	√	√	X	19
4B-11	√	√	√	√	√	8	√	√	√	√	√	10
4B-12	√	√	√	√	√	4	√	√	√	√	√	5
4C-1	X	√	√	√	X	13	X	X	√	X	X	62
4C-2	X	√	√	√	X	8	X	√	√	X	X	58
4C-3	√	√	√	√	X	2	X	√	√	X	X	49
4C-4	√	√	√	√	X	1	X	√	√	X	X	41

	Sine Wave (69.8°F ± 1.8°F, 50% RH ± 10%)						ASHRAE 160-2009, Cooling Assumed					
	ASHRAE Criteria	OSB MC	Assembly MC	Isopleths, Interior	Isopleths, MDSPF	Condensation Potential (%)	ASHRAE Criteria	OSB MC	Assembly MC	Isopleths, Interior	Isopleths, MDSPF	Condensation Potential (%)
4C-5	X	√	√	√	X	14	X	√	√	X	X	62
4C-6	√	√	√	√	√	9	√	√	√	X	X	58
4C-7	√	√	√	√	√	3	√	√	√	X	X	50
4C-8	√	√	√	√	√	1	√	√	√	X	X	42
4C-9	√	√	√	√	X	14	√	√	√	X	X	63
4C-10	√	√	√	√	X	9	√	√	√	X	X	59
4C-11	√	√	√	√	X	3	√	√	√	X	X	50
4C-12	√	√	√	√	√	1	√	√	√	X	X	43
5A-1	X	√	√	√	X	24	X	√	√	X	X	49
5A-2	X	√	√	√	X	18	X	√	√	X	X	40
5A-3	X	√	√	√	X	10	X	√	√	X	X	22
5A-4	X	√	√	√	X	6	X	√	√	X	X	10
5A-5	X	√	√	√	X	24	X	√	√	X	X	50
5A-6	√	√	√	√	X	19	X	√	√	X	X	42
5A-7	√	√	√	√	X	10	X	√	√	X	X	24
5A-8	√	√	√	√	√	7	X	√	√	X	X	12
5A-9	X	√	√	√	X	24	X	√	√	X	X	50
5A-10	√	√	√	√	X	19	√	√	√	X	X	42
5A-11	√	√	√	√	X	11	√	√	√	X	X	25
5A-12	√	√	√	√	X	7	√	√	√	X	X	13
5B-1	X	√	√	√	X	27	X	√	√	√	X	29
5B-2	X	√	√	√	X	22	X	√	√	√	X	21
5B-3	X	√	√	√	X	14	X	√	√	√	X	9
5B-4	X	√	√	√	X	10	X	√	√	√	X	3
5B-5	√	√	√	√	X	28	√	√	√	√	X	30
5B-6	√	√	√	√	X	23	√	√	√	√	X	23
5B-7	√	√	√	√	X	15	√	√	√	√	√	11
5B-8	√	√	√	√	√	11	√	√	√	√	√	5
5B-9	√	√	√	√	X	28	√	√	√	√	X	30

	Sine Wave (69.8°F ± 1.8°F, 50% RH ± 10%)						ASHRAE 160-2009, Cooling Assumed					
	ASHRAE Criteria	OSB MC	Assembly MC	Isopleths, Interior	Isopleths, MDSPF	Condensation Potential (%)	ASHRAE Criteria	OSB MC	Assembly MC	Isopleths, Interior	Isopleths, MDSPF	Condensation Potential (%)
5B-10	√	√	√	√	X	18	√	√	√	√	√	15
5B-11	√	√	√	√	X	16	√	√	√	√	√	12
5B-12	√	√	√	√	X	11	√	√	√	√	√	5
6A-1	X	√	√	√	X	23	X	√	√	X	X	33
6A-2	X	√	√	√	X	15	X	√	√	X	X	12
6A-3	X	√	√	√	X	10	X	√	√	X	X	5
6A-4	√	√	√	√	X	23	X	√	√	X	X	35
6A-5	√	√	√	√	√	16	√	√	√	X	X	15
6A-6	√	√	√	√	√	10	√	√	√	X	X	7
6A-7	√	√	√	√	X	23	√	√	√	X	X	35
6A-8	√	√	√	√	X	16	√	√	√	X	X	16
6A-9	√	√	√	√	X	11	√	√	√	X	X	8
6B-1	X	√	√	√	X	17	X	√	√	√	X	10
6B-2	X	√	√	√	X	10	X	√	√	√	X	3
6B-3	X	√	√	√	X	7	√	√	√	√	X	0
6B-4	√	√	√	√	√	18	√	√	√	√	√	11
6B-5	√	√	√	√	√	11	√	√	√	√	√	3
6B-6	√	√	√	√	√	7	√	√	√	√	√	0
6B-7	√	√	√	√	X	18	√	√	√	√	√	12
6B-8	√	√	√	√	X	12	√	√	√	√	√	3
6B-9	√	√	√	√	X	8	√	√	√	√	√	0
7-1	X	√	√	√	X	21	X	√	√	X	X	8
7-2	X	√	√	√	X	15	X	√	√	X	X	2
7-3	X	√	√	√	X	9	X	√	√	X	X	1
7-4	√	√	√	√	√	23	√	√	√	X	X	11
7-5	√	√	√	√	√	16	√	√	√	X	X	4
7-6	√	√	√	√	√	10	√	√	√	X	X	2
7-7	√	√	√	√	X	23	√	√	√	X	X	11
7-8	√	√	√	√	√	16	√	√	√	X	X	4
7-9	√	√	√	√	√	10	√	√	√	X	X	2

3.4 Discussion

3.4.1 Comparison to Fiberglass-Only Insulation

Although the results show many failures, conclusions should not be drawn without comparison to a typical code wall. How do commonly constructed, 2 × 6 walls with only fiberglass batts in the cavities compare to the walls analyzed in this study?

To answer this question, CARB ran the same type of analysis on a code wall in climate zone 5A, which is one of the more problematic zones with respect to moisture control. Condensation potential, ASHRAE 30-day averages, total assembly MC, and MC in the OSB were evaluated for a code built, 2 × 6 wall with R-20, kraft-faced fiberglass batts in the cavity and no MDSPF. The kraft facing on the fiberglass is considered a Class II vapor retarder and was modeled as having a rating of 1 perm. It is mandatory in climate zone 5A that walls without exterior rigid insulation or 2 lb foam in the cavity be constructed with either a Class I or Class II vapor retarder if they do not have an approved vented cladding. Other than this, the construction is similar to the other walls in this section. The results are displayed in Table 8.

Table 8. Comparison of Failure Criteria Results for Climate Zone 5A: R-20, Fiberglass Batt Code Wall Versus R-25 Hybrid Wall with MDSPF and Blown Fiberglass

		Fiberglass Only	**MDSPF + Fiberglass**	
Wall Details	Wall ID	5A-R20	5A-1	5A-5
	MDSPF R-value	0	7.5	7.5
	Fiberglass batt R-value	20	17.38	17.38
	Perm Rating	1	10.7	1
ASHRAE Criterion	30-day moving average	Fail	Fail	Fail
OSB MC %	average over 3 years	14	15	13
ASHRAE Criteria (%)	Maximum over 3 years	17	18	16
OSB MC % **Assembly MC (lb/ft^2)**	Decreasing?	Yes	Yes	Yes
	Start	0.380	0.375	0.375
	Finish	0.326	0.333	0.316
Assembly MC (lb/ft^2) **Condensation Potential**	Decreasing?	Yes	Yes	Yes
	Number of hours over 3 years	18,084	12,995	13,113
	% over 3 years	69	49	50
Isopleths	Interior and condensing surfaces	Yes	Yes	Yes

Note that the interior face of the OSB on the fiberglass-only case was assumed to be the condensing surface. On the hybrid walls, the interior face of the MDSPF was assumed to be the condensing surface. Consequently, condensation potential and ASHRAE 160-2009 criteria were evaluated at those respective surfaces.

Two walls containing MDSPF were compared to the fiberglass-only case. The first, wall 5A-1, is a code minimum wall, containing the least amount of MDSPF that can be installed when combined with a Class III vapor retarder. Wall 5A-5 also has the minimum level of spray foam (R-7.5 MDSPF), but is coupled with a Class II (1 perm) vapor retarder.

Note that all fail the 30-day average ASHRAE 160-2009 criteria, but the MDSPF wall with the Class III retarder fails all 3 of the 160 averages. In fact, 66% of the 30-day averages fail, while the FG-only wall fails 39% of the time. This is because the OSB on the code wall gets so much colder than the interior face of the MDSPF, producing unfavorable conditions for mold growth. The surface RH of the OSB on the fiberglass-only wall is actually predicted to be greater than 80%—more than 75% of the 30-day averages—but because the OSB gets so cold, it fails the 30-day criteria only 39% of the time. That is why, even though the condensation potential for the fiberglass-only wall is much higher than the MDSPF wall, it does better in the ASHRAE 160-2009 criteria.

Other than these two criteria, the two code minimum walls—5A-R20 and 5A-1—perform fairly similarly. They both show drying over time in both the assembly MC and the OSB MC % categories, and neither exceeds the 20% threshold for OSB MC. Again, all the isopleths show the potential for mold growth both on the interior surface of the drywall and the condensing surface, but these are thought to be overly pessimistic when using the ASHRAE 160-2009 indoor conditions as was done here.

Wall 5A-5 performs the best of all three, although it is not predicted to pass the ASHRAE 30-day criteria and the condensation potential is quite high. Installing a vapor retarder on the interior, however, while having a vapor semi-impermeable insulation on the exterior of the cavity, is not recommended unless a smart vapor retarder is employed. A smart vapor retarder changes its permeance with humidity, becoming more vapor open as humidity inside the building cavity increases. Without this capability, if moisture did get into the cavity, it would have a difficult time getting out with both an interior and an exterior vapor retarder.

3.5 Conclusions

After extensive analysis of the predicted hygrothermal performance for walls in climate zones 4A through 7 using different combinations of vapor barrier strategies and levels of MDSPF, the analysis team came to the following conclusions:

1. Although the majority of the walls analyzed fail the ASHRAE 160-2009 30-day criteria, the walls with Class III vapor retarders and the lowest levels of MDSPF required by code fail the ASHRAE criteria by a much higher margin than the rest. Note that a code-compliant wall with only fiberglass batts in the cavity also fails these criteria.
2. All walls modeled in the B regimes show a consistent tendency to dry out over time.
3. The predicted hygrothermal performance in the dry B climate zones was slightly worse when generating the interior boundary conditions using a typical sine curve than the predicted performance using the ASHRAE 160-2009 interior conditions.
4. The predicted hygrothermal performance in the moist A and marine C climate zones was drastically worse when generating the interior boundary conditions using the ASHRAE 160-2009 interior conditions as opposed to a typical sine curve.

Although many failures were predicted, when hybrid walls in climate zone 5A were compared to standard, commonly built walls that are insulated with fiberglass only, predicted hygrothermal performance was quite similar. The fiberglass-only wall performed slightly better with respect to the ASHRAE 160-2009 criteria, indicating a slightly reduced potential for mold growth, but according to these methods of predicting hygrothermal performance, the potential still exists. These predictions need to be tempered with the fact that millions of homes in the United States are built with only fiberglass insulation inside the wall cavities. These homes are not rotting or experiencing discernible mold growth. Although these methods provide valuable feedback when comparing different wall constructions to each other and the effects of different operating conditions, they should not be taken as absolute predictions of hygrothermal performance.

4 High-R Walls

4.1 Wall Construction Details

CARB evaluated three different methods of constructing high-R walls. In climate zones 4A and 5A, R-40 walls were evaluated, and in climate zones 6A and 7, R-60 walls were modeled. Two of the high-R walls analyzed consisted of wood framing, wood clapboard siding (vented and unvented), a weather resistant layer of spun bonded polyolefin, OSB sheathing, closed cell spray polyurethane foam (SPF) or extruded polystyrene (XPS) at varying thicknesses, blown fiberglass insulation in the wall cavity, gypsum board, and a latex paint coating on the inside. These walls can be seen in Figure 10 and Figure 11.

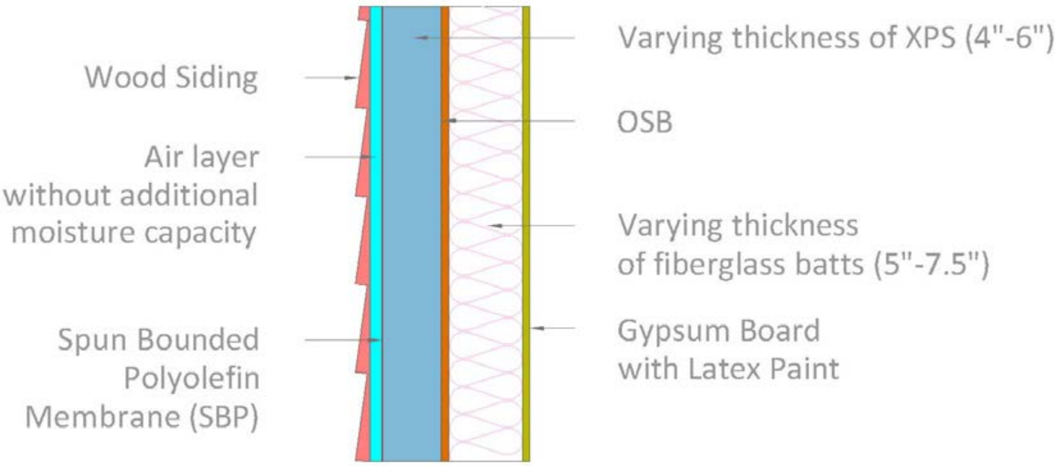

Figure 10. Typical high-R wall with exterior XPS insulation

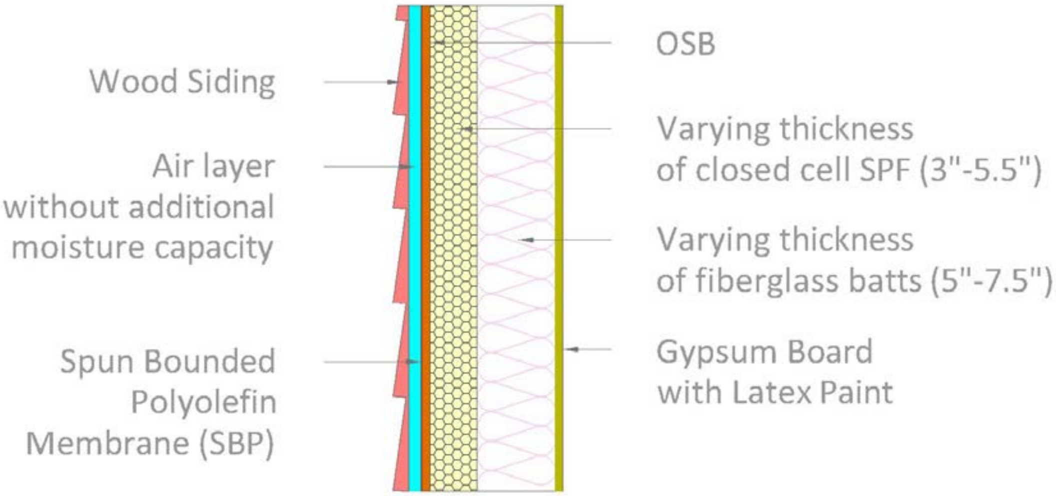

Figure 11. Typical high-R wall with SPF insulation

Given the results of the code wall analysis and previous modeling performed for other projects, CARB set the minimum level of foam to 50% of the cavity R-value.

In addition to these options using hybrid insulation strategies, double stud walls dense-packed with cellulose, another commonly constructed high R-value wall, were evaluated for zones 5A and 7 (Figure 12).

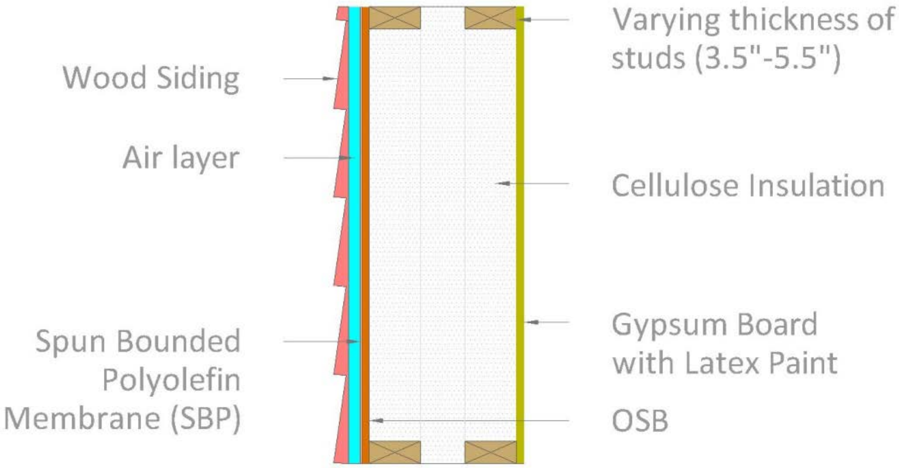

Figure 12. Typical double stud high-R wall with cellulose insulation

Insulation resistances per inch used for this analysis were R-6.9 for MDSPF, R-5 for XPS, R-3.6 for cellulose, and R-4 for fiberglass insulation. A Class III vapor retarder with a 10.7 perm rating (equivalent to latex paint) was analyzed for the assemblies with foam. A Class II vapor retarder was assumed for the cellulose walls. Table 9 lists each high-R wall analyzed in WUFI.

Table 9. High-R Wall Assemblies Evaluated

Wall Identification	Vapor Retarder Perm Rating	XPS/ MDSPF R-value	Fiberglass/ Cell R-value	Cavity R-value	XPS/MDSPF % of Total R-value
	(perm-in)	(h·ft²·°F/Btu)	(h·ft²·°F/Btu)	(h·ft²·°F/Btu)	
4A-XPS	10.7	19.6	19.8	39.4	50
4A-SPF	10.7	20.82	19.8	40.6	51
5A-XPS	10.7	19.6	19.8	39.4	50
5A-SPF	10.7	20.82	19.8	40.6	51
5A-Cell	1.0	n/a	40	40	n/a
6A-XPS	10.7	29.4	29.7	59.1	50
6A-SPF	10.7	31.23	29.7	60.9	51
7-XPS	10.7	29.4	29.7	59.1	50
7-SPF	10.7	31.23	29.7	60.9	64
7-Cell	1.0	n/a	60	60	n/a

4.1.1 Vented Cladding Assumption

Previous hygrothermal modeling conducted by CARB and others of high R-value walls has indicated a serious potential for moisture damage to the wood sheathing if located on the exterior of the wall just beneath the cladding, especially in cold, moist climates (Straube and Smegal 2009). Therefore, high-R walls with and without ventilated cladding were analyzed for this report.

Ventilated claddings are often recommended for wall assemblies to aid in the drying of the exterior layers. They also act as a capillary break and a drainage plane. Although vented/ventilated cavities within wall assemblies have been researched extensively, contradictory conclusions have been encountered. Several studies concluded that vented cladding has little to no effect on the drying rate of the exterior components of the wall (Hansen et al. 2002; Jung 1985; Kunzel and Mayer 1983). More current studies, however, conclude that vented or ventilated claddings can significantly increase the drying rate of the exterior components of the building assembly (Karagiozis and Kunzel 2009; Straube and Finch 2009; Shi and Burnett 2007; ASHRAE 1091 2004a).

To emulate a vented cladding in WUFI, a constant air change source of 10 air changes per hour (ACH) was introduced in a 0.75-in. air cavity behind the cladding. This value was chosen based on results from ASHRAE research report 1091(2004), which states that the equivalent permeance of the wall assembly is drastically increased once the minimum threshold of 10 ACH is reached. This value is also seen as a conservative estimate based on research conducted by Straube and Finch (2009b), which concluded that ventilation rates in a 0.75-in. vented cavity can range from 12 ACH to 100 ACH depending on vent size and location, solar exposure, wind direction and speed, and temperature gradients.

4.2 Results

4.2.1 Moisture Content in Oriented Strand Board (Rot/Decay)

Figure 13 shows the OSB % MC for each wall analyzed. Based on the construction and conditions outlined in the previous sections, maximum MC of the OSB is generally higher in walls with XPS insulation on the exterior side of the OSB.

In climates 5A, 6A, and 7, the MC in the OSB in walls with SPF plus fiberglass insulation increased over the 3-year modeling period, as did the double cellulose walls in zones 5A and 7. Additionally, the walls with XPS in climate zone 7 also increased over time and surpassed the 20% threshold in year 3. The walls with SPF and the double cellulose walls perform much better in all climates with the addition of a vented cladding. The vented cladding has little to no effect on the XPS walls, because, unlike the other two, the OSB is sandwiched in the center of the wall reducing the effect of the ventilation on that component.

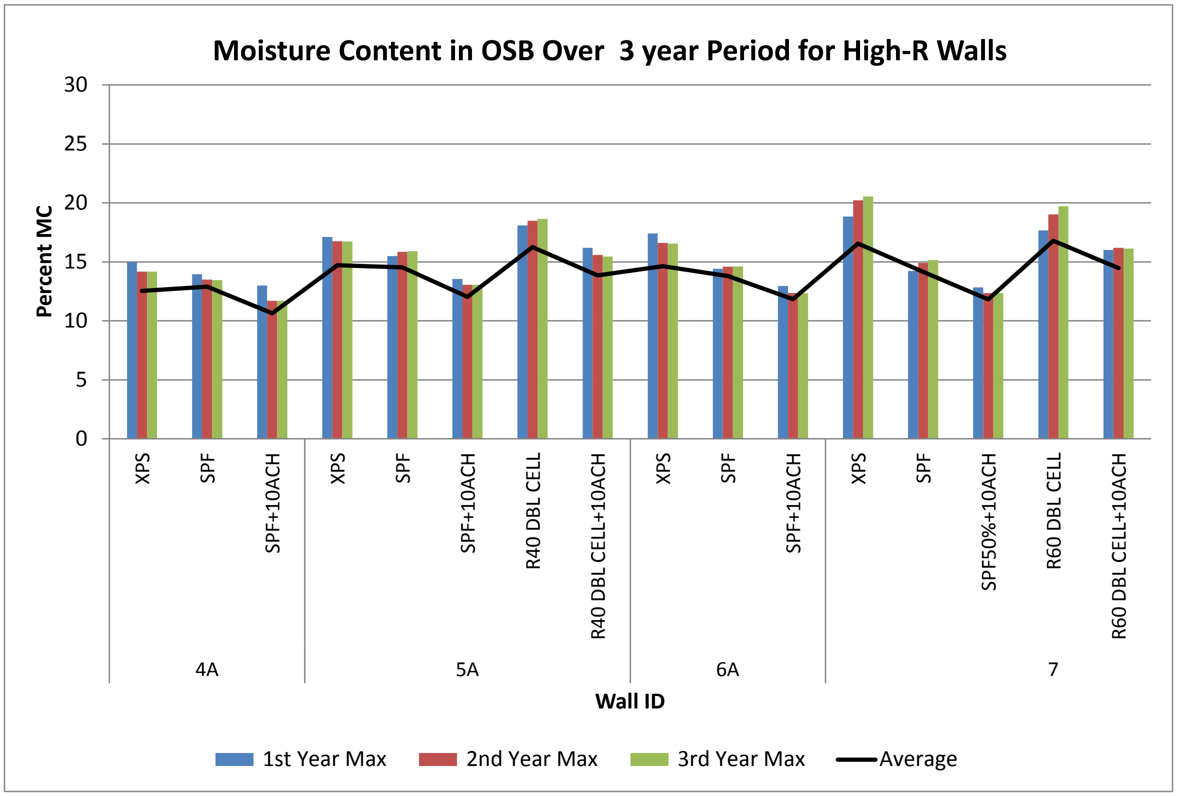

Figure 13. High-R walls: predicted % MC in OSB when using the ASHRAE 160-2009 method to generate the indoor conditions (cooling was assumed in all climates)

4.2.2 Assembly Moisture Content

The initial and final MC for the entire assembly was evaluated for each case (Table 10). For ASHRAE 160-2009 interior conditions, the 5-SPF and 5-DBL CELL wall and the 7-XPS, 7-SPF, and 7-DBL CELL walls modeling predicts an increase in assembly MC over the 3-year period.

When modeled with a vented cladding, the SPF and double cellulose wall assemblies show drying over the 3-year period. The assemblies that increase in MC over the 3 year period are highlighted in red in Table 10.

Table 10. High-R Walls: Difference in Predicted Assembly Moisture Content From Beginning to End of Modeling Period

		Assembly MC (lb/ft^2)			
Climate Zone	**Wall Identification**	**Start**	**Finish**	**Delta**	**%**
4A	XPS	0.38	0.31	–0.08	–20
	SPF	0.39	0.36	–0.03	–8
	SPF+10ACH	0.39	0.33	–0.06	–15
5A	XPS	0.38	0.36	–0.02	–5
	SPF	0.39	0.41	0.01	4
	SPF+10ACH	0.39	0.36	–0.03	–8
	R40 DBL CELL	0.60	0.64	0.03	6
	R40 DBL CELL+10ACH	0.60	0.52	–0.08	–13
6A	XPS	0.41	0.37	–0.04	–10
	SPF	0.42	0.41	–0.01	–2
	SPF+10ACH	0.42	0.37	–0.05	–12
7	XPS	0.41	0.45	0.04	10
	SPF	0.42	0.47	0.05	12
	SPF50%+10ACH	0.42	0.41	–0.01	–3
	R60 DBL CELL	0.76	0.96	0.21	27
	R60 DBL CELL+10ACH	0.76	0.72	–0.04	–5

4.2.3 Condensation Potential

Using the hourly results from WUFI and isotherms from THERM, CARB analyzed the condensation potential for each wall. The critical junctures analyzed were the MDSPF/fiberglass interface in the SPF walls, the OSB/fiberglass interface in the XPS walls, and the OSB/cellulose interface in the double stud walls. Table 11 displays the condensation potential for each case as predicted by WUFI. Assemblies with a high potential for condensation have been highlighted in red.

Table 11. Condensation Potential for High R-Value Walls

		Condensation Potential	
Climate Zone	Wall Identification	Hours Over 3 Years	% Over 3 Years
4A	XPS	2,278	9
	SPF	2,151	8
5A	XPS	4,149	16
	SPF	3,875	15
	R40 DBL CELL	20,082	76
6A	XPS	5,055	19
	SPF	3,957	15
7	XPS	7,711	29
	SPF	6,931	26
	R60 DBL CELL	25,022	95
	SPF 60%	345	1

Results from WUFI indicate that condensation potential for the double cellulose walls is extremely high because the OSB in those wall assemblies is entirely outside of the insulation. All walls in climate zone 7 exhibit elevated condensation potential as well.

To evaluate the condensation potential using THERM, the average outdoor temperature for the coldest 3 months of the year (December, January, and February) was calculated for each location. These values are displayed in Table 12. The temperature of the first condensing surface in the foam walls is above the average dew point temperature of the interior air. The interior air winter temperature was assumed to be 70°F as was used in WUFI.

Table 12. THERM Analysis of Temperatures at the Interior Face of the Foam

Climate Zone	Climate File	Average Outdoor Temperature (°F)	Average Dew Point Temperature (December, January, February) (°F)	Interior of First Condensing Surface (°F)
4A	Nashville, Tennessee	38	51	55
5A	Detroit, Michigan	27	45	50
6A	Madison, Wisconsin	18	42	45
7	International Falls, Minnesota	6	39	40

4.2.4 ASHRAE Criteria

The ASHRAE 160-2009 criteria were applied to the first condensing surface in each wall assembly: OSB for both the double cellulose and XPS walls, and the interior surface of the MDSPF for the spray foam walls. All the high-R walls fail this criterion by a significant margin when the ASHRAE 160-2009 interior conditions with cooling are assumed. All the cases fail the

30-day running average. Figure 14 shows which walls fail the ASHRAE 160-2009 criteria and to what extent.

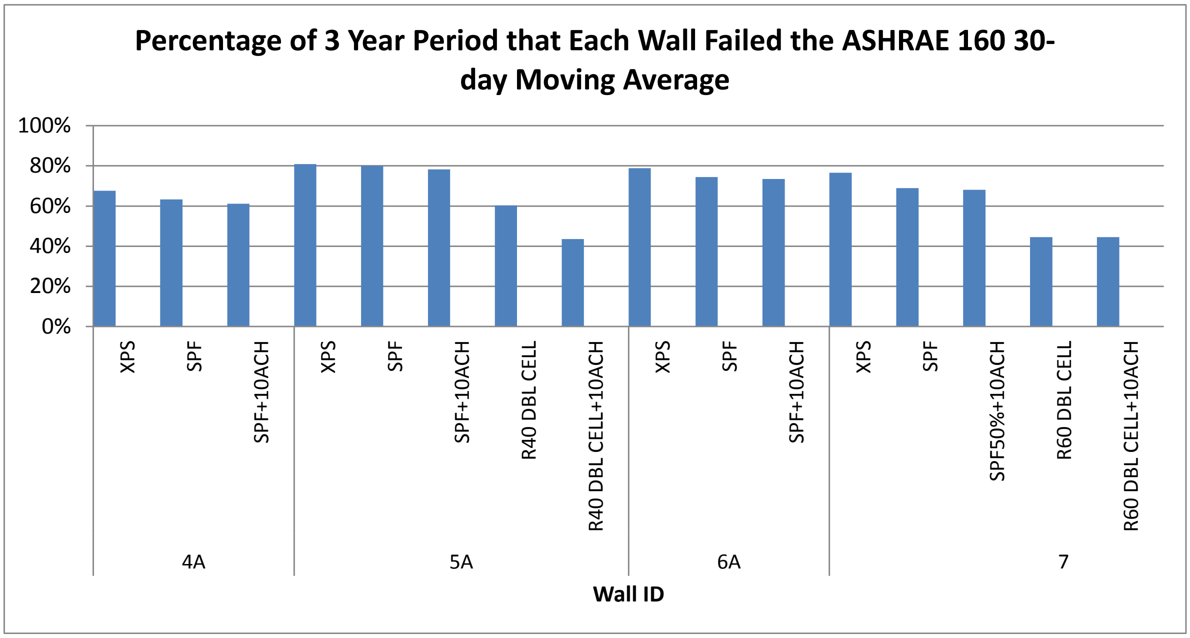

Figure 14. High-R walls: percentage of averages that each wall failed the ASHRAE 160-2009 criteria.

4.2.5 Isopleths

For all high-R walls, the ASHRAE 160-2009 indoor conditions result in isopleths that indicate the potential for mold on both the interior surface of the drywall and the interior face of the first condensing surface.

4.3 Discussion

The modeling results for the high-R walls suggest that vented cladding is essential to ensure proper drying of these wall assemblies. In climate zone 7, this is particularly important and has a more significant effect on the wall performance than increasing the impermeable to permeable insulation (foam versus fiberglass) ratio from 50% to 60%.

Although this increase in foam does significantly reduce the condensation potential at the interior face of the foam from 26% to 1%, it does not eliminate the failures in the other categories. Without the vented cladding, the OSB and total assembly MC still increase over the 3-year period.

5 Brick Walls With Interior Insulation

5.1 Introduction

The thermal resistance provided by uninsulated brick walls (R-3 to R-5) is often insufficient for occupant thermal comfort and energy efficiency in most climates. To increase the R-value, the wall can be insulated either from the exterior or the interior. But, because of the costs of retrofitting a building façade and social pressure to preserve the original exterior brick, retrofits to brick buildings are usually conducted from the interior.

Adding interior insulation significantly affects the thermal and hygric behavior of the masonry wall because the masonry is now separated from the conditioned space. In cold climates, this causes the temperature to drop within the masonry wall, increasing the potential risk of damage due to interstitial condensation and freeze-thaw cycles. Lower masonry wall temperatures also affect the drying capacity of the wall.

Another problematic side effect of adding interior insulation is that it can inhibit drying to the inside, whereas an uninsulated wall can dry to the exterior as well as the interior. If a Class I or Class II vapor retarder or insulation such as MDSPF or XPS is used, the wall is forced to dry to the exterior only. This reduces the drying rate and leads to higher levels of moisture accumulation.

To evaluate the effects of interior insulation, CARB evaluated 12-in.-thick brick walls with varying hygrothermal properties and levels of insulation. Because the properties of brick can vary so drastically, these walls were only evaluated in climate zone 4A. Describing methods for evaluating performance is the focus of this section as opposed to providing specific recommendations for type and amount of insulation for different climate zones.

5.2 Wall Construction Details

Twelve-inch-thick walls with solid bricks without any chips, cracks, and voids were assumed. A three header section of the wall was modeled with a ½-in. type-N mortar joint (predominantly used in above-grade exterior walls). Figure 15 displays cross sections of the insulation strategies evaluated, and Table 13 lists the R-values assumed.

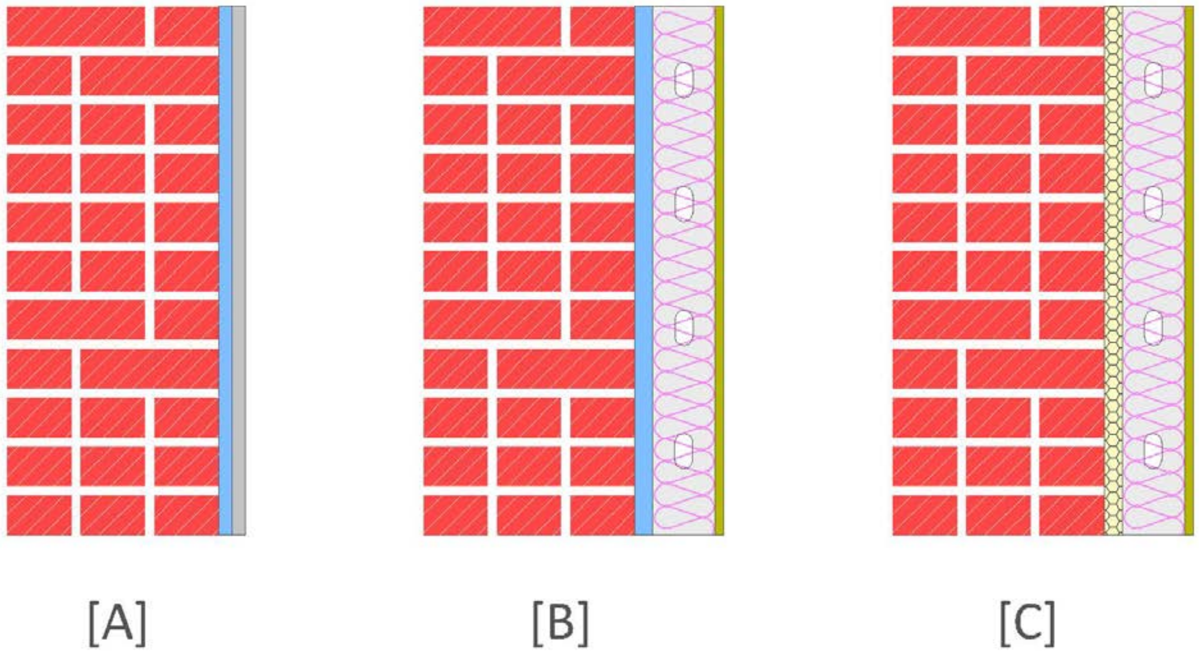

Figure 15. Cross sections of the 12-in.-thick brick walls evaluated: (A) uninsulated, interior plaster finish; (B) 1-in. air gap, 2 × 4 steel studs with R-13 fiberglass batt insulation and gypsum board interior finish; and (C) 1-in. R-5 foam, 2 × 4 steel studs with R-13 fiberglass batt insulation and gypsum board interior finish

Table 13. Masonry Wall Assemblies Evaluated

Wall Construction	Wall Identification	Vapor Retarder Perm Rating	XPS R-Value	Fiberglass R-Value
		(perm-in)	(h·ft^2·°F/Btu)	(h·ft^2·°F/Btu)
High density face brick + 2 wythes fill bricks	4A-1-Uninsulated	10.7	0	0
	4A-1-fiberglass batt	10.7	0	13
	4A-1-FOAM	10.7	5	13
3 wythes of medium-density fill bricks	4A-2-Uninsulated	10.7	0	0
	4A-2-fiberglass batt	10.7	0	13
	4A-2-FOAM	10.7	5	13

Uninsulated walls were finished with a 1-in. wood furring strip followed by a ¾-in.-thick cement plaster on metal lath. For walls with interior insulation, an interior gypsum board with a Class III vapor retarder of 10.7 perm (latex paint) was modeled. The short-wave absorptivity of the façade was adjusted to 0.68 (red brick). Initial temperature and RH of the materials were set to 68°F and 80%, respectively. ASHRAE 160-2009 interior boundary conditions (with cooling) were assumed.

West was determined as the worst-case orientation for climate zone 4A. This was based on analyzing the annual wind driven rain load for cold year and warm year weather files.

5.3 Material Properties

Brick characteristics, especially of existing buildings, are often varied and are not easily known. Before retrofitting a brick wall, it is suggested that the brick be tested to gather basic material properties. If possible, bricks from the outer wythe as well as the inner wythes should be tested separately. Typically, the material properties of the face brick differ from the fill bricks. A better grade, denser, more durable and freeze-thaw-resistant brick is often used as a face. Because the inner wythes are not directly subjected to the elements, they can be less weather resistant than the outermost wythe.

Bricks are available in a variety of densities based on the material properties, composition, and manufacturing process. According to ASHRAE Fundamentals 2009, fired clay bricks can vary in densities between 70 to 150 lb/ft^3 with conductivities ranging from 2.5 to 10.2 Btu·in./h·ft^2·°F, respectively.

Based on the materials available in the WUFI database, CARB modeled two variations of the masonry wall:

1. 12-in. masonry wall with one exterior wythe of high-density face brick and two interior wythes of medium-density fill bricks.
2. 12-in. masonry wall with three wythes of medium-density fill bricks.

These variations are meant to mimic a well-preserved exterior wall with higher grade face brick and a wall with a lower grade face brick with significant cracks and chips. Modeling these variations illustrates the drastic difference in the hygrothermal performance of two different brick walls in the same climate.

Material properties were chosen from the materials database included in WUFI Pro 5.1. Table 14 shows properties for the selected brick (in bold) from the WUFI database. Red matt clay brick with a density of 120 lb/ft^3 and permeability of 0.93 perm in was used as the face brick. Solid brick extruded with a density of 103 lb/ft^3 and a permeability of 13.55 perm in was chosen as a medium-density fill brick, which is consistent with the tested properties of a typical fill brick (Straube and Schumacher 2007).

Table 14. Material Properties for Brick from WUFI Pro 5.1

Name	Density (lb/ft^3)	Thermal Conductivity (Btu/h·ft·°F)	Permeability (perm in)	Free Saturation	
				W_f (lb/ft^3)	W_f (%)
Brick Old	104.2	0.231	8.05	12.19	12
Buff Matt Clay Brick	107.3	0.248	4.396	0.43	0
Red Matt Clay Brick	**120.8**	**0.286**	**0.935**	**3.50**	**3**
Calcium Silicate Brick	123.1	0.358	0.7	8.99	7
Solid Brick Masonry	118.6	0.347	12.88	11.86	10
Solid Brick Extruded	**103**	**0.347**	**13.55**	**23.09**	**22**
Solid Brick Historical	112.3	0.347	8.58	14.35	13
Solid Brick Hand Formed	107.68	0.347	7.57	12.48	12

5.4 Additional Failure Criteria (Masonry Walls)

With the exception of OSB MC, all the same failure criteria that were applied to the frame walls in the previous sections were applied to the brick walls. In addition, the potential for freeze-thaw damage and long-term drying were evaluated.

5.4.1 Freeze-Thaw Damage

Damage can occur when damp masonry wall assemblies are exposed to frequent freeze-thaw cycles. The two factors that influence freeze-thaw damage the most are the MC on freezing and the number of freeze-thaw cycles (Straube and Schumacher 2006).

Typically, the number of zero crossings (times when the wall's temperature falls below or climbs above freezing, 0°C or 32°F) are calculated at the external face of the brick: the higher the number of cycles, the more potential for freeze-thaw damage (Sedlbauer and Kunzel 2000).

For damage to occur, however, moisture levels in the brick must be above the critical MC. For brick, the critical MC is commonly assumed to be 90% of free saturation (Straube and Schumacher 2006). The MC of a material at free saturation corresponds to an RH of 100% in the material's pores. Table 15 displays the saturation values for the brick used in this analysis.

Table 15. Free Saturation and Critical Saturation of Brick Analyzed

Material	Density (lb/ft^3)	Free Saturation (W_f)			Critical Saturation (W_{90})		
		(lb/ft^3)	Mass %	Vol %	(lb/ft^3)	Mass-	Vol %
Red Matt Clay Brick	120.8	3.5	2.9	5.6	3.2	2.6	5.1
Solid Brick Extruded	103	23.09	22.4	37.1	20.8	20.2	33.3

WUFI usually gives the MC as water density (pounds of water per cubic foot of material), but the results can also be expressed as volume percent (cubic foot of water per cubic foot of building material) or mass percent (pounds of water per pound of dry building material) as shown in Table 15 (WUFI).

The exterior face brick and the interior first fill brick were evaluated for freeze-thaw damage. The freezing temperature for the brick was assumed to be lower than 32°F because of the dissolved salts in brick pores (Said et al. 2003). A freezing temperature threshold of 23°F and thawing threshold of 32°F were used to estimate the number of freeze-thaw cycles within the brick wall (Straube and Schumacher 2006).

5.4.2 Drying of Masonry Walls

Along with assessing freeze-thaw damage, CARB evaluated the drying capacity of masonry walls with and without the addition of interior insulation. A masonry wall fitted with interior insulation dries slower than an uninsulated wall because the temperature within the masonry wall decreases with the addition of interior insulation.

Drying performance of the walls was evaluated by calculating the number of years it takes for the masonry wall to reach the practical MC (W_{80}) of that material. Practical MC corresponds to the equilibrium moisture at a RH of 80%. Where unavailable, the practical MC was extrapolated from the moisture storage function graphs within WUFI.

5.5 Results

5.5.1 ASHRAE Criteria

All of the walls fail this criterion when ASHRAE 160-2009 interior conditions with cooling are assumed (Figure 16). For this criteria, CARB evaluated surfaces within the assembly that have the most potential to condense: the interior side of the third wythe for the uninsulated walls and for the walls with a 1-in. gap and R-13 fiberglass cavity insulation. For walls with foam insulation, the interface between the foam and the cavity insulation was evaluated.

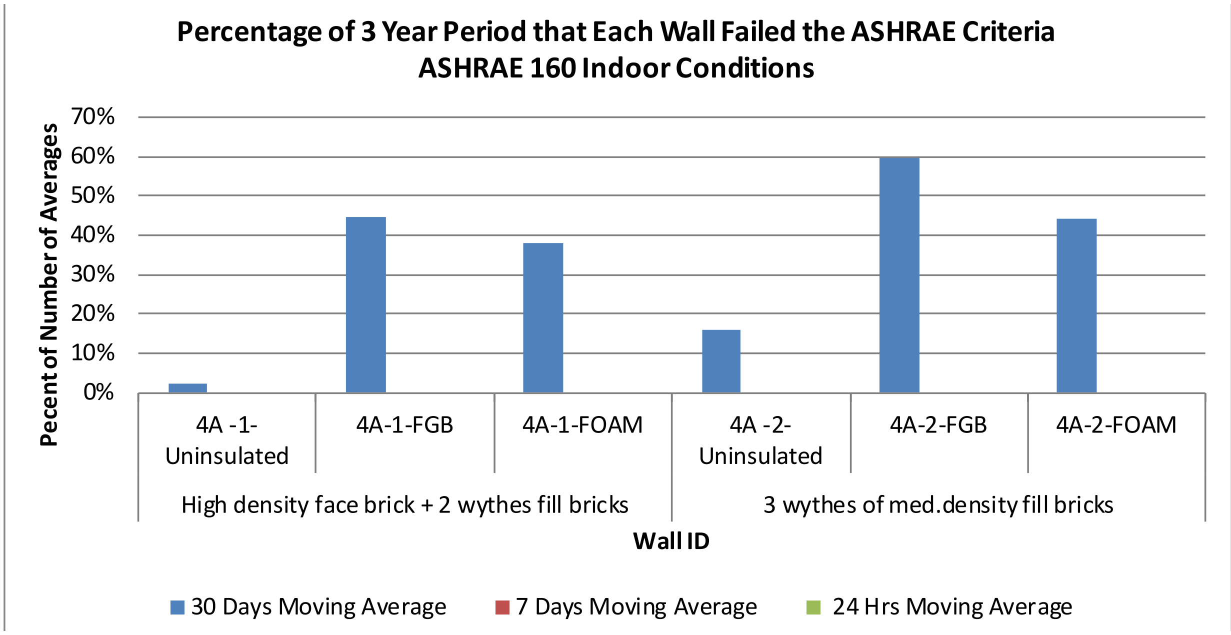

Figure 16. Percent of averages that each wall failed the ASHRAE 160-2009 criteria

5.5.2 Condensation Potential

Using the hourly results from WUFI and isotherms from THERM, CARB analyzed the condensation potential for each wall. Condensation potential was calculated at different surfaces for each wall based on the wall composition. The interior side of the third wythe was determined to be the condensing surface for the uninsulated walls and for the walls with a 1-in. gap and R-13 fiberglass cavity insulation. For walls with foam insulation, the interface between the foam and the cavity insulation was chosen as the potential condensing plane. Figure 17 illustrates the condensation potential for each case as predicted by WUFI.

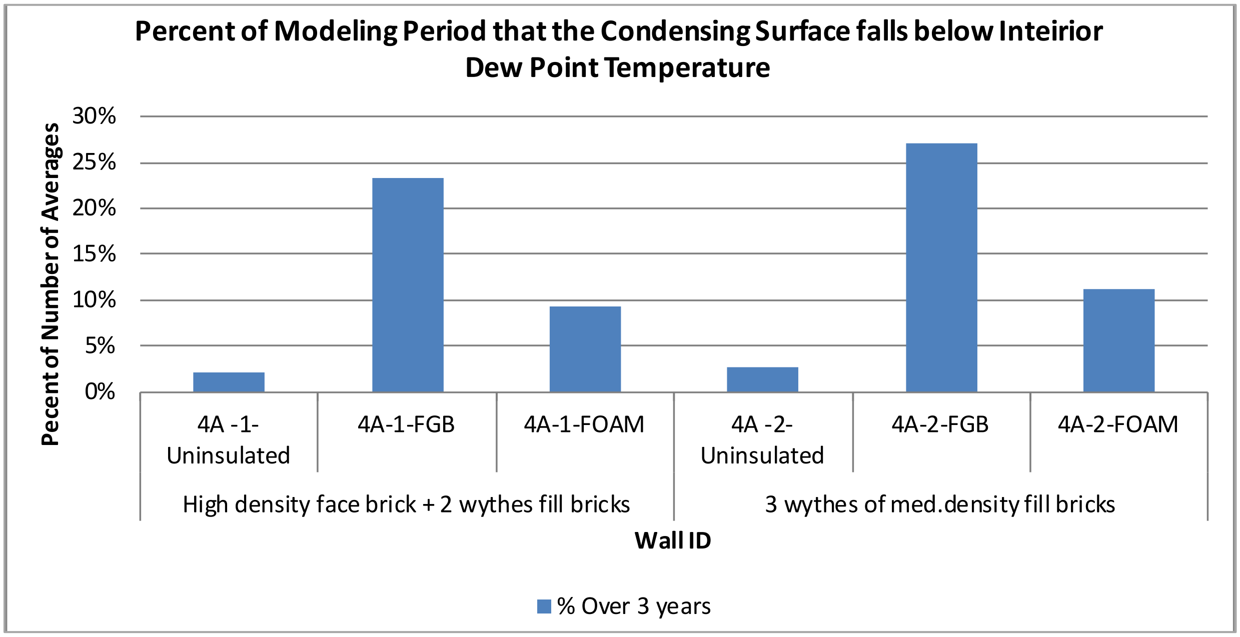

Figure 17. Condensation potential for the masonry walls

Based on WUFI results, walls with the 1-in. gap and fiberglass cavity insulation are at a higher risk than the walls with foam.

Results of the THERM analysis are displayed in Figure 18. Based on the boundary conditions for Nashville, and an interior air temperature of 70°F, the temperature gradient across the wall was calculated. This gradient was then compared to the dew point temperature of the interior air. The pink dotted line indicates the potential condensation surface. Walls [A] and [C] do not show high risk of condensation because the temperature at the condensing surface is near or higher than the average dew point temperature. Wall [B] is potentially at risk because the temperature at the condensing plane lies below the average dew point. Results from THERM concur with the results from the WUFI condensation analysis.

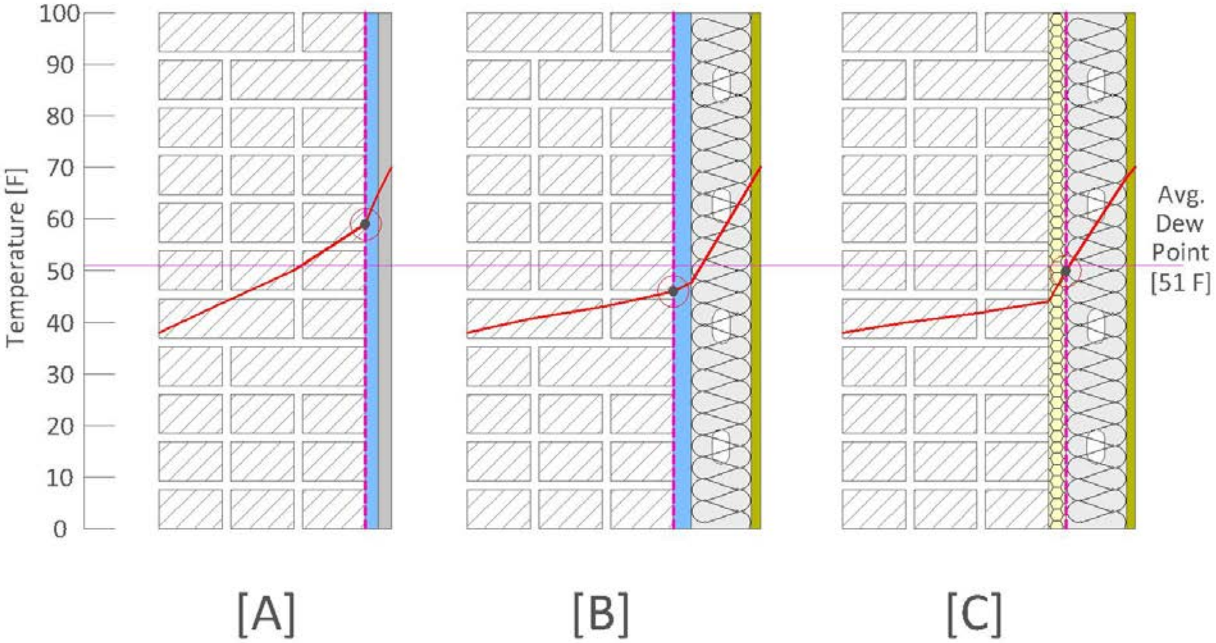

Figure 18. Temperature gradient across the wall sections (highlighted dotted line indicates potential condensation plane)

5.5.3 Freeze-Thaw Damage

The hygrothermal simulations predict a very low risk of freeze-thaw damage in the walls in climate zone 4A. Figure 19 and Figure 20 show the temperature and MC in wythe 1 of the uninsulated wall with low- and high-permeability face bricks. The temperature graph shows the freezing limit at 23°F and thawing limit at 32°F. For damage to occur, freezing must take place when the MC surpasses the critical saturation threshold.

The exterior face brick encounters freeze-thaw cycles in winter when the temperature falls below the freezing limit of 23°F. However, the MC in this wythe lies significantly below the critical saturation threshold, thus eliminating the potential risk of freeze-thaw damage.

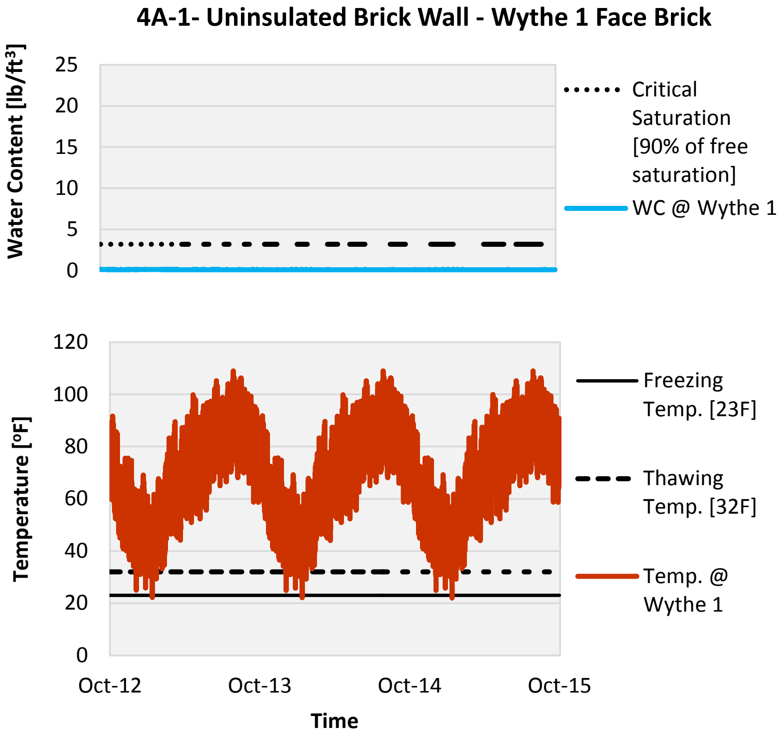

Figure 19. Freeze-thaw potential of an uninsulated wall with high-density, low-permeability face brick

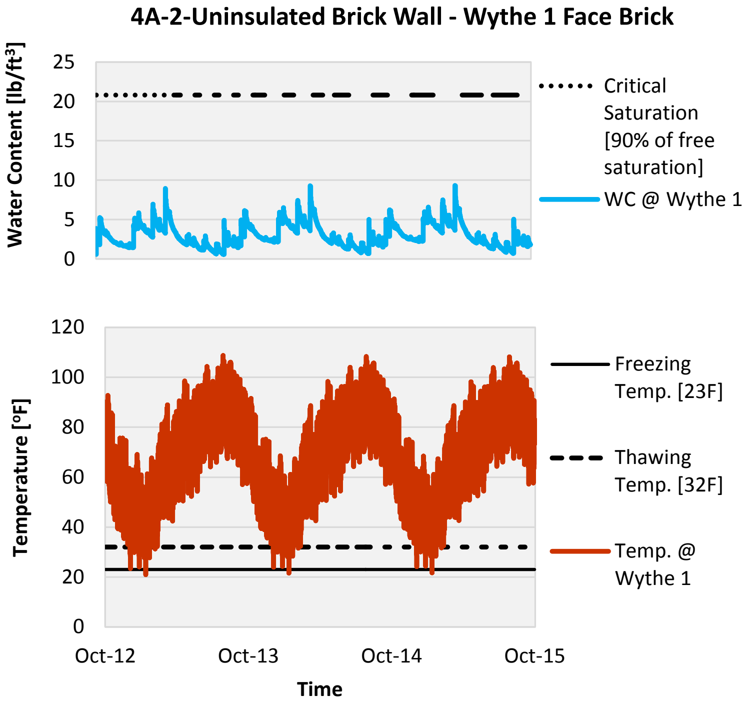

Figure 20. Freeze-thaw potential of uninsulated wall with medium-density, high-permeability face brick

The third wythe of the 4A-1-FGB and 4A-1-FOAM walls is colder in winter and warmer in summer when compared to the temperature of the third wythe of the uninsulated wall. This is evident from Figure 21 and Figure 22. A similar trend is observed in walls with low-density, high-permeability face brick, but the decrease in temperature during the winter does not result in an increased potential for freeze-thaw damage because the MC remains well below the critical saturation threshold.

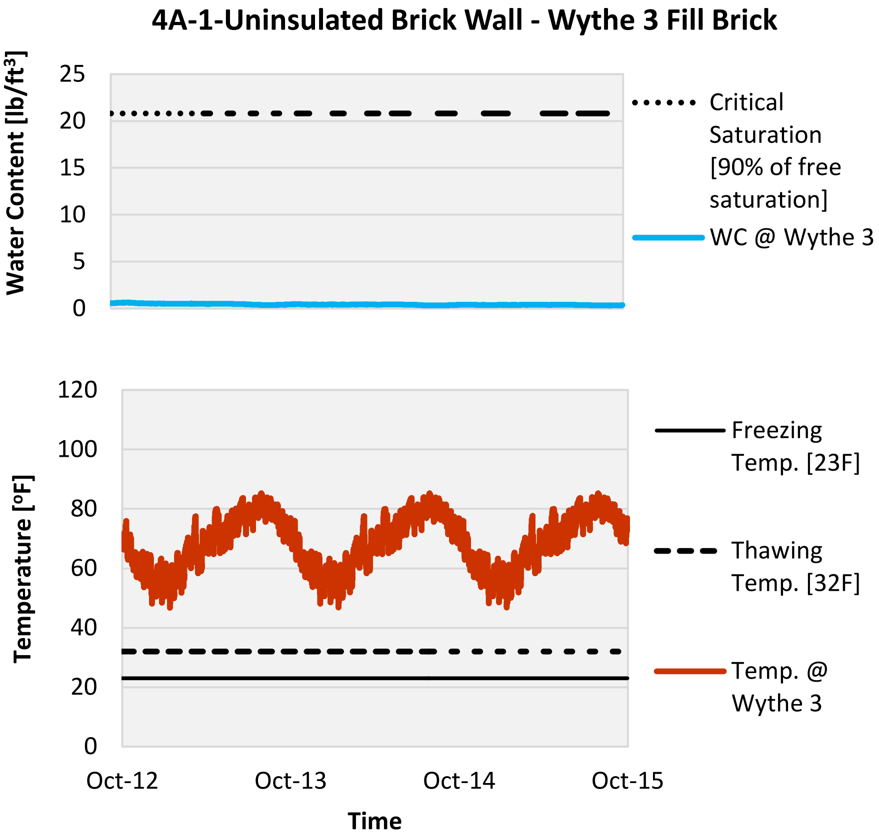

Figure 21. Freeze-thaw potential of an uninsulated wall with high-density, low-permeability face brick

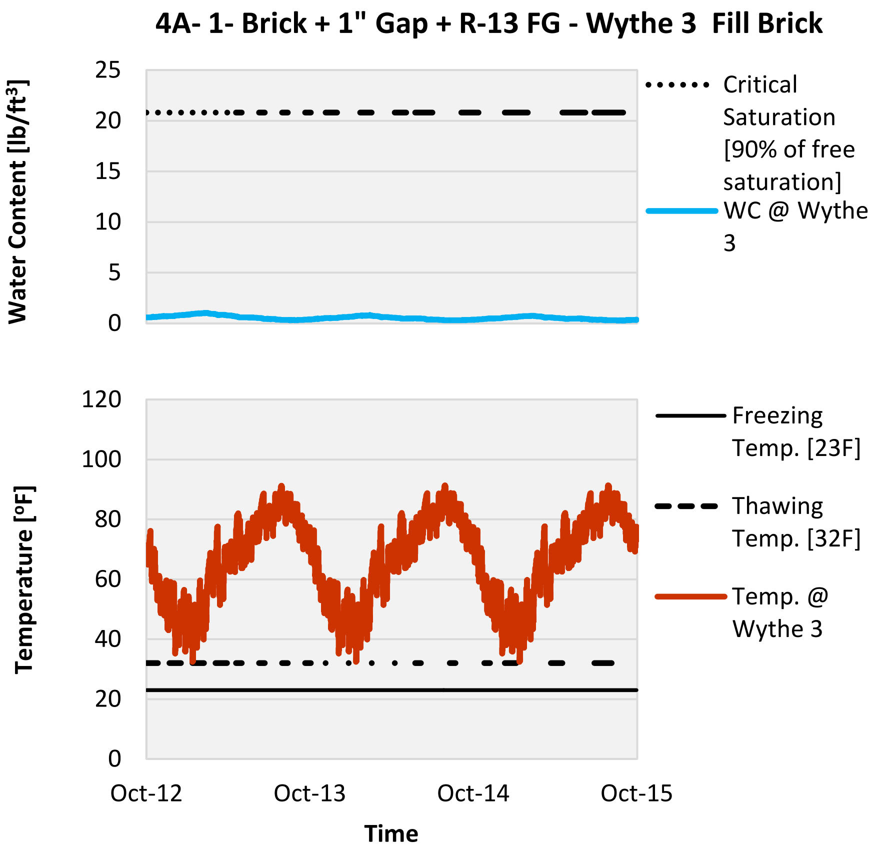

Figure 22. Freeze-thaw potential of a wall with fiberglass cavity insulation and high-density, low-permeability face brick

5.5.4 Maximum Moisture Content

Comparing the maximum MC within all the walls (shown in Figure 23) over a 10-year modeling period reveals that the walls with high-density, low-permeability face brick consistently experience lower maximum MC levels than walls with medium-density, high-permeability face brick.

In the first case, the MC in the third wythe is consistently higher than that of the outer two wythes, and is highest in the wall with the fiberglass cavity insulation and no foam. In the latter case, wythe 1 experiences the highest MC levels because of the high permeability of the face brick. The MC in wythes 2 and 3 increases with the addition of interior insulation. However, the maximum MC of both the high- and the low-permeability bricks are way below their respective critical MC thresholds. The critical MC for the low-permeability brick is 5.04 vol %, and the critical MC for the high-permeability brick is 33.25 vol %.

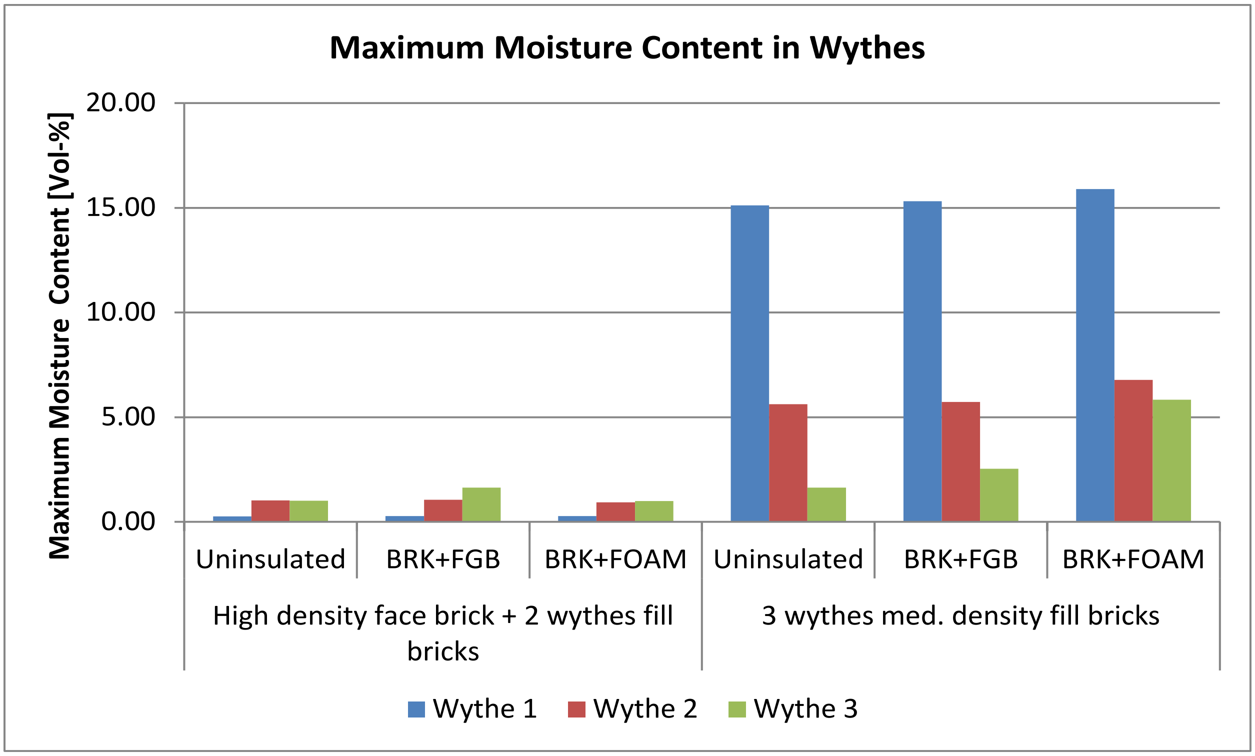

Figure 23. Comparison of the maximum MC in each of the three wythes of all the walls

5.5.5 Drying of Masonry Walls

Drying potential of the wall is predicted by plotting the mean MC in volume percent over time. It is evident from Figure 24 and Figure 25 that all variations of the walls with high-density, low-permeability face brick dry over time, with the wall with foam on the inside taking the longest to reach a steady state of MC. Though the uninsulated wall and the wall with fiberglass insulation start with higher initial MC, they reach a steady MC in 2–3 years' time. The wall with foam takes 4–5 years to reach that level.

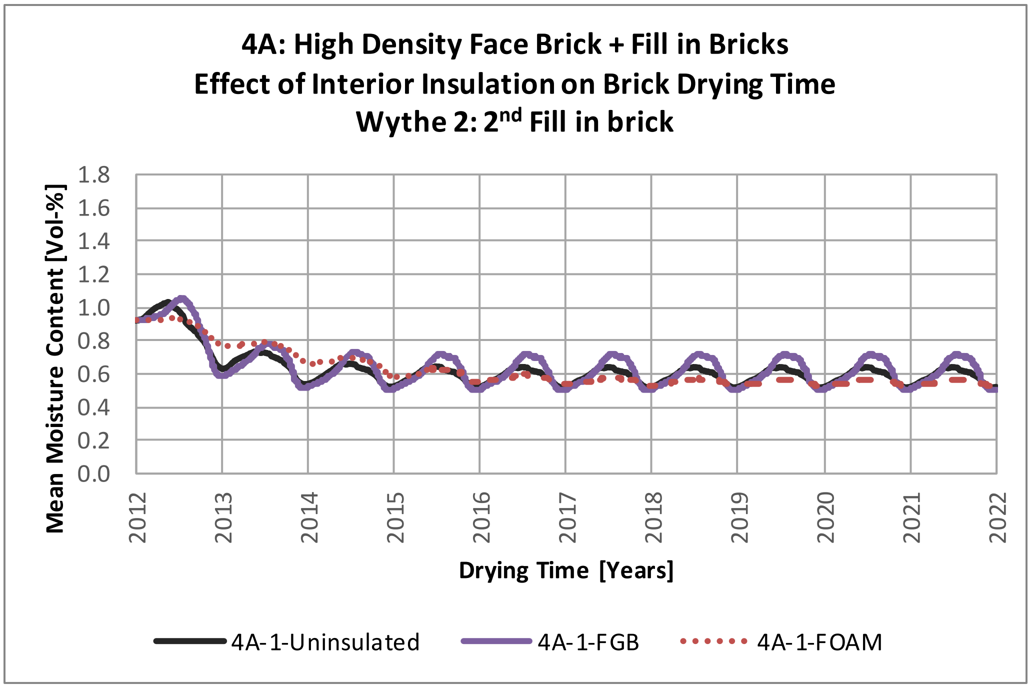

Figure 24. Effect of interior insulation on the drying time of wythe 2 in all the walls with high-density, low-permeability face brick

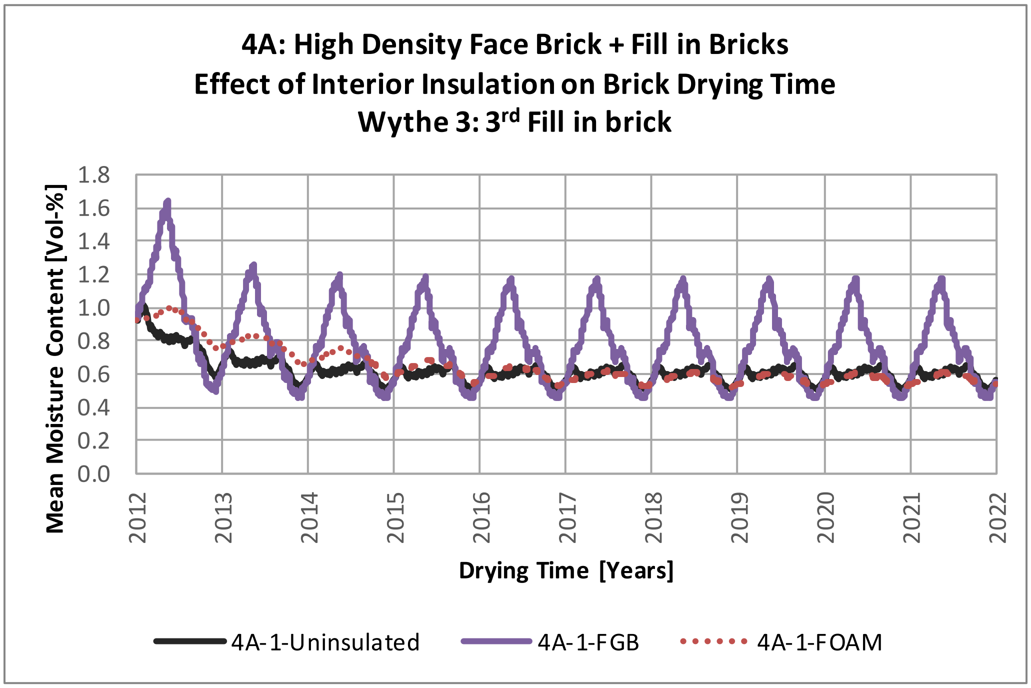

Figure 25. Effect of interior insulation on the drying time of wythe 3 in all the walls with high-density, low-permeability face brick

In walls with the medium-density, high-permeability face brick, the MC increases steadily for approximately 5 to 7 years in all three wythes and for all variations of interior insulation, with the interior foam resulting in the biggest increase, particularly in wythe 2 and wythe 3 (Figure 26 and Figure 27). The foam insulation acts as a vapor barrier restricting drying to the interior.

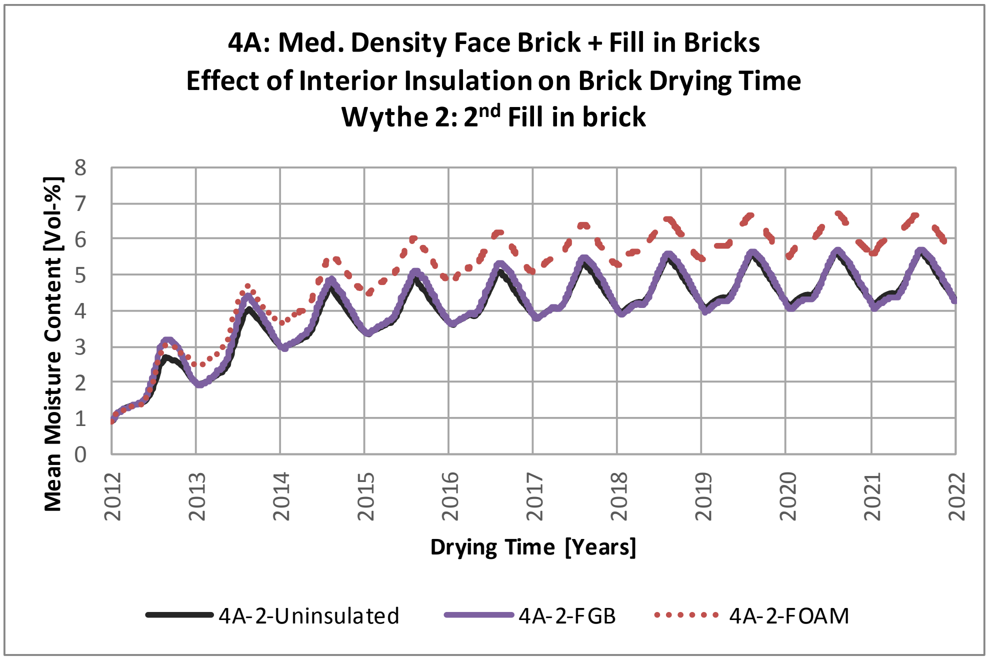

Figure 26. Effect of interior insulation on the drying time of wythe 2 in all the walls with medium-density, high-permeability face brick

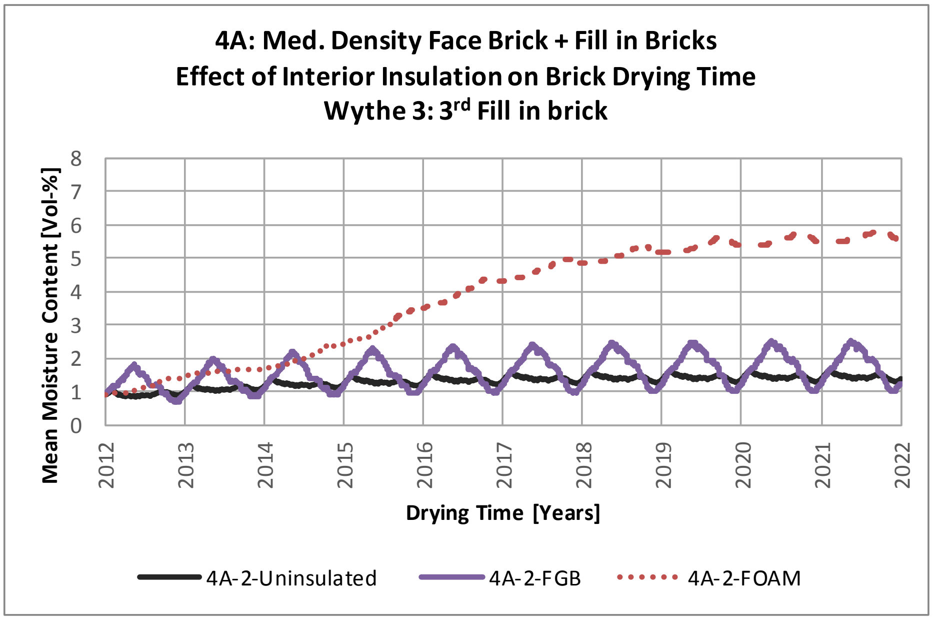

Figure 27. Effect of interior insulation on the drying time of wythe 3 in all the walls with medium-density, high-permeability face brick

5.5.6 Isopleths

For all masonry walls with interior insulation in climate zone 4A, the ASHRAE 160-2009 indoor conditions result in isopleths that indicate the potential for mold on both the interior surface of the drywall and the condensing surfaces.

5.6 Discussion

The analysis conducted on the two types of brick construction supports the hypothesis that determining the hygric properties of the brick are imperative in order to make sound recommendations for insulation retrofits. In one case, foam between the stud and the brick results in the best option. In the other, adding foam exacerbates the predicted moisture accumulation over time. The key parameters to evaluate have been defined, but a sound insulation strategy can be employed only after the brick properties are known.

6 General Discussion

6.1 Condensation Potential

The failure criteria used in this study were based on previous research studies, manuals on moisture control in buildings, and available standards. All resources are listed in the References section of this report. But this is far from an exact science. For example, condensation potential can be calculated more than one way. As was done in this report and in many other works by leading moisture specialists, the dew point of the interior air was compared to the temperature of the condensing surface. Every work listed in the References section that deals with condensation potential in building assemblies uses the interior air as the metric for determining moisture and durability risks. This assumes that air leakage from the interior will be the driving force for condensation. This method represents a worst-case scenario in the absence of a bulk water leak or other major failure in the building.

Condensation potential can also be evaluated based on vapor drive. Software like WUFI predicts the dew point temperature of various surfaces in the wall based on diffusion. This analysis yields different, typically much less severe results. Depending on construction quality, materials chosen, and occupant behavior, among other factors, the true answer will likely be somewhere in between these two methods. There is no recommended maximum threshold for condensation potential in the industry at this time. This value needs to be taken into account with all the other criteria and assessed on a climate-by-climate and assembly-by-assembly basis.

6.2 ASHRAE 160-2009 Failure Criteria

Another criterion that is open to interpretation is the ASHRAE 160-2009 running average criteria. During a December 2011 Building America Standing Technical Committee call on vapor impermeable exterior sheathing, it was noted that other research has indicated that the ASHRAE 160-2009 30-day criteria might be too stringent and might need to be reevaluated. Other experts in the field contend that the method from which these criteria were derived was meant for the interior surface of the building assembly alone. This modeling supports that suspicion, especially in the cases where failures happen in the first few months of the modeling period based on initial conditions, but do not occur again over the remaining 3-year period.

Finally, isopleths were evaluated for all cases examined. In every circumstance, these graphs indicated the potential for mold growth on the interior face of the drywall in the moist A and marine C climate zones when the ASHRAE 160-2009 interior conditions were used. From years of living in these regions and working in hundreds of buildings, it is the opinion of this researcher that these results are flawed. Except for under-ventilated bathrooms and perhaps cool damp basements, little mold is found inside homes unless there is an unusually high rate of moisture introduced into the space such as a bulk water leak from rain, leaking pipes, or unusually high occupancy. These isopleths should be used in context with the results of the other failure criteria evaluated.

7 General Conclusions

The conclusions in this report are based on extensive modeling and review of existing research. To validate the methods and assumptions used in the modeling, CARB is currently installing sensors in an R-40, double stud wall insulated with cellulose in climate zone 5A and a brick retrofit in zone 4A. Results are expected at the end of 2012.

Although many failures were predicted in the walls built to minimum code levels, when hybrid walls in climate zone 5A were compared to standard, commonly built walls that are insulated with fiberglass only, similar failures were predicted. The fiberglass-only wall performed slightly better with respect to the ASHRAE 160-2009 criteria, indicating a slightly reduced potential for mold growth, but according to these methods of predicting hygrothermal performance, the potential still exists. These predictions need to be tempered with the fact that there are millions of homes in the United States built with only fiberglass insulation inside the wall cavities which are not rotting or experiencing discernible mold growth. Although these methods of evaluating the potential for moisture problems inside building assemblies yield valuable feedback when comparing different wall constructions to each other and the effects of different operating conditions, each on its own should not be taken as an absolute prediction of hygrothermal performance.

High R-value walls constructed with the OSB on the exterior of all the insulation should employ a vented cladding to assist in drying of that layer. Drying to the interior is severely limited in these walls. Modeling suggests that increasing the wall's capacity to dry to the exterior reduces the risk for moisture-related damage.

High R-value walls constructed with the OSB sandwiched between a permeable insulation on the interior and an impermeable insulation on the exterior should maximize the ratio of impermeable to permeable insulation to keep the OSB as warm as possible. This reduces the potential for condensation and promotes drying to the interior. Based on these modeling results, a minimum of 50% of the total cavity wall R-value should be provided by the impermeable insulation in climate zones 4 through 6, and 60% is recommended in climate zone 7.

Before insulation retrofits are undertaken in buildings with structural brick walls, the hygrothermal properties of the brick should be determined. Properties vary so widely across the country that no generic recommendations for insulation strategies can be given here. Analysis shows that the insulation strategies appropriate for one type of brick are not necessarily appropriate for another. Criteria that should be analyzed include freeze-thaw cycles in conjunction with the critical saturation threshold and drying potential of the masonry. Analysis longer than 3 years is recommended when modeling.

Further research into the appropriateness of the ASHRAE 160-2009 interior conditions in moist climates should be conducted. Interior RH levels generated with this method are extremely high, reaching 90% in all cases even though air conditioning is assumed. This results in overly pessimistic predictions for mold growth on the interior of the assembly.

Considering almost every wall in this study failed the ASHRAE 30-day criteria, it is recommended that industry professionals reevaluate this threshold.

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