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High-R Walls for the Pacific Northwest–A Hygrothermal Analysis of Various Exterior Wall Systems

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Abstract:

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Introduction

Many concerns, including the rising cost of energy, climate change concerns, and demands for increased comfort, have lead to the desire for increased insulation levels in many new and existing buildings. Building codes are being modified to require higher levels of thermal control than ever before. The manner in which additional thermal insulation is added to framed wall assemblies is critical to their durability when considered over time. This report considers a number of promising wall systems that can meet the requirement for better thermal control. Unlike previous studies, this one considers performance in a more realistic matter, including some two and three-dimensional heat flow and analysis of the relative risk of moisture damage.

In some cases, increasing the quantity of insulation may result in an increased risk of moisture-related issues when the exterior surfaces of the enclosure are kept colder in cold weather, and the interior surfaces are kept cooler in warm weather. This may result in increased condensation, and increased freeze thaw potential or decay potential of the assembly in different situations. Analysis is required to predict the potential hygrothermal risks due to increasing the amount of insulation (R-value) in the enclosure.

Previous work, largely stemming from research in the 1970's and 1980's, involved postulating newer assemblies with improved R-values. R-value was, and often still is, defined as the "clear wall" R-value (no framing effects accounted for) or the total amount of insulation installed in the assembly. The increased moisture risks were rarely considered.

Building Science Consulting has conducted field testing of full scale test walls in an field exposure hut on the lower mainland of British Columbia, which experiences similar temperatures and moisture loads to both Portland OR, and Seattle WA, and some of those results will be shown here to compare actual measured results in the field to predicted results by hygrothermal simulations.

Objective

The objective of this study is to compare commonly built construction techniques in the Pacific Northwest with some promising less commonly constructed wall systems based on selected criteria, resulting in a durable, but affordable, and resource efficient wall system that provides a comfortable living environment in Portland, OR, Seattle, WA and the surrounding areas. This report will present the analysis of different enclosure wall strategies and present their advantages and disadvantages according to several comparison criteria.

Scope

This study was conducted specifically for Portland OR, but is mostly applicable throughout the Pacific Northwest. Construction techniques vary locally, and nationally, but with local guidance, the most typical wall construction strategies were simulated for this report. Some higher R-value walls were also included that may not be as commonly constructed to assess the advantages and disadvantages of higher R-value wall systems.

Approach

This study examines thermal and moisture control, durability, constructability, cost and material use. The quantitative analysis for each wall system is based on a two-dimensional steady-state heat flow modeling program and a one-dimensional dynamic heat and moisture (hygrothermal) model. Portland OR, in IECC climate Zone 4C was used for all of the hygrothermal analysis.

Analysis

Wall Assemblies Reviewed

There are a number of variables possible for each wall system depending on the local practices, climate, and architect or general contractor preferences. An attempt was made to choose the exterior wall systems most commonly used in the Pacific Northwest and make notes and comments about other possible alternatives during the analysis. Some of the wall systems selected for analysis are not common to the Pacific Northwest but are used in other locations and may be good wall construction options in the Pacific Northwest. This list of chosen systems is explained in more detail in the analysis section for each wall system. In some cases, small variations were made to the chosen walls and a sensitivity analysis was conducted. For example the smart vapor retarder (SVR) may be changed to a kraft paper vapor control to determine the importance of the vapor control layer. A smart vapor retarder provides variable vapor permeance by altering the vapor permeance depending on the surrounding relative humidity. These analysis are not reflected in the wall list, but are identified later in the analysis sections.

- Wall 1 : Standard construction with 2x6 framing
- Wall 2 : Advanced framing
- Wall 2b : Advanced framing with OSB sheathing
- Wall 3 : Advanced framing with 1" of exterior XPS insulation
- Wall 4 : Advanced framing with 2" of exterior XPS insulation
- Wall 5 : Advanced framing with 4" of exterior XPS insulation
- Wall 6 : Advanced framing with 1" of exterior XPS insulation and blown cellulose in the stud cavity
- Wall 7 : Advanced framing with 2x8 construction
- Wall 8 : Advanced framing with 2x8 construction and 1" of exterior XPS insulation
- Wall 9 : Standard construction with 2x4 framing, 2" of exterior XPS insulation and no insulation in the stud cavity
- Wall 10 : Standard construction with 2x4 framing, 2" of exterior XPS insulation and fiberglass batt insulation in the stud cavity
- Wall 11: Advanced framing with 0.5 pcf spray foam
- Wall 12: Advanced framing with 2.0 pcf spray foam
- Wall 13: Hybrid wall with 2.0 pcf spray foam and fiberglass batt (i.e. "flash and batt")
- Wall 14: Double stud wall with an exterior structural wall
- Wall 15: Double stud wall with an interior structural wall
- Wall 16: Structural Insulated Panels (SIPs)
- Wall 17: Insulated Concrete Forms (ICF)

Analysis Criteria

A comparison matrix will be used to quantitatively compare all of the different wall system strategies. A value between 1 (poor performance) and 5 (excellent performance) will be assigned, upon review of the analysis, to each of the comparison criteria for each wall. An empty comparison matrix is shown below in Table 1 as an example.

Table 1: Criteria comparison matrix

	Thermal Control	Durability (wetting/drying)	Constructability	Cost	Material Use	Total
Criteria Weighting	1	1	1	1	1	
Wall 1: Standard 2x6 Construction - fiberglass batt						
Wall 2: Advanced Framing - fiberglass batt						
Wall 3: Advanced Framing - 1" exterior XPS, fgb						
Wall 4: Advanced Framing - 2" exterior XPS, fgb						
Wall 5: Advanced Framing - 4" exterior XPS, fgb						
Wall 6: Advanced Framing - 1" ext. XPS, cellulose						
Wall 7: Advanced Framing with 2x8, blown fg						
Wall 8: Advanced Framing with 2x8, 1" ext. XPS						
Wall 9: Std 2x4 construction, 2" XPS, none in cavity						
Wall 10: Std 2x4 construction, 2" XPS. FG in cavity .						
Wall 11: Advanced framing with 0.5pcf spray foam						
Wall 12: Advanced framing with 2.0pcf spray foam						
Wall 13: Advanced framing with hybrid insulation						
Wall 14: Double stud, exterior structural, cellulose						
Wall 15: Double stud, interior structural, cellulose						
Wall 16: Structural Insulated Panels (SIPs)						
Wall 17: Insulated Concrete Forms (ICF)						

The criteria scores will be summed for each test wall, and the walls with the highest scores are the preferred options assuming all of the comparison criteria are weighted equally. It is also possible to weight the different comparison criteria asymmetrically depending on the circumstances surrounding a particular building design and the goals involved in the design of that building. For example, durability or cost may be considered more important than thermal control or energy performance by some design teams or may be weighted equally by others. The weightings for each wall will fall between 1 (least important) and 5 (most important). The weighting is multiplied by the comparison criteria score and added to other weighted values. An example of the weighted conclusion matrix will be shown in the Conclusions section.

One of the benefits of using a comparison matrix is that it allows a quantitative comparison when some of the criteria, such as cost may be poorly defined or highly variable. For example, even though the exact amounts of different materials may be uncertain for the Material Use criteria, standard construction will use less framing lumber than double stud walls, but use more framing lumber than advanced framing in the same wall system, so these systems can be ranked accordingly regardless of the actual material consumed. The cost analysis in this report represents the current Portland, OR construction market at the time of writing.

Heat flow analysis

Two and three dimensional heat flow analysis was conducted for each test wall using THERM 5.2, a two-dimensional steady-state finite element software package developed by the Lawrence Berkeley National Laboratory at the University of California. Three-dimensional heat flow analysis was conducted by modeling the assembly in one view (e.g. plan view) and then using an effective conductivity for the measured assembly in a different view (e.g. elevation view). Therm was used to calculate the thermal performance of each of the different proposed assemblies including thermal bridging effects.

In many cases, it is generally assumed that installing an R13 fiberglass batt into a 2x4 stud wall leads to wall performance of R13. This does not take into account thermal bridging of the wall framing including the studs, rim joist and top and bottom plates which allows heat to bypass the insulation, decreasing the whole wall R-value. Therm can predict the impact of thermal bridging and determine a whole wall R-value that considers the rim joist, wall framing and top and bottom plate(s).

The effect of thermal bridging and different framing details requires a metric more complex than just a single R-value to allow for meaningful comparisons. Five R-values have been and are used in the building industry. Oak Ridge National Labs (ORNL) proposed a number of definitions (Christian and Kosny 1995). We have found it useful to add some and extend their definitions.

1. Installed Insulation R-value

This R-value is commonly referenced in building codes and used by industry. This is simply the R-value labeled on the product installed in the assembly.

2. Center-of-Cavity R-value

The R-value at a line through an assembly that contains the most insulation, and the least framing, typically, the middle of a stud-bay in framed construction.

3. Clear wall R-value

R-value of an assembly containing only insulation and minimum necessary framing materials at a clear section with no windows, corners, columns, architectural details, or interfaces with roofs, foundations or other walls.

4. Whole-wall R-value

R-value for the whole opaque assembly including all additional structural elements (such as double studs), and typical enclosure interface details, including wall/wall (corners), wall /roof, and wall/floor connections.

5. True R-value

The R-value of an enclosure assembly that includes all thermal bridging, air leakage, wind washing, convective loops, radiation enhancements, thermal and hygric mass, and installation defects.

Each of these measures is progressively more realistic. The True R-value is very difficult to measure without field samples.

The whole-wall R-value will be approximated in this analysis. To accurately calculate this whole-wall R-value, the wall in question was divided into three sections, modeled individually, and then the results were combined.

The R-value of the wall section was simulated in plan view to best represent the thermal bridging effects of wall studs as shown in Figure 1. This section is similar to a clear-wall R-value except that the studs are placed closer together to more accurately represent actual numbers of wood framing elements used in real wall systems. The height of the wall section for simulation purposes is 96 inches.

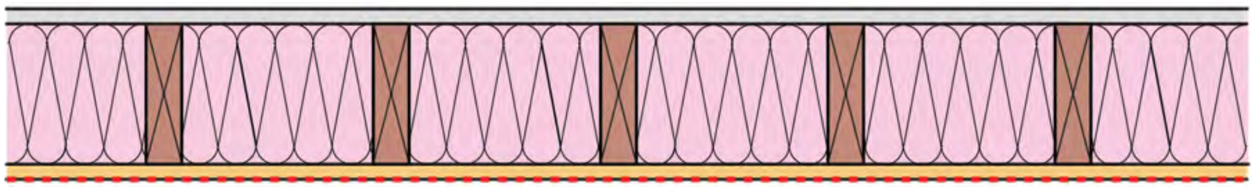


Figure 1 : Plan view of wall section for Therm simulation

To best capture the thermal bridging effects of the top plate, bottom plate and rim joist in a multistory building, the wall was analyzed in a vertical section from the mid-height of one story to the mid-height of the story above (Figure 2). For this analysis, a traditional framing method was used, with the rim joist and floor joists resting directly on top of the lower wall although Walsh Construction uses modified platform framing on many projects. The thermal performance difference is approximately R1 and is shown in Figure 4.

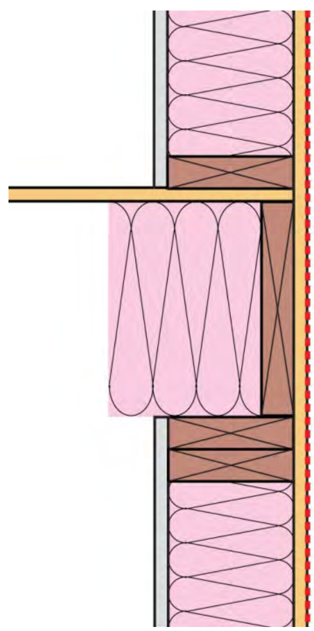


Figure 2 : Rim joist simulation

Although Therm is a two-dimensional modeling program, it was used to model three-dimensional geometries. For example, at the rim joist, there are floor joists connected to the rim joist alternating with pockets of insulation. When this is drawn and modeled in plan view (Figure 3), the effective R-value of just this section through the assembly can be determined.

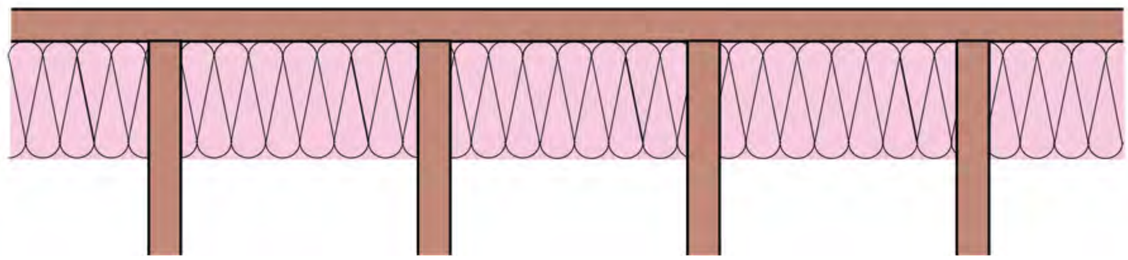
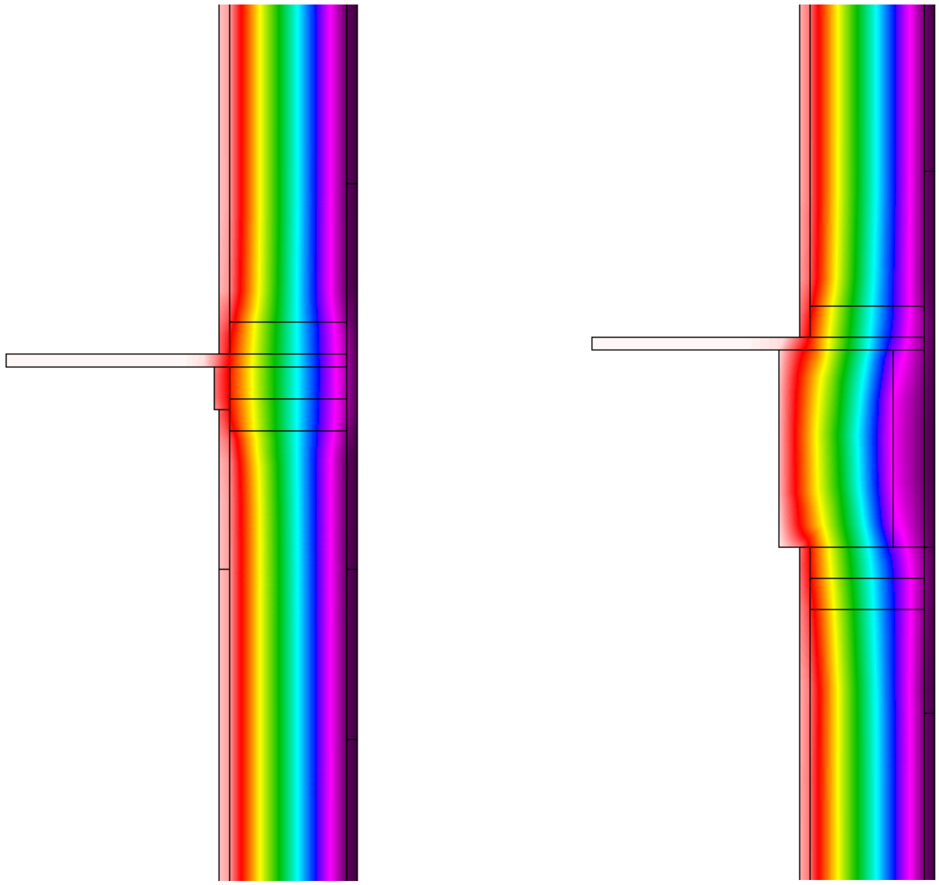


Figure 3 : Plan section of rim joist, floor joists, and fiberglass batt insulation

A fictitious material is then made in the Therm library that has the effective thermal properties of the insulation and floor joists and used in the section profile for modeling of the rim joist system (shown in red in Figure 2). The same technique was used to determine the equivalent R-value of the alternating wall studs and insulation in Figure 1, and used for the cavity insulation in the analysis in Figure 2.

In Portland, Walsh Construction generally uses a modified platform framing approach at the floor line. Wall studs are longer and the top plates are placed just below the subfloor sheathing. Floor joists are then hung from the wall using top flange hangers attached to the top plates. To compare the thermal differences resulting from these two methods, two identical walls were constructed in Therm, one with a traditional framing approach at the rimjoist, and one with modified platform framing. The whole-wall R-value of the traditional wall is R16.2 and the whole-wall R-value of the wall with modified platform framing is R17.1. There is a small improvement in whole wall R-value with the modified platform framing approach, but as with all wall constructions, any small improvements in R-value can be overcome by convection losses if the assembly is not airsealed adequately.



Modified Platform Framing R17.1 Traditional Rim joist framing R16.2

Figure 4 : Thermal Performance Comparison Between Tradition Rim Joist Framing and Modified Platform Framing

One drawback of Therm is that it cannot accurately represent air leakage and insulation installation defects, both of which can significantly lower the true R-value of the assembly by bypassing the insulation in the wall system. There are four main ways in which air leakage effects interact with the enclosure as shown in Figure 5.

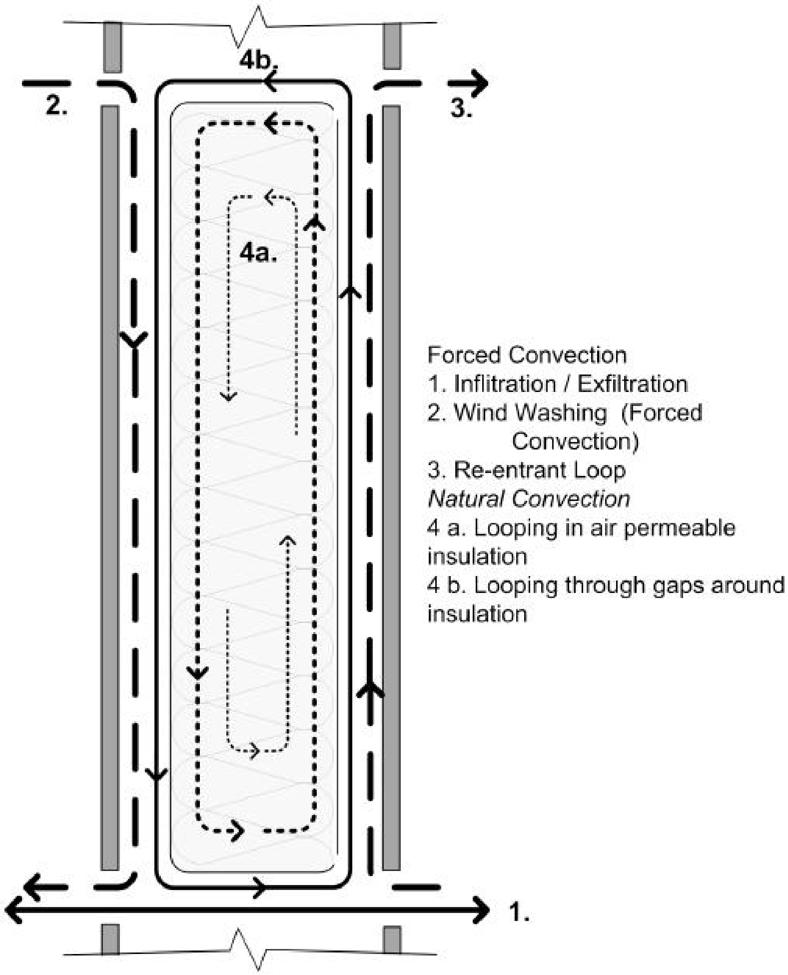


Figure 5 : Common Convective Heat Flow Paths in Enclosures

One of the most common areas for air leakage is at the rim joist where fiberglass batts are often stuffed into the cavities between the ceiling joists. In buildings that are constructed using this method it is quite common to feel air leakage through the assembly at the rim joist bypassing the insulation even without imposing a significant pressure difference across the enclosure. Air tightness of the building enclosure has begun to improve in colder climates for the most part to address occupancy comfort issues and improve energy performance.

Both cellulose and fiberglass batt insulation have similar R-values per inch according to ASTM testing standards, but in practice, standard installation for both fiberglass batt and cellulose generally results in higher true R-values for cellulose compared to fiberglass batt. Fiberglass batts are almost always installed with air gaps against either the drywall or exterior sheathing and fiberglass installers are generally not careful installing fiberglass batts, leading to air gaps around plumbing, electrical and other obstacles in the stud space. These air gaps can lead to convective looping in the stud space and poorly insulated locations resulting in cold spots around obstacles (such as plumbing, electrical wiring, and junction boxes) that could increase the risk of moisture condensation in these areas. Blown in fiberglass is becoming more popular in the construction industry and, similar to cellulose, will reduce the air gaps and convective looping common with fiberglass batts.

Cellulose insulation is blown into place, and fills the entire stud space between the exterior sheathing and drywall, around all obstacles without leaving air gaps. Cellulose has also been shown to have better convection suppression resulting in less convective looping and, in some studies, tighter building enclosures. Neither cellulose nor fiberglass batt are an air barrier, so an air barrier should always be used with either insulation.

Since air leakage cannot be simulated using Therm, the increased convective looping and air movement around poorly installed batt insulation relative to cellulose insulation, and to a lesser extent blown-in or sprayed fiberglass cannot be captured numerically in this study. Also, the convection suppression through the cellulose insulation relative to the fiberglass batt insulation cannot be fully appreciated using this analysis.

All of the Therm analysis were conducted with an interior temperature of 68°F (20°C) and an exterior temperature of 14°F (-10°C) so the results could be compared. Because the R-value is a weak function of the temperature difference across the enclosure, the results may vary slightly for different temperatures.

A list of some of the most common materials and their respective conductivities used in the two dimensional Therm analysis are shown in Table 2. Where there was some discrepancy in the choice of conductivity that should be used for modeling, values from the ASHRAE Handbook of Fundamentals were selected.

Film conductance values of 8.3 W/m^{2}K for the interior surface and 34.0 W/m^{2}K for the exterior surface were used for all Therm simulations.

Table 2 : Conductivity values used for two dimensional heat flow analysis

Enclosure Component	Conductivity k [W/mK]	per inch [hr·°F·ft^2/Btu]
R14 Fiberglass Batt (3.5")	0.036	4.0
R21 Fiberglass Batt (5.5")	0.038	3.8
Blown Fiberglass	0.035	4.1
Extruded Polystyrene (XPS)	0.029	5.0
Expanded Polystyrene (EPS)	0.038	3.8
Framing lumber and sheathing	0.140	1.0
Cellulose Insulation	0.039	3.7
0.5 pcf spray foam	0.039	3.7
2.0 pcf spray foam	0.024	6.1

One of the considerations for thermal modeling was the number of framing components in the wall system. This is usually measured as using the "framing factor", or percentage of a wall cross-sectional area that is comprised of framing elements. For example, a 2x6 stud spacing in a typical wall system is sixteen inches (405 mm) on center. Modeling the wall with a stud spacing of 16 inches o.c. (Figure 6) results in a framing factor of approximately 9%. This method of analysis ignores many of the framing members present in real walls including double studs at windows, partition walls, corners, etc. (See definition of Whole Wall R-value on page 5).

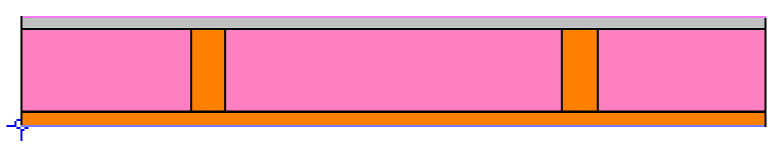


Figure 6 : Typical framing 16"o.c. - 9% framing factor

Field studies have shown that the actual average framing factor, using 16" o.c. framing, including studs, bottom plate and top plates throughout an entire house are closer to 23-25% (Carpenter and Schumacher 2003).

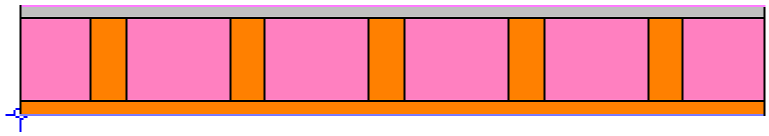


Figure 7 : Actual average framing factor of 25% in standard construction

Most of the framed walls in this analysis were proposed with Advanced Framing techniques (also described in some places as Optimum Value Engineering framing, OVE framing) that include 2x6 framing, 24" on center. Field studies have also been conducted on advanced framed walls in single family residential housing, and it was found that the average framing factor is approximately 16%. In Portland, analysis was conducted of multistory residential buildings constructed with advanced framing, and the framing factor was found to be approximately 19%.

Modeling was conducted to investigate the impact on clear Wall R-value for wall systems with framing factors of 25%, 19% and 16%.

It was found that the clear Wall R-value of a wall section insulated with R19 fiberglass batt decreased from R16.4 to R15.7 when the framing factor was increased from 16% to 19%, and decreased further from R15.7 to R14.4 when the framing factor was increased further to the 25% typical of standard construction.

The reason that none of the wall sections achieved a clear wall R-value of 19 is because of the thermal bridging effects of the studs. This is one of the underlying issues in using Installed Insulation R-values to describe enclosure systems.

For comparison purposes, all of the standard wood framed wall sections in this study were simulated with a framing factor of 25% and the advanced framed walls were modeled with 19% framing factor.

Table 3 shows all of the whole wall R-values calculated using Therm simulations. The whole wall R-value uses the clear wall R-value, calculated for the framing and insulation, and takes into account the rimjoist, top plate, and bottom plate. The thermal performance is further discussed for each wall system in the following sections.

Table 3 : R-values for analyzed wall systems

Wall	Description	Installed Insulation R-value	Whole Wall R-value	Framing Factor
1	2x6, 16"oc, R21FG, (25%ff)	21	16.2	25%
2	2x6 AF, 24"oc, R21FG batt,	21	17.2	19%
3	2x6 AF, 24"oc, R21FG batt, + 1" R5 XPS	26	22.2	19%
4	2x6 AF, 24"oc, R21FG batt, + 2" R10 XPS	31	27.2	19%
5	2x6 AF, 24"oc, R21FG batt, + 4" R20 XPS	41	37.3	19%
6	2x6 AF, 24"oc, R19 blown cellulose +1" R5 XPS	24	21.9	19%
7	2x8 AF, 24"oc, R31 blown fiberglass	31	22.2	19%
8	2x8 AF, 24"oc, R31 blown fiberglass + 1" R5 XPS	36	27.2	19%
9	2x4, 16"oc, no cavity insulation +2" R10 XPS, (25%ff)	10	12.6	25%
10	2x4, 16"oc, R14 FG batt, 2" R10 XPS, (25%ff)	24	21.5	25%
11	2x6 AF, 24"oc, R23 0.5pcf SPUF	23	16.3	19%
12	2x6 AF, 24"oc, R35 2.0pcf SPUF	35	19.0	19%
13	2x6 AF, 24"oc, R14 2.0pcf SPUF, R14 FG batt	28	18.5	19%
14	Double stud with 9.5" R34 blown cellulose, ext. structural	34	29.9	25%
15	Double stud with 9.5" R34 blown cellulose, int. structural	34	30.3	25%
16	SIPs - 6" (5.0" EPS)	24	21.5	-
17	ICF - 8" foam ICF (4" EPS)	16	16.4	-

*AF - Advanced Framing

Hygrothermal Analysis

Hygrothermal analysis is the combined analysis of heat and moisture movement. For this research, WUFI® from the Fraunhofer Institut Bauphysik was used to determine the hygrothermal performance of the chosen wall systems.

WUFI® was used only to investigate wood framed walls. ICF and SIPs walls are not subject to the same moisture-related failure mechanisms as wood framed walls and hence, to model with WUFI® would provide little useful information.

Fiber cement siding was chosen as the cladding system for the analysis at the request of Walsh Construction because it is one of the most common cladding materials used on multi-unit residential buildings in the Northwest. It should be noted that the use of different cladding materials could alter the results of the hygrothermal analysis for each wall system.

Portland, OR was chosen as the climate to compare all of the wall systems. Portland is in DOE climate zone 4C, which experiences cold wintertime temperatures and has a humid marine climate. The climate of Seattle, WA is similar to Portland, and the results of the analysis are largely applicable to wall systems in the Seattle area.

According to the 2010 Oregon Structural Specialty Code, a Class I or II vapor retarder is required on the interior of the framing in zones 5, and marine 4. A class III vapor retarder is permitted where any one of the conditions in Table 1405.3.1 (From Oregon Structural Specialty Code) is met. For Portland, in marine zone 4, class III vapor retarders are permitted for:

- Vented cladding over OSB, plywood, fiberboard or gypsum sheathings
- Insulated sheathing with R-value ≥ 2.5 over 2x4 wall
- Insulated sheathing with R-value ≥ 3.75 over 2x6 wall

All of the walls in this analysis are ventilated, so the vapor control required is a Class III (1.0 < perm ≤ 10 perm). The vapor permeance requirement in Portland, OR according to the Oregon Structural Specialty Code is the same in the International Residential Code (IRC).

WUFI® was used to simulate three different scenarios which can cause performance problems for wall systems; wintertime condensation, summer inward vapor drives, and simulated drying following a wetting event.

Moisture Balance

Assessing moisture related durability risks involves three different moisture processes; wetting, drying and moisture redistribution. These three processes in combination with the capacity of the assembly materials to safely store moisture will determine the risk of moisture damage to a building enclosure assembly (Figure 8).

Wetting of the enclosure is most often caused by rain, air leakage condensation, vapor condensation, plumbing leaks and built in construction moisture. Minimizing these sources with good design details for air tightness, vapor control and shedding rain will help decrease the risk of moisture related durability failures.

Drying is important since nearly all building enclosures will experience wetting at some point. Assemblies that can dry to both the interior and exterior generally have an advantage and can manage more frequent wettings.

The safe storage capacity of an individual material or enclosure system is fundamental to good building design. Over the last 50 years, there have been changes to buildings that decrease the safe storage capacity and increase the risk of moisture related durability. Four of these changes are listed below (Lstiburek 2007).

1. Increasing the thermal resistance and airtightness of the building enclosure
2. Decreasing the permeability of the layers that we put on the interior and exterior of the enclosure
3. Increasing the mold and water sensitivity of the building materials
4. Decreasing the buildings ability to store and redistribute moisture.

These changes to building enclosures and materials increase the need for good enclosure design with water management details and maximizing the drying potential. It is rarely economical to build an enclosure with no risk of wetting but managing the risk is important. In any building enclosure, building materials should be chosen based on moisture tolerance that correlate to the risk of moisture in the enclosure. In all cases drying should be maximized, and attention to good design details should be used.

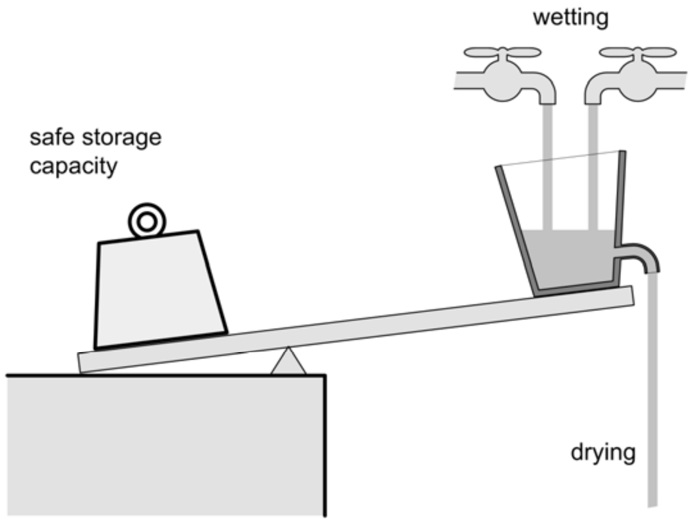


Figure 8 : Moisture balance

Wintertime Condensation

Wintertime vapor diffusion and air leakage condensation potential was determined for each case. The diffusion condensation potential was determined by analyzing the moisture content of the sheathing throughout the year. The interior relative humidity for these simulations was sinusoidal condition varying from a minimum of 40% in the winter to a maximum of 60% in the summer. The interior relative humidity is strongly correlated to occupancy behavior and ventilation strategies. Typically, the indoor relative humidity in a Portland climate will decrease to between 30% and 40% in the winter months. In extremely cold climates this could decrease even further. If humidification is used, or there is inadequate ventilation in a relatively airtight enclosure, the RH could increase to 40 or 50% which increases the risks significantly. Risks are increased because interior humidity will move through the enclosure, by either air leakage or vapor diffusion and many cases of moisture related durability issues of the sheathing have been observed.

The air leakage condensation potential was estimated by determining the dew point of the interior air for every hour of the year, and the temperature of the potential condensation plane. The condensation plane was usually the interior surface of the sheathing, but in walls where spray foam was used, the condensation surface was the interior surface of the spray foam. When the temperature of the condensation plane was below the dew point of the interior air, condensation would occur if air leakage resulted in interior air reaching the condensation plane. The hours of potential condensation for the year were summed.

The number of hours of potential condensation are dependent on both the interior moisture loads and exterior temperatures, and therefore should be used as a comparison between the wall systems, but the actual numbers are relative to the conditions, and therefore it is difficult to define failure criteria.

Figure 9 shows a comparison of the sheathing moisture content caused by vapor diffusion at the sheathing for Walls 1 to 6 and shows the sensitivity of the sheathing moisture content to interior humidity with and without exterior XPS or EPS insulation. Walls 1 and 2 are graphed together since the only difference is the framing factor, and that does not influence the sheathing moisture content. Walls 1 and 2 representing the traditional construction approach reach approximately 22% sheathing moisture content. Changing the smart vapor retarder (SVR) in Walls 1 and 2 to

Kraft paper (Wall 1,2-b), the moisture content increases by approximately 1%. Wall 2b with OSB sheathing instead of plywood sheathing has lower sheathing moisture content than the same walls with plywood. This result is due to the physical differences between the two sheathings. Because plywood has a lower density than OSB, the same amount of moisture added will result in high moisture content percentage.

Walls 3, 4, 5 each decrease in moisture content as the amount of XPS insulation is increased on the exterior which limits the moisture ingress from the exterior and increases the temperature of the condensation plane. Wall 6 performs very similar to Wall 3, the only difference being cellulose insulation instead of fiberglass batt in the stud cavity. Wall 3B uses EPS insulation instead of XPS insulation and the results are similar to Wall 3.

Wall 3c is an experimental wall system that has been proposed for multi-unit residential buildings in the Portland area which has 1" of EPS insulation installed directly to the studs, and the plywood installed on the exterior of that. This wall system has the highest moisture content of all the walls in Figure 9, exceeding 25% for a few weeks during the winter months.

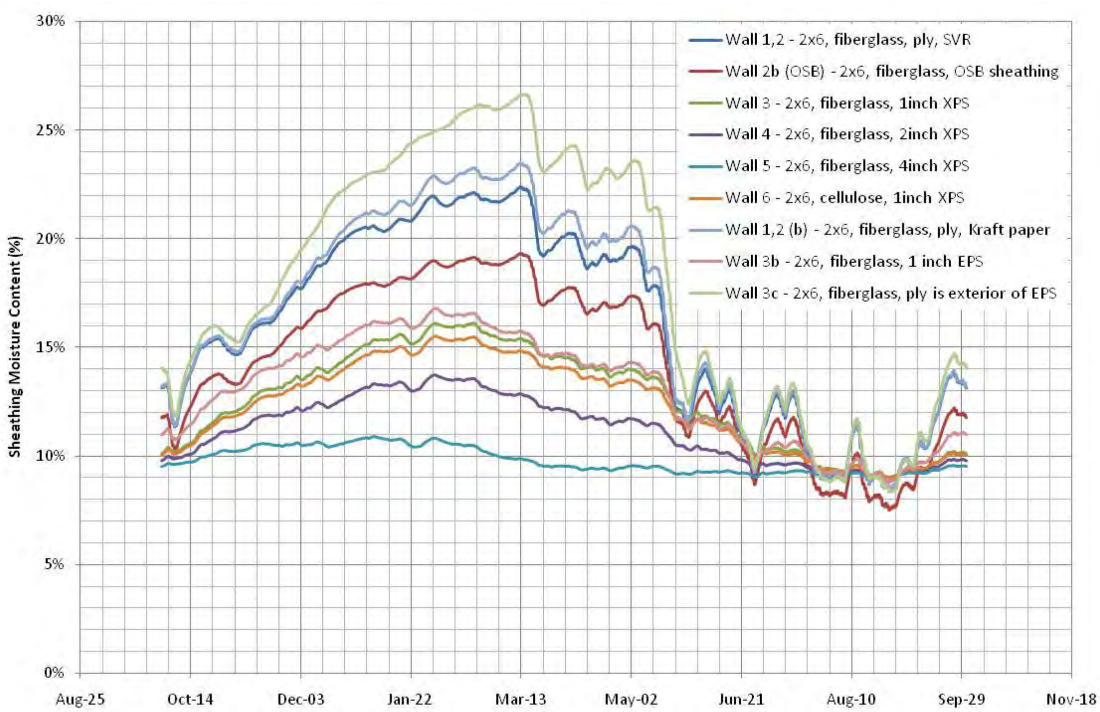


Figure 9 : Winter time sheathing moisture content for Walls 1 to 6

Figure 10 shows the potential for air leakage condensation for Wall 1 and Wall 2. This analysis shows the dewpoint of the interior air and the temperature of the sheathing for both Wall 1 and Wall 2. When the temperature of the sheathing falls below the interior dewpoint line (black line) the potential for air leakage condensation exists. The severity of condensation increases the further below the dewpoint line the sheathing temperature falls and the length of time the sheathing temperature is below the interior air dewpoint line, since drying is minimal during periods of condensation. Walls 1, and 2b have approximately 2850 and 2900 hours of predicted condensation potential due to air leakage in one year.

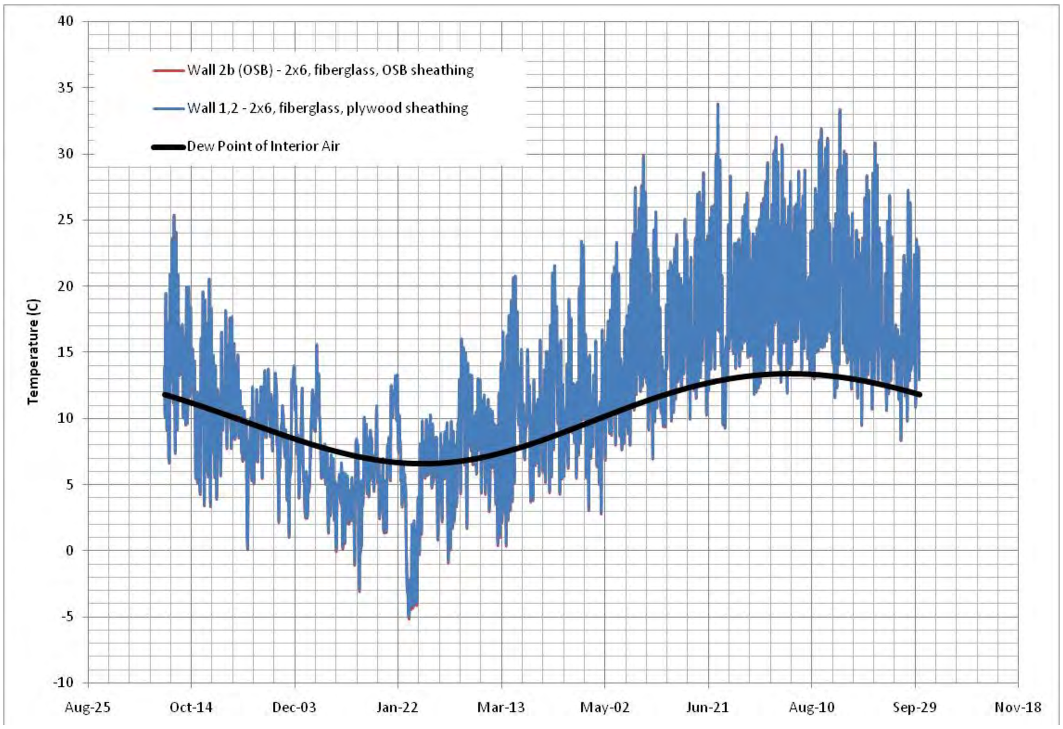


Figure 10 : Winter air leakage condensation potential for Wall 1 and Wall 2

Figure 11 shows the air leakage condensation potential for the 2x6 exterior insulated walls. There are fewer hours of condensation potential as the exterior insulation increases due to the increased temperature of the sheathing. Walls 3 and 6, with 1 inch of exterior insulation have approximately 1000 and 730 hours respectively of potential air leakage condensation, and Wall 4 with 2" of exterior insulation and Wall 5 with 4" of exterior insulation have 210 and zero hours of potential air leakage condensation respectively.

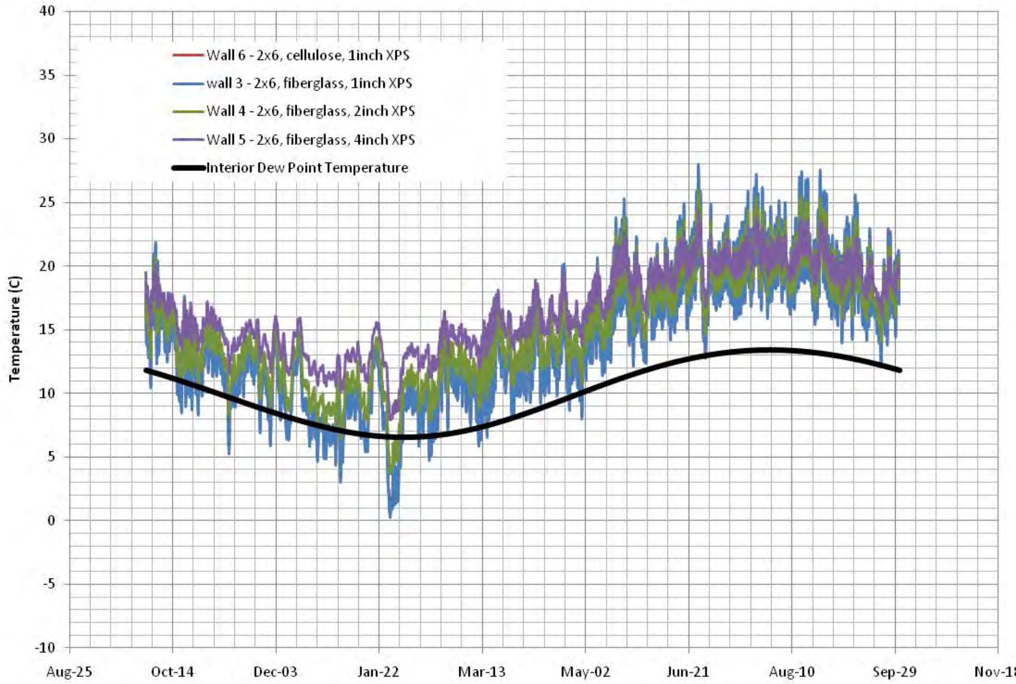


Figure 11 : Winter air leakage condensation potential for Walls 3, 4, 5, and 6

The sheathing moisture contents for Walls 7 to 12 are shown in Figure 12. The walls that exceed sheathing moisture contents of 20% are the spray foam walls, both open and closed cell, and the 2x8 with fiberglass.

The lowest sheathing moisture contents in Figure 12 are Walls 9 and 10 which have a self adhered air and water barrier on the exterior of the sheathing, impermeable to liquid water and water vapor.

Walls 7 with SVR reaches approximately 23% moisture content, approximately 1% higher than the 2x6 framing with fiberglass due to the colder sheathing temperature with the extra 1 ¾" of fiberglass insulation. Changing the SVR vapor control to Kraft paper results in moisture contents exceeding 25% in the winter months. Adding 1" of XPS to the 2x8 wall decreases the moisture risk substantially by increasing the temperature of the interior surface of the framing.

Hygrothermal simulations show that there is some elevated sheathing moisture contents and some risk of moisture related issues in the sheathing of the 2x8 framing wall without exterior insulation and spray foam insulated walls. It is important to remember that in the winter months when the sheathing moisture content is the highest the temperatures are the coldest so the potential for mold growth is low. Also, the sheathing completely dries in the summer, and the safe storage capacity (assuming no bulk water leakage from poor enclosure detailing) may not be exceeded.

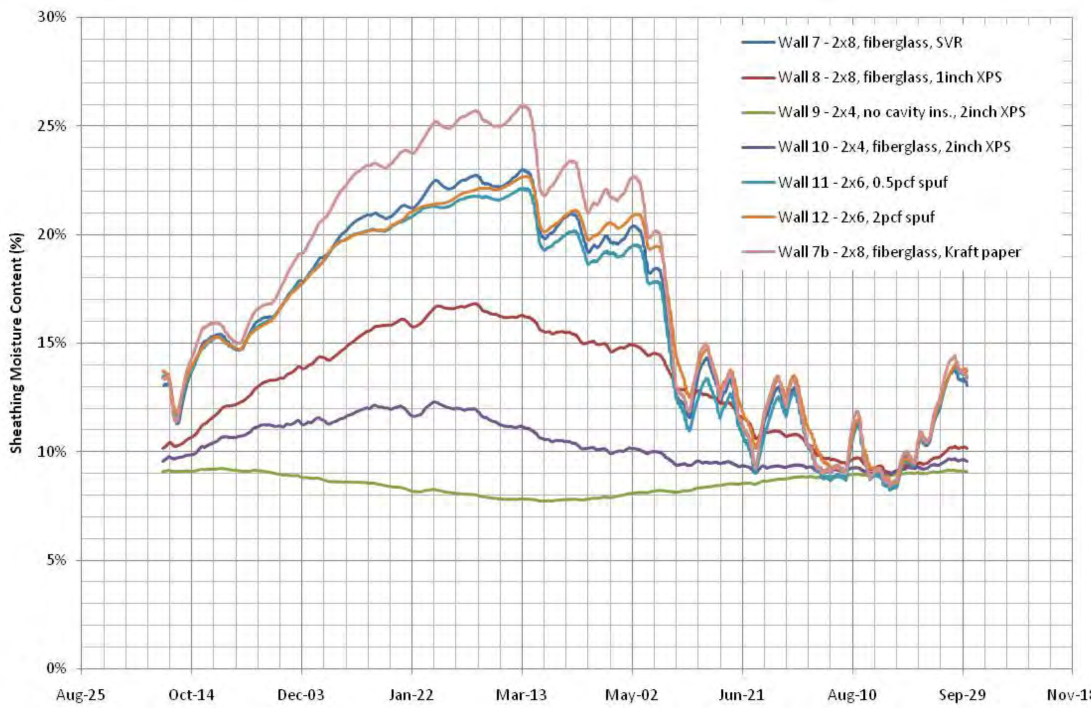


Figure 12 : Winter time sheathing moisture content for Walls 7 to 12

Figure 13 shows the potential for wintertime air leakage condensation for Walls 7 to 10. Wall 7 is the only wall in this group without exterior insulation and has the greatest potential for air leakage condensation with approximately 3000 hours of potential condensation. Wall 8 is improved from Wall 7 because of the exterior XPS insulation with 1500 hours throughout the year.

Wall 9 is 2x4 framing with 2" of exterior insulation and no stud cavity insulation. This means that the sheathing temperature is very close to the interior temperature, and because of that, there are zero hours of potential condensation at the sheathing for Wall 9. Wall 10 is the same construction but with R14 fiberglass batt in the stud cavity which decreases the temperature of the sheathing and increases the potential for air leakage condensation to approximately 70 hours for the year.

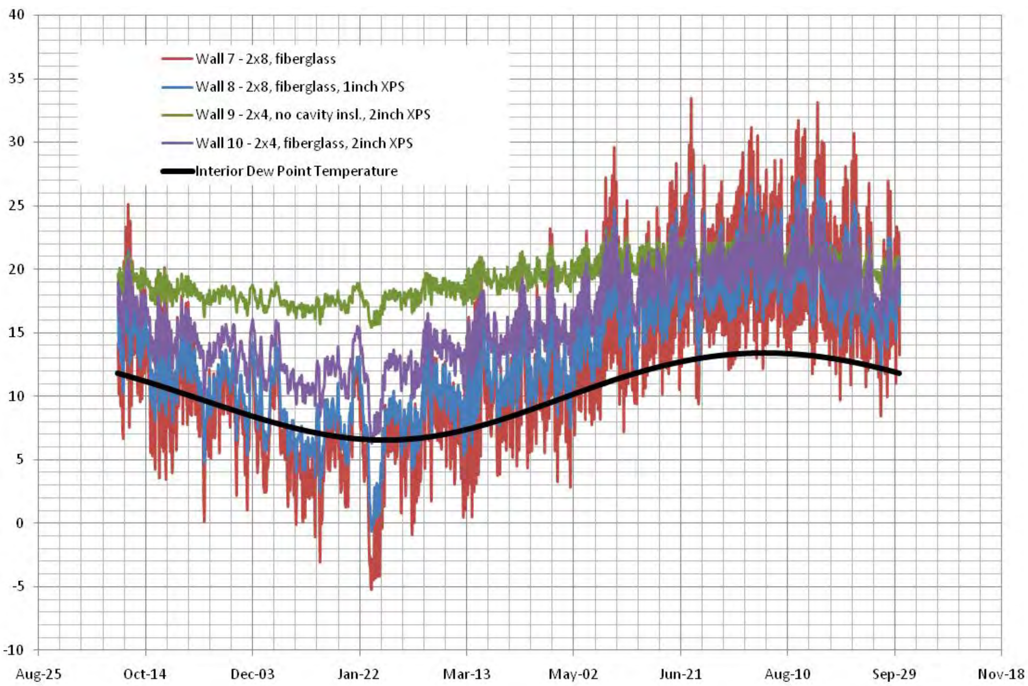


Figure 13 : Winter air leakage condensation potential for Walls 7 to 10.

Figure 14 indicates the potential for wintertime air leakage condensation for Walls 11, 12, and 13. Walls 11 and 12 are both constructed with spray foam in the stud cavity which forms an air barrier if properly installed. The potential air leakage condensation is zero since the interior surface of the spray foam is very near the interior temperature. Wall 13 is a hybrid wall and combines 2" of spray foam and fiberglass batt. Because the interior surface of the foam is kept colder in this construction technique, there are 55 hours of potential condensation throughout the year.

There are many more moisture related enclosure failures caused by air leakage condensation than by vapor diffusion condensation and spray foam in the stud cavity minimizes the risk of air leakage condensation.

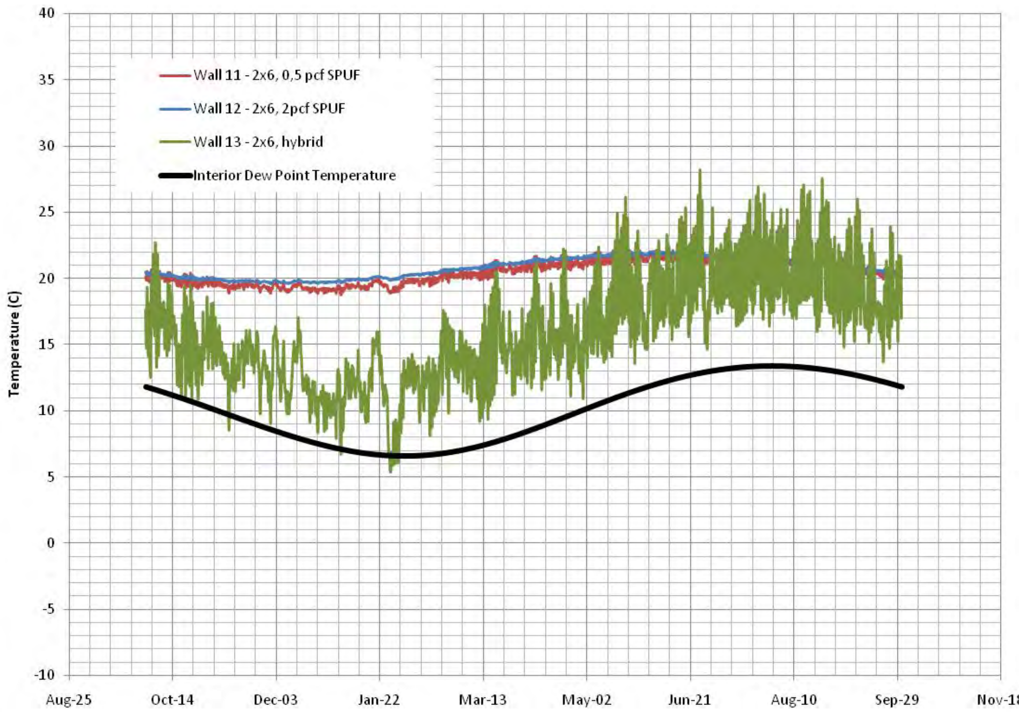


Figure 14 : Winter air leakage condensation potential for Walls 11, 12, and 13

Figure 15 shows the sheathing moisture contents for Walls 13, 14, and 15. The moisture content for Wall 13, the hybrid wall, is very similar to the other spray foam walls shown on a previous graph. Wall 14 with 9.5" of cellulose insulation also has elevated winter time sheathing moisture contents from moisture accumulation. Wall 15 has fiberboard sheathing, which is much more vapor permeable, and able to dry much more quickly to the surroundings. Wall 15 exceeds 16% for the entire winter but does not exceed 20%.

Figure 15 : Winter time sheathing moisture content for Walls 13, 14, and 15

The air leakage condensation potential of Walls 14 and 15 are shown in Figure 16. The sheathing temperatures are nearly identical since both Walls 14 and 15 are constructed with 9.5" of cellulose insulation. There are approximately 3000 hours of potential wintertime air leakage sheathing condensation in both Walls 14 and 15.

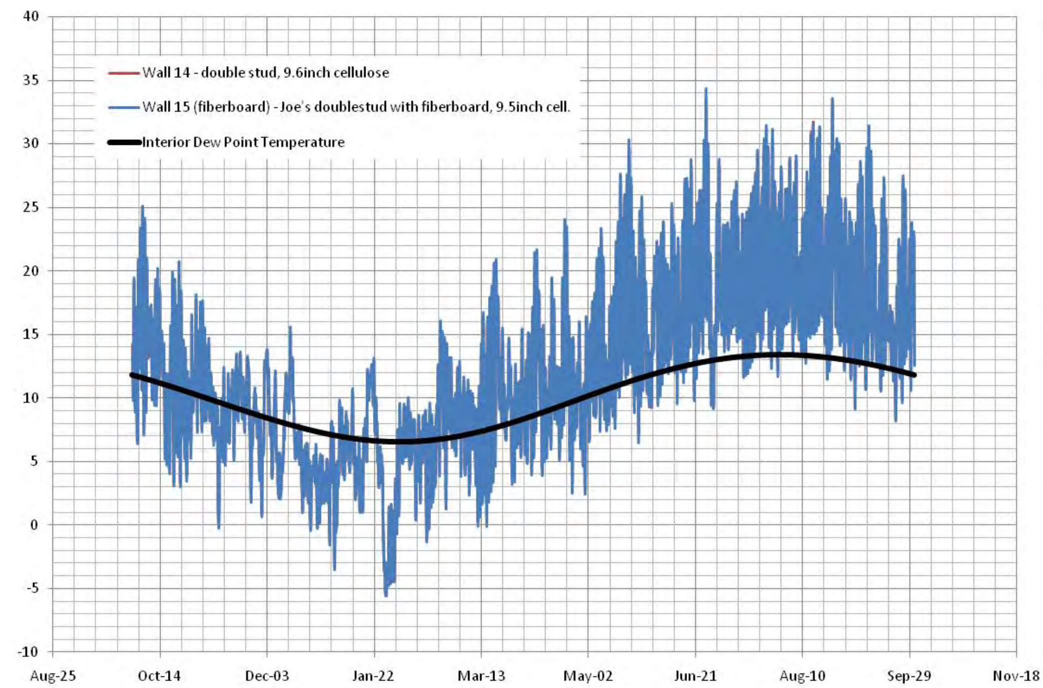


Figure 16 : Winter air leakage condensation potential for Walls 14 and 15

Summer Inward Vapor Drives

Summer inward vapor drives occur when moisture stored in the cladding is heated and driven into the enclosure by a large vapor pressure gradient. Both field testing and modeling have shown that assemblies that have reservoir claddings such as stucco, brick, and fiber cement that absorb and store water, are much more susceptible to summer inward vapor drives. During field testing, moisture has been observed condensing on the interior vapor barrier and may run down to the bottom plate if enough water condenses.

Inward vapor drives were compared in this analysis using fiber cement siding as the cladding, but there are no Class I vapor retarders (< 0.1 perms) such as polyethylene on the interior of any of the analysis walls. This means that all of the walls are allowed to dry to the interior and analysis showed that inward vapor drives are not a problem.

To illustrate the potential effects of inward vapor drive, even in Portland OR, Wall 1 was analyzed and compared to a similar construction with a brick cladding, and an interior polyethylene air and vapor barrier.

Analysis was conducted by graphing the relative humidity at the vapor barrier, or drywall surface in the absence of a vapor barrier, on the south orientation, between the months of May and September.

In Figure 17, Wall 1 is the base case and has the lowest drywall relative humidity of all four analyzed. By either changing the smart vapor retarder to polyethylene, or blocking the ventilation behind the cladding, the humidity at the drywall increased approximately 10% for most of the summer but still remained within a safe range. By changing the cladding to directly applied stucco, and the smart vapor retarder to a polyethylene vapor barrier, the inward vapor drive was significant and the relative humidity was sustained above 95% at the polyethylene vapor barrier for over two months.

Care should be taken to ensure that the risks of summer time inward vapor drive are minimized as much as possible by ventilating the cladding, controlling the moisture drive from the exterior by selecting construction materials with appropriate vapor control, and allowing moisture in the wall to dry to the interior.

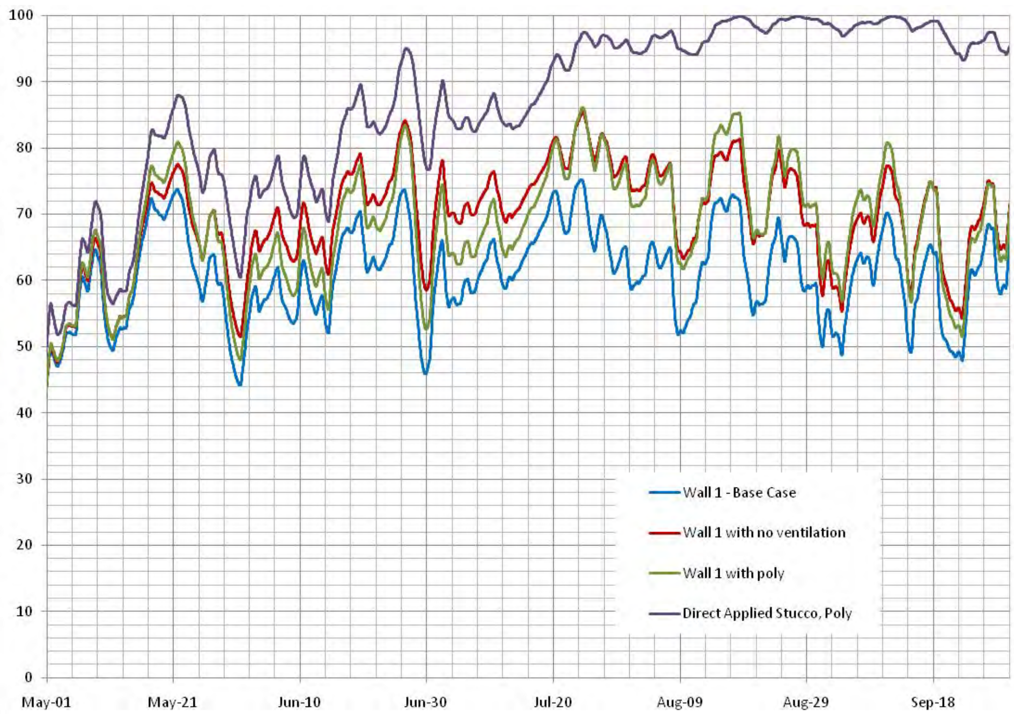


Figure 17 : Inward Vapor Drive Analysis

Wall Drying

The third analysis conducted by using WUFI® hygrothermal modeling is the drying ability of the different wall systems. Drying was quantified by beginning the simulation with an elevated sheathing moisture content of 250 kg/m3 (approximately 50%) in the wall systems and observing the drying curve of the wetted layer. Drying is a very important aspect of durability since there are many sources of possible wetting including rain leakage, air leakage condensation and vapor diffusion condensation. If a wall is able to dry adequately, it can experience some wetting without any long-term durability risks.

The drying analysis is more of a comparison of relative drying potential since it's difficult to predict when and how much a wall will be wetted.

Good enclosure water management design details will minimize the risk of wetting, but drying potential should not be forgotten during enclosure design.

Figure 18 shows the drying curves for all of the analysis walls that do not have exterior XPS sheathing. The quickest drying are the walls with air permeable insulation and the slowest are the walls with spray foam in the cavity.

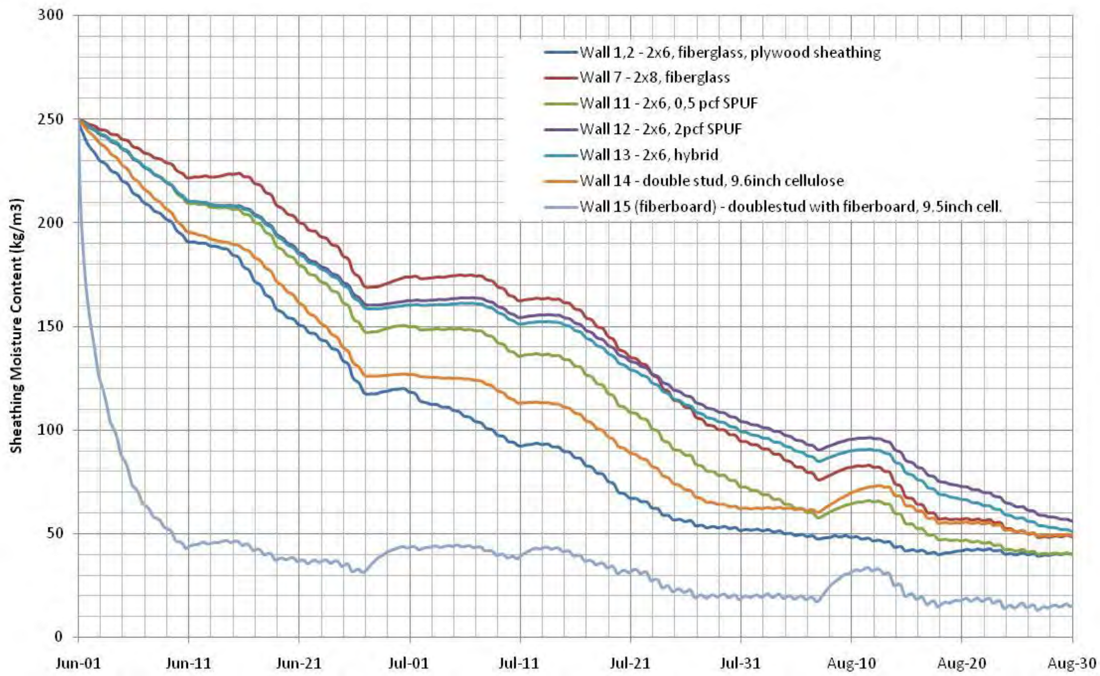


Figure 18 : Analysis of Drying Curves of Walls without Exterior Insulation

Figure 19 shows the drying curves for all of the walls that are constructed with exterior XPS insulation. Wall 9, without cavity insulation dries the quickest of these walls, but all of the other walls perform very similarly in the drying analysis since all of the walls can only dry significantly to the interior.

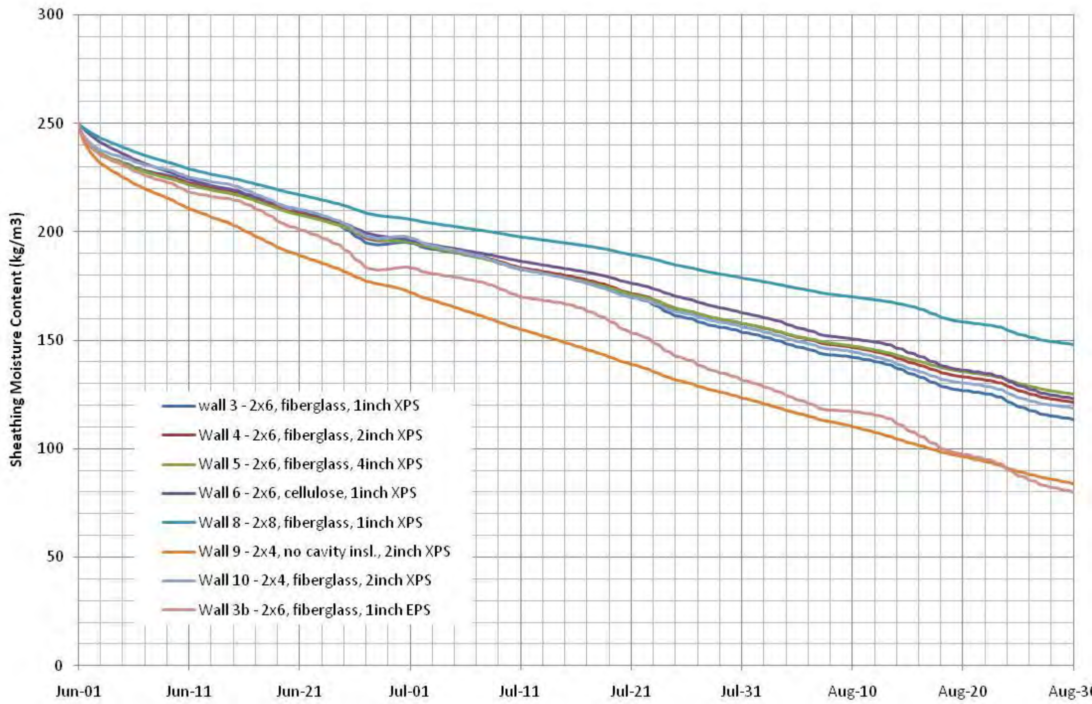


Figure 19 : Analysis of Drying Curves of Walls With Exterior Insulation

Enclosure Durability

Durability of the building enclosure system was also used to classify the different wall construction scenarios. Durability is used in this report to group together multiple durability related criteria such as rain control, drying of water leakage events, condensation, built in moisture, and susceptibility of different building materials to moisture related issues. The durability assessment will be determined from hygrothermal modeling, as well as qualitatively based on the knowledge and experience of building material characteristics such as vapor permeability, and hygric buffering capacity, and susceptibility to moisture related damage.

Constructability

Constructability is an important comparison criteria for practical purposes. Often the general contractor and trades will influence design decisions based on the perceived complexity of different construction techniques or deviation from their standard practice. Any enclosure system and detailing should be buildable on a production level to achieve the greatest benefit even though the trades are often resistant to changes in construction practices. The susceptibility of the enclosure system to poorly constructed water management details and poor workmanship is also considered in constructability. Walsh Construction Company has provided detailed input to Building Science Corporation on this criterion for the purpose of this report.

Material Use

Material use is becoming a critical design issue with the increasing concerns of depleting resources, and increasing costs of materials and energy. Some construction strategies use more construction materials such as the double stud wall, and the advantages of increased thermal control should be balanced against the disadvantages of increasing the building materials and embodied energy. In some cases, materials that have less embodied energy, or recycled material, such as cellulose insulation could be used instead of the more energy intensive fiberglass batt or spray foam insulations. Walsh Construction Company has provided detailed input to Building Science Corporation on this criterion for the purpose of this report.

Cost

The factor which generally has the greatest influence on implementation of a building enclosure strategy, particularly within the context of affordable housing, is cost. Because the cost of some materials varies significantly depending on location and case-specific relationships between builders and suppliers, the cost of a building enclosure system will be perceived relative to other systems. In this analysis, detailed construction cost estimates were requested from local trades in Portland to determine the comparison costs of different wall systems. Walsh Construction Company has provided detailed input to Building Science Corporation on this criterion for the purpose of this report.

Results

Wall 1: Standard 2x6 Construction

For this analysis, standard construction practice includes plywood sheathing, 2x6 framing 16" oc, fiberglass batt insulation, a smart vapor retarder and taped and painted ½" drywall. (Figure 20)

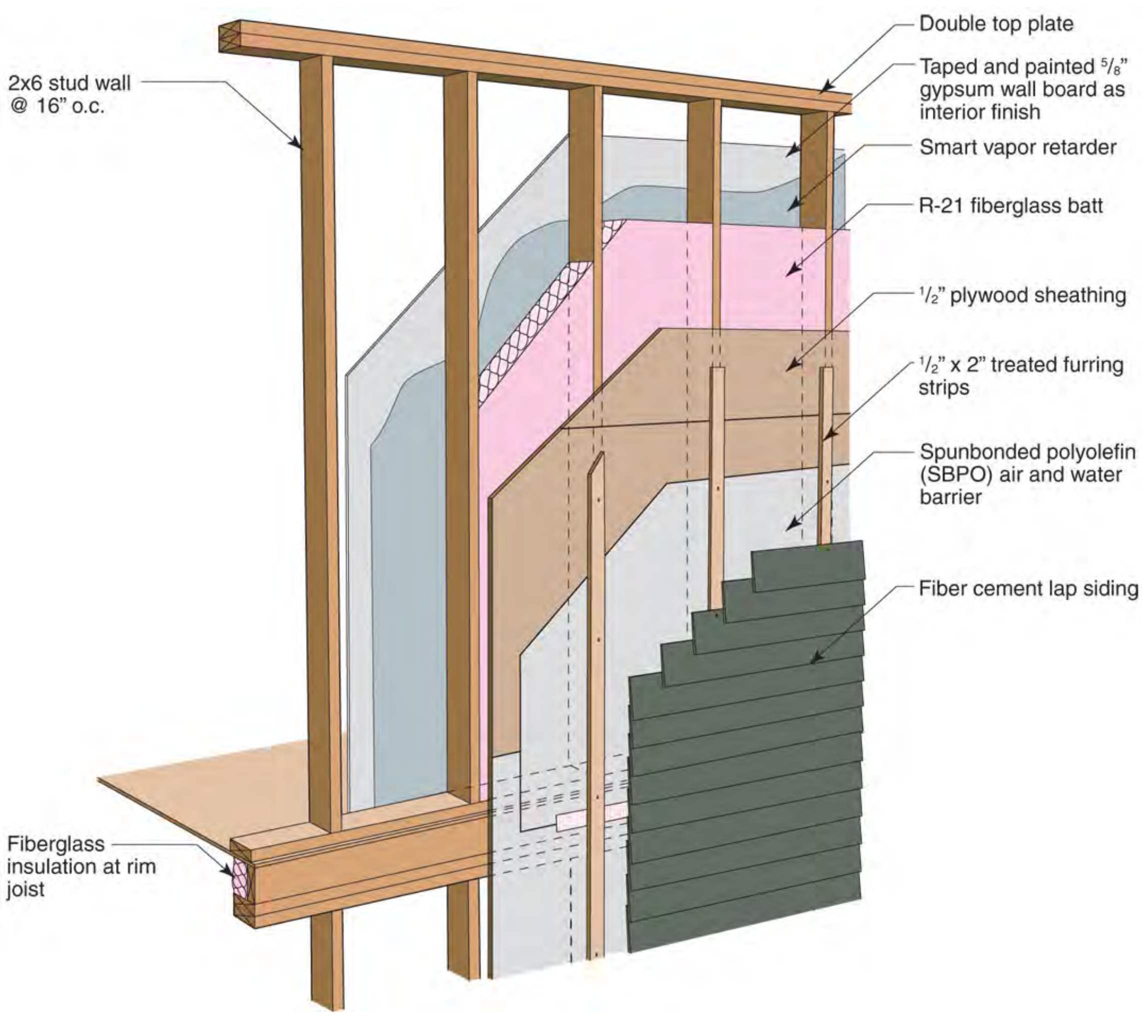


Figure 20 : Standard 2x6 construction practice

Thermal Control

Fiberglass batt installed in a 2x6 wall system has an installed insulation value of R21. Other insulations that could be used in this assembly include densepack or spray applied cellulose, spray applied fiberglass, and spray foam. Regardless of the insulation used in the cavity space, the framing components of the wall act as thermal bridges between the interior drywall and the exterior sheathing and this affects the whole wall R-value of the assembly. Figure 21 shows the vertical wall section used in Therm to determine the whole wall R-values for standard construction practices.

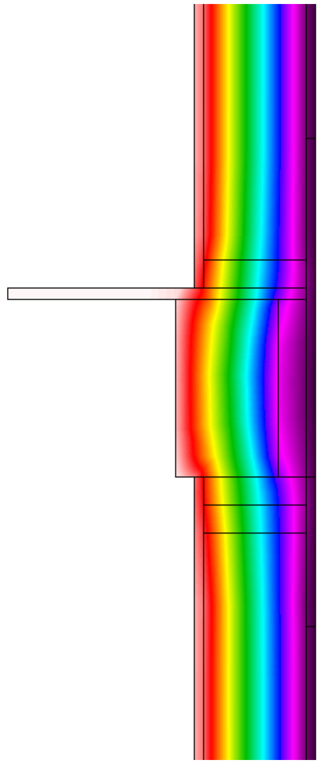


Figure 21 : Therm modeling of Wall 1 – Standard 2x6 construction

As stated previously, studies have shown that even when using a stud spacing of 16"o.c., which corresponds to a framing factor of approximately 9%, the actual average framing factor can be considerably higher, between 23 and 25%. For Wall 1, a framing factor of 25% was simulated and a whole Wall R-value of 16.2 was achieved.

Neither of the two most common insulations, fiberglass or cellulose, control air flow. Cellulose does a better job of suppressing convection because it fills the gaps that are typically left during typical fiberglass batt installation. Blown-in fiberglass also helps address the gaps left during fiberglass batt installation but is relatively new, and not as widely used as cellulose.

Air tightness can be significantly improved by using an airtight insulation such as sprayfoam at the rim joist, and reducing the air leakage condensation and energy losses.

Moisture Control

Condensation potential occurs when the temperature of the exterior sheathing is less than the dew point of the interior air. Analysis of the air leakage condensation potential from a poorly detailed air barrier results in approximately 2850 hours of potential condensation for 2x6 standard construction. These walls are able to dry to both the interior and exterior, and have one of the fastest drying rates of all the test walls in the drying analysis section. Because of this balance of wetting and drying, there is little likelihood of moisture damage or durability problems with this wall type.

Most simulations for this study utilize a smart vapor retarder in the wall assembly to provide vapor diffusion control. This material has a variable perm rating that is advantageous for moisture control in wood framed wall assemblies. It is common practice in the Pacific Northwest to use batt insulation with kraft paper facing to provide vapor diffusion control. Simulations showed that substituting SVR for Kraft paper vapor control resulted in increases of sheathing moisture content of approximately 1% in the winter months.

Constructability and Cost

Wood framed walls sheathed with plywood or OSB and insulated with fiberglass batt insulation are the most common wall assembly used in the construction of multi-unit residential buildings in the Pacific Northwest. Designers, builders, trades and material suppliers are well equipped to specify and construct these walls with good productivity rates at relatively low cost when compared to the other wall types under study. Cladding attachment is straightforward, as is the detailing around window openings and other wall penetrations. The only education necessary may be airtightness detailing to improve overall building performance. As with all walls included in this study, careful attention to detailing for water and air infiltration control is essential to the long term durability of this assembly. Careful attention to installation practices when using batt insulation is essential to achieving the maximum insulating value of the product.

Table 4 - Unit Cost Table for Wall 1

Wall	Framing	Exterior Sheathing	Cavity Insulation	Exterior Insulation	Water/Air Control Layer	Vapor Control Layer	Detailing at Openings	Total $/sf
1	2x6 @ 16" o.c.	½" plywd.	R-21 FG batt	none	SBPO sheet	Smart retarder	Casing + head flashing	
	$3.73	$0.77	$0.49	$0.00	$0.49	$0.78	$0.54	$6.79

Other Considerations

Standard construction uses less framing and wood sheathing than a double stud wall construction, but more than advanced framing wall construction. Using cellulose insulation instead of fiberglass not only increases the fire resistance for the enclosure wall, it also decreases the embodied energy used in construction.

Wall 2: 2x6 Advanced Framing

Advanced framing techniques are becoming more popular for residential and light commercial construction because of several advantages. These practices have been adopted by some smaller home builders, but not on many large scale production developments. Walsh Construction has worked with design teams to utilize these techniques on many projects. The main difference with advanced framing is 2x6 framing lumber at 24" o.c. Depending on the structural considerations and height of the buildings single top plates are often used. The idea of advanced framing is to reduce the framing factor of the wall system in the corners and around penetrations by good design. A single top plate may be structurally possible if stack framing is used, which means the framing from one floor is lined up directly with the framing above and below it to create a continuous load path.

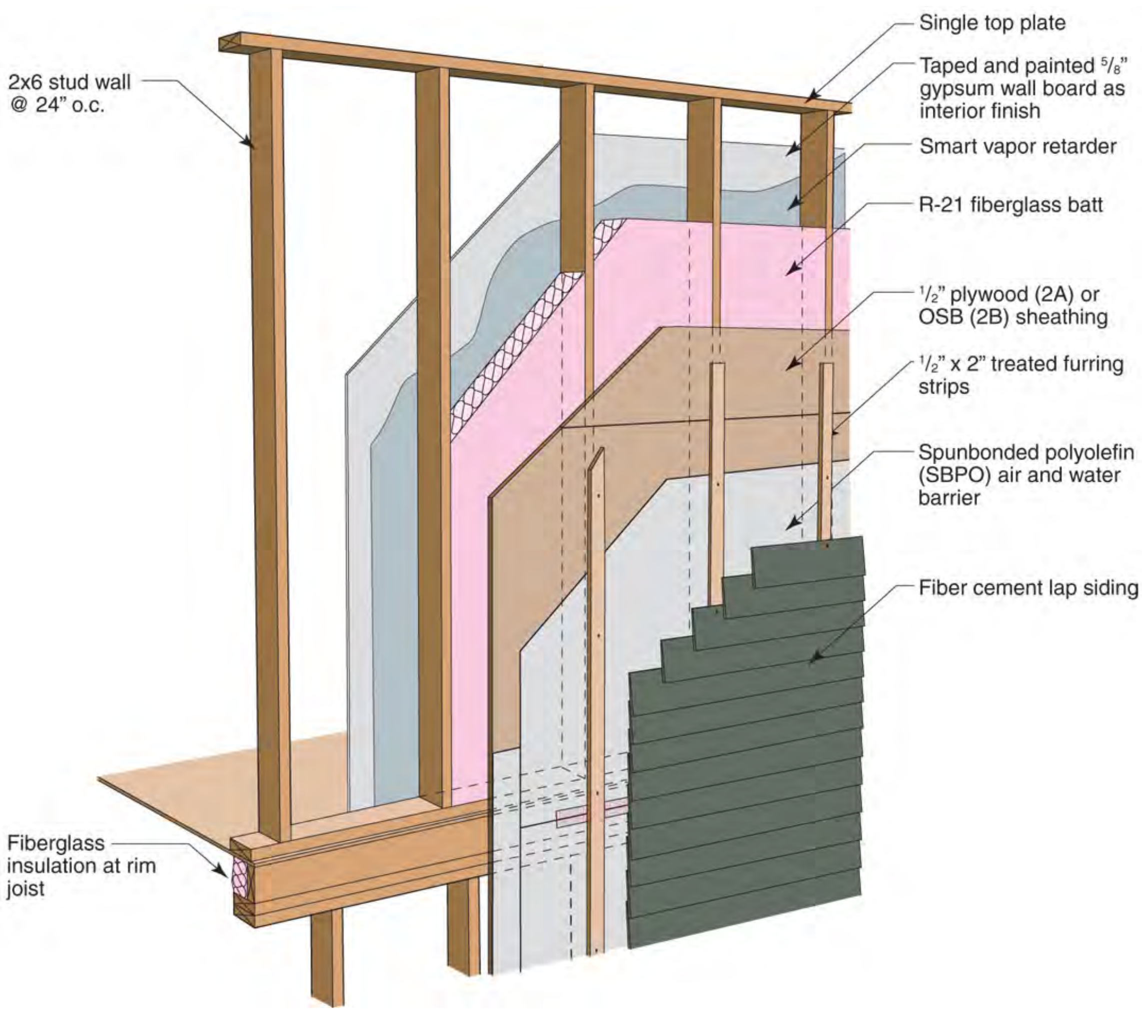


Figure 22 : 2x6 advanced framing construction

Thermal Control

Thermal control for Wall 2 is only slightly improved over Wall 1 caused by reducing the framing factor from 25% to 19%. This decreased framing factor results in a whole wall R-value of 17.2, an increase of R1 over Wall 1.

Drawings from Therm show the vertical section which indicating thermal bridging at the rim joist area similar to Wall 1.

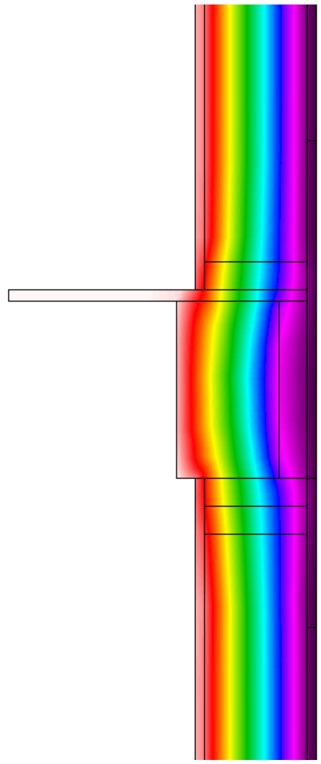


Figure 23 : Therm modeling of Wall 2 – 2x6 advanced framing with fiberglass batt insulation

Moisture Control

Analysis of the air leakage condensation potential from a poorly detailed air barrier results in approximately 2850 hours of potential condensation for the 2x6 advanced framed wall when the temperature of the exterior sheathing is less than the dew point of the interior air.

These walls are able to dry to both the interior and exterior, and have one of the fastest drying rates of all the test walls in the drying analysis section.

Constructability and Cost

Wood framed walls sheathed with plywood or OSB and insulated with fiberglass batt insulation are the most common wall assembly used in the construction of multi-unit residential buildings in the Pacific Northwest. Designers, builders, trades and material suppliers are well equipped to specify and construct these walls, however there is some education and training required for successful utilization of advanced framing methods. Coordination of opening layout and ensuring that studs stack from floor to floor to maintain a continuous load path is usually required. This entails additional diligence and planning on the part of the framing contractor. Once accomplished however, improved productivity rates and slightly reduced quantity of framing material result in the lowest cost of all walls included in this study. Reduced structural capacity due to the increased spacing on exterior walls may result in interior walls providing lateral resistance, which may increase member size in those interior walls. Cladding attachment and detailing around window openings and other wall penetrations is typically straightforward, however attachments may be impacted by the 24" spacing of the studs depending on the cladding type. Careful attention to installation practices when using batt insulation is essential to achieving the maximum insulating value of the product and to minimize convective looping.

Table 5 : Unit Cost Table for Walls 2 and 2b

Wall	Framing	Exterior Sheathing	Cavity Insulation	Exterior Insulation	Water/Air Control Layer	Vapor Control Layer	Detailing at Openings	Total $/sf
2	2x6 @ 24" o.c.	½" plywd.	R-21 FG batt	none	SBPO sheet	Smart retarder	Casing + head flashing	
	$3.61	$0.77	$0.49	$0.00	$0.49	$0.78	$0.54	$6.67
2b	2x6 @ 24" o.c.	½" OSB	R-21 FG batt	none	SBPO sheet	Smart retarder	Casing + head flashing	
	$3.61	$0.67	$0.49	$0.00	$0.49	$0.78	$0.54	$6.57

Other Considerations

The amount of material used in this type of construction is the standard against what other walls will be compared. Standard construction uses less framing and wood sheathing than a double stud wall construction, but more than advanced framing material. Using cellulose insulation instead of fiberglass not only increases the fire resistance for the enclosure wall, it also decreases the embodied energy used in construction.

Wall 3, 4, and 5: Advanced Framing with Exterior XPS Insulation

In many cases of advanced framing, insulated sheathing is used either instead of or in combination with wood sheathing. This is important for thermal performance to minimize thermal bridging effects.

For this analysis, 1", 2" and 4" insulated sheathing is considered for Walls 3, 4, and 5. Insulating sheathing up to 1.5" thick does not change any of the other details such as windows installation and cladding attachment, but insulating sheathing at thicknesses of 2" and greater requires some slightly different design details for window and door installation as well as cladding attachment. Most of these details have already been designed and can be found in building science resources. Walsh has developed conceptual details conditions, which are reflected in the cost analysis.

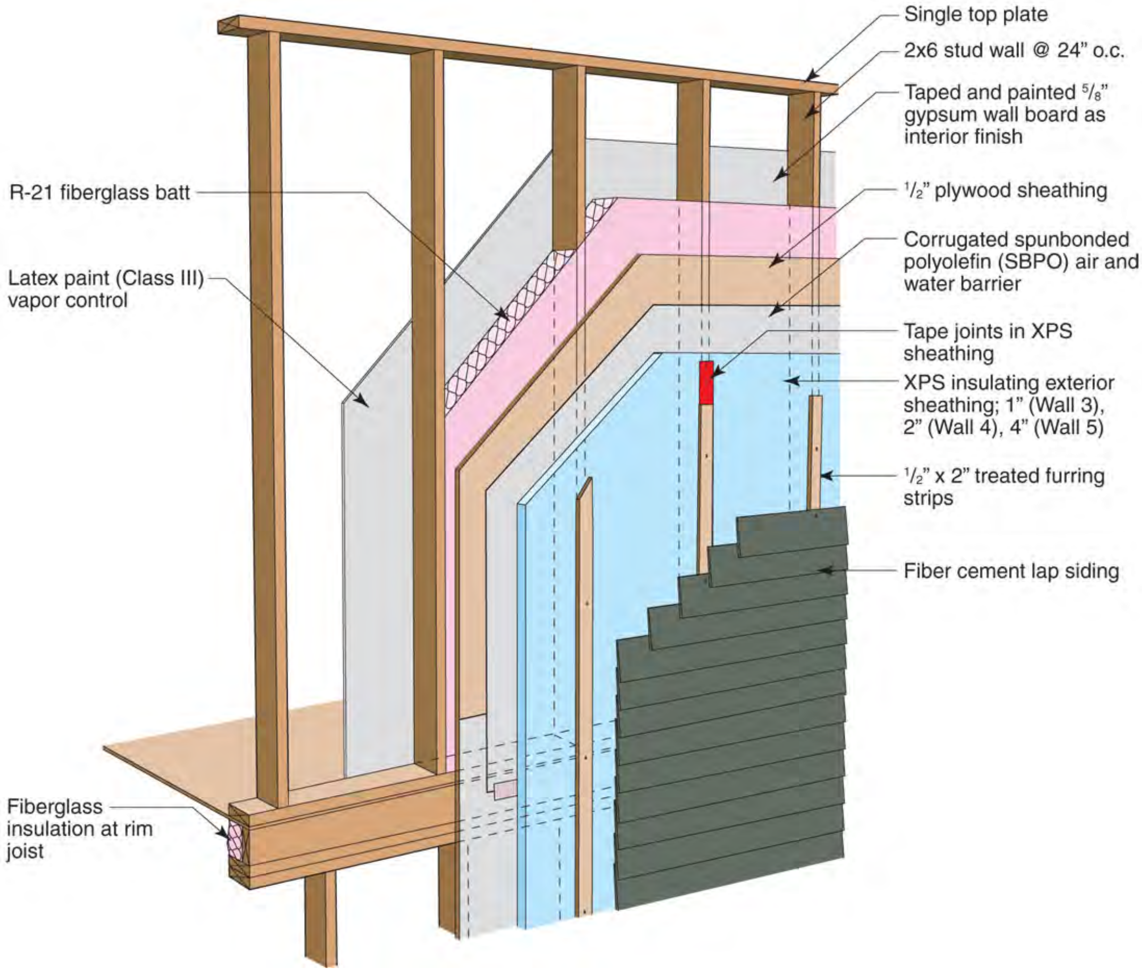


Figure 24 : 2x6 advanced framing construction with exterior XPS insulation

Thermal Control

Thermal control is improved over standard construction practices by utilizing advanced framing techniques and adding insulating sheathing to the exterior of the sheathing. This insulation is typically board foam which includes expanded polystyrene (EPS), extruded polystyrene (XPS) and polyisocyanurate (PIC). PIC is often reflective aluminum foil faced which also helps control radiation losses in some cases, but should be used only with careful hygrothermal analysis since it places a Class I vapor retarder on the exterior of the wall system. Thicknesses of insulation have been installed that range from ¾” to 4” on wall systems. Often times, when 4” of insulation is added, it will be done with two 2” layers with the joints offset both horizontally and vertically. Fiberglass batt, blown fiberglass or cellulose could be used in the stud space. The biggest thermal advantage of the insulating sheathing is decreasing the thermal bridging of the framing members through the thermal barrier. Additionally, it helps boost the overall R-value of the wall, without requiring additional framing material.

Analysis has shown that by adding board foam insulation over the sheathing of a wall system, the increase in the clear wall R-value can be slightly greater than the R-value of the foam due to the thermal break benefits. If the framing factor was higher, or metal studs were used, an even greater increase in the R-value for 1” of XPS can be seen. This is an example of the importance of reducing the thermal bridging through the enclosure.

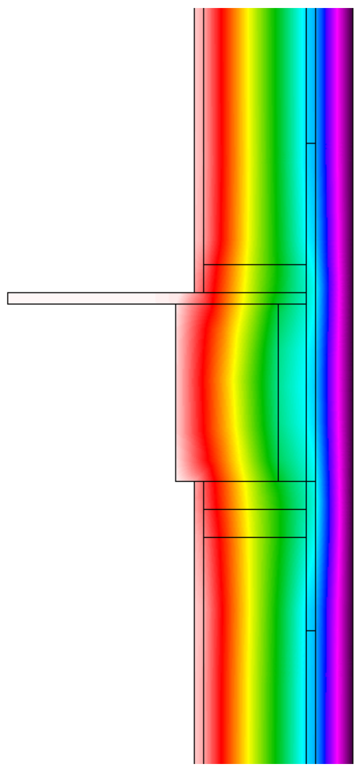


Figure 25 : Therm modeling of advanced framing with fiberglass cavity insulation and 2” XPS exterior insulation

The Whole wall R-value of Walls 3, 4, and 5 are shown in Table 6.

Table 6 : Calculated R-value of advanced framed walls with exterior insulation

Case	Description	Whole Wall R value
3	2x6 AF, 24"oc, R21FG batt, + 1" R5 XPS	22.2
4	2x6 AF, 24"oc, R21FG batt, + 2" R10 XPS	27.2
5	2x6 AF, 24"oc, R21FG batt, + 4" R20 XPS	37.3

Moisture Control

The Therm results show that the interior surface of the plywood sheathing is at a higher temperature than the standard construction wall which will decrease the potential for both vapor diffusion condensation and air leakage condensation.

Air leakage condensation may still be a concern, although not as great as with standard construction. There are approximately 1000 hours, 215 hours, and zero hours of potential air leakage condensation when the temperature of the insulated sheathing is below the dew point of the interior air for 1” of XPS, 2” of XPS and 4” of XPS respectively.

Both of the advanced framing walls dry slower than the standard construction walls because drying to the exterior is throttled by the low vapor permeance XPS.

It should be noted that the wall types with exterior insulated sheathing also incorporate a corrugated SBPO house wrap to facilitate drainage of any incidental water between the exterior insulation and housewrap. This feature will likely improve overall moisture performance of the wall system, however this impact is not reflected in the hygrothermal analysis.

It should also be noted that the wall types with exterior insulated sheathing are relatively vapor open on the interior side of the wall. In other words, a Type III vapor control layer (ie. Latex paint, 1.0 < perm ≤ 10 perm) has been used. This allows a some drying to the interior that is important for overall hygrothermal performance. If a more resistant vapor control layer were used for these wall types (ie. Class I or Class II vapor retarders), moisture problems could result.

Constructability and Cost

Wood framed walls sheathed with plywood or OSB and insulated with fiberglass batt insulation are the most common wall assembly used in the construction of multi-unit residential buildings in the Pacific Northwest. Designers, builders, trades and material suppliers are well equipped to specify and construct these walls, however there is some education and training required for successful successful utilization of advanced framing methods. Coordination of opening layout and ensuring that studs stack from floor to floor to maintain a continuous load path is usually required. This entails additional diligence and planning on the part of the framing contractor. Reduced structural capacity due to the increased spacing on exterior walls may result in interior walls providing lateral resistance, which may increase member size in those interior walls. Careful attention to installation practices when using batt insulation is essential to achieving the maximum insulating value of the product and to minimize convective looping.

The use of 1” thick insulation at the exterior side of Wall 3 does not significantly alter the constructability of the wall. The use of thicker layers of exterior insulation at Walls 4 & 5 (i.e. thickness > 1”) tends to increase the complexity of detailing around windows, doors and other penetrations through the wall. Details for these penetrations must be carefully considered. Window frames, for example, are typically fastened to the wall at or near the plane of exterior sheathing. With the use of thicker insulation at the exterior, sheet metal or other trim elements are needed to close the gap from the window frame to the face of the cladding system. Alternatively, plywood boxes can be constructed at the window opening to allow the window to be moved outward so that it is in line with the face of cladding. Cladding support and attachment also becomes more complex with the use of thicker layers of exterior insulation. With many cladding systems, the cladding is fastened to vertically-oriented furring strips which are in turn fastened through exterior insulation to the framing. It is essential for the installer to ensure that the furring is connected into framing and this coordination becomes more difficult as the thickness of the insulation increases. Similarly, it is incumbent on the design team to verify the fastening requirements for a cladding system not connected directly into the framing and for the construction team to execute to manufacturer approved fastening specifications. The increased amount of material and number of components, plus the increased complexity (which impacts productivity) tends to drive costs for these walls significantly higher than the costs for Walls 1, 2 & 3. However these walls are the most cost effective options where higher whole wall r-values (i.e. >R-25) are sought.

Table 7 : Unit Cost Table for Walls 3, 4, and 5

Wall	Framing	Exterior Sheathing	Cavity Insulation	Exterior Insulation	Water/Air Control Layer	Vapor Control Layer	Detailing at Openings	Total $/sf
3	2x6 @ 24" o.c.	½" plywd.	R-21 FG batt	1" XPS	SBPO sheet	none	Casing + head flashing	
	$3.61	$0.77	$0.49	$1.86	$0.44	$0.00	$0.76	$7.92
4	2x6 @ 24" o.c.	½" plywd.	R-21 FG batt	2" XPS	SBPO sheet	none	Casing + head flashing	
	$3.61	$0.77	$0.49	$2.46	$0.44	$0.00	$1.09	$8.85
5	2x6 @ 24" o.c.	½" plywd.	R-21 FG batt	4" XPS	SBPO sheet	none	Casing + head flashing	
	$3.61	$0.77	$0.49	$5.17	$0.44	$0.00	$1.21	$11.68

Other Considerations

The clear wall R-value of a wall system can be increased more than the added value of insulation by minimizing the thermal bridging with exterior insulating sheathing. Advanced framing techniques use less framing lumber than traditional construction, which is a savings of both money and embodied energy while reducing the framing fraction. Similar to traditional construction, using cellulose in the stud space will decrease the embodied energy of the insulation and increase the fire resistance of the wall system.

EPS was substituted for XPS, in Wall 3b, for the moisture analysis in Figure 9, and performed very similarly with respect to moisture. Wall 3c is also shown in Figure 9 and uses EPS installed against the exterior of the studs, with plywood sheathing installed to the exterior of that. This wall had the highest sheathing moisture content of all simulated walls. The risk of moisture related issues in the sheathing is high as compared to all other wall types.

Wall 6: Advanced Framing with Cellulose and 1" exterior XPS insulation

Wall 6 is very similar to Wall 3, but uses cellulose cavity insulation instead of fiberglass batt. This alternative was chosen for analysis to help determine if the choice of cellulose insulation rather than fiberglass batt would have any beneficial impacts on hygrothermal performance.

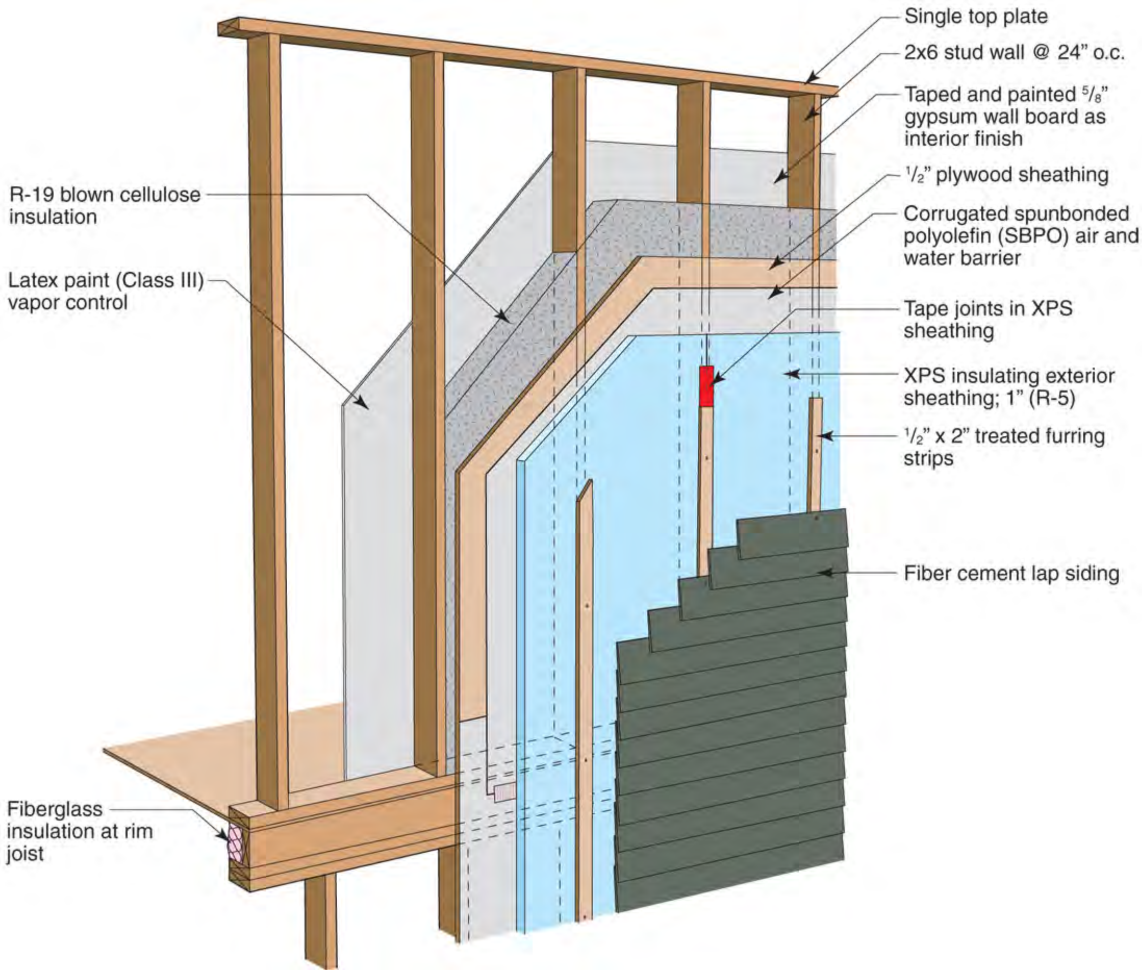


Figure 26 : Advanced framing with cellulose cavity insulation and 1" of XPS exterior insulation

Thermal Control

Similar To Wall 3, there are significant thermal benefits to adding exterior insulation on top of the plywood sheathing. The clear wall R-value can be increased slightly more than the value of the added insulation due to the effectiveness of the thermal break.

The whole wall R-value is predicted to be R21.9, a slight decrease in R-value from Wall 3. Depending on the type of cellulose insulation installed, (ie. damp spray vs. dense packed), this R-value may increase slightly.

Figure 27 shows the Therm analysis model for Wall 6.

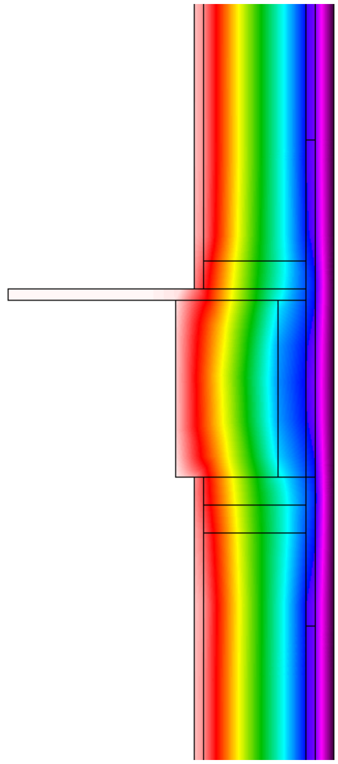


Figure 27 : Therm modeling of Wall 6 - of an advanced framing with cellulose cavity insulation and 1" XPS exterior insulation

Moisture Control

There are significant moisture control benefits to adding exterior XPS insulation. The plywood sheathing surface temperature is elevated resulting in less risk of vapor diffusion or air leakage condensation on the sheathing than in standard construction. There are approximately 730 hours of potential air leakage condensation on the interior surface of the plywood sheathing.

The low permeance of the XPS throttles any summer inward vapor drives, but does result in slow drying if the plywood were to get wet, since the plywood can only dry to the interior. The cellulose insulation in the stud cavity acts as a moisture buffer and will redistribute small amounts of moisture unless the safe moisture storage capacity is exceeded.

Constructability and Cost

See comments on wall assemblies 3, 4, and 5 regarding the use of advanced framing techniques and exterior insulation.

Cellulose insulation represents only about 5% of the installed insulation market in the Pacific Northwest (PNW). For this reason, architects and contractors are not as likely to design or have experience in constructing walls insulated with cellulose. Diligence is required in the specification and installation of cellulose insulation to ensure that a dry pack system is specified and that the product is installed per manufacturer's instructions, as many of the application systems are proprietary. Even dry pack systems contain moisture and may hold moisture during installation, which will require additional dry out time to ensure that wood framing is at acceptable moisture levels prior to installing interior gypsum wallboard. Additionally, it is important to ensure sufficient density of the installed insulation to achieve maximum R value and to minimize settlement.

Cellulose insulation in the PNW market tends to cost significantly more than fiberglass batts or blown-in fiberglass (installed cost of $1.40/sf for cellulose vs. $0.49/sf for fiberglass batt or $1.05/sf for blown-in fiberglass). All other components being equal, this results in an increased cost for Wall 6 as compared to Wall 3. Properly installed cellulose will provide a higher degree of airtightness than fiberglass batts, however if there is an air control layer in the wall assembly otherwise, this should not be a distinguishing factor leading to the selection of cellulose rather than fiberglass.

Table 8 : Unit Cost Table for Wall 6

Wall	Framing	Exterior Sheathing	Cavity Insulation	Exterior Insulation	Water/Air Control Layer	Vapor Control Layer	Detailing at Openings	Total $/sf
6	2x6 @ 24" o.c.	½" plywd.	R-19 cellulose	1" XPS	SBPO sheet	none	Casing + head flashing	
	$3.61	$0.77	$1.40	$1.86	$0.44	$0.00	$0.76	$8.83

Other Considerations

Cellulose insulation in Wall 6 increases the fire resistance of the wall system, and allows for buffering and redistribution of enclosure moisture as long as the buffering capacity is not overwhelmed. Advanced framing practices results in less lumber used than standard construction practices.

Wall 7: 2x8 Advanced Framed Wall with blown fiberglass

This analysis is done with lowrise and midrise multifamily concepts in mind, and more so than in single family residential, the 2x8 can be used to minimize the framing while still supporting the necessary loads. Another reason for choosing this alternative is that framing lumber costs have reduced significantly in recent years, and this has created an opportunity for designing walls with wider framing cavities to accommodate increased amounts of exterior wall insulation in a potentially more cost-effective manner.

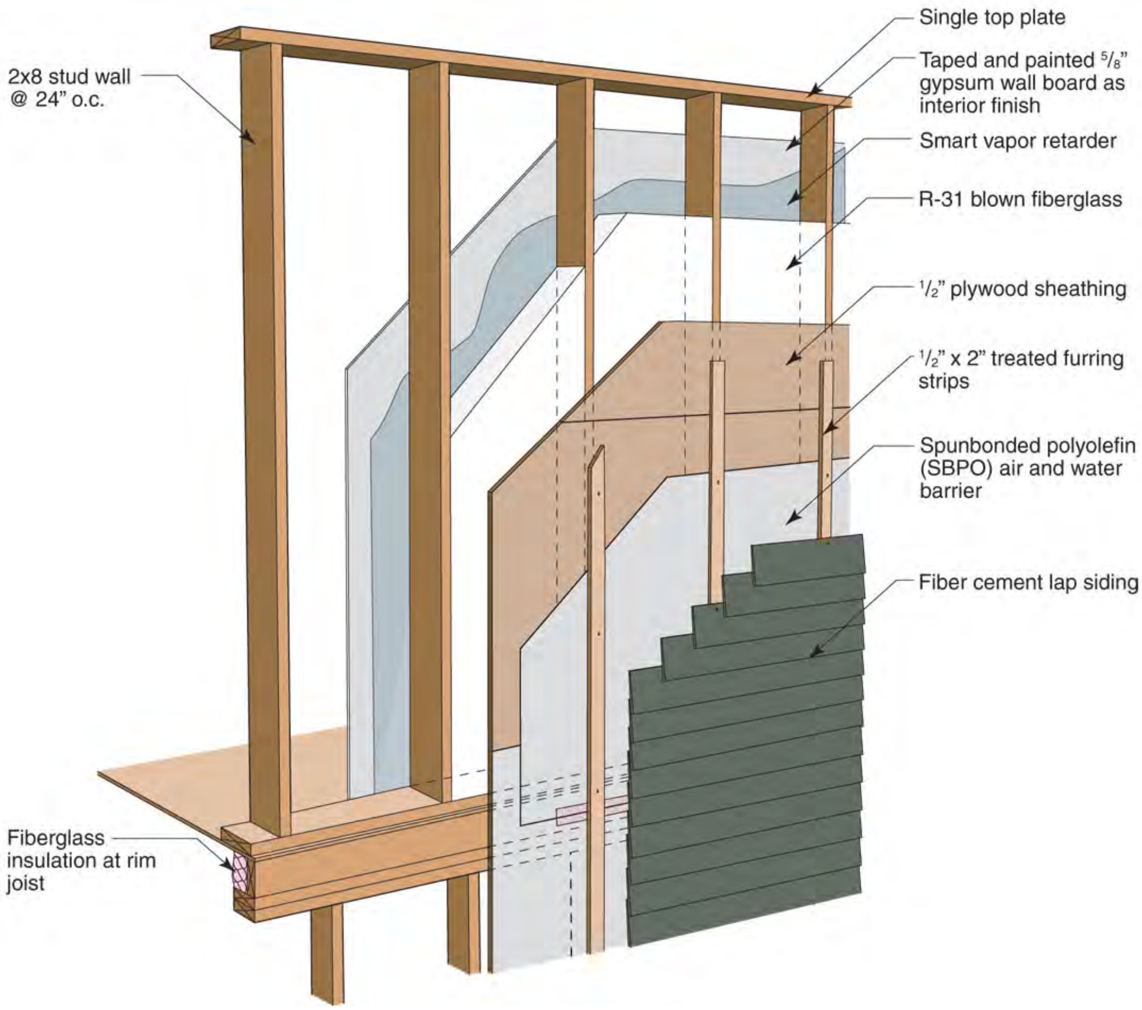


Figure 28 : 2x8 advanced framing with blown fiberglass insulation

Thermal Control

Blown fiberglass is superior in performance to fiberglass batts because it can be installed around obstacles in the wall such as electrical wiring and conduit, although it is relatively new to the marketplace. Even though the insulation R-value is increased, the thermal bridging of the framing in the wall system is not addressed.

Blown fiberglass is air permeable, and air leakage can occur through the insulation, significantly reducing the effective R-value, if the air barrier details are not finished correctly.

The calculated whole-wall R-value from Therm is R22.2 only slightly higher than Wall 6 with 2x6 framing and 1” of exterior insulation.

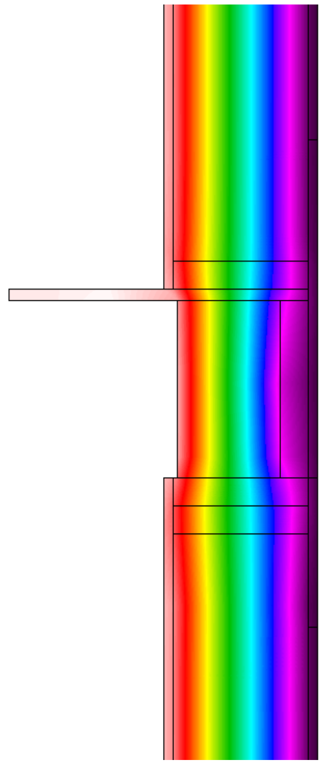


Figure 29 : Therm modeling of Wall 7 - of the 2x8 advanced framing with blown fiberglass

Moisture Control

Vapor diffusion and air leakage control are particularly important in this assembly since it has an increased cavity R-value with no exterior insulation. This means that the interior surface of the sheathing temperature will be colder than standard construction. There are approximately 3020 hours of potential air leakage condensation on the sheathing in this wall but this wall is able to dry to both the interior and exterior. Sheathing moisture contents under normal operating conditions do not exceed 16% in the winter months, therefore this wall can be considered to have little risk of moisture damage and durability related problems.

The blown fiberglass suppresses convective looping better than fiberglass batt, but may not perform in this regard as well as cellulose insulation.

Constructability and Cost

See comments on wall assemblies 3, 4, and 5 regarding the use of advanced framing techniques.

Blown in insulation is quickly gaining market share in the Pacific Northwest and there are increasing numbers of subcontractors with the skills and experience to install it. The installed cost of blown in fiberglass is about twice that of fiberglass batts but significantly less than cellulose. It is important to ensure sufficient density of the installed insulation to achieve maximum R value and to minimize settlement. This typically entails pounding on the scrim after initial blown in installation to encourage settling and then adding additional blown in insulation to ensure that the stud cavity is completely filled. One serious limitation with blown in fiberglass (and blown cellulose) is that at areas where small spaces exist between framing members, it is difficult if not impossible to insert the nozzle between the framing members due to the small dimension. In these conditions, batt insulation is typically inserted instead of installing blown in insulation, resulting in a less effective installation at areas already subject to thermal bridging at framing members.

Increasing the wall framing from 2x6 to 2x8 adds very little additional cost given current lumber market pricing, yet provides a wider cavity to allow for more insulation. Cladding attachment and detailing around window openings and other wall penetrations at this wall is typically straightforward, similar to Walls 1 & 2. The net result is a highly cost effective and constructable option to achieve a whole wall r-value of 22.2

Table 9 : Unit Cost Table for Wall 7

Wall	Framing	Exterior Sheathing	Cavity Insulation	Exterior Insulation	Water/Air Control Layer	Vapor Control Layer	Detailing at Openings	Total $/sf
7	2x8 @ 24" o.c.	½" plywd.	R-31 blown FG	none	SBPO sheet	Smart retarder	Casing + head flashing	
	$4.00	$0.77	$1.40	$0.00	$0.49	$0.78	$0.54	$7.98

Other Considerations

Framing using 2x8s can be helpful for structural reasons instead of using a higher framing factor of 2x6 framing because we know that the whole wall R-value is inversely proportional to the amount of framing used. If 2x6 framing can be used, it may be beneficial to add exterior insulation to increase the R-value instead of increasing the framing size to 2x8.

Wall 8: 2x8 Advanced framing with exterior insulation

Wall 8 was constructed by adding 1" of exterior XPS insulation to Wall 7. This will improve the thermal and moisture performance from Wall 7 by reducing thermal bridging and condensation potential.

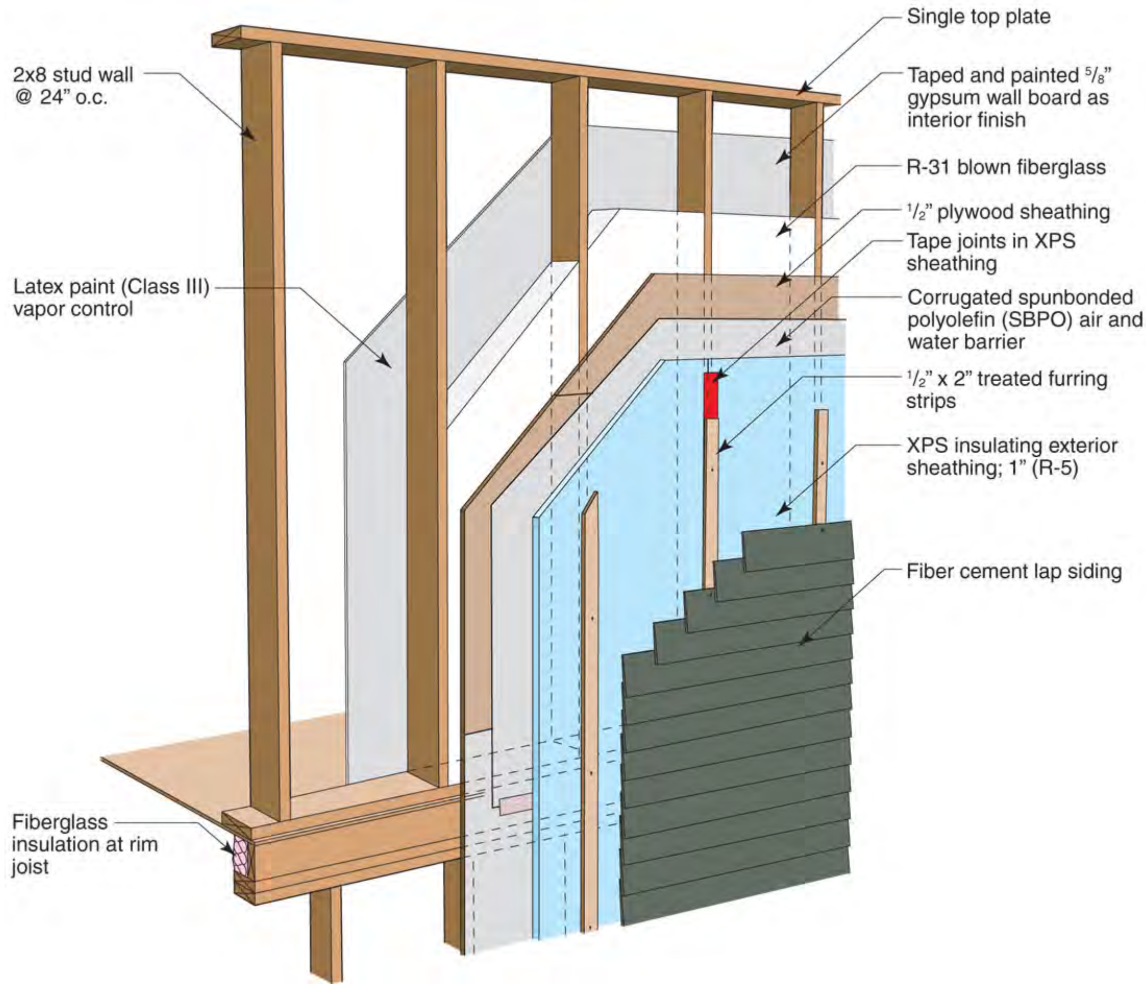


Figure 30 : 2x8 advanced framing with blown fiberglass cavity insulation and exterior insulation

Thermal Control

The exterior insulation installed on Wall 8, improves the thermal control by reducing the thermal bridging through the wall framing. The blown fiberglass in the stud cavity reduces the convective looping compared to fiberglass batt insulation so less energy is lost.

Therm analysis of Wall 8 resulted in a Whole wall R-value of R27.2.

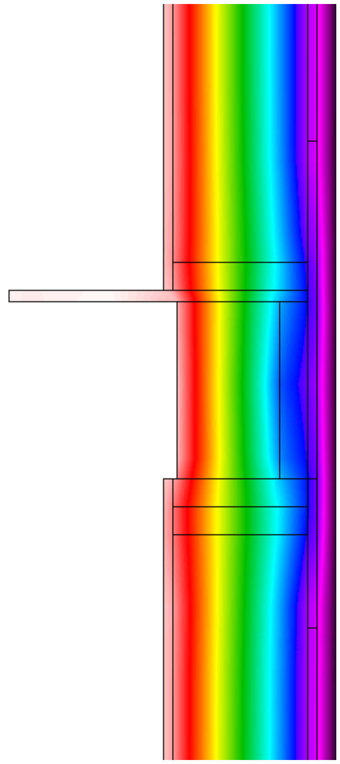


Figure 31 : Therm modeling of Wall 8 - 2x8 advanced framing with blown fiberglass cavity insulation and exterior insulation

Moisture Control

Moisture control in Wall 8 is improved with the exterior foam insulation. The plywood sheathing temperature is increased so condensation potential is decreased. The hours of potential winter time air leakage condensation is 1500, a decrease in over 1500 hours over Wall 7 without the exterior foam insulation

The exterior foam insulation will result in slower drying of the plywood, since all of the drying must be to the interior, but will decrease any inward moisture drives that are present.

Constructability and Cost

See comments on earlier wall assemblies regarding the use of advanced framing techniques, blown in fiberglass and rigid exterior insulation.

Increasing the wall framing from 2x6 to 2x8 adds very little additional cost given current lumber market pricing, yet provides a wider cavity to allow for more insulation. The use of 1" thick insulation at the exterior side of this wall allows does not significantly alter the constructability of the wall. The net result is a cost effective and constructable option to achieve a whole wall r-value of 27.2.

Table 10 : Unit Cost Table for Wall 8

Wall	Framing	Exterior Sheathing	Cavity Insulation	Exterior Insulation	Water/Air Control Layer	Vapor Control Layer	Detailing at Openings	Total $/sf
8	2x8 @ 24" o.c.	½" plywd.	R-31 blown FG	1" XPS	SBPO sheet	none	Casing + head flashing	
	$4.00	$0.77	$1.40	$1.86	$0.44	$0.00	$0.76	$9.23

Other Considerations

Framing using 2x8s can be helpful for structural reasons instead of using a higher framing factor of 2x6 framing because we know that the whole wall R-value is inversely proportional to the amount of framing used. If 2x6 framing can be used, it may be beneficial to add exterior insulation to increase the R-value instead of increasing the framing size to 2x8.

Wall 9: 2x4 framing with exterior XPS insulation and no stud cavity insulation

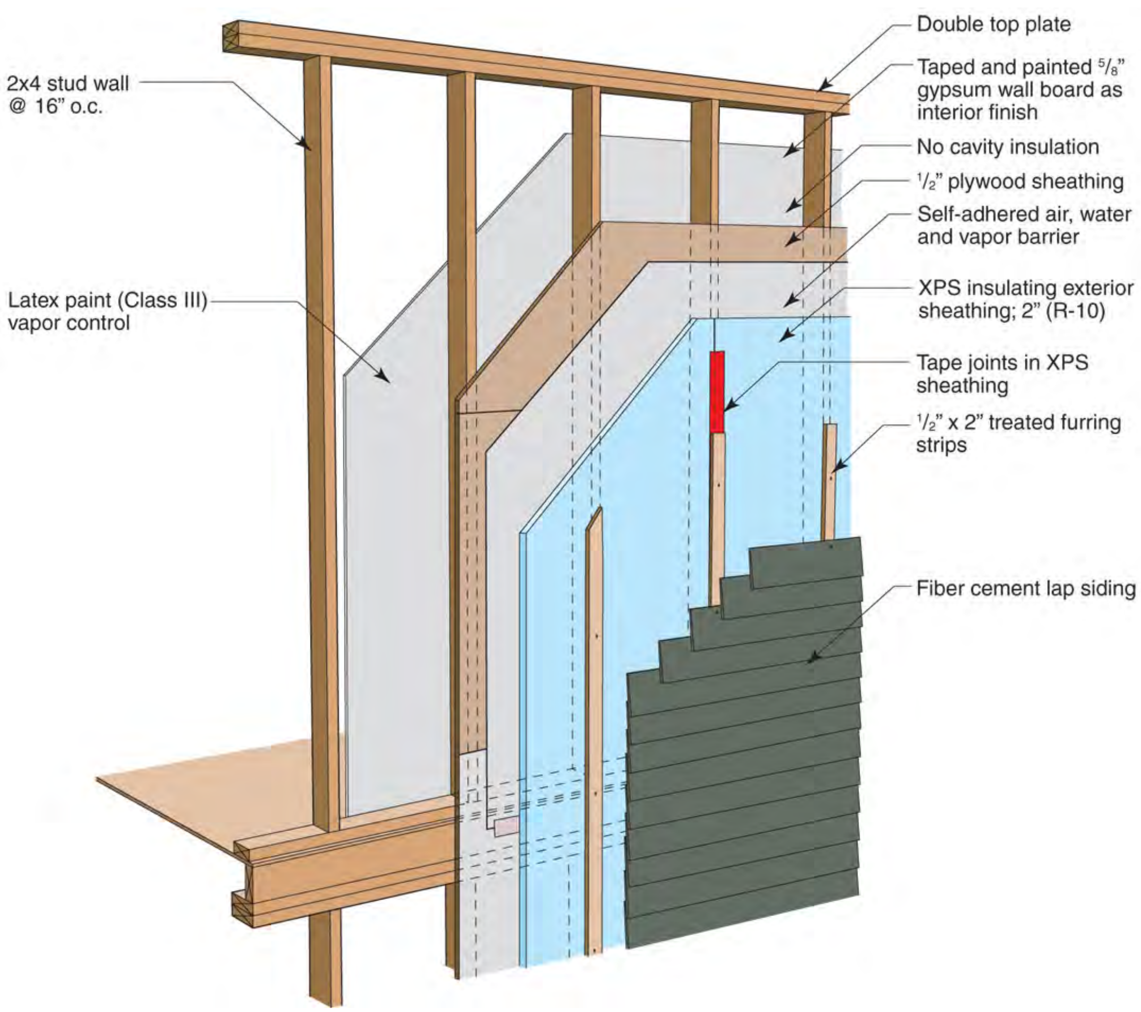


Figure 32 : 2x4 wall with exterior XPS insulation, without stud cavity insulation

Thermal Control

The R-value of this wall is quite low compared to most other walls in this study with a whole wall R-value of only R12.6, because there is no insulation in the stud cavity, and two inches of exterior XPS foam insulation.

The exterior foam insulation controls the thermal bridging through the framing members, but would likely not be used in residential construction because of the poor energy related performance. It may be more suitable to small commercial buildings of wood frame construction.

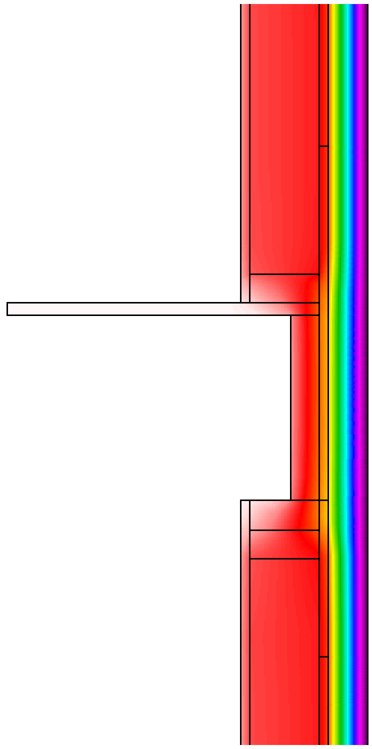


Figure 33 : Therm modeling of Wall 9 - 2x4 framing with 2" XPS exterior insulation and no stud cavity insulation

Moisture Control

This wall performs quite well from a moisture perspective which is one of the key benefits of an exterior only insulation approach. Because there's no insulation in the stud cavity, the plywood surface temperature is not cool enough to condense vapor diffusion or air leakage moisture. The sheathing moisture content analysis is the lowest of all analyzed walls.

There are no times when the temperature of the sheathing is below the dew point of the interior air. From a drying perspective, this wall dries the most quickly of all the walls with exterior insulation, but still does not dry as quickly as walls without exterior insulation.

The foam insulation will also help control any summer time inward vapor drives that occur.

Constructability and Cost

See comments on earlier wall assemblies regarding the use of wood framing techniques, fiberglass batts and rigid exterior insulation.

The cost effectiveness of this wall type is questionable due to the relatively low whole wall r-value achieved with its use. The additional requirements for temporary protection and the building dryout process associated with the use of impermeable self-adhering membrane (see "Other Considerations" below) will likely drive overall costs even higher than indicated in the cost analysis.

Table 11 : Unit Cost Table for Wall 9

Wall	Framing	Exterior Sheathing	Cavity Insulation	Exterior Insulation	Water/Air Control Layer	Vapor Control Layer	Detailing at Openings	Total $/sf
9	2x4 @ 16" o.c.	½" plywd.	none	2" XPS	SAM sheet	none	Casing + head flashing	
	$3.42	$0.77	$0.00	$2.46	$2.09	$0.00	$1.09	$9.82
10	2x4 @ 16" o.c.	½" plywd.	R-14 FG batt	4" XPS	SAM sheet	none	Casing + head flashing	
	$3.42	$0.77	$0.42	$5.17	$2.09	$0.00	$1.21	$13.08

Other Considerations

This wall is more common in extreme cold climates like Alaska or parts of Canada where there is a much greater risk of condensation on the surface of the sheathing, but is likely not a necessary precaution in the Pacific Northwest (climate zone 4C).

The use of a self-adhered air, water and vapor barrier material as part of this assembly must be considered in the context of construction phase moisture exposure that is typically experienced in the Pacific Northwest. Even when dry framing and sheathing materials are procured for projects, exposure to weather conditions during the wet months of the year can lead to a high degree of wetting during the construction process. Consideration should be given to the need for temporary protection at walls that are to receive a self-adhered air, water, vapor barrier, such that this material is not installed over a saturated substrate. Additionally, there may be a need to introduce temporary heat and/or dehumidification to facilitate the dryout process at wall areas where self-adhered, impermeable materials have been installed at the exterior side of wood framed walls.

Wall 10: 2x4 wall construction with exterior XPS insulation and fiberglass batt

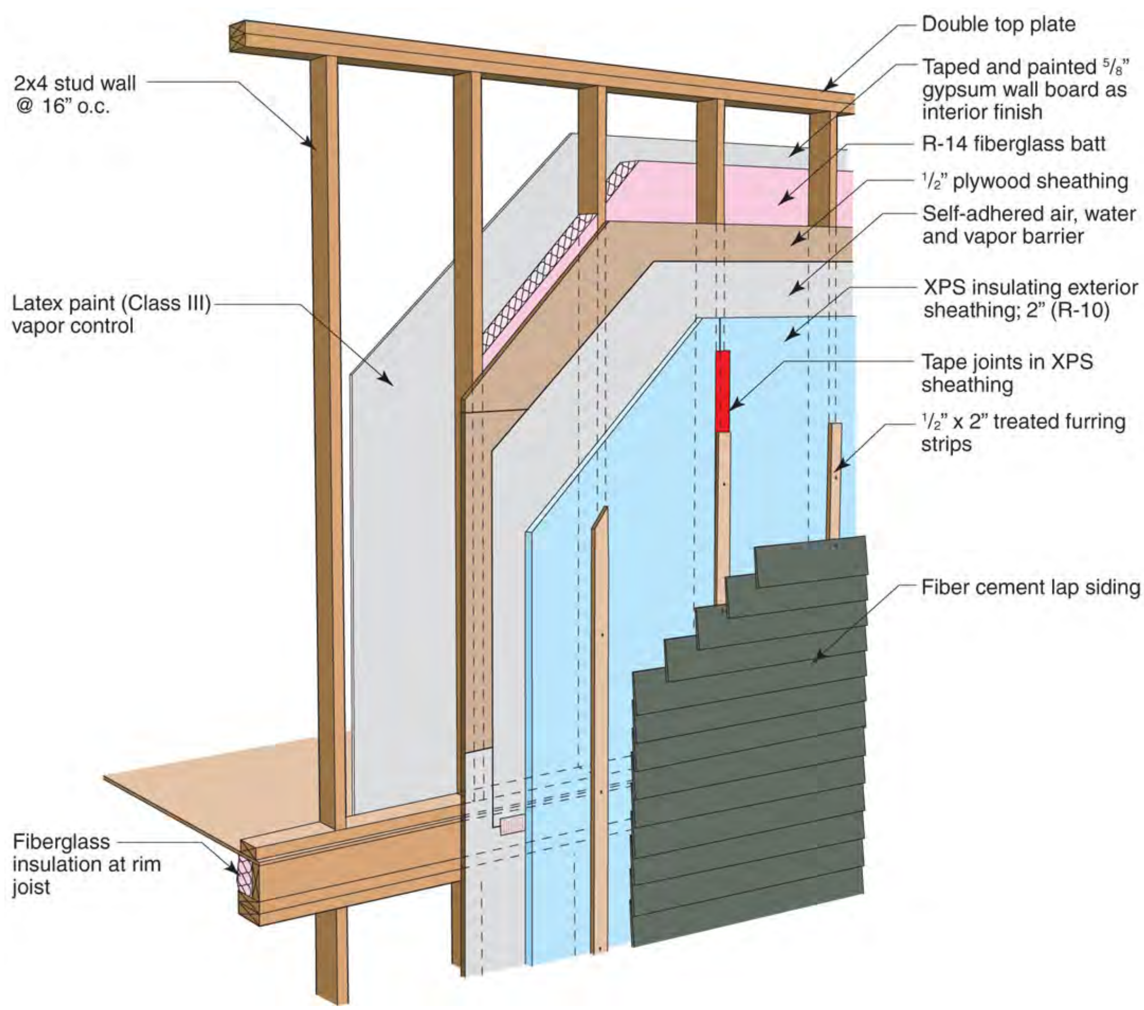


Figure 34 : 2x4 wall construction with XPS insulation and fiberglass batt

Thermal Control

The thermal control of Wall 10 is improved over Wall 9 with the addition of fiberglass batt cavity insulation. Therm analysis results in a Whole wall R-value of 21.5, a significant improvement over R13.

Fiberglass batt insulation installation tends to leave voids around the insulation that may result in convective looping and decreased effective R-values.

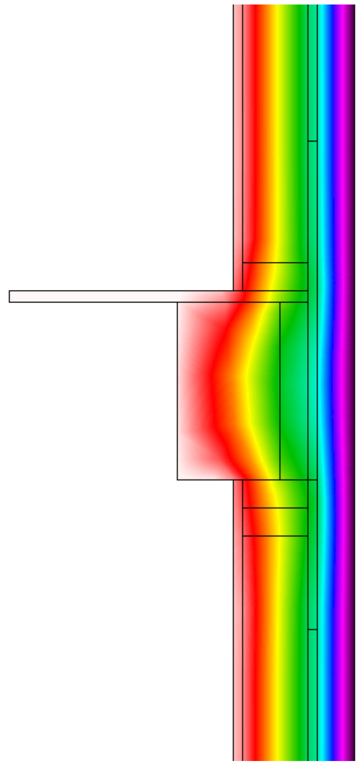


Figure 35 : Therm modeling of Wall 10 - 2x4 construction with exterior insulation and fiberglass batt

Moisture Control

Under normal operating conditions, the sheathing wood moisture content does not exceed 12% so there is no risk of moisture related durability issues. The reason for the low moisture content is the minimal insulation to the inside of the condensation plane. In most other walls there is at least 5.5" of air permeable stud cavity insulation, but in Wall 10, there is only 3.5" inside the sheathing.

There are approximately 70 hours of potential winter time air leakage condensation in Wall 10.

The foam sheathing does limit the rate of drying of the sheathing, but also throttles the summer time inward vapor drive.

Constructability and Cost

See comments on earlier wall assemblies regarding the use of wood framing techniques, fiberglass batts and rigid exterior insulation.

The cost effectiveness of this wall type is questionable due to the relatively low whole wall r-value achieved with its use. The additional requirements for temporary protection and the building dryout process associated with the use of impermeable self-adhering membrane (see "Other Considerations" below) will likely drive overall costs even higher than indicated in the cost analysis.

Table 12 : Unit Cost Table for Wall 10

Wall	Framing	Exterior Sheathing	Cavity Insulation	Exterior Insulation	Water/Air Control Layer	Vapor Control Layer	Detailing at Openings	Total $/sf
9	2x4 @ 16" o.c.	½" plywd.	none	2" XPS	SAM sheet	none	Casing + head flashing	
	$3.42	$0.77	$0.00	$2.46	$2.09	$0.00	$1.09	$9.82
10	2x4 @ 16" o.c.	½" plywd.	R-14 FG batt	4" XPS	SAM sheet	none	Casing + head flashing	
	$3.42	$0.77	$0.42	$5.17	$2.09	$0.00	$1.21	$13.08

Other Considerations

The use of a self-adhered air, water and vapor barrier material as part of this assembly must be considered in the context of construction phase moisture exposure that is typically experienced in the Pacific Northwest. Even when dry framing and sheathing materials are procured for projects, exposure to weather conditions during the wet months of the year can lead to a high degree of wetting during the construction process. Consideration should be given to the need for temporary protection at walls that are to receive a self-adhered air, water, vapor barrier, such that this material is not installed over a saturated substrate. Additionally, there may be a need to introduce temporary heat and/or dehumidification to facilitate the dryout process at wall areas where self-adhered, impermeable materials have been installed.

Wall 11: Advanced Framing with 0.5pcf Open Cell Spray Foam

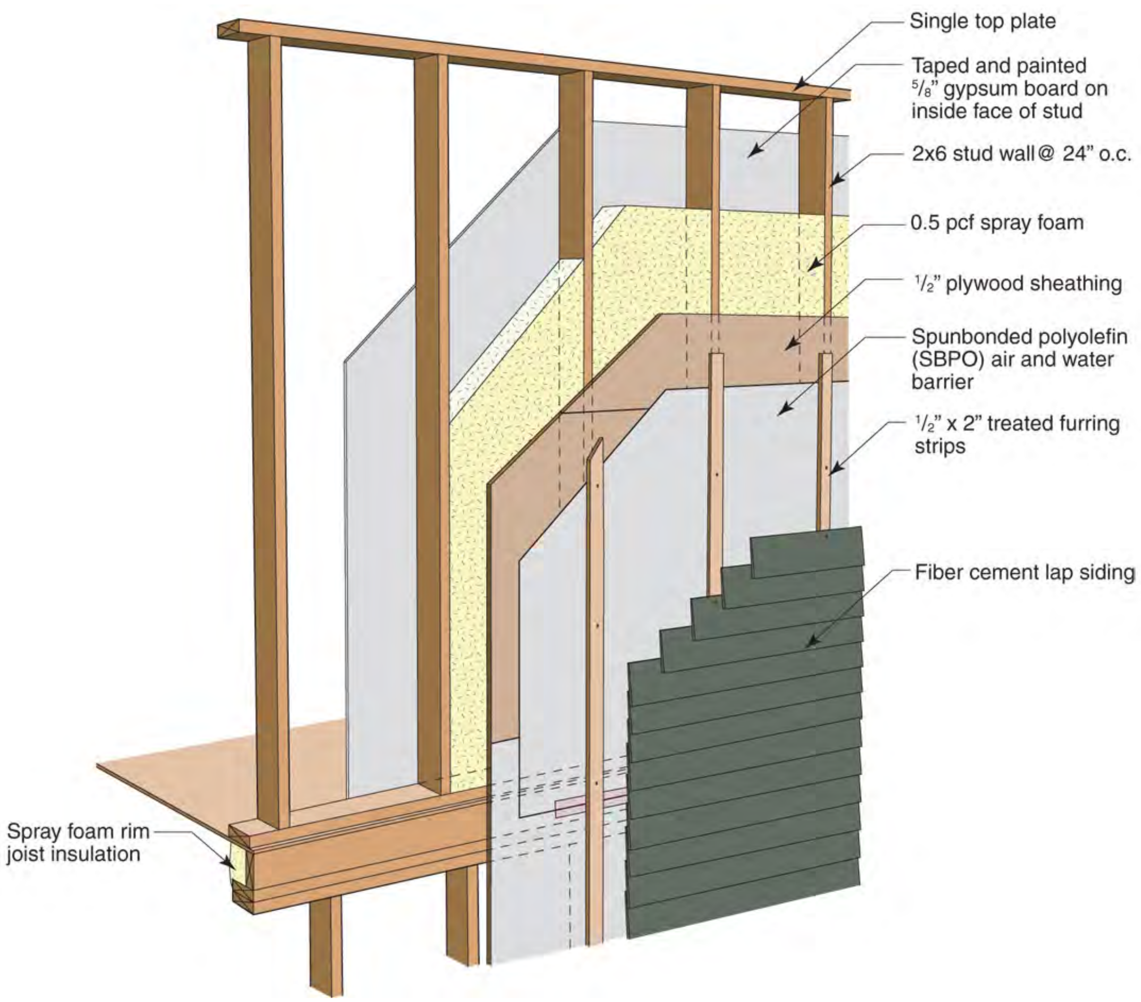


Figure 36 : 2x6 advanced framing with 0.5pcf Spray Foam

Thermal Control

Because thermal control deals with both convection and conduction, spray foam is ideal for thermal control because it eliminates convection when installed properly. The lack of convection currents and air infiltration result in a greater true R-value over walls insulated with air permeable insulation.

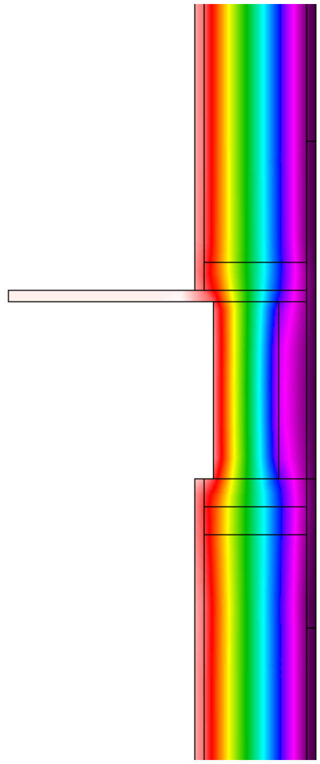


Figure 37 : Therm analysis of Advanced Framing with 0.5pcf Spray Foam

Moisture Control

Open cell (0.5 pcf) spray foam is air impermeable, so air leakage condensation will not occur on the sheathing. Water vapor can move through open cell foam, so vapor diffusion condensation should be considered.

The plywood sheathing moisture content exceeds 22% in the winter months. This sheathing moisture appears to come from the exterior and is unable to dry quickly to the interior due to the spray foam. The moisture content risk depends also on the temperature of the sheathing during the periods of elevated moisture content and the duration of the elevated moisture content.

While the moisture content in the sheathing is slightly elevated, the majority of condensation related moisture failures are from air leakage condensation which is eliminated by the spray foam insulation.

In the case of a wetting event, the spray foam insulated walls dry the slowest of all walls without XPS exterior insulation.

Constructability and Cost

See comments on earlier wall assemblies regarding the use of advanced framing techniques.

The use of spray foam insulation in stud cavities should be examined relative to schedule implications. Low density spray foam requires that surface temperatures of framing members and the inside of exterior sheathing are high enough to ensure a positive bond between the insulation and the sheathing. During cold months of the year, this can have an impact on scheduling (at temperatures around 20 degrees F). There are reports also of quality control issues with two part foam products and incomplete curing of the components resulting in off-gassing. Once fully cured, low density spray foam does not off-gas. It would be prudent to locate piping and wiring toward the interior surface of the spray foam to ensure that the piping is closer to room temperature and so that the wiring can be serviced in the future. Unlike high density closed cell foam, open cell foam can be installed 5.5" thick in only one lift. Finally, it should be noted that Membrain Smart Vapor retarder has not been tested for use with wet spray insulation systems and is not at this point in time recommended by the manufacturer (Certainteed).

While most open cell spray foam has a Class A fire rating, few if any complete fire tested assemblies exist that address this particular wall type. Additional research to determine the fire rating of this wall is required. Use of this wall should be limited to buildings that do not have a requirement for fire rating at exterior walls.

The installed cost of open cell spray foam is more than double the cost of blown in fiberglass and over four times the cost of fiberglass batt. This results in a relatively high cost while achieving a relatively low whole wall r-value.

Table 13 : Unit Cost Table for Wall 11

Wall	Framing	Exterior Sheathing	Cavity Insulation	Exterior Insulation	Water/Air Control Layer	Vapor Control Layer	Detailing at Openings	Total $/sf
11	2x6 @ 24" o.c.	½" plywd.	R-23 0.5lb foam	none	SBPO sheet	Smart retarder	Casing + head flashing	
	$3.61	$0.77	$2.25	$0.00	$0.49	$0.78	$0.54	$8.43

Other Considerations

When choosing which spray foam to use, there are currently options that do not contain greenhouse gases. The level of greenhouse gas emissions from a spray foam relative to other insulating options should be considered.

Wall 12: Advanced Framing with 2.0pcf Closed Cell Spray Foam

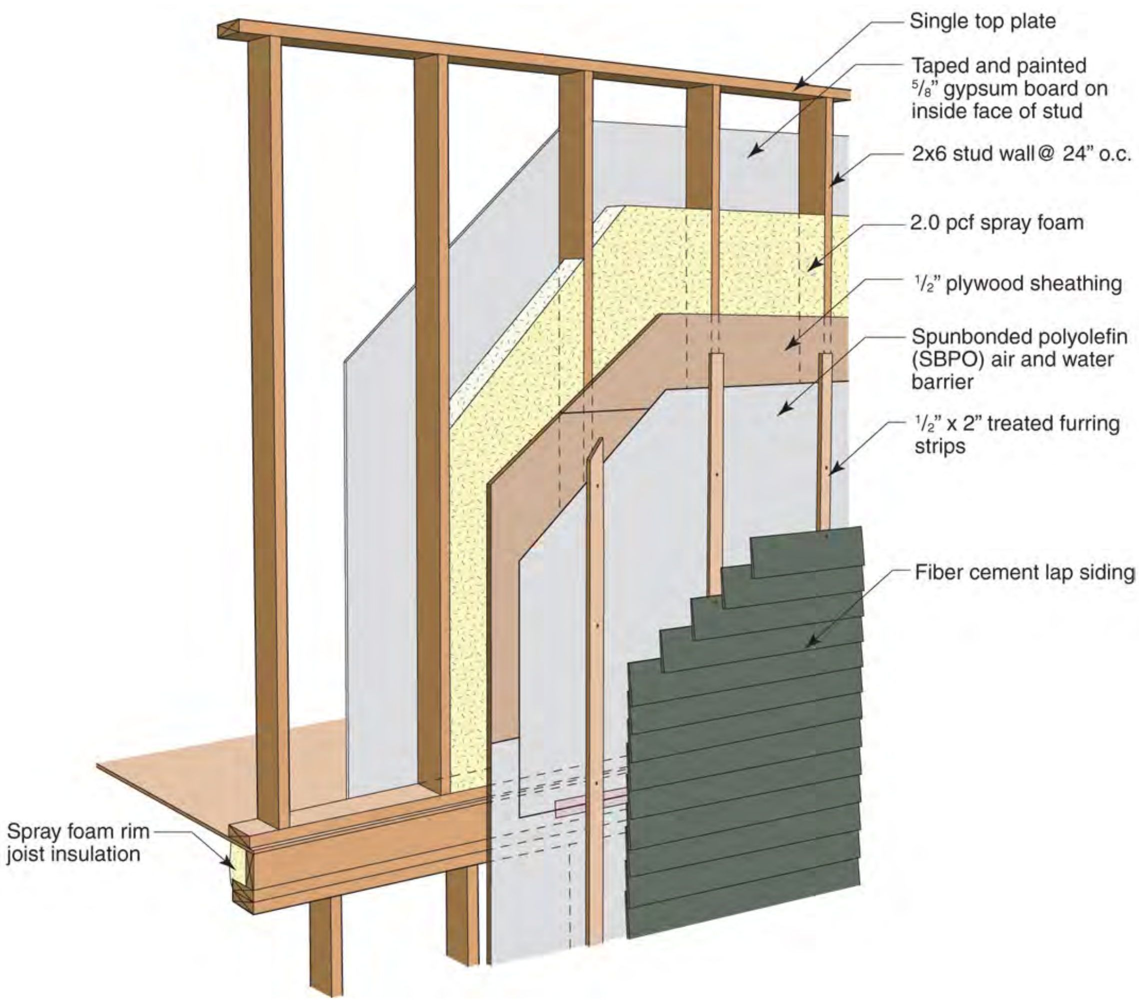


Figure 38 : 2x6 advanced framing with 2.0pcf Spray Foam

Thermal Control

Similar to Wall 11 with open cell spray foam, closed cell spray foam is ideal for thermal control because it eliminates convection when installed properly. The lack of convection currents and air infiltration result in even bigger savings in R-value than the calculated R19.0 over walls insulated with air permeable insulation.

At R6.1/inch, closed cell spray foam has one of the highest R-values of all insulations. In some cases, the insulation value of spray foam degrades over time, as some of the gases escape the spray foam.

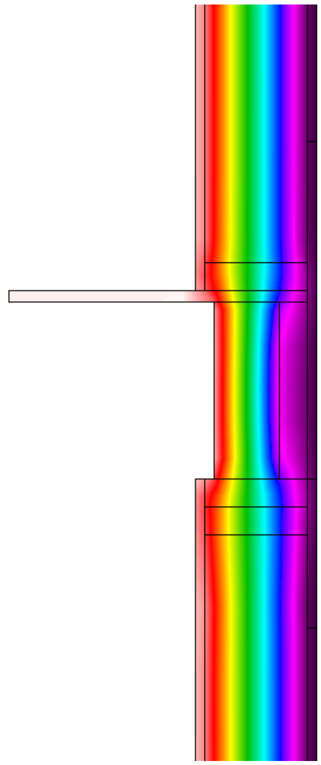


Figure 39 : Therm modeling of Wall 12 - Advanced framing with 2.0pcf Spray Foam

Moisture Control

Closed cell (2.0pcf) spray foam is air and vapor impermeable, so air leakage and vapor condensation will not occur on the sheathing.

The plywood sheathing moisture content exceeds 22% in the winter months. This sheathing moisture appears to come from the exterior and is unable to dry quickly to the interior due to the spray foam. The moisture content risk depends also on the temperature of the sheathing during the periods of elevated moisture content and the duration of the elevated moisture content.

While the moisture content in the sheathing is slightly elevated, the majority of condensation related moisture failures are from air leakage condensation which is eliminated by the spray foam insulation.

In the case of a wetting event, the spray foam insulated walls dry the slowest of all walls without XPS exterior insulation.

Constructability and Cost

See comments on earlier wall assemblies regarding the use of advanced framing techniques.

The use of closed cell high density spray foam needs to be examined relative to schedule implications due to the fact that closed cell foam can be installed in lifts of 2” maximum. To achieve 5.5” of thickness of spray foam, it will need to be installed in a minimum of three lifts with cure time in between. Typically, because of the fumes associated with the installation of closed cell spray foam, other trades cannot be in the immediate or adjacent areas during installation and cure, which can have an impact on overall schedule. Closed cell spray foam requires that surface temperatures of framing members and the inside of exterior sheathing are high enough to ensure a positive bond between the insulation and the sheathing. During cold months of the year, this can have an impact on scheduling (at temperatures around 20 degrees F).

While most closed cell spray foam has a Class B fire rating, few if any complete fire tested assemblies exist that address this particular wall type. Additional research to determine the fire rating of this wall is required. Use of this wall should be limited to buildings that do not have a requirement for fire rating at exterior walls.

The installed cost of closed cell spray foam is quite high compared to all other insulation options. When installed as cavity insulation, the performance of closed cell spray foam is hampered by the effects of thermal bridging through the studs. From an overall cost vs. performance perspective, this is not a cost effective assembly option for achieving a higher whole wall r-value.

Table 14 : Unit Cost Table for Wall 12

Wall	Framing	Exterior Sheathing	Cavity Insulation	Exterior Insulation	Water/Air Control Layer	Vapor Control Layer	Detailing at Openings	Total $/sf
12	2x6 @ 24" o.c.	½" plywd.	R-35 2.0lb foam	none	SBPO sheet	Smart retarder	Casing + head flashing	
	$3.61	$0.77	$5.25	$0.00	$0.49	$0.78	$0.54	$11.43

Other Considerations

When choosing which spray foam to use, there are currently options that do not contain greenhouse gases. Always check to see what the level of greenhouse gas emissions is for a spray foam relative to other options since the emissions associated with these materials are much higher.

Wall 13: Advanced Framing with Hybrid Cavity Insulation

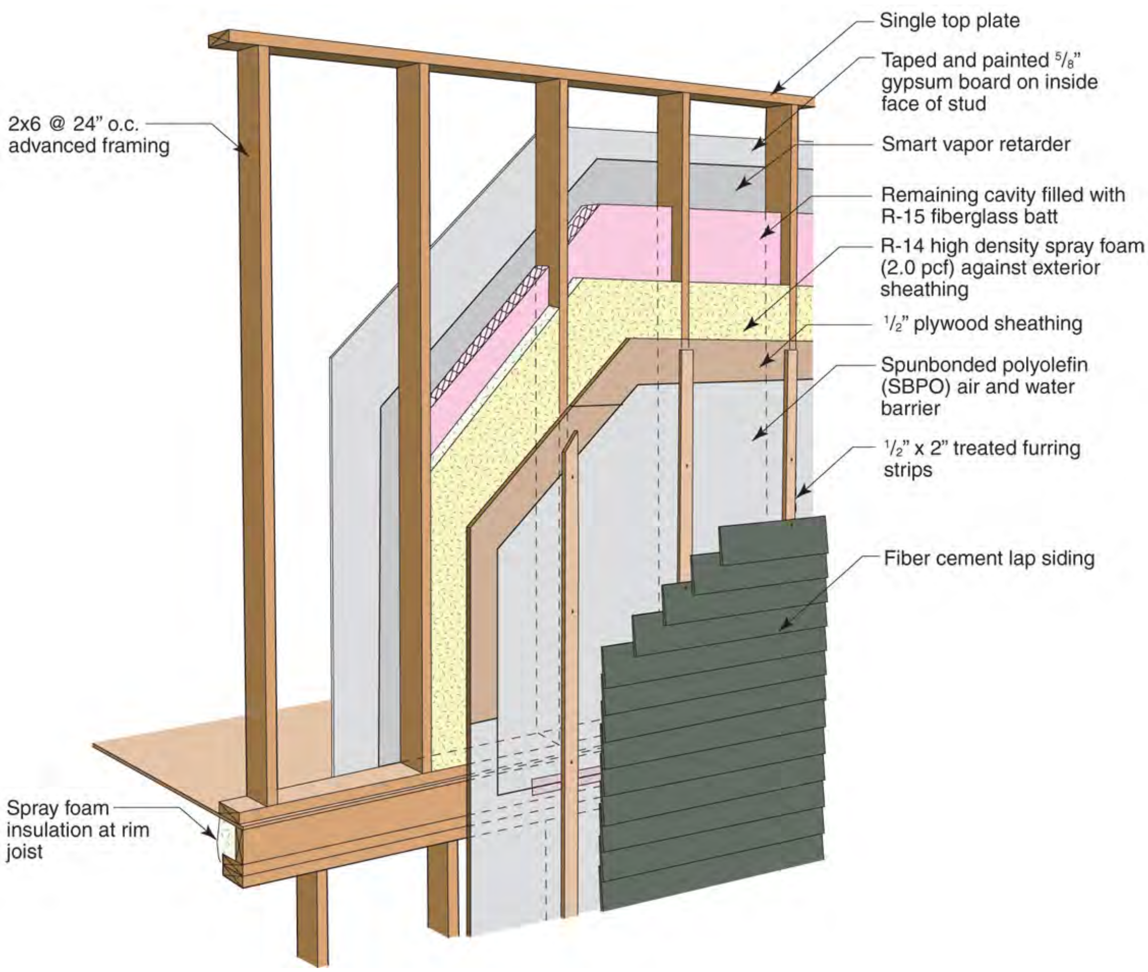


Figure 40 : Advanced framing with hybrid cavity insulation (Flash and Batt)

Thermal Control

This wall, utilizing a hybrid approach to cavity insulation known as "flash and batt", provides an increase in thermal control over the standard wall construction. Unfortunately, adding a high quality, air tight insulation between the framing does not address the issue of thermal bridging of the framing materials. Heat lost by air leakage can be greatly reduced by using the spray foam insulation, thus increases the whole wall and true R-value.

The whole wall R-value increases from R17.2 to R18.5 when comparing the same framing strategy with only fiberglass insulation (Wall 2) to Wall 13. This improvement alone may not be enough to justify the added cost, but the heat lost from air leakage would also be greatly reduced through the wall and rim joist, improving energy efficiency, occupant comfort, and potentially indoor air quality.

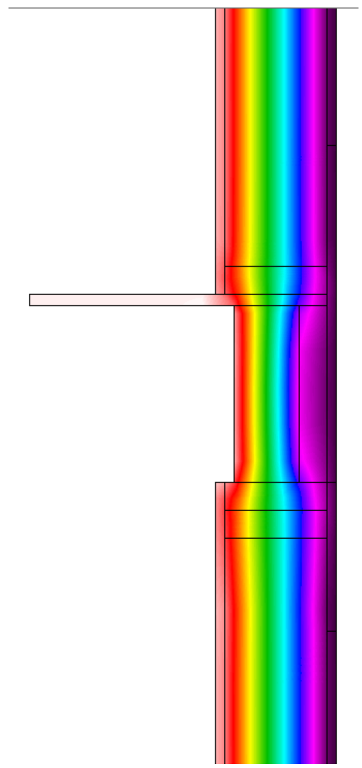


Figure 41 : Therm modeling of Wall 13 – Advanced framing with hybrid cavity insulation (ie. Flash and Batt)

Moisture Control

During the winter months, there is a significant improvement in the potential air leakage condensation (56 hours for Wall 13, compared to 2850 for Wall 2) on the condensation plane in the hybrid wall, from the standard construction wall, because the condensation plane is kept warmer by the vapor impermeable spray foam insulation.

Similar to the other walls with spray foam in the stud cavity, the plywood moisture content for Wall 13 exceeds 22% MC. This could be considered risky but is likely to not cause any moisture related issues, especially when the elevated moisture content is in the winter, when any mold growth is greatly decreased by the colder temperatures.

The drying curve for Wall 13 is very similar to Wall 12 with closed cell spray foam. Wall 13 dries faster than all analysis walls with exterior foam insulation but slower than all of the other analysis walls without XPS exterior sheathing.

Constructability and Cost

See comments on earlier wall assemblies regarding the use of advanced framing techniques, fiberglass batt insulation, and closed cell spray foam insulation.

The hybrid approach to cavity insulation at this wall is intended to improve both the cost effectiveness and constructability of the assembly. The closed cell foam is installed in one 2" thick lift, thus eliminating the need for multiple passes by the installer. The closed cell foam is sprayed against the exterior sheathing, providing very good air sealing of the opaque wall assembly in addition to the high r-value provided. Fiberglass batts are installed to fill the remaining wall cavity, and at relatively low cost for the r-value provided. The batts can only be installed once the closed cell foam has cured. This sequence adds to the schedule of the job, but has less impact than the three lifts required at Wall 12.

Table 15 : Unit Cost Table for Wall 13

Wall	Framing	Exterior Sheathing	Cavity Insulation	Exterior Insulation	Water/Air Control Layer	Vapor Control Layer	Detailing at Openings	Total $/sf
13	2x6 @ 24" o.c.	½" plywd.	R-14 2lb foam + R-15 FG batt	none	SBPO sheet	Smart retarder	Casing + head flashing	
	$3.61	$0.77	$2.42	$0.00	$0.49	$0.78	$0.54	$8.60

Other Considerations

Adding high density spray foam insulation in the cavity increases the stiffness and strength of the wall systems. This could be particularly helpful in high wind loads or when impact resistance is required as in tornado or hurricane zones. Spray foam is the most reliable method to achieve air tightness in residential construction and comes with the added bonus of thermal insulation. High density foam is easy to transport to remote locations, and increases the moisture related durability of the enclosure because it eliminates air leakage condensation which results in many moisture related durability issues.

Wall 14: Double Stud – Exterior Structural Wall

Double stud walls are most commonly used as interior partition walls in multifamily construction because of their noise reducing effect and increased fire resistance. They can also be used as a highly insulated exterior enclosure wall in cold climates.

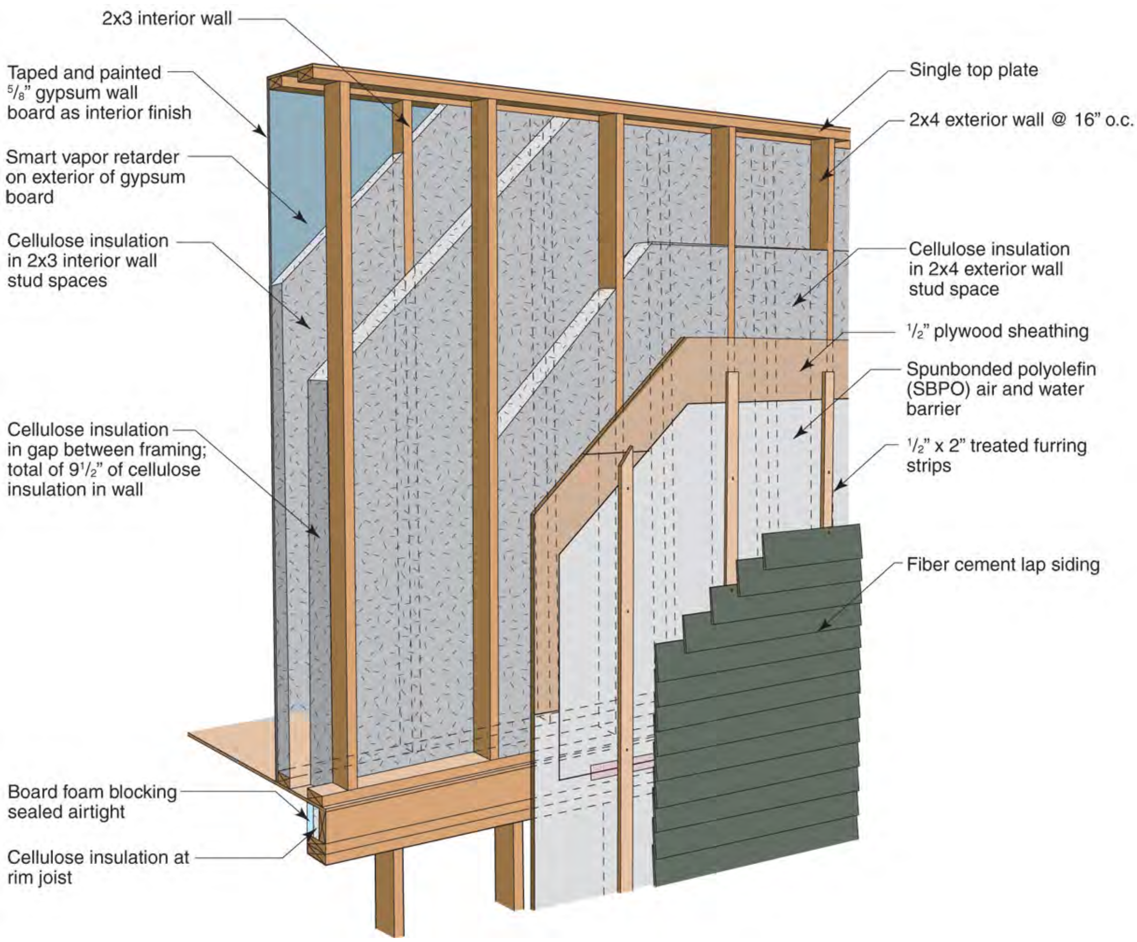


Figure 42 : Double Stud wall with an exterior structural wall

Thermal Control

This wall is typically built with an exterior 2x4 structural wall using standard construction practices, a gap on the interior filled with insulation, and a second wall that is non-structural, used to support services and drywall. The interior wall studs are often installed further than 16" o.c. since it is not used for structural purposes. For the Therm simulation the exterior structural members were spaced 16" oc with a 25% framing factor. and the interior framed wall used to support the drywall and insulation was spaced at 24" oc resulting in a 19% framing factor. The framing spacing becomes less important for simulations, and field installation, when there is a significant thermal break between the exterior and interior environments. The actual placement and alignment of interior and exterior framing members will depend on many variables such as windows, doors, corners, and the building practices of the framing crew. It is also common to use a double top plate on the exterior structural wall but for this analysis a single top plate was simulated. As with the framing members, a single or double top plate has less impact on the thermal performance for walls with significant thermal breaks between the interior and exterior.

The insulation of choice is cellulose because it is easy to install in wide wall cavities, and will not have the spaces that can occur if fiberglass batt were installed incorrectly (as it commonly is).

The Therm model (Figure 43) shows the space between the two separate walls that helps act as thermal break. Since the gap between the walls can be changed, the R-value will depend on the designed wall thickness. In this analysis, 9.5" of cellulose was used which has an installed insulation R-value of approximately R34.

The calculated Therm whole wall R-value for this wall is R29.9.

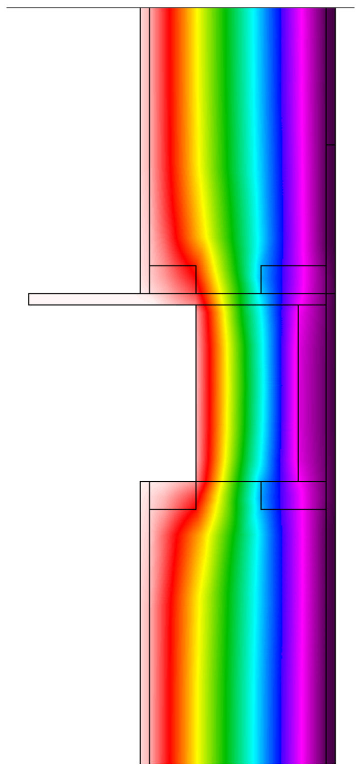


Figure 43 : Thermal modeling of Wall 14 - Double stud wall with an exterior structural wall

Moisture Control

Moisture control in the form of air leakage condensation and vapor diffusion condensation is controlled with a smart vapor retarder installed directly behind the drywall

Because of the greatly increased thermal performance, the sheathing is kept colder than standard construction and therefore the probability and intensity of vapor diffusion and air leakage condensation increases. There are approximately 3010 hours of potential wintertime condensation hours.

In the drying analysis, the double stud wall performs well, because it is able to dry both to the interior and exterior, and uses the cellulose insulation to buffer and redistribute small amounts of moisture as long as the safe storage capacity of the cellulose is not exceeded.

Traditional double stud wall construction requires interior relative humidity control, and perfect air barrier details to decrease the moisture related risk. Due to the sensitivity of this wall system, other high R-value wall systems may be more desireable due to the lower risk of moisture-related durability problems.

Constructability and Cost

The primary constructability issue with the double framed wall is the large amount of framing material that goes into the assembly and the associated lower productivity rate to build it. Diligent quality control will be required to ensure fully insulating the space between walls, as it is possible that “shadowing” can occur on the exterior sides of the inner wood wall, resulting in voids in the cellulose in which convective looping can occur.

The increased amount of framing material, plus the increased complexity (which impacts productivity) leads to significantly higher cost for the double framed wall compared to other walls that achieve a similar whole wall r-value with single wall framing.

Table 16 : Unit Cost Table for Wall 14

Wall	Framing	Exterior Sheathing	Cavity Insulation	Exterior Insulation	Water/Air Control Layer	Vapor Control Layer	Detailing at Openings	Total $/sf
14	Double stud – 2x4 ext/2x3 int	½" plywd.	R-34 blown cellulose	none	SBPO sheet	Smart retarder	Casing + head flashing	
	$7.10	$0.77	$1.80	$0.00	$0.49	$0.78	$0.54	$11.47

Other Considerations

There is considerable extra framing required for the double stud wall which should be considered during design. If the exterior dimensions of the building are fixed, there is also a significant reduction in the interior floor area because of the thickness of the walls. Cellulose increases the fire resistance of the wall system, and allows for buffering and redistribution of enclosure moisture as long as the buffering capacity is not overwhelmed.

Wall 15: Double Stud – Interior Structural Wall

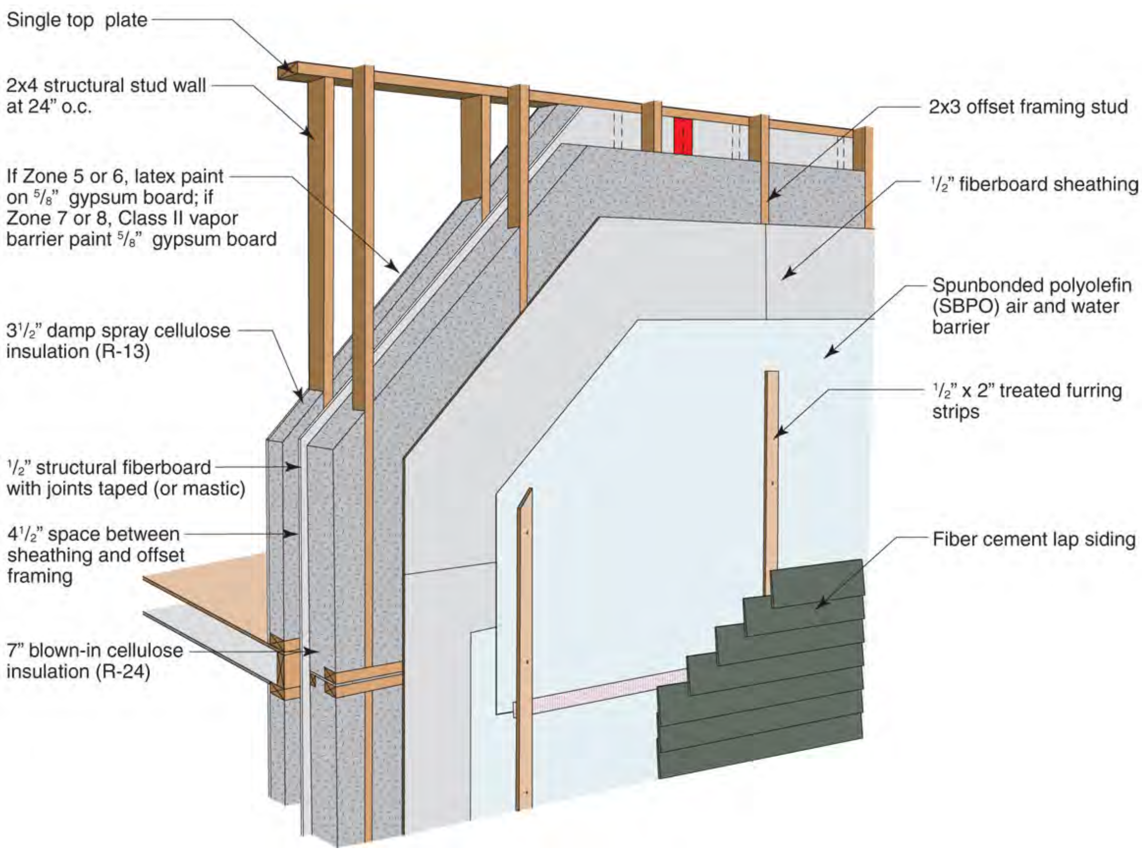


Figure 44 : Double Stud wall with an interior structural wall

Wall 15 is a double stud wall, and performs very similarly to Wall 14 in almost every way. The differences between the two walls include the more permeable fiberboard sheathing, and the interior structural wall.

Thermal Control

This wall is not typically built but is an attempt to improve on some of the issues with Wall 14.

Cellulose does suppress much of the convection found in fiberglass batt walls, but is not an air barrier, and some air movement sill still occur. The intermediate layer of structural fiberboard in Wall 15 decreases the risk to air leakage condensation found in Wall 14. Because all of the services can be run inside the interior framed wall, there will be very few penetrations through the structural fiberboard resulting in a good quality air barrier.

The calculated whole wall R-value in Therm is 30.3, a negligible improvement because of the addition of the fiberboard but decreasing the convective looping around and through the insulation with the fiberboard also will improve the effective R-value further.

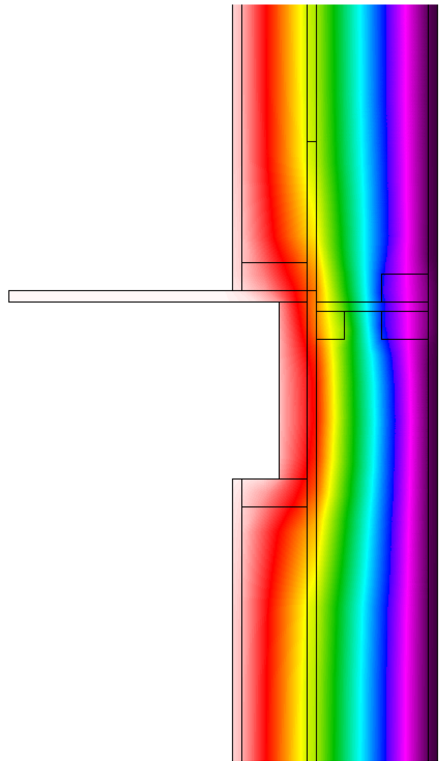


Figure 45 : Thermal modeling of Wall 15 - Double stud wall system with an interior structural wall

Moisture Control

The moisture performance varied slightly from Wall 14 because of the different physical properties of the fiberboard sheathing. Fiberboard is more permeable than plywood and therefore will dry more quickly as can be seen in the drying analysis.

There are approximately the same number of potential winter time condensation hours as Wall 14 but Wall 15 has a more reliable air barrier that will decrease the risk, and fiberboard sheathing which will dry any accumulated moisture more quickly.

The sheathing moisture content for Wall 15 does not exceed 20% through the year so there is little risk of moisture related issues from vapor diffusion.

Constructability and Cost

This alternate version of the double framed wall presents some complications in terms of sequence and the transfer of lateral and gravity loads. As the exterior wall is carrying both lateral loads and the weight of cladding materials, careful consideration of structural connections for the exterior wall to the building frame will need to be detailed that are constructable. In addition, the cantilever of connecting elements or the thermal bridging associated with possible ledger supports will need to be taken into account. Because there is a 4.5" gap between the face of the interior wall exterior sheathing and the interior face of the outside wall, a robust and complete method of ensuring water and airtightness will be required at the bottom of the wall.

The cost of this wall is slightly higher than that of the other double framed wall (Wall 14).

Table 17 : Unit Cost Table for Wall 15

Wall	Framing	Exterior Sheathing	Cavity Insulation	Exterior Insulation	Water/Air Control Layer	Vapor Control Layer	Detailing at Openings	Total $/sf
15	Double stud – int. struct. wall	Struct. fiberboard	R-34 blown cellulose	none	SBPO sheet	Smart retarder	Casing + head flashing	
	$7.05	$1.15	$1.80	$0.00	$0.49	$0.78	$0.54	$11.81

Other Considerations

This wall improves some of the issues with the traditional double stud wall with regards to air leakage, and condensation as well as increasing the interior living space for the same size footprint.

Wall 16: Structural Insulated Panels (SIPs)

SIPs are constructed by sandwiching foam board on both sides with OSB. The foam most commonly used is EPS because of its low cost and availability, but SIPs have also been produced with XPS and even PIC in some cases to increase the R-value per inch.

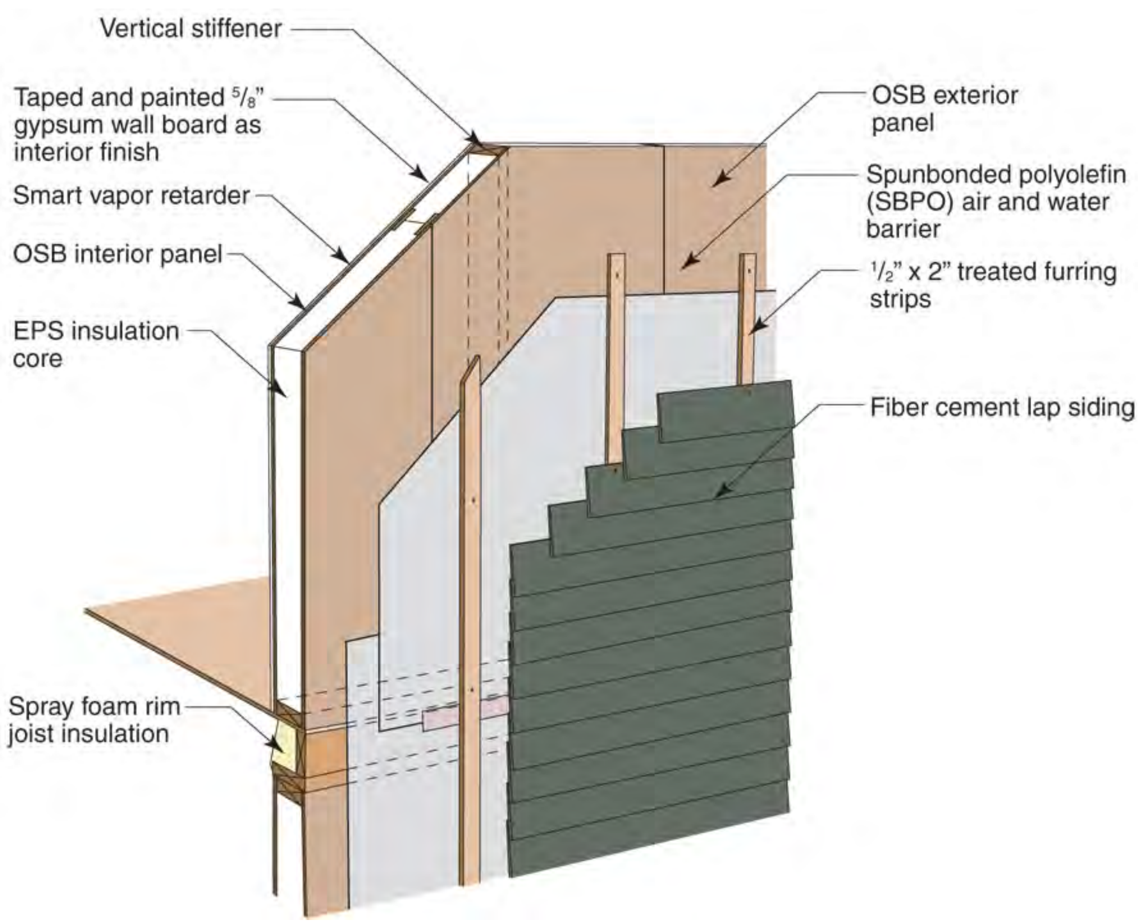


Figure 46 : Wall construction using SIPs

Thermal Control

SIPs are generally constructed with a thickness of EPS foam that matches the thickness of standard framing lumber (ie. 3.5", 5.5", 7.25"). This allows framing lumber to be inserted between the sheets of OSB in places where it is structurally required. EPS has a range of conductivity values but was modeled for this report using an R-value of R3.7/inch.

SIPs panels provide a fairly continuous plane of insulation, but quite often there are considerable thermal bridges around punched openings, the top and bottom of the panels, and sometimes through vertical reinforcement between panels.

Generally the cladding is applied directly to the exterior over a sheathing membrane, and possibly a drainage cavity, and the drywall is applied directly to the inside face. It is possible to increase the R-value of the assembly by adding insulation to the interior or exterior of the SIPs panel but it may not be cost effective.

Moisture Control

The plane of the SIPs wall provides a good air and vapor barrier between the interior and exterior environments. Historically, there were problems at the joints between SIPs panels where air would leak from the interior space to the exterior surface and condense against the back of the sheathing during the heating season in cold climates (SIPA 2002). Many SIPs failures have been reported to be caused by this air leakage condensation mechanism.

Currently there are better practice guides and standards applied to the installation and construction of SIPs panels and in new buildings these moisture-related durability issues are rare.

Constructability and Cost

SIPs have been used relatively infrequently in the Pacific Northwest and because of the unfamiliarity with this system, builders may see this as an expensive system. There are far fewer suppliers for SIPs than standard framing lumber, therefore there tends to be less competition in the supply chain, which impacts the pricing of these systems.

Construction with SIPs requires training and education about construction techniques and design details. Careful consideration during the design of a building using SIPs will be required to conform to available panel sizes and to minimize field modification. Generally, buildings that utilize SIPs have very simple layouts and roof designs to help simplify the design of details at SIPs joints and roof-wall interfaces. The integration of services such as plumbing and electrical wiring requires consideration. It would be prudent to not locate plumbing waste stacks in exterior SIPs as a large waste stack would require removal of much insulation, reducing the thermal benefits of this wall. Similarly, electrical wiring will need to be cut into these panels unless precut runs are available from the manufacturer.

Panel weights affect crew sizes as an 8' tall, 6" thick panel weighs just over 110 pounds and will require a minimum two person crew per panel. Careful consideration must be given to limiting air leakage at the floor connection and between panels as degradation of the panel facing can occur if not detailed properly. Coordination with cladding / window manufacturers should happen early to ensure proper structural connection of cladding components to the SIPs sheathing layer. The outer sheathing layer of the panel may not provide sufficient thickness to serve as a fastening base for some cladding materials/systems.

Table 18 : Unit Cost Table for Wall 16

Wall	Framing	Exterior Sheathing	Cavity Insulation	Exterior Insulation	Water/Air Control Layer	Vapor Control Layer	Detailing at Openings	Total $/sf
16	6" SIPS	none	none	none	SBPO sheet	Smart retarder	Casing + head flashing	
	$8.80	$0.00	$0.00	$0.00	$0.49	$0.78	$0.54	$10.61

Other Considerations

This is a fairly simple, yet durable solution if constructed properly. EPS foam is the least energy intensive to produce of all the board foams, and this technique requires far less framing lumber than other standard techniques, but twice as much OSB as normal framing with a single layer of exterior sheathing. During field installation it has been observed that there are often significant thermal bridges around penetrations, and depending on the structural loading of the SIPS panel, there may be multiple vertical stiffeners which also act as thermal bridges. As with all cases, the whole wall R-value makes assumptions regarding the occurrence of framing member thermal bridging, and in the field it is likely that the whole wall R-value is slightly lower than simulations indicate.

Wall 17: Insulated Concrete Form (ICF)

The most common type of ICF consists of two sides of EPS of varying thickness and a poured in place concrete core. This combination of insulation and concrete provides both the thermal component and the structural component of the enclosure. Some ICFs are constructed of a cement wood fiber instead of EPS, and have varying amounts of insulation.

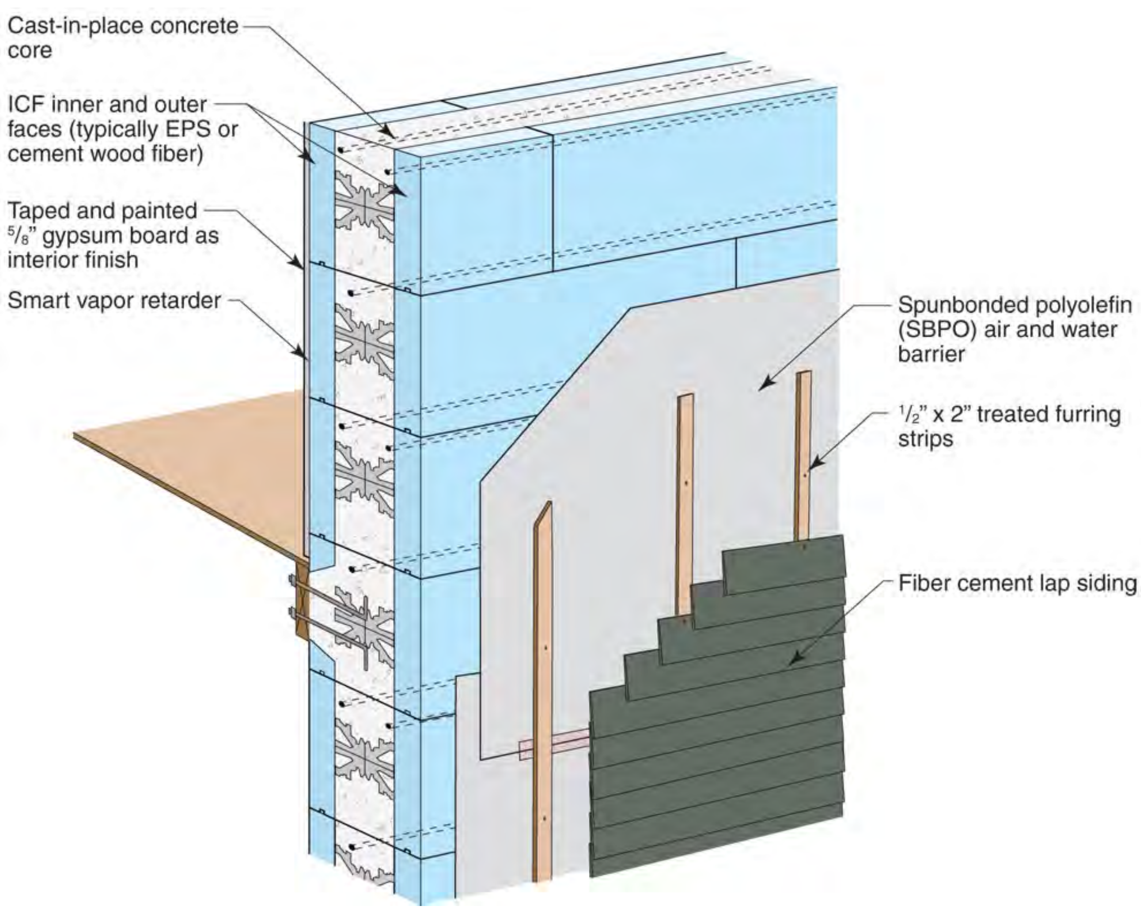


Figure 47 : Wall construction using ICF

Thermal Control

The ICF wall provides a barrier to both vapor and air flow across the enclosure. Care must still be taken at the penetrations for windows, doors and services to prevent air from moving through the enclosure, reducing the effectiveness of the insulation.

Therm analysis was used to determine the whole wall R-value of an ICF systems Figure 48 shows an 8" ICF with 2" of EPS on both the interior and exterior, and 4" of concrete. This has an R-value of 16.4.

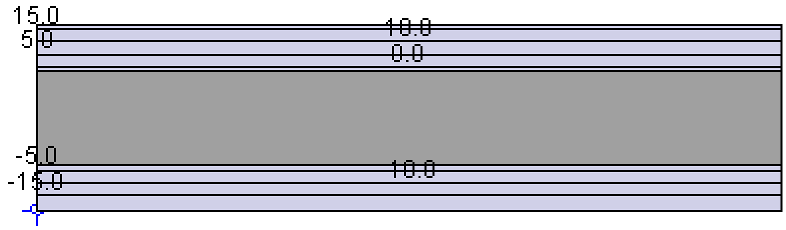


Figure 48 : Eight inch foam ICF with four inches of EPS

ICF walls could be combined with an interior insulated framed wall or a layer of spray foam on the exterior to increase the thermal performance. The good airtightness, and the use of convection-immune rigid foam insulation means that the thermal performance is reliably delivered.

Moisture Control

Most ICF walls are vapor barriers that do not allow vapor to pass through easily. This also means that the wet concrete in the ICF form will retain an elevated moisture content for an extended period of time. The ICF wall system should be designed to allow to dry as easily as possible, in both directions if possible.

One of the failure mechanisms of ICF walls is improperly flashed openings that allow water to drain into the enclosure through windows, and doors, and service penetrations. Since there is no storage component to the enclosure materials, all of the water will pass through, affecting the interior finishes.

Constructability and Cost

ICFs have been used relatively infrequently in the Pacific Northwest due to their cost and the building industry's lack of familiarity with them. The cost of the ICF wall is the highest of all walls included in this study, by a considerable margin. From a construction standpoint, there is a steep learning curve to make sure that the wall system is installed correctly, however once through the learning curve, ICFs are generally easy to use.

ICFs typically need to be installed directly on the footing as they are very heavy. As such, waterproofing for the below grade section of the wall needs to be robust and should be installed early, prior to backfill. Bracing of ICFs periodically up the vertical dimension of the wall presents some scheduling and access issues and need to be carefully considered.

Tolerances with ICFs can present some issues, as the rebar that typically is found in boundary conditions require very exact placing to ensure full coverage of the rebar. This is especially critical as one moves up into upper stories of the building. Other potential issues that have been reported include gaps left in the concrete or blocks breaking under the internal pressure of the concrete, and there may be issues with lining up the interior edges of the ICF blocks to provide a suitable substrate for drywall installation.

Much like SIPS, utilities in exterior walls need to be considered as large waste pipes will not fit into outside walls. As a rule of thumb, plumbing should be moved to interior partitions. Coordination with cladding and window manufacturers should happen early to ensure proper structural connection of cladding components to the ICF form plastic webbing.

Table 19 : Unit Cost Table for Wall 17

Wall	Framing	Exterior Sheathing	Cavity Insulation	Exterior Insulation	Water/Air Control Layer	Vapor Control Layer	Detailing at Openings	Total $/sf
17	8" ICF	none	none	none	SBPO sheet	Smart retarder	Casing + head flashing	
	$17.50	$0.00	$0.00	$0.00	$0.49	$0.78	$0.54	$19.31

Other Considerations

An ICF wall uses less concrete than the comparison structural wall made of only concrete, but concrete requires significantly more embodied energy than some other building materials such as wood framing. ICFs appear to be ideally suited to use in areas where there is a risk of flooding or severe moisture damage, since it is much more tolerant of severe wetting events. The resistance to hurricane wind loads and debris damage is also very high.

There are many different design possibilities for ICF construction with regards to design details, which may have an effect on both the durability and thermal performance. Field investigations have shown that this construction strategy is not immune to serious moisture related risks such as bulk water leakage, window leakage, and mold if installed incorrectly.

Conclusions

Whole wall R-values for all of the assemblies were calculated using Therm and the summary is shown in Table 20 below. In some of the analyzed cases, different types or thicknesses of insulation may be used depending on climate zone and local building practice. An attempt was made to choose the most common strategies and list all assumptions made for wall construction. The thermal control ratings from Table 20 are used in the wall comparison matrix (Table 22).

Table 20 : Summary of all calculated R-values

Wall	Description	Installed Insulation R-value	Whole Wall R-value	Framing Factor	Thermal Control Rating
9	2x4, 16"oc, no cavity insulation +2" R10 XPS, (25%ff)	10	12.6	25%	1
1	2x6, 16"oc, R21FG, (25%ff)	21	16.2	25%	2
11	2x6 AF, 24"oc, R23 0.5pcf SPUF	23	16.3	19%	2
17	ICF - 8" foam ICF (4" EPS)	16	16.4	-	2
2	2x6 AF, 24"oc, R21FG batt,	21	17.2	19%	2
13	2x6 AF, 24"oc, R14 2.0pcf SPUF, R14 FG batt	28	18.5	19%	2
12	2x6 AF, 24"oc, R35 2.0pcf SPUF	35	19.0	19%	2
10	2x4, 16"oc, R14 FG batt, 2" R10 XPS, (25%ff)	24	21.5	25%	3
16	SIPs - 6" (5.0" EPS)	24	21.5	-	3
6	2x6 AF, 24"oc, R19 blown cellulose +1" R5 XPS	24	21.9	19%	3
7	2x8 AF, 24"oc, R31 blown fiberglass	31	22.2	19%	3
3	2x6 AF, 24"oc, R21FG batt, + 1" R5 XPS	26	22.2	19%	3
8	2x8 AF, 24"oc, R31 blown fiberglass + 1" R5 XPS	36	27.2	19%	4
4	2x6 AF, 24"oc, R21FG batt, + 2" R10 XPS	31	27.2	19%	4
14	Double stud with 9.5" R34 blown cellulose, ext. structural	34	29.9	25%	4
15	Double stud with 9.5" R34 blown cellulose, int. structural	34	30.3	25%	4
5	2x6 AF, 24"oc, R21FG batt, + 4" R20 XPS	41	37.3	19%	5

*AF - Advanced Framing

The potential for wintertime air leakage condensation was compared for all test walls, and the summary of the results are shown in Table 21. The walls were ranked from the least hours of potential condensation to the greatest. Most of the walls with exterior insulation had less hours of potential air leakage condensation because of the insulation on the exterior of the condensation surface increasing the temperature of the condensation surface. This potential winter time air leakage condensation is only an issue if the airtightness details aren't constructed properly. Inspections of typical construction quality leads to skepticism regarding the quality of the air barrier in most wall systems. It is always good building practice to design enclosures that will perform as well as possible regardless of the human construction factor.

The hours of potential air leakage condensation were one of the main factors used in assessing the durability ranking in the durability ranking in the wall comparison matrix (Table 22). The other main factors for the durability ranking are rain control, drying of water leakage events, condensation, built in moisture, and susceptibility of different building materials to moisture related issues.

Table 21 : Hours of potential winter time air leakage condensation

	Hours of Potential Condensation in 1 yr
Wall 5 - 2x6, fiberglass, 4inch XPS	0
Wall 9 - 2x4, no cavity insl., 2inch XPS	0
Wall 11 - 2x6, 0,5 pcf SPUF	0
Wall 12 - 2x6, 2pcf SPUF	0
Wall 13 - 2x6, hybrid	56
Wall 10 - 2x4, fiberglass, 2inch XPS	68
Wall 4 - 2x6, fiberglass, 2inch XPS	214
Wall 6 - 2x6, cellulose, 1inch XPS	730
Wall 3 - 2x6, fiberglass, 1inch XPS	997
Wall 8 - 2x8, fiberglass, 1inch XPS	1496
Wall 1,2 - 2x6, fiberglass, plywood sheathing	2851
Wall 2b (OSB) - 2x6, fiberglass, OSB sheathing	2903
Wall 15 (fiberboard) double stud, 9.5" cell., int structural wall	2924
Wall 14 - double stud, 9.5" cellulose, ext. structural wall	3015
Wall 7 - 2x8, fiberglass	3019

The comparison matrix was completed using information developed over the course of this study. Criteria weighting was based on the goals typical to most projects that Walsh Construction is involved with, where performance and cost management are both priorities. Criteria weighting can be changed to reflect a different set of priorities depending on the goals for any specific project. The walls were ranked from highest to lowest following the scoring. The highest scoring wall was Wall 3, 2x6 advanced framing with fiberglass batt cavity insulation and 1" of exterior insulation.

The top seven scoring walls using this analysis criteria were only separated by two points and have similar overall performance. The results will vary if the criteria weighting are prioritized differently.

Since the comparison matrix can be easily manipulated, it is best used as a tool to help determine the best choices for wall construction, but should be considered along with all other design tools. To ensure the selection of wall types that will result in long term performance, design teams should consider Durability to be the criterion that is weighted highest within any matrix.

Table 22 : Wall Comparison Matrix

	Thermal Control	Durability (wetting/drying)	Constructability	Cost	Material Use	Total
Criteria Weighting	3	4	2	3	1	
Wall 3: Advanced Framing - 1" exterior XPS, fgb	3	4	4	4	4	49
Wall 5: Advanced Framing - 4" exterior XPS, fgb	5	5	2	2	3	48
Wall 2: Advanced Framing - fiberglass batt	2	3	5	5	5	48
Wall 6: Advanced Framing - 1" ext. XPS, cellulose	3	4	4	3	5	47
Wall 4: Advanced Framing - 2" exterior XPS, fgb	4	4	3	3	4	47
Wall 7: Advanced Framing with 2x8, blown fg	3	3	5	4	4	47
Wall 1: Standard 2x6 Construction - fiberglass batt	2	3	5	5	4	47
Wall 11: Advanced framing with 2.0pcf spray foam	2	4	4	4	3	45
Wall 16: Structural Insulated Panels (SIPs)	3	5	3	2	3	44
Wall 8: Advanced Framing with 2x8, 1" ext. XPS	4	3	4	3	3	44
Wall 13: Advanced framing with hybrid insulation	2	4	4	3	3	42
Wall 17: Insulated Concrete Forms (ICF)	2	5	3	1	3	38
Wall 10: Std 2x4 construction, 2" XPS. FG in cavity	3	4	3	1	4	38
Wall 9: Std 2x4 construction, 2" XPS, none in cavity	1	4	3	3	4	38
Wall 12: Advanced framing with 0.5pcf spray foam	2	4	3	2	3	37
Wall 14: Double stud, exterior structural, cellulose	4	2	3	2	2	34
Wall 15: Double stud, interior structural, cellulose	4	2	2	2	2	32

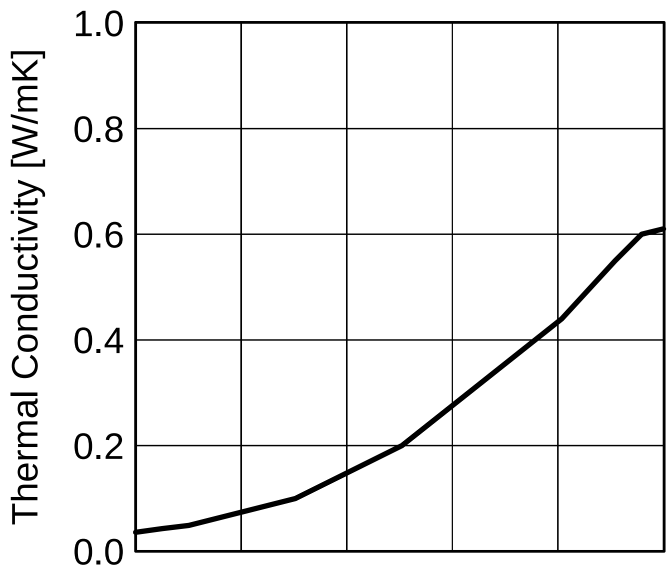
Appendix

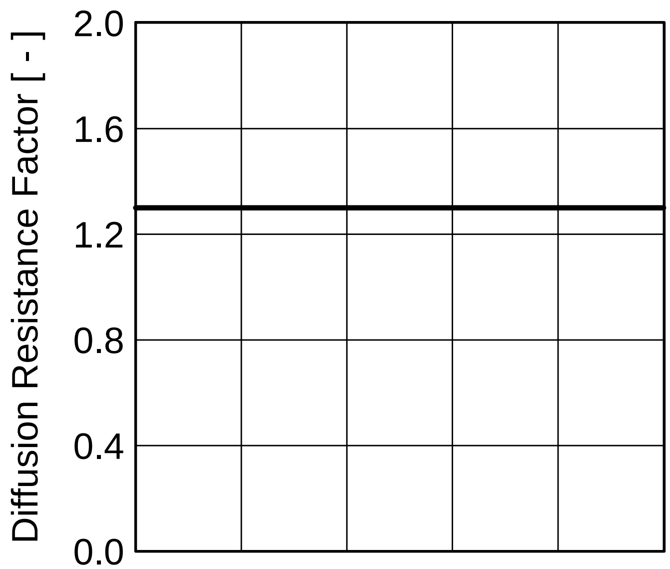
WUFI Hygrothermal Analysis Material Properties

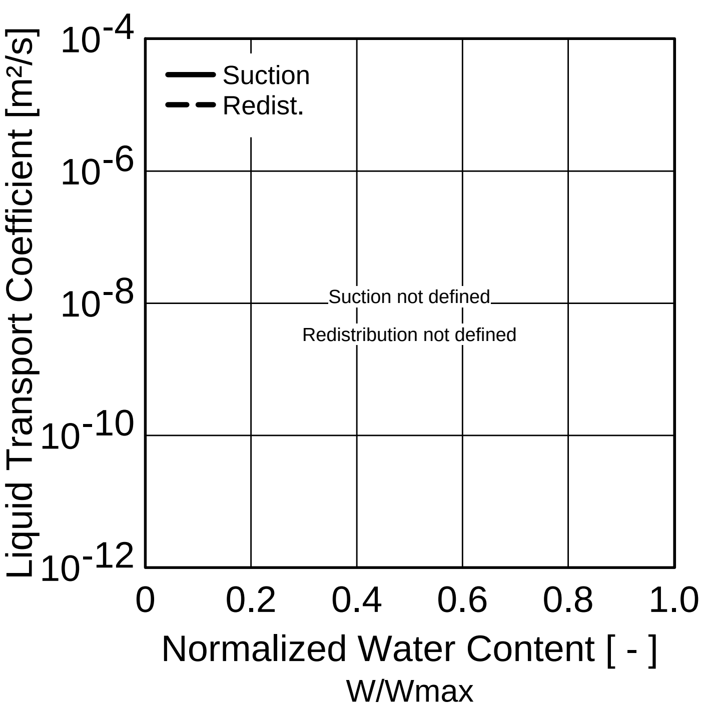
Material : R14 Fiberglas Batt

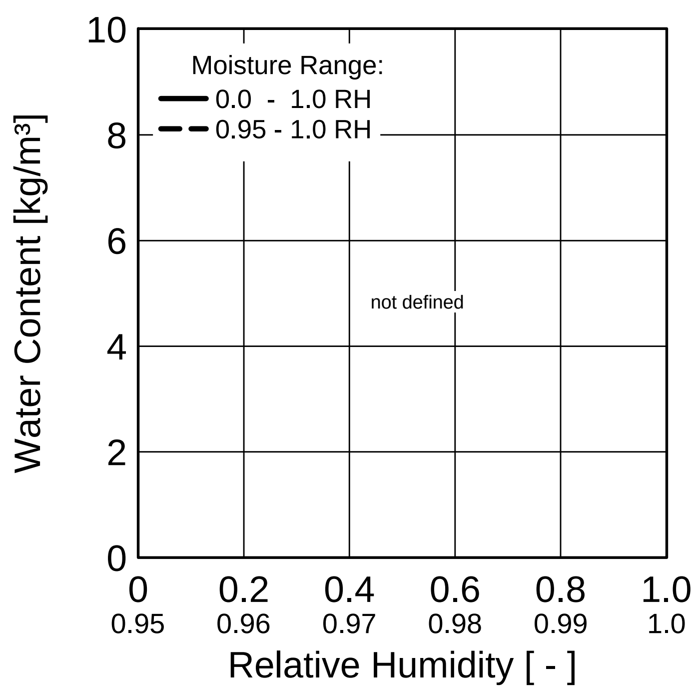
Checking Input Data

Property	Unit	Value
Bulk density	[kg/m³]	48
Porosity	[m³/m³]	0,99
Specific Heat Capacity, Dry	[J/kgK]	840,0
Thermal Conductivity, Dry	[W/mK]	0,036
Water Vapour Diffusion Resistance Factor	[-]	1,3





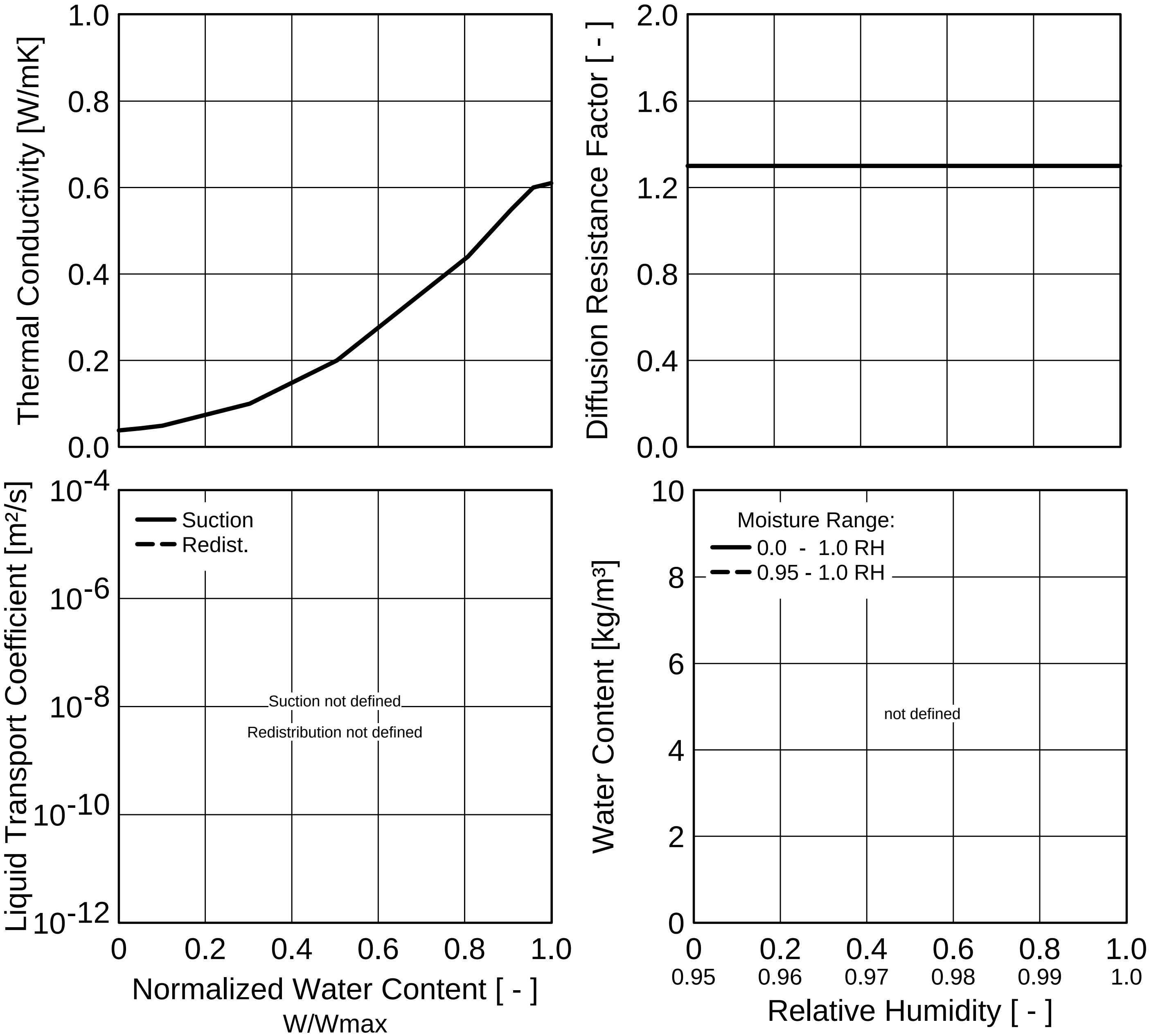




Material : R21 Fiberglass batt

Checking Input Data

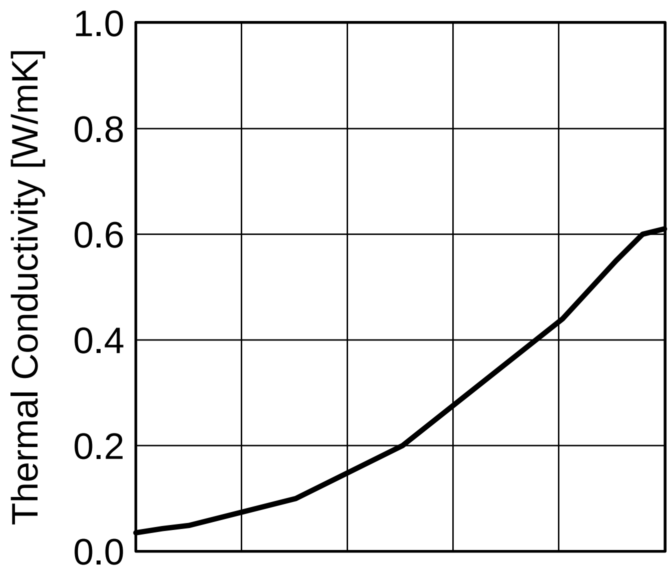
Property	Unit	Value
Bulk density	[kg/m³]	48
Porosity	[m³/m³]	0,99
Specific Heat Capacity, Dry	[J/kgK]	840,0
Thermal Conductivity, Dry	[W/mK]	0,038
Water Vapour Diffusion Resistance Factor	[-]	1,3

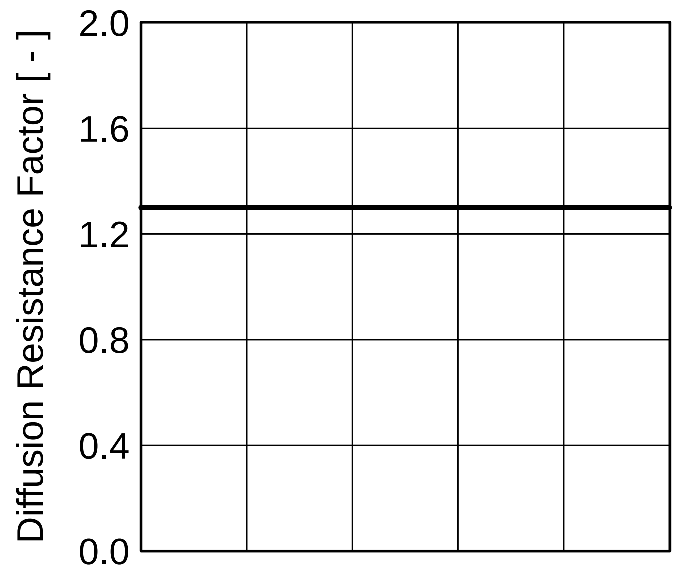


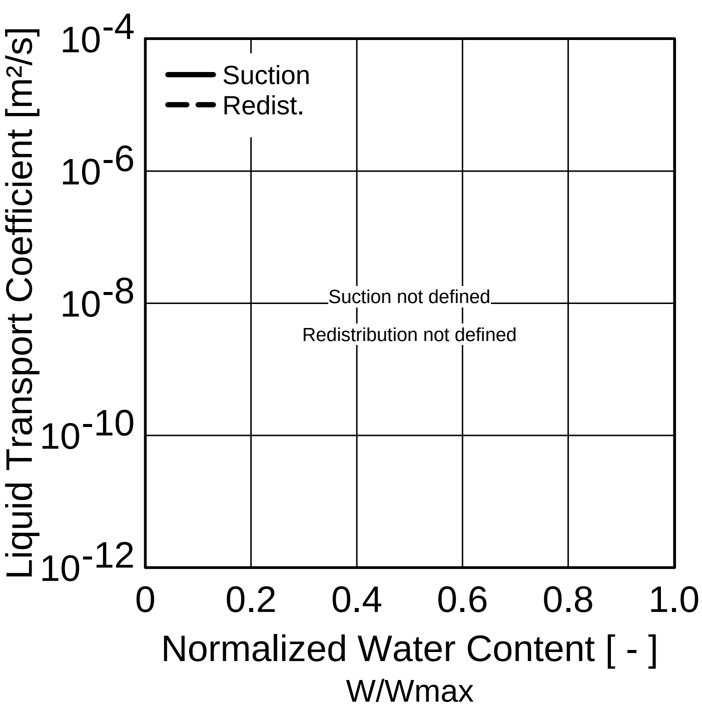
Material : Blown Fiberglass

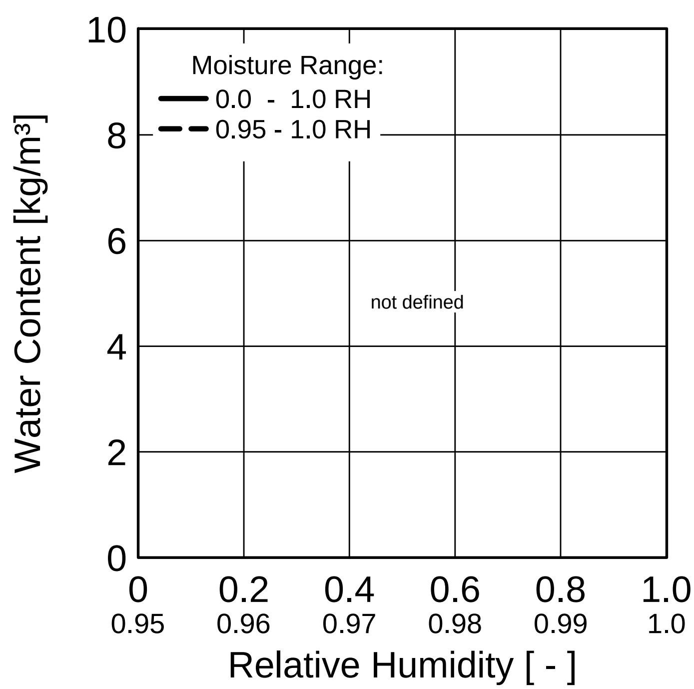
Checking Input Data

Property	Unit	Value
Bulk density	[kg/m³]	22.4
Porosity	[m³/m³]	0,99
Specific Heat Capacity, Dry	[J/kgK]	840,0
Thermal Conductivity, Dry	[W/mK]	0,035
Water Vapour Diffusion Resistance Factor	[-]	1,3





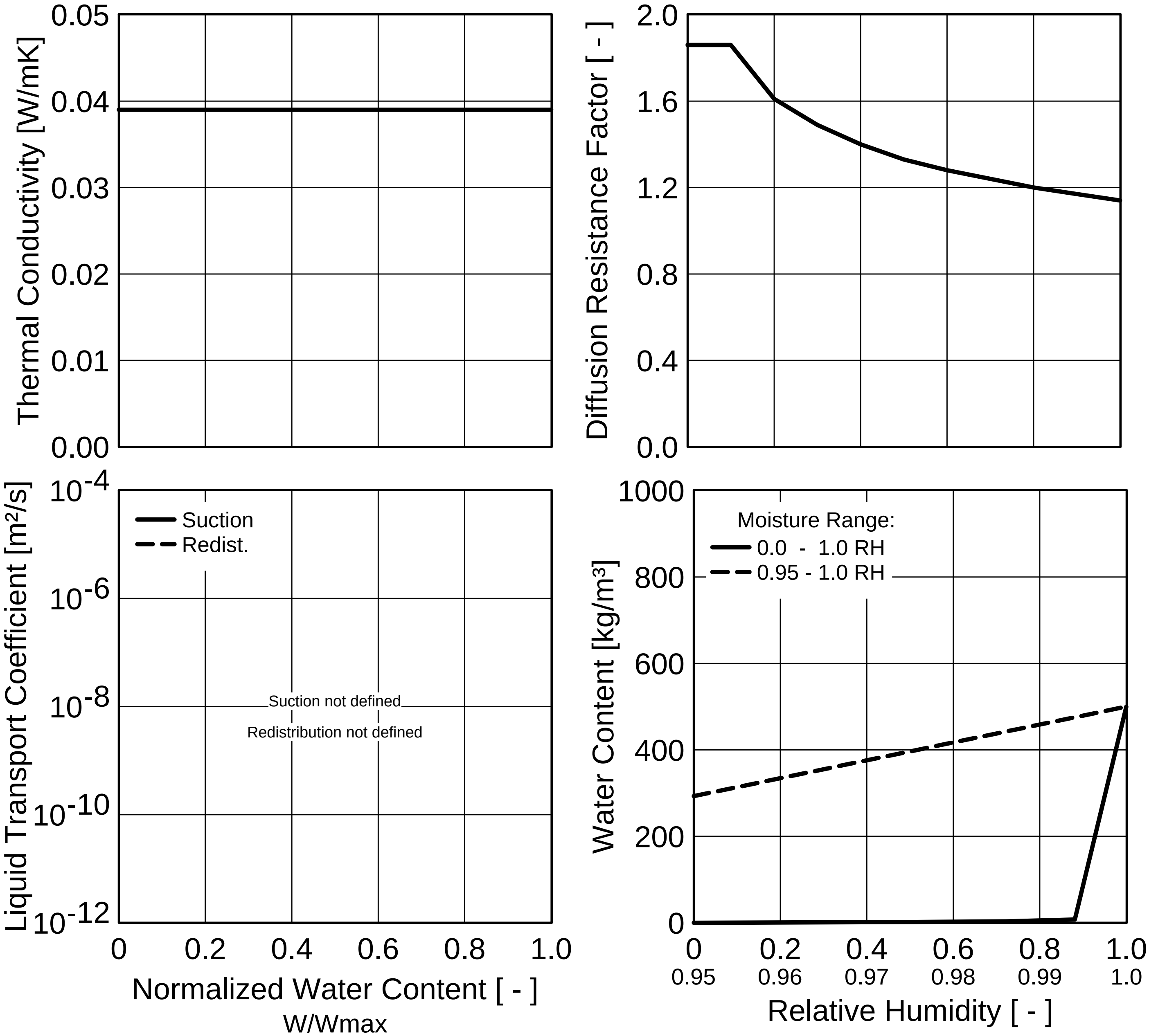




Material : Cellulose Fibre Insulation

Checking Input Data

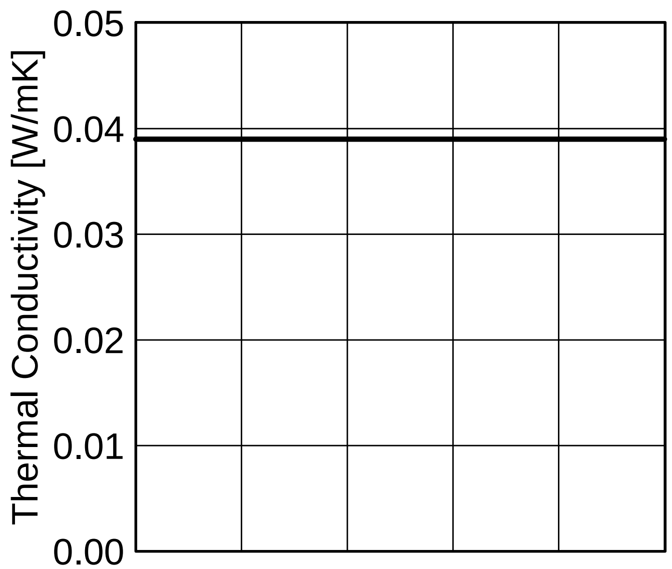
Property	Unit	Value
Bulk density	[kg/m³]	56
Porosity	[m³/m³]	0,99
Specific Heat Capacity, Dry	[J/kgK]	1880,0
Thermal Conductivity, Dry	[W/mK]	0,039
Water Vapour Diffusion Resistance Factor	[-]	1,86

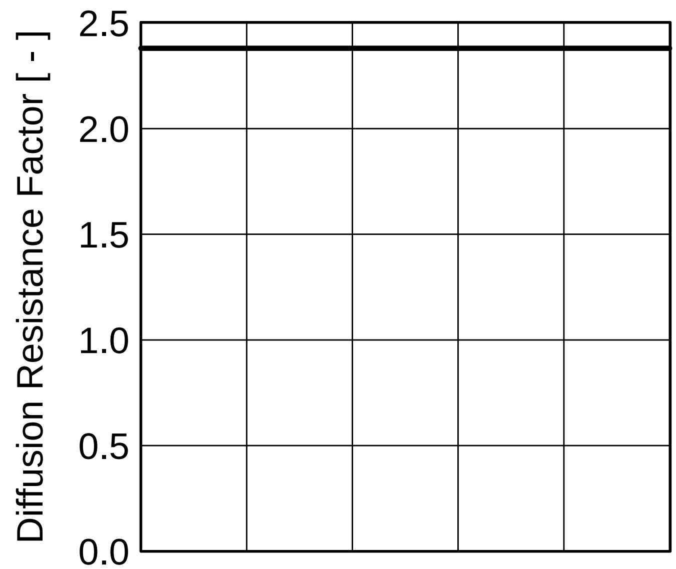


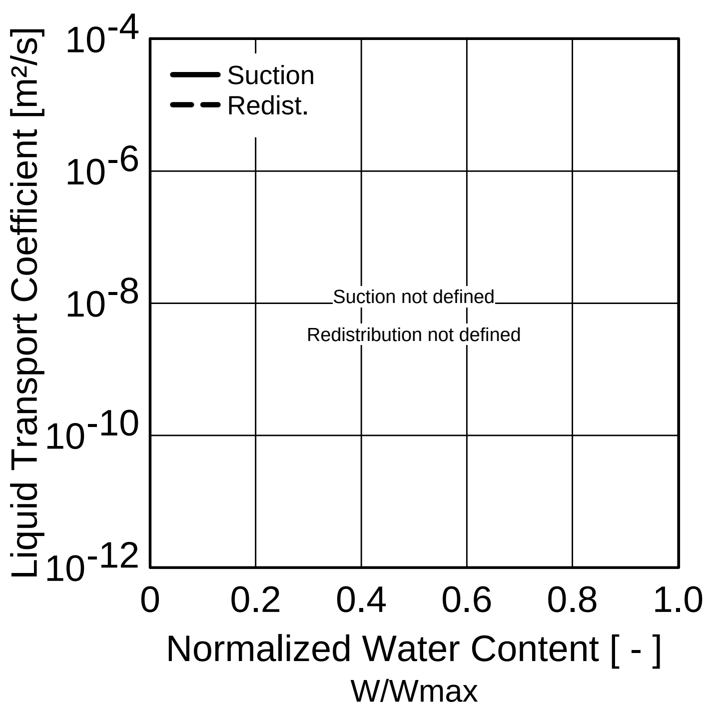
Material : Sprayed Polyurethane Foam; open cell

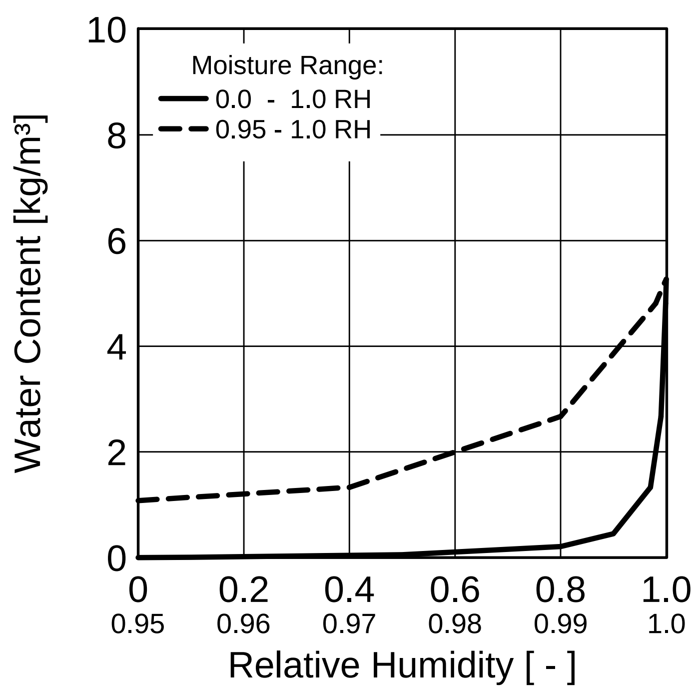
Checking Input Data

Property	Unit	Value
Bulk density	[kg/m³]	8.0
Porosity	[m³/m³]	0,99
Specific Heat Capacity, Dry	[J/kgK]	1470,0
Thermal Conductivity, Dry	[W/mK]	0,039
Water Vapour Diffusion Resistance Factor	[-]	2,38





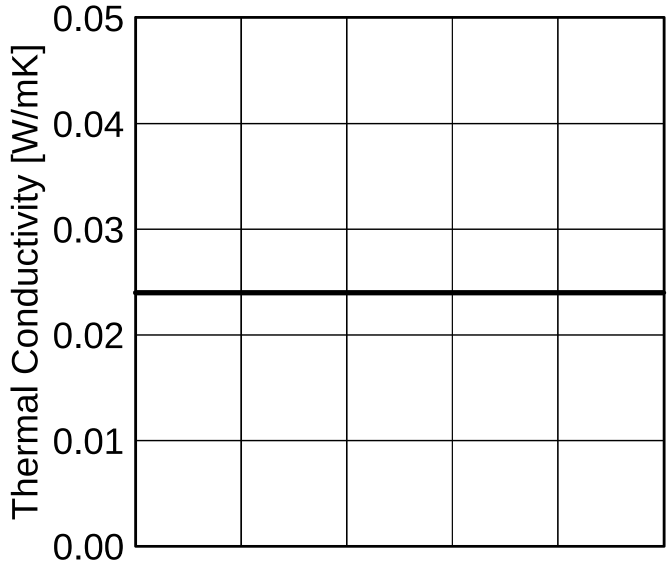


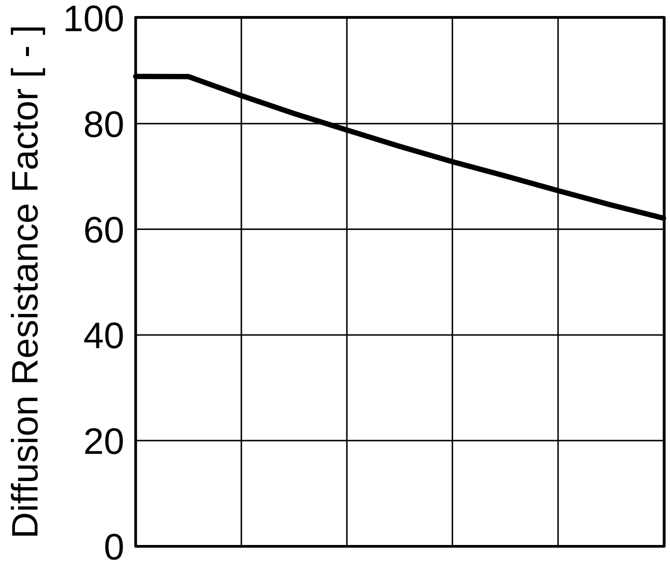


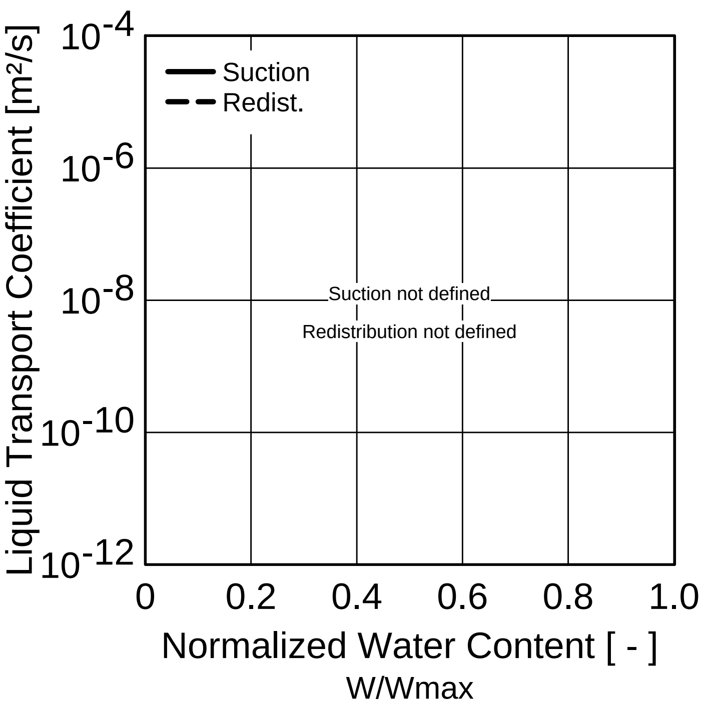
Material : Sprayed Polyurethane Foam; closed cell

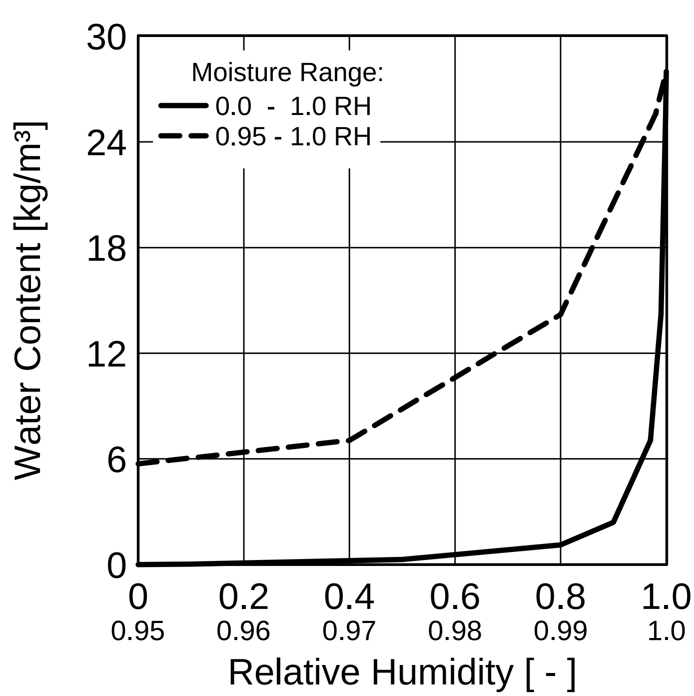
Checking Input Data

Property	Unit	Value
Bulk density	[kg/m³]	32.0
Porosity	[m³/m³]	0,99
Specific Heat Capacity, Dry	[J/kgK]	1470,0
Thermal Conductivity, Dry	[W/mK]	0,024
Water Vapour Diffusion Resistance Factor	[-]	88,93





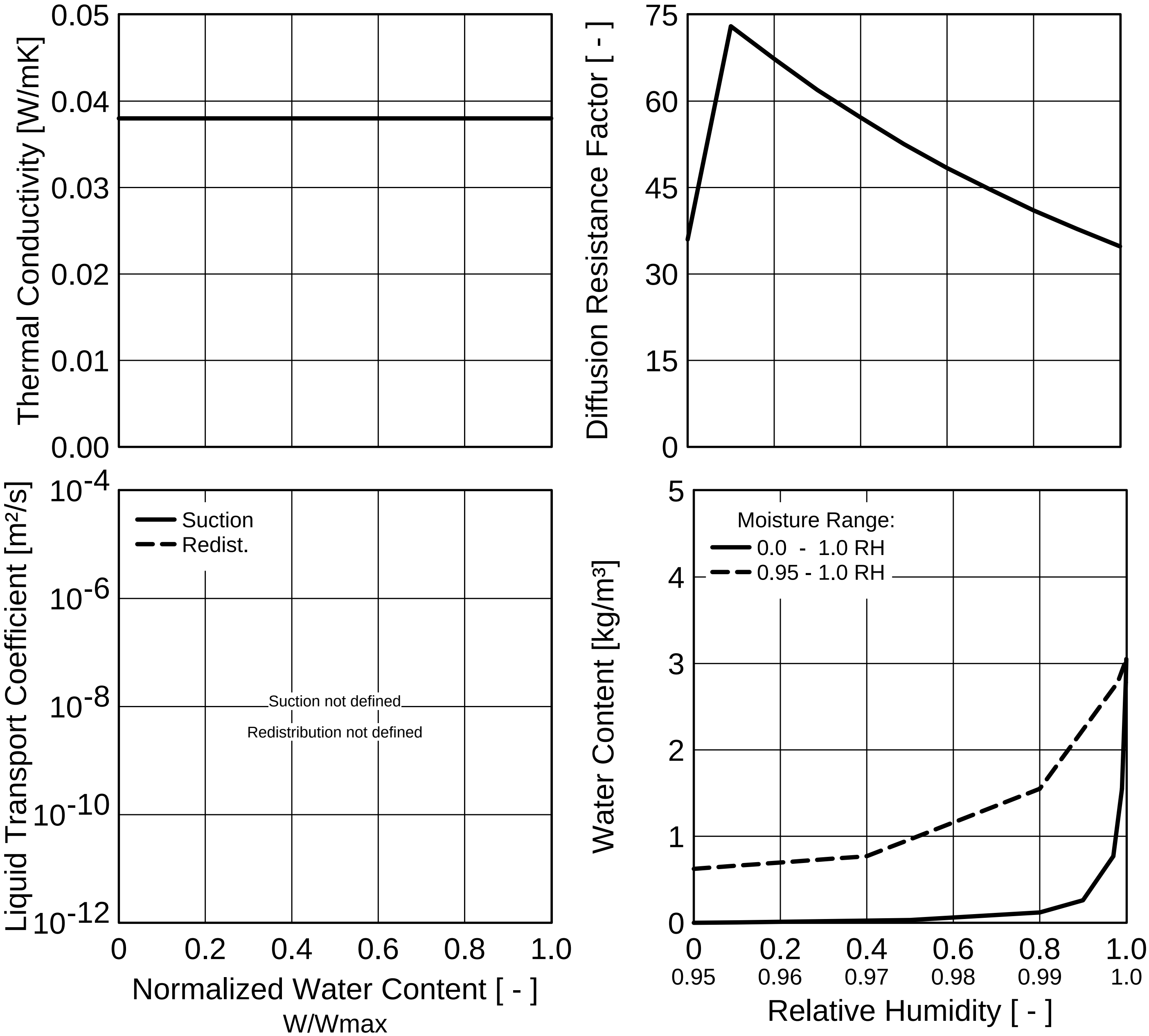




Material : Expanded Polystyrene Insulation (EPS)

Checking Input Data

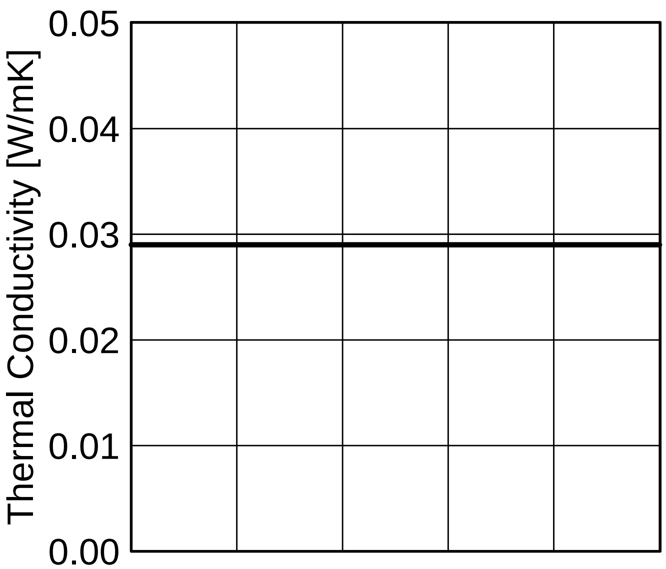
Property	Unit	Value
Bulk density	[kg/m³]	14,8
Porosity	[m³/m³]	0,99
Specific Heat Capacity, Dry	[J/kgK]	1470,0
Thermal Conductivity, Dry	[W/mK]	0,038
Water Vapour Diffusion Resistance Factor	[-]	36

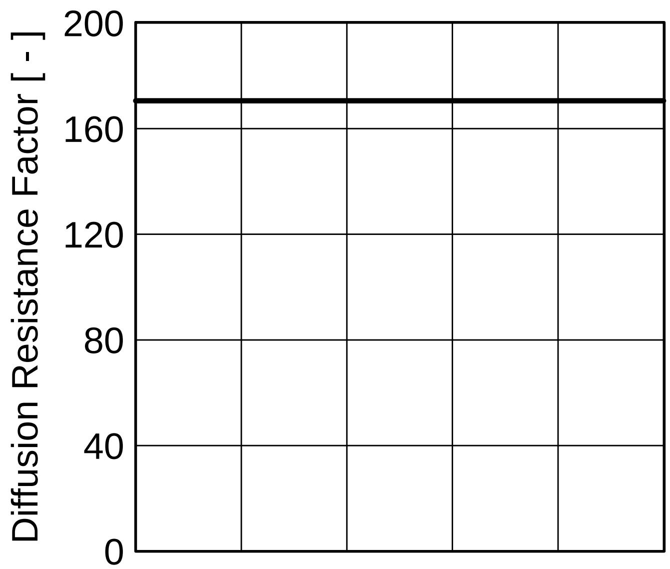


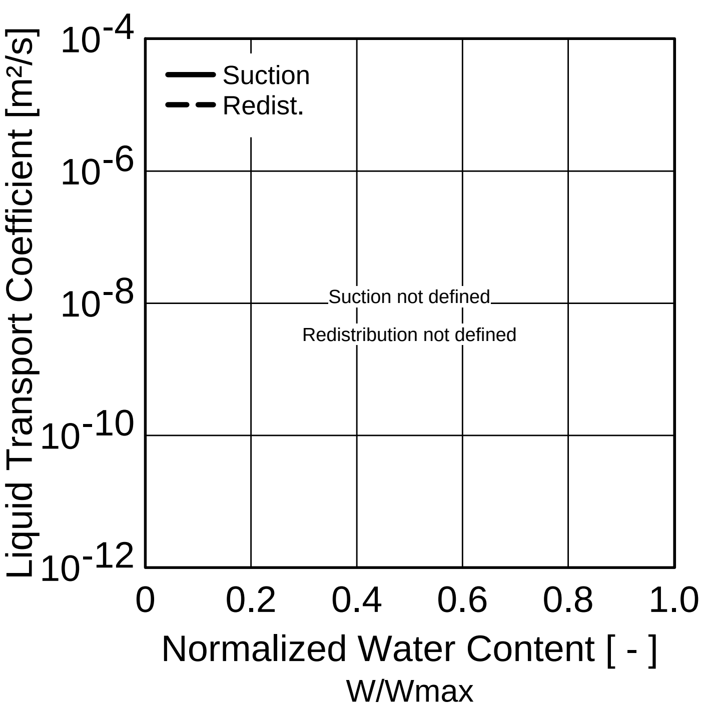
Material : Extruded Polystyrene Insulation (XPS)

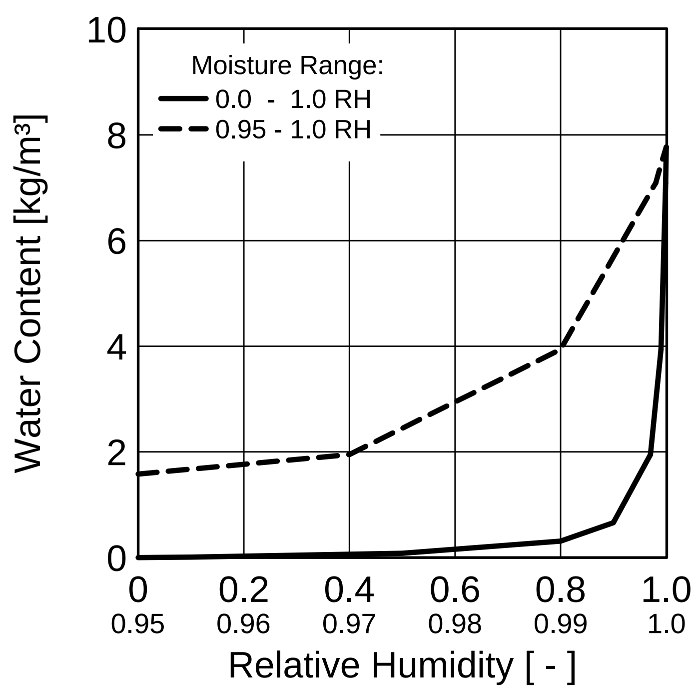
Checking Input Data

Property	Unit	Value
Bulk density	[kg/m³]	28,6
Porosity	[m³/m³]	0,99
Specific Heat Capacity, Dry	[J/kgK]	1470,0
Thermal Conductivity, Dry	[W/mK]	0,029
Water Vapour Diffusion Resistance Factor	[-]	170,56





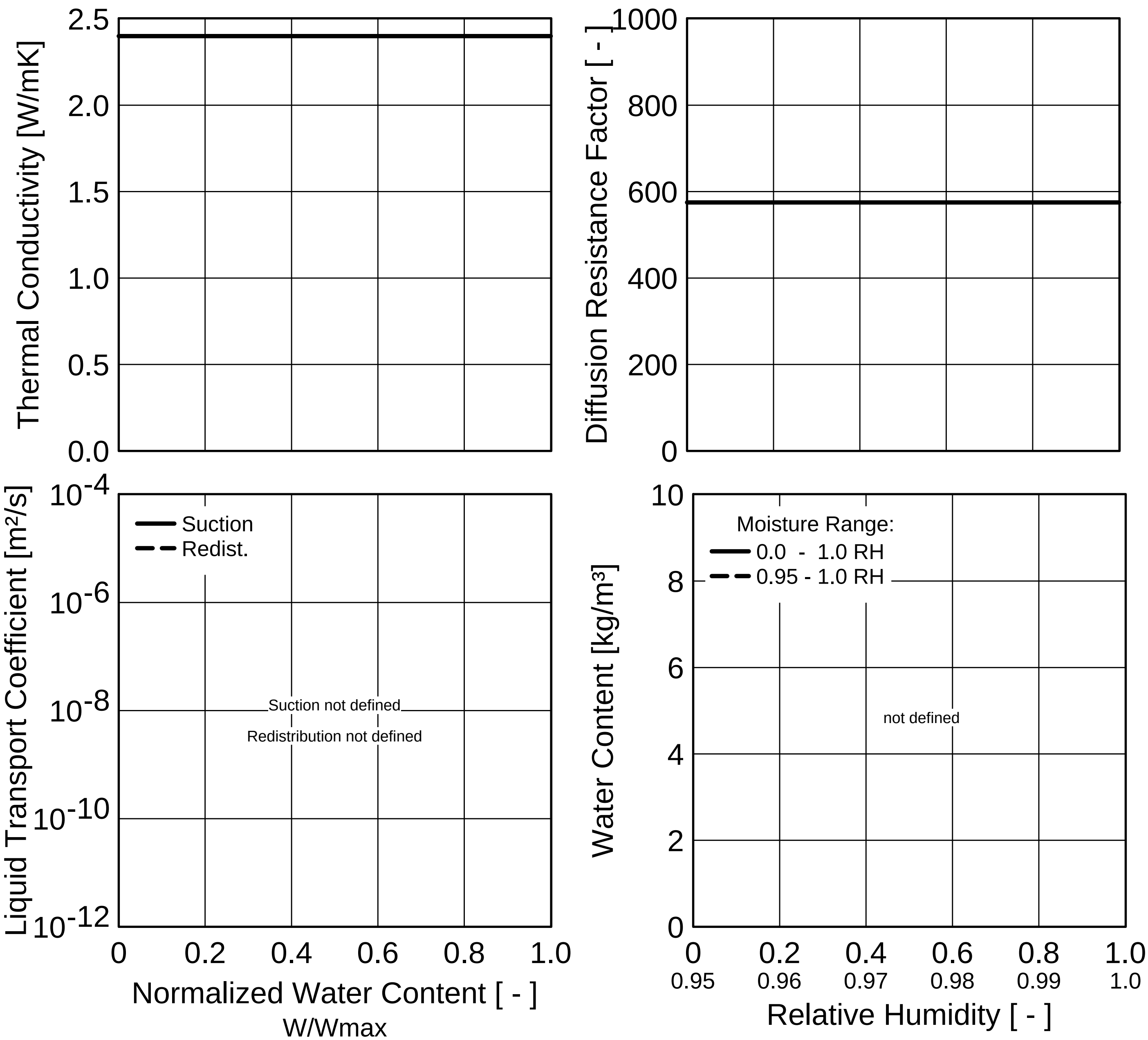




Material : Spun Bonded Polyolefine Membrane (SBP)

Checking Input Data

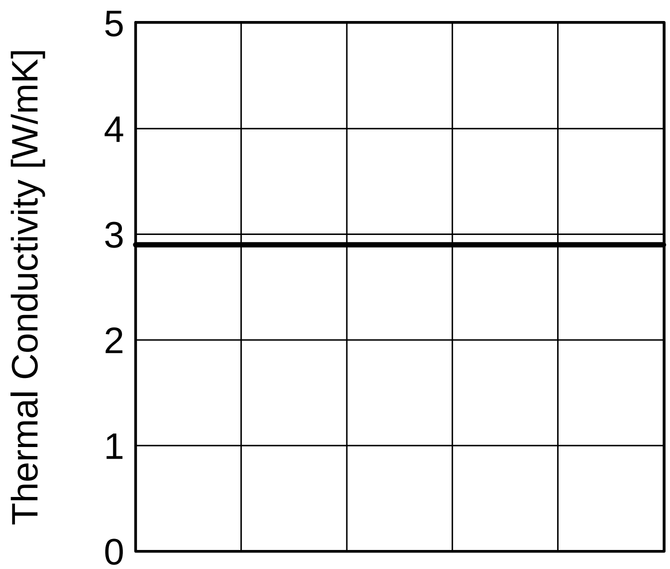
Property	Unit	Value
Bulk density	[kg/m³]	448,0
Porosity	[m³/m³]	0,001
Specific Heat Capacity, Dry	[J/kgK]	1500,0
Thermal Conductivity, Dry	[W/mK]	2,4
Water Vapour Diffusion Resistance Factor	[-]	575

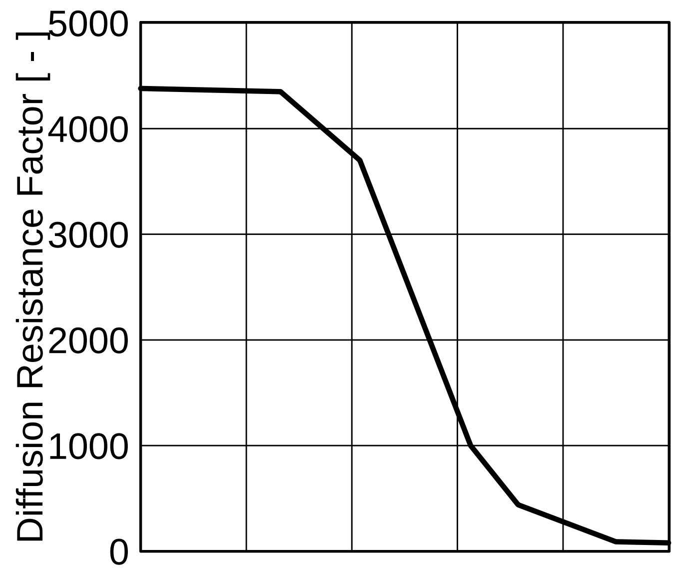


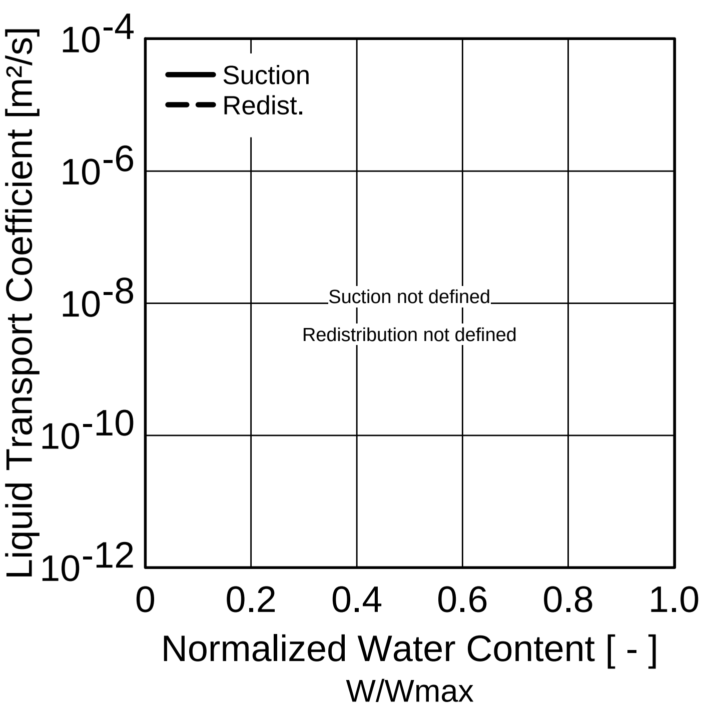
Material : Smart Vapor Retarder

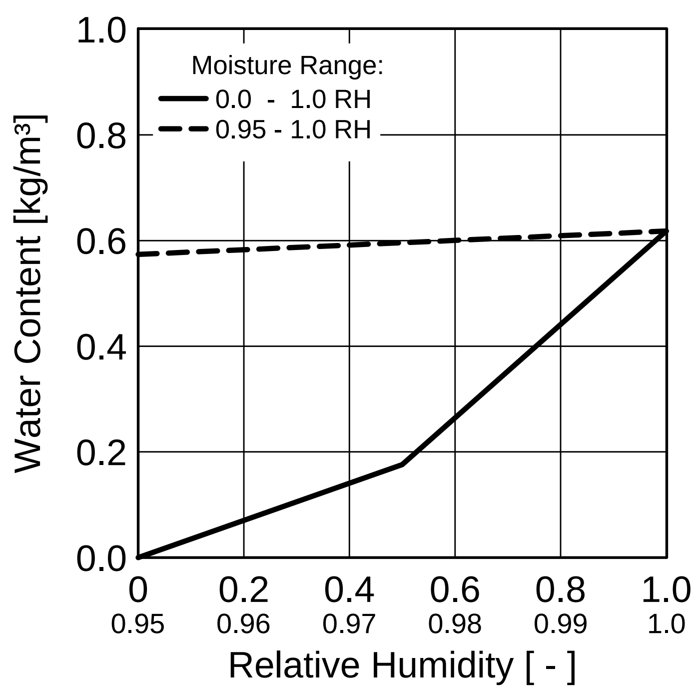
Checking Input Data

Property	Unit	Value
Bulk density	[kg/m³]	65,0
Porosity	[m³/m³]	0,001
Specific Heat Capacity, Dry	[J/kgK]	2300,0
Thermal Conductivity, Dry	[W/mK]	2,9
Water Vapour Diffusion Resistance Factor	[-]	4380,0





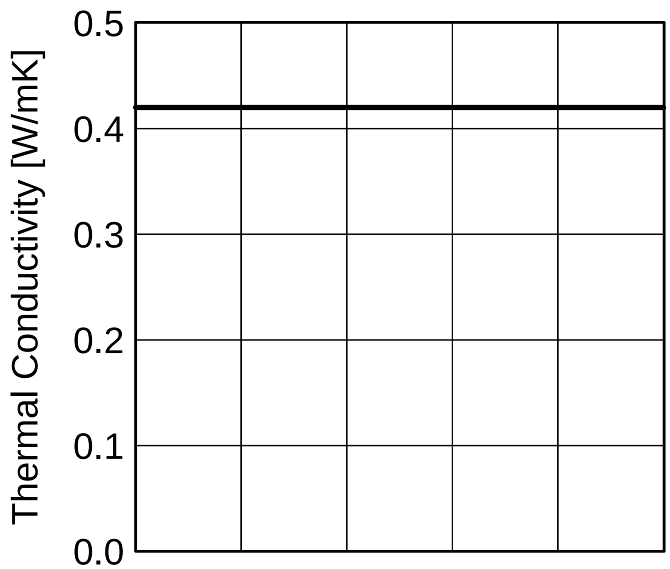


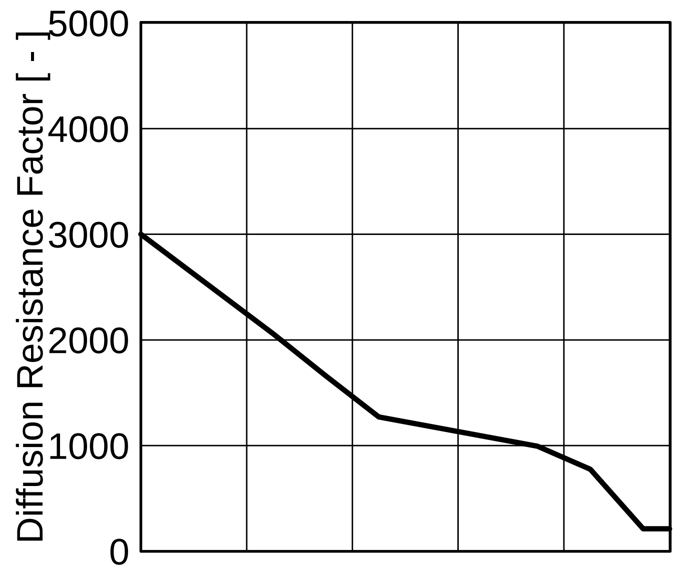


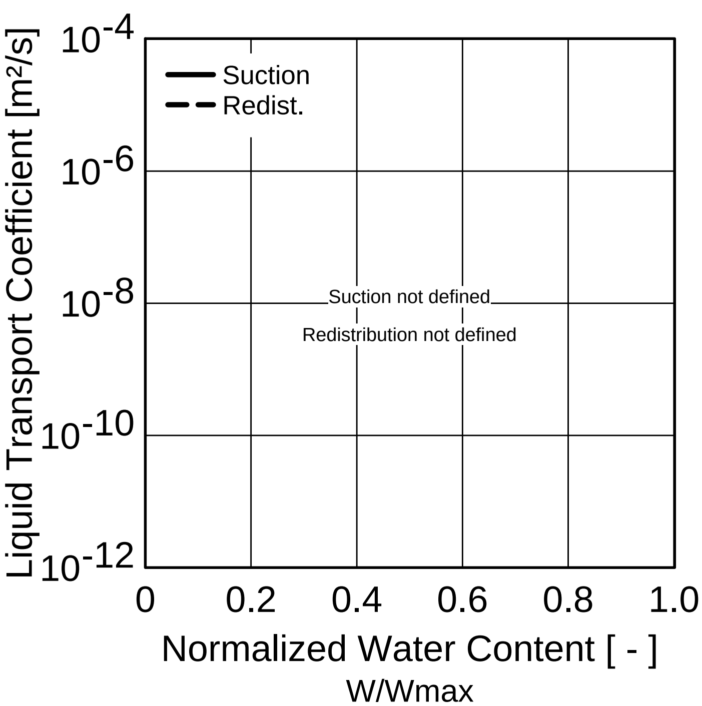
Material : Kraft Paper-variable RH

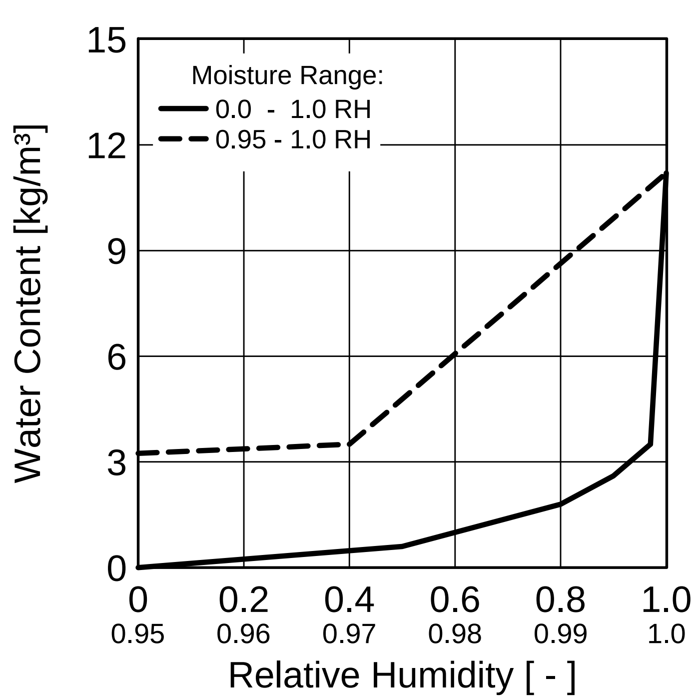
Checking Input Data

Property	Unit	Value
Bulk density	[kg/m³]	120,0
Porosity	[m³/m³]	0,6
Specific Heat Capacity, Dry	[J/kgK]	1500,0
Thermal Conductivity, Dry	[W/mK]	0,42
Water Vapour Diffusion Resistance Factor	[-]	3000,0





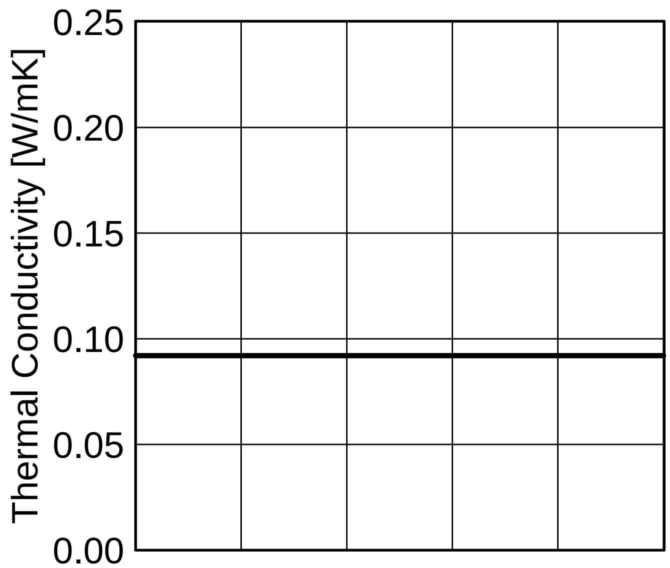


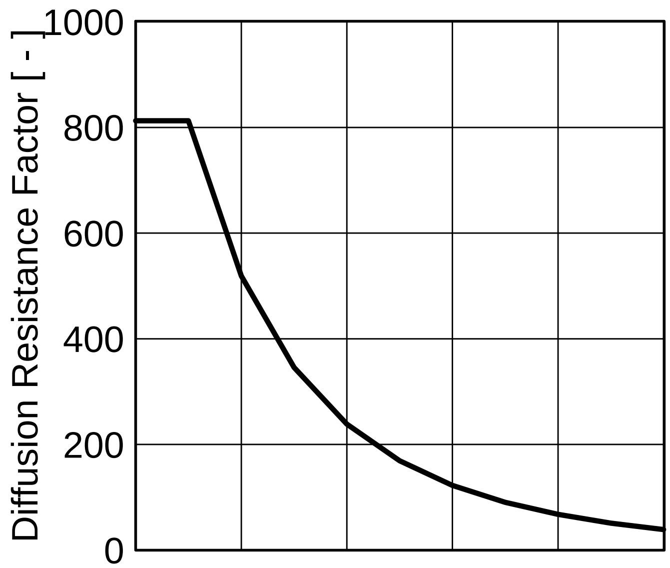


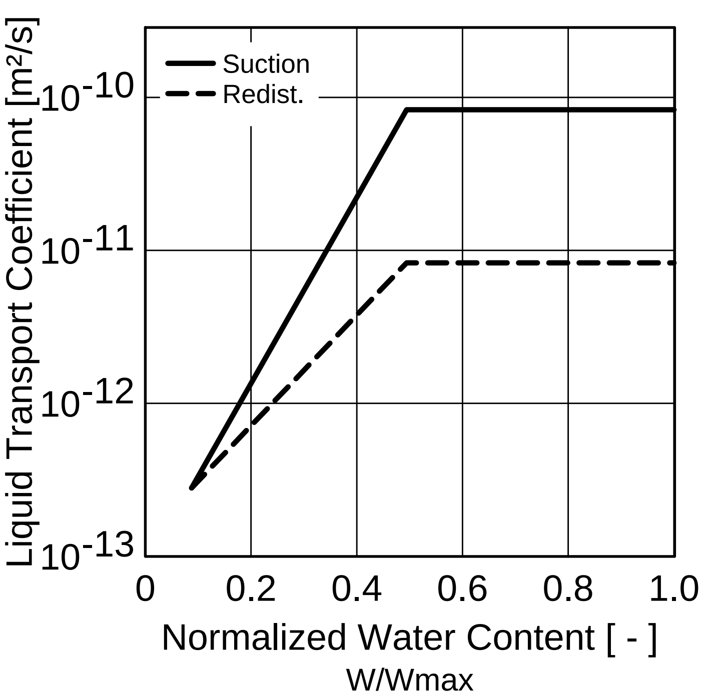
Material : Oriented Strand Board

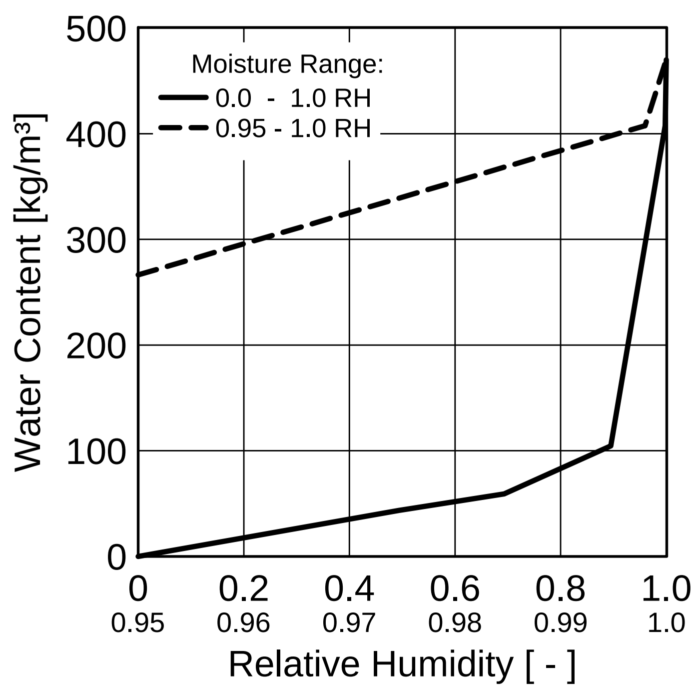
Checking Input Data

Property	Unit	Value
Bulk density	[kg/m³]	650,0
Porosity	[m³/m³]	0,95
Specific Heat Capacity, Dry	[J/kgK]	1880,0
Thermal Conductivity, Dry	[W/mK]	0,092
Water Vapour Diffusion Resistance Factor	[-]	812,8
Reference Water Content	[kg/m³]	83,3
Free Water Saturation	[kg/m³]	470,0
Water Absorption Coefficient	[kg/m²s^0.5]	0,0022





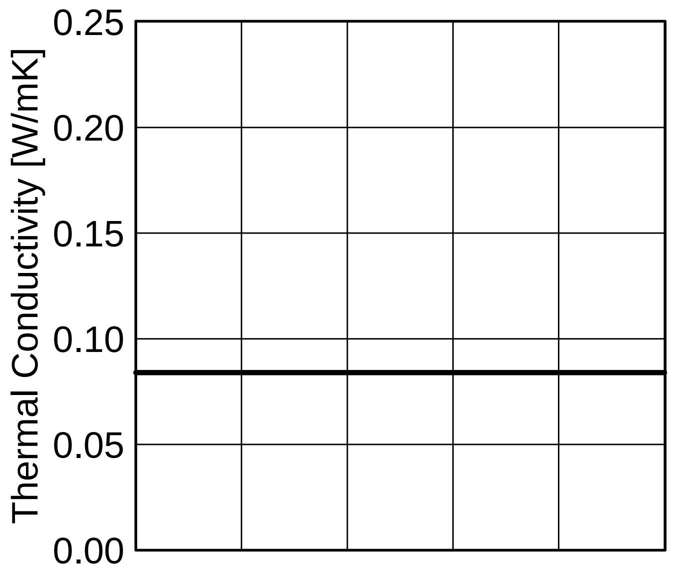


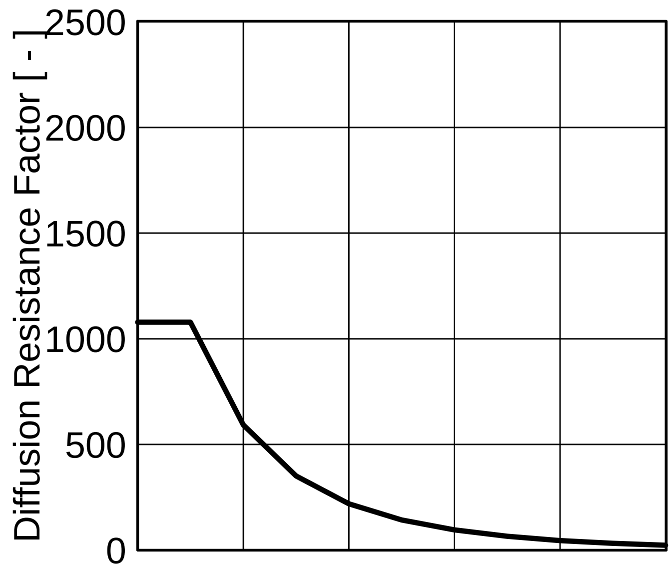


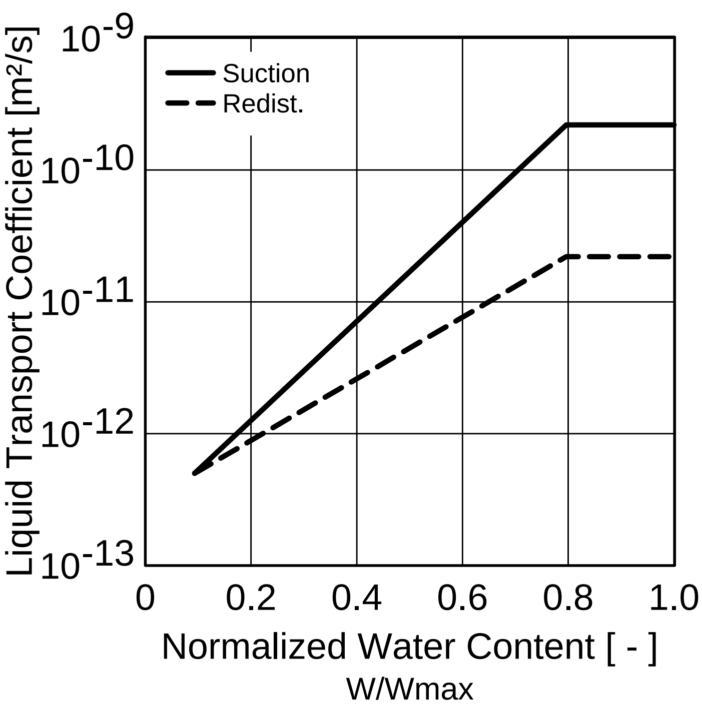
Material : Plywood

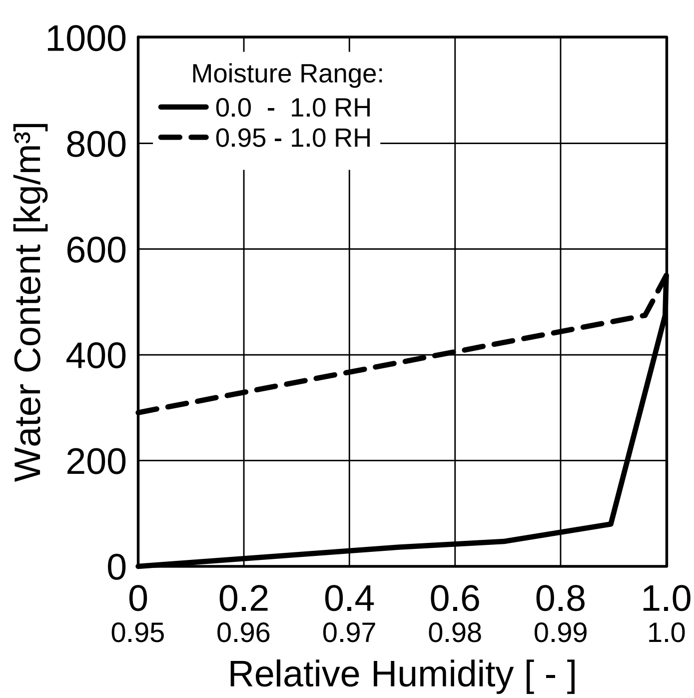
Checking Input Data

Property	Unit	Value
Bulk density	[kg/m³]	470,0
Porosity	[m³/m³]	0,69
Specific Heat Capacity, Dry	[J/kgK]	1880,0
Thermal Conductivity, Dry	[W/mK]	0,084
Water Vapour Diffusion Resistance Factor	[-]	1078,2
Reference Water Content	[kg/m³]	64,4
Free Water Saturation	[kg/m³]	550,0
Water Absorption Coefficient	[kg/m²s^0.5]	0,0042





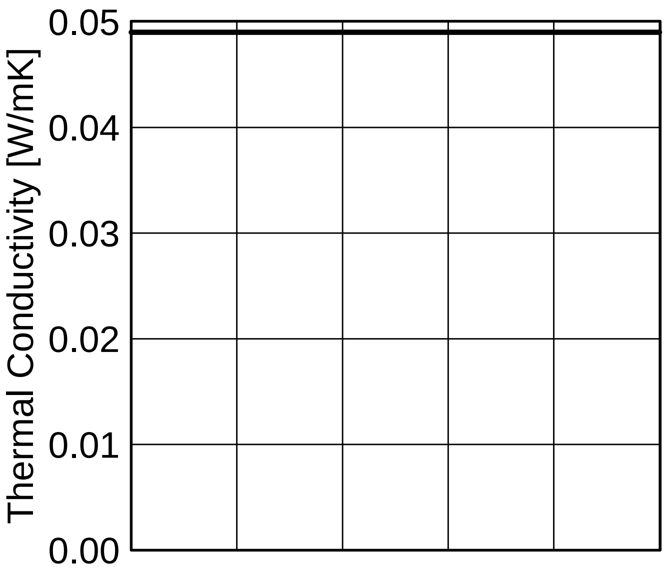


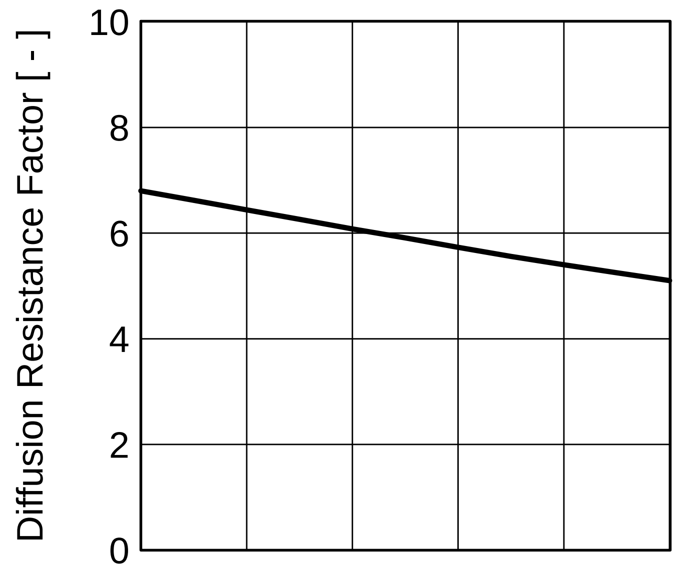


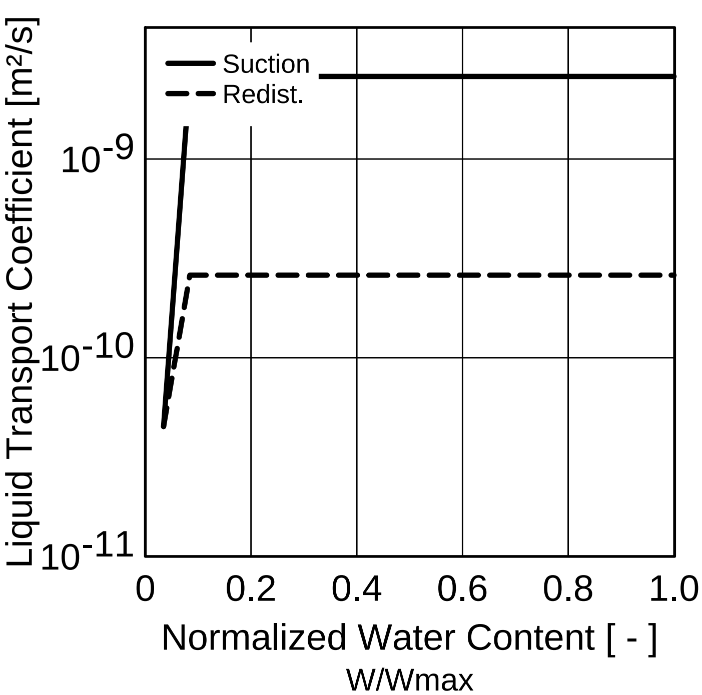
Material : Fiberboard - Wall 15

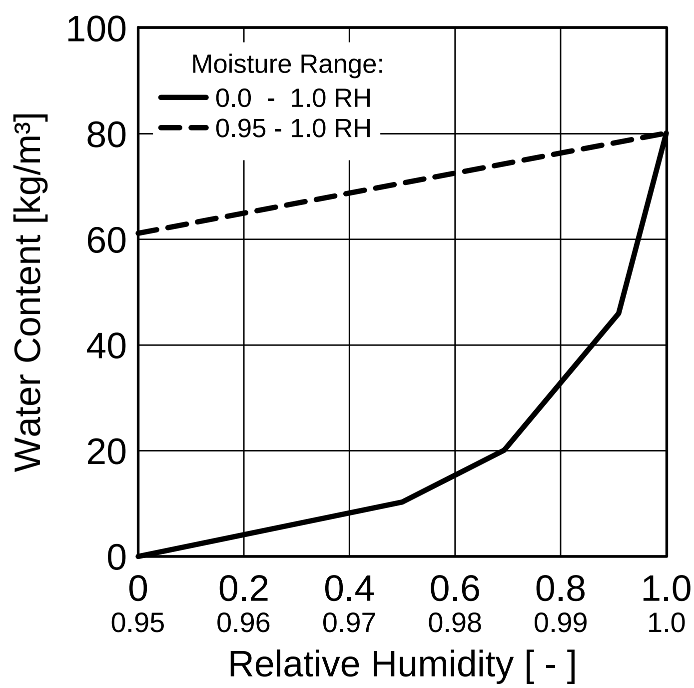
Checking Input Data

Property	Unit	Value
Bulk density	[kg/m³]	264,5
Porosity	[m³/m³]	0,95
Specific Heat Capacity, Dry	[J/kgK]	1880,0
Thermal Conductivity, Dry	[W/mK]	0,049
Water Vapour Diffusion Resistance Factor	[-]	6,8
Reference Water Content	[kg/m³]	32,9
Free Water Saturation	[kg/m³]	80,128
Water Absorption Coefficient	[kg/m²s^0.5]	0,0021









About the Authors

Jonathan Smegal's work at BSC includes laboratory research, hygro-thermal modeling, field monitoring of wall performance, and forensic analysis of building failures.

John Straube teaches in the Department of Civil Engineering and the School of Architecture at the University of Waterloo. More information about John Straube can be found at www.buildingscienceconsulting.com.

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