1.5.1. Influence of Air Flow on Heat Loss in High R-value Enclosures

by John Straube, December 2009

Building America High R-value Enclosures Research Project:

Influence of Air Flow on Heat Loss in High R-value Enclosures

John Straube, Ph.D., P.Eng.
Building Science Corporation, Somerville, MA
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Abstract:

This report investigates the role of airflow in heat transfer through high R-value building enclosures, particularly the effect of airflow that is not captured by blower test data converted to heat loss (High R-value enclosures are those with about double the R-value of current enclosure assemblies). The analysis and literature review points to the need for increased airtightness standards for both whole houses and assemblies for high-R wall, roof and basement systems. For wall and roof assemblies with R-values in the order of 30 to 60, airflow affects can dominate performance, whereas for traditional walls (R-10 to R-15 true r-value) the impacts were small enough they could be ignored. Airtightness targets that approach 1.0 l/s/m^2@75 Pa of enclosure area for total building airtightness should be sought for homes that use very high R-value walls and roofs (e.g. R-40/R-60).

Influence of Air Flow on Heat Loss in High R-value Enclosures

It has long been recognized that the control of air flow is a crucial and intrinsic part of heat and moisture control in modern building enclosures [Wilson 1963, Garden 1965]. That this statement is true for all climates has been a more recently developed awareness [Lstiburek 1994]. A large fraction of a modern, well-insulated building's space conditioning energy load is due to uncontrolled air leakage. Wintertime condensation of water vapor in exfiltrating air (or summertime condensation of infiltrating air) within assemblies is one of the two major sources of moisture in the above-grade enclosure (driving rain being the other). Air flow through the enclosure can also carry, exhaust gases, odors, and sounds through enclosures as well as mold spores and off gassing generated within the enclosure. Uncontrolled air leakage through the enclosure is therefore often a major cause of performance (e.g. comfort, health, energy, durability, etc.) problems.

This report investigates the role of airflow in heat transfer through high R-value building enclosures, particularly the effect of airflow that is not captured by blower test data converted to heat loss. High R-value enclosures are those with about double the R-value of current enclosure assemblies, i.e., high R-value enclosure true R-values are in the range of R-25 to R-50 for walls, 40 to 80 for roofs and basement walls have R-values of 15 to 30.

Airflow transports heat in a well-understood manner. The heat transfer of any fluid can be calculated by:

$$q = dm/d\theta \; c_o \cdot \Delta T \qquad [1]$$

where θ represents time and

$dm/d\theta$ is the mass flow rate of the fluid (kg/s) per unit time,

c_o is heat capacity of the fluid (J / (kg·K)), and

and ΔT is the temperature difference (K).

Equation (1) can be re-written in volumetric terms and US standard units as

$$Q = 1.08 \; dV/d\theta \quad \text{(in Btu/hr/°F/cfm)} \qquad [1b]$$

Air leaking out of a building must be replaced with infiltrating outdoor air which requires energy to condition it. Approximately 30% to 50% of space conditioning energy consumption in many well-insulated buildings is due to air leakage through the building enclosure. This is well known and can be controlled both by increasing the airtightness of the enclosure and reducing excessive air pressures across it.

The air flow rate is typically measured in Air Changes per Hour (ACH). The volumetric flow of air per second is then:

$$dV/d\theta = (ACH) \cdot V \cdot (1 \text{ hour} / 3600 \text{ seconds}) \qquad [2]$$

where V is the volume of the buildings conditioned space (m^3).

Hence, heat flow, Q (in Watts/°C) as a function of ACH is

$$Q = c_o \cdot \rho \cdot dV/d\theta \cdot \Delta T = c_o \cdot \rho \cdot (ACH) \, V / 3600 \cdot \Delta T \qquad [3]$$

which for room temperature (20°C / 68 °F) air with a density of 1.2 kg/m^3 (0.75 lb/ft^3) and a heat capacity of 1000 J/kg, heat flow becomes:

$$Q = 1\,000 \cdot 1.2 \cdot (ACH) \cdot V / 3600 \cdot \Delta T \qquad [4a]$$

$$= 0.3 \cdot (ACH)\ V \cdot \Delta T \text{ (in Watts/°C)}$$

In US standard units of Btu/hr, °F, and cubic feet, equation 4 can be re-written as:

$$Q = 0.0177 \cdot (ACH)\ V \cdot \Delta T \qquad \text{(in Btu/hr/°F)} \qquad [4b]$$

Sherman [1998] cites a widely used rule of thumb, that a house under natural conditions will exchange approximately (within about 20%) ACH natural = ACH@50Pa/20. Therefore, for houses with blower door test data of 2 to 4 ACH@50 (a common range of Building America research houses[1]), natural exchange rates are between about 0.1 and 0.2 ACH.

The pressure that acts across a wall over the heating season is in the order of 4 Pa (ASHRAE 2009) but varies with exposure to wind, height of the house, and temperature difference. This pressure difference is often used by ASHRAE standards in assessing airflow across walls and windows. For one-storey homes in mild climates 4 Pa significantly overestimates the average stack effect (buoyancy) pressures that will act on the home. However, 4 Pa is a reasonable estimate of a multi-storey house in cold weather when the effects of wind are considered in addition to stack effects.

Building enclosures as a whole or as components (e.g., windows, walls) are often tested for their air flow characteristics by imposing a series of pressure differences, monitoring the flow rate at each pressure, and fitting the data to a standard equation with test-specific coefficients. A general power law has been found to fit the data from most such leakage tests [Baker et al 1987]. This equation has the form:

$$dV/d\theta = C \cdot (\Delta P)^n \qquad [5]$$

where n is the flow exponent and C is a flow coefficient

In this equation, the flow coefficient is a measure of the leakage of the tested enclosure assembly and includes the area, flow path, flow regime, friction, and temperature-density effects. The flow exponent through normal building enclosures is very often in the range of 0.6 to 0.7, and is widely assumed to be 0.65. Equation 5 allows us to convert test data at one pressure to airflow under another pressure difference.

The U.S. Department of Energy Building America Program sets an enclosure air permeance requirement of 1.65 l/s/m^2@75 Pa (0.325 cfm/sf@0.3in w.c.) for residential buildings. ASTM E-1677-00 *Standard Specification for an Air Retarder Material or System for Low-Rise Framed Building Walls* currently calls for an assembly air permeance requirement of 0.30 l//s/m^2@75 Pa (0.06 cfm/sf @0.3in w.c.)

Using Equation 5 to convert airflow at a test pressure of 75 Pa to airflow at a pressure representative of in-service (4 Pa) one can merely multiply by (4/75)^0.65 or 0.149. Hence the BA overall enclosure value can be converted to 0.245 l/s/m^2@4 Pa (0.048 cfm/sf) and the ASTM enclosure value is 0.045 l/s/m^2@4 Pa (0.009 cfm/sf).

The preceding information allows one to estimate the impact of airflow on thermal transfers through High-R walls. By considering the range between the whole building Building America

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[1] Tbe Building America Program is a housing research program sponsored by the US Department of Energy. For more information, visit www.buildingamerica.gov.

standard (0.045 cfm/sf) and ASTM assembly tightness (0.009 cfm/sf), the heat flow by conduction through opaque elements and the flow by convection can be compared. Note that this is a pressure suitable for cold climates and two or three storey homes.

Figure 1 shows the influence of airflow on enclosure heat transfer. For the Building America overall enclosure target of 1.65 l/s/m2@75 Pa, the contribution of air to heat flow (using equation 1) can be seen to significant. If this level of airtightness is tolerated, the contribution of air leakage to heat flow can rise to 50% at an R-value of only R-20 (heat flow via conduction is 3.5 Btu/hr/sf at R-20, whereas the heat flow is 7 Btu/hr/sf when air leakage is included).

Most of the enclosure air leakage is leaking through joints, penetrations, and windows not the wall or roof assembly. The much stricter assembly tightness target of 0.30 l//s/m^2@75 Pa (0.06 cfm/sf @0.3in w.c.) is difficult for many walls and some roofs to achieve. However, it can be seen from the figure that even at this tightness level, airflow comprises 25% of the total flow for an enclosure of R-25, and 1/3 of the total heat flow for an R-50 enclosure. For roof assemblies with R-100, fully half of the heat flow will be carried by air leakage even with strict assembly air leakage targets.

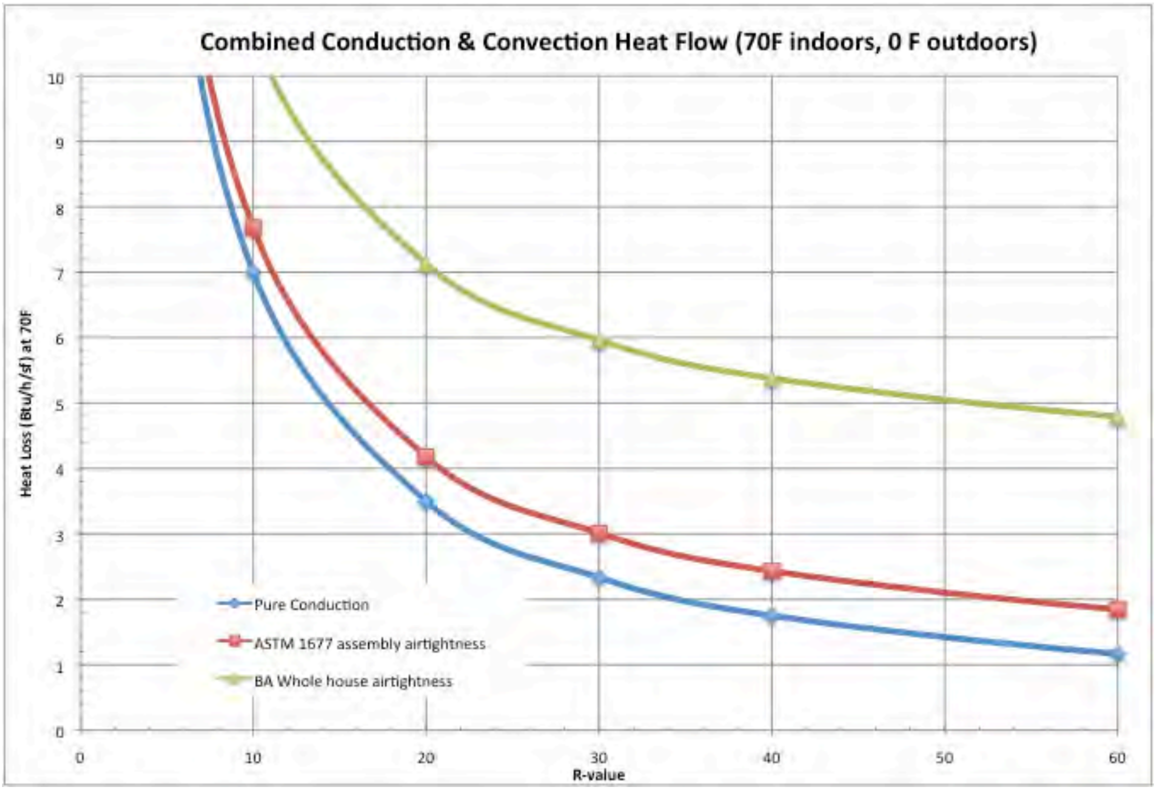

Figure 1: Airflow Contribution to cross-enclosure heat flow for two different air leakage rates

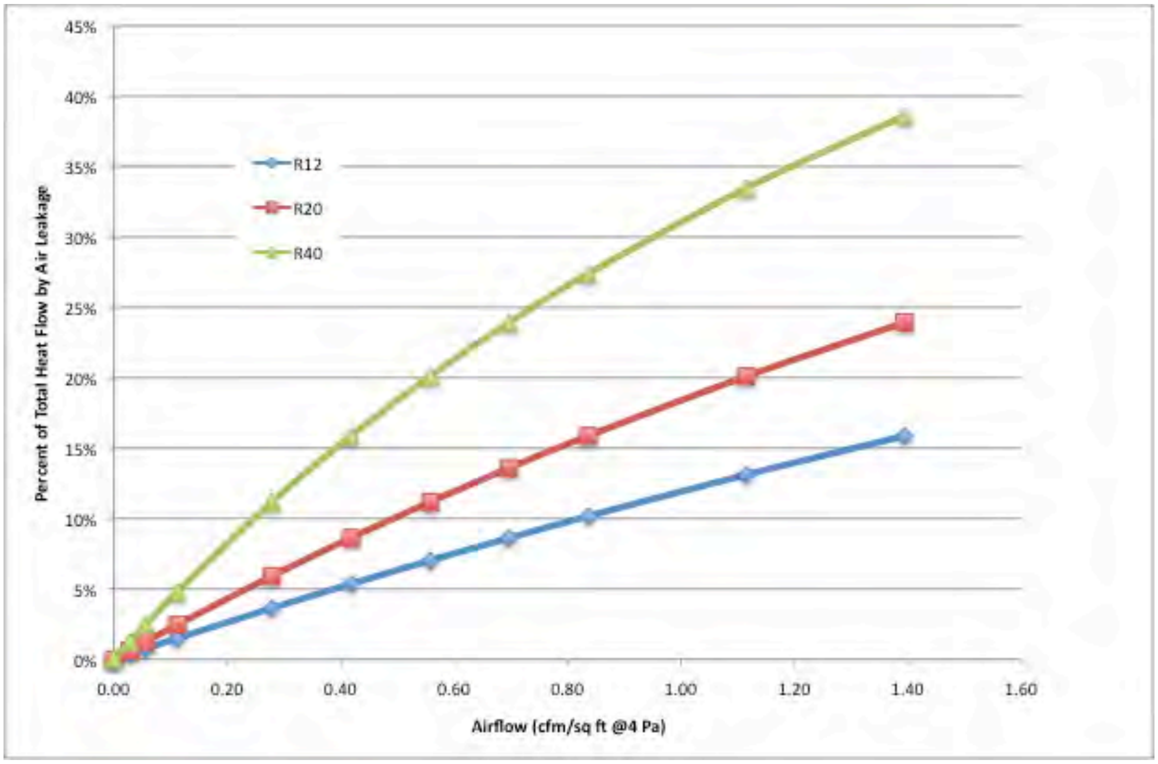

Figure 2: Proportion of heat flow carried by air leakage as function of air leakage and base R-value

Experimental Measurements of Airflow and Energy

The only comprehensive tests made of airflow through enclosure walls in a hot box where conducted by Jones, Ober, and Goodrow (1995). They undertook the hot box measurements of 40 different assemblies with and without air leakage. The base wall was a traditional nominal R-12 2x4 wall with R-2.5 foam sheathing. The air leakage of the walls covered a wide range from as little as 0.3 l/s/m2@75 Pa to over 1.2 l/s/m2@75 Pa. They showed that for simple exfiltration: “Test results for the wall assemblies reveal that airflow rates as low as 0.2 L/s/m^2 can produce a 46% increase in apparent thermal conductance”. The influence of wind washing, although not studied in detail due to equipment limitations, was projected to reduce the thermal resistance by 18%. These percentages would be much higher for high R walls.

Using a combination of field measurements and calculations, Ten Wolde et al (1995) concluded that airflow in a ventilated wall with modest airtightness (about 0.6 l/s/m^2@75) experienced a 33% reduction in thermal resistance from the nominal R-19 during winter conditions in Madison WI. These measured results are in the order of those calculated above for the same conditions.

This analysis and literature review points to the need for increased airtightness standards for both whole houses and assemblies for high-R wall, roof and basement systems.

Airflow through an enclosure can change the flow of heat within insulation by changing the relative contribution of radiative and conductive heat flow. It is often assumed that the heat flow through an airtight insulated assembly

$$Q = 1/R \cdot A \cdot \Delta T \qquad [6]$$

Can be added to Equation 1 to predict the total heat flow:

$$Q = [dm/d\theta \, c_o + 1/R \cdot A] \cdot \Delta T \qquad [7]$$

Yarbrough and Graves [1996] presented results of airflow through fibrous insulation in a modified ASTM C518 apparatus. They found that Equation 7 failed to predict heat flow by almost +/-15% at high airflows. At lower, more representative of service, flow rates, the deviation between theory and measurement was closer to 5%. They conducted tests in both infiltration and exfiltration unlike most of the literature. Unfortunately, this work was not extended to full-scale walls, and no explanation for the deviation has been developed.

ASHRAE has sponsored significant work on this topic at the University of Alberta [Ackerman 2006-1, ASHRAE 2006-2]. As heat flow is difficult to measure directly, these researchers measured temperatures within wall samples in a cold chamber and inferred from these that infiltration could have 10% or more less heat flow than predicted by Equation 7 because of heat recovery. When the researchers conducted a field test hut study to carefully measure the energy flows through the walls, no impact could be found. It was postulated that the highly variable airflow and temperature around real buildings may have masked any small impact.

This concept of infiltration heat recovery through insulation walls has been studied as the “Dynamic Wall” concept for several decades. Timusk [1988] is the only known researcher in North America who has built and monitored a Dynamic wall house. Taylor et al [1996] developed equations that predicted additional (above that of Equation 7) heat gain from infiltration and additional heat loss during exfiltration. The attached plot from Taylor et al (Figure 3) shows total heat flux/static heat flux increasing with airflow outward in cold weather and decreasing with inward flow in cold weather. For low insulation levels, the effect is smallish (note the log plot) and at low R-value (RSI 1.28=R8) the curves are nearly symmetrical. However, as the R-value increases, even small airflows can result in impacts on predicted heat flow that are well over 10%, and asymmetrical (exfiltration heat loss is more than infiltration heat gain).

No controlled hotbox studies have been conducted to accurately study this phenomenon, likely because such equipment is not widely available.

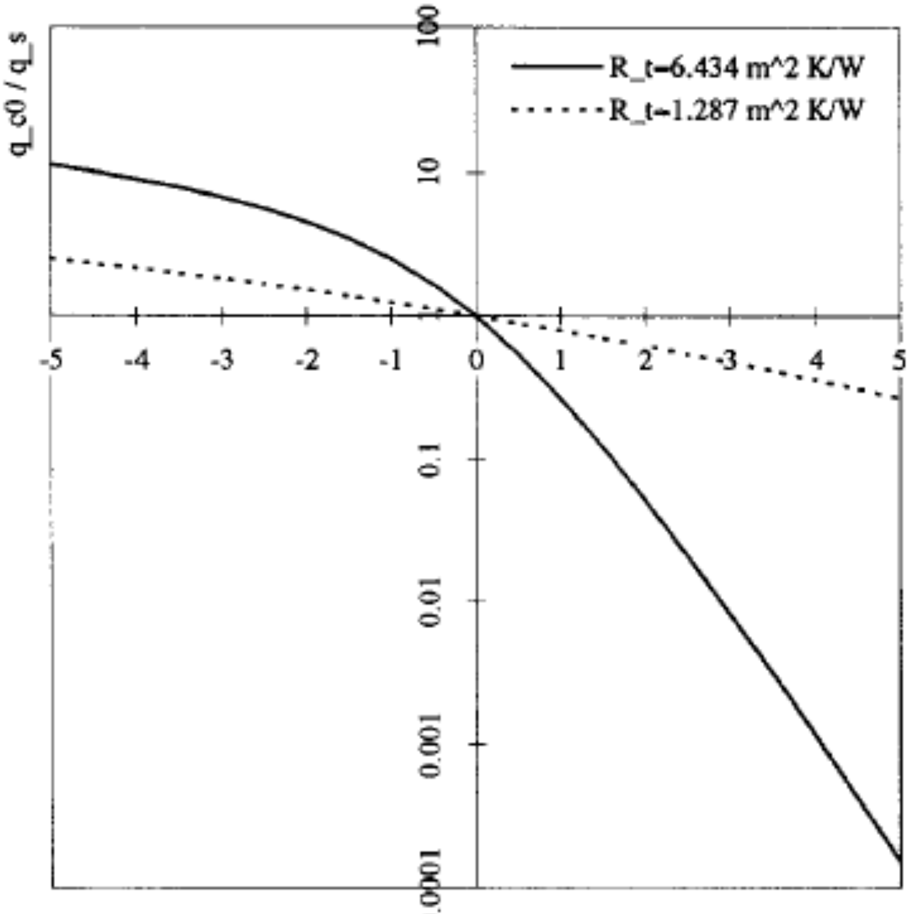

Figure 3: Ratio of total heat flux to (q_{c0}) to heat flux with no airflow ($q_{\_s}$) as a function of airflow rate and insulation level

Other Flow Paths

There are numerous paths that airflow can take through an assembly insulated with air permeable insulation. These paths are shown in Figure 4. Path 1 is the airflow path that has been considered in preceding discussion.

Flow paths that combine 1, 2 and 3 are complex and increase the contact time and thus the potential impact on heat flow. Very little research has been undertaken in this area, but Chebil et al (2003) did investigate these impacts using a computer model, and showed significant influences 8 to 15% changes in heat flow for reasonable ranges in air leakage depending on flow path.

Both thermal buoyancy (i.e., *natural convection* or stack effect) and differential wind pressures cause natural and forced convective air flows *within* building enclosures. These internal airflows can short-circuit thermal insulation and bypass air barriers with the attendant increase in heat transfer and risk of moisture deposition. Providing an excellent air barrier system will not necessarily control these problems, since no air flow need occur through an ABS for either of these phenomena to cause performance problems.

These are other types of airflow can play an important role in thermal performance. For enclosure assemblies with lower R-values, eg true R-value of 10, these secondary airflow effects play a small role. As the R-value of an assembly increases (to R-20 or R-40) even small flows can begin to comprise a significant proportion of total heat loss.

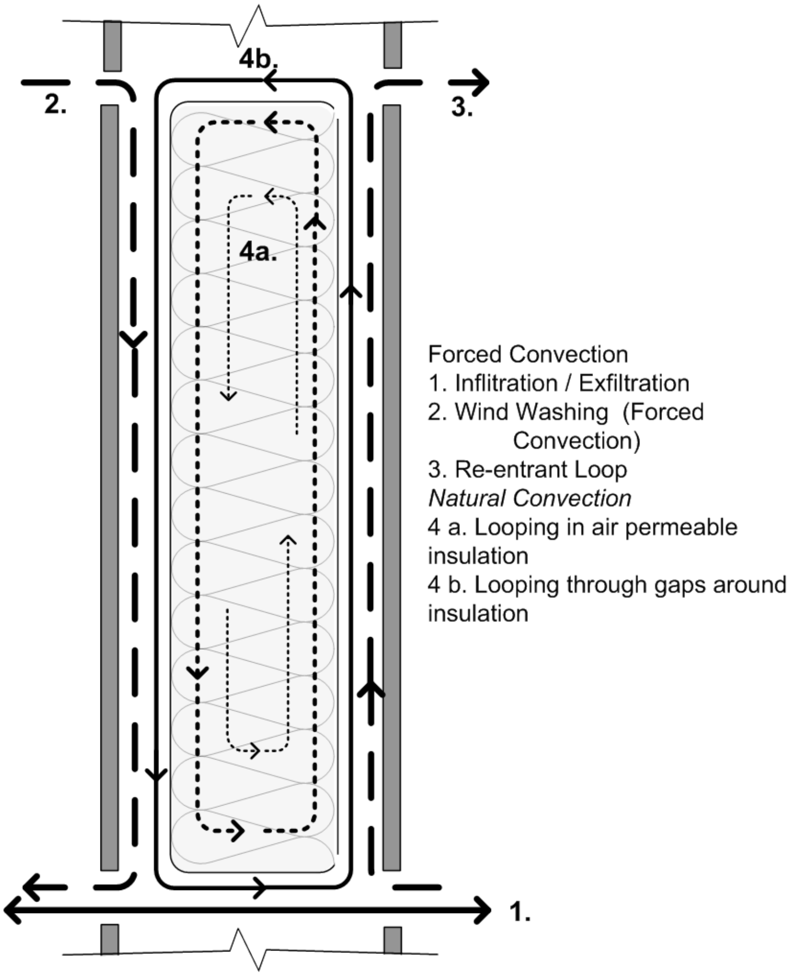

Figure 4: Airflow paths within and through an insulated enclosure

Natural Convection

The density of air varies with temperature. The greater the height of a column of air, the greater the potential difference in pressure if that column is at a different temperature. The pressure difference generated by a column of air h meters high with temperature difference between indoor and outdoor air at standard temperature and pressure is approximately:

$$\Delta P = 3465 \cdot \Delta h \cdot (\overline{\quad} - \overline{\quad}) \text{ [Pa]} \qquad [5]$$

where To and Ti are the outdoor and indoor temperatures respectively, (in Kelvin = Celsius + 273).

For example, if the air in a one meter high cylinder, open at the bottom and containing room temperature air (20 °C/68 °F) is connected to a space at a temperature of -10 °C (14 °F), an outward pressure of 1.34 Pa would act at the top. An inspection of Equation 5 shows that the size of the pressure driving buoyancy-induced flow is primarily affected by two factors: the magnitude of the temperature difference and the difference in height. The amount of air flow that can be moved by this pressure is of course dependent on the geometry of the flow path and/or the air permeability of the material along the path.

As the thickness of insulation increases to meet high R-value targets, the temperature differences across the insulation increases. This increases the pressure difference that drives loops. At the same time, as R-value increases, the impact, as a proportion of the total heat flow, of very small airflows increases. Countering this trend is the movement to higher density (and thus usually higher air flow resistance) insulation to achieve higher R-values per inch. The R-value and airflow resistance to flow through an insulation increases linearly with thickness, but the heat flow across the insulation decreases as the inverse, $^{1}/_{R}$. Hence, for thick layers, the increase in airflow resistance of flow paths through the insulation increases faster than the temperature difference across the insulation, and thus convective loops are less of a challenge. However, the driving force for air loops *around* insulation continues to grow with high-R walls, and this mechanism becomes more and more important proportionately.

If a continuous air loop, even 1 mm ($^{1}/_{25}$") in width, connects two sides of a layer of insulation a convective loop can form, robbing energy efficiency and causing moisture problems (Figure 3). Research [e.g., Lecompte 1990] has shown that significant heat losses and moisture transport can result from connected air gaps of only 1-2 mm width. To ensure no flow paths connect air spaces on the warm side of the insulation to the cold side, insulation with sufficiently low air permeability should always be placed in tight contact along at least one surface. Semi-rigid cavity insulation must be firmly attached to one side of the air space in which it is installed to avoid such convection loops. Full bed or serpentine adhesive patterns are preferred to isolated daubs (which create continuous vertical gaps) for the same reasons.

Flow within air permeable insulation usually occurs if large temperature differences act across a thin layer of insulation – the pressure difference is large if the temperature difference is large and the flow resistance is small as the airflow path distance (the thickness) is small. This is often a concern in horizontal insulation (e.g., attics). One solution is the use of higher density blown-in insulation which reduces the air permeability of the material, and thus its propensity for convection losses. The use of multiple layers (i.e., in the form of insulating sheathing or layers of batts) reduces the temperature drop across each layer and thus the driving force for convection. Very thick layers of attic insulation (e.g., 12"/300 mm or more) helps increases the flow resistance as well.

Batt insulation with low airflow resistance (roughly correlated to density) may not restrict air loops even within its body when driven by large temperature-induced pressure differences (see Figure 4), whereas semi-rigid or rigid insulation usually does. Modern batt insulation products are designed with sufficient air flow resistance as to control internal looping if the batts are installed to perfectly fills the stud cavity, and temperature differences are kept within normal ranges.

Batt insulation is manufactured slightly oversized so that when it is compressed (or friction fit) by the drywall gaps and wrinkles are minimized. If installation is not careful, and experience has shown that sufficiently careful installation is rare, small gaps will form and allow loops to form around the batt. The pressure generated by the mechanism shown in Figure 5A and Figure 6 increases linearly with height (usually 8 ft or 2.44 m for residential walls) and practically linearly with temperature difference. Research at IRC [Brown et al 1993] has shown that small gaps, such as shown in Figure 5, can greatly impact heat flow (from 15% at $\Delta T=25°C$ to 35% at $\Delta T=55$ C).

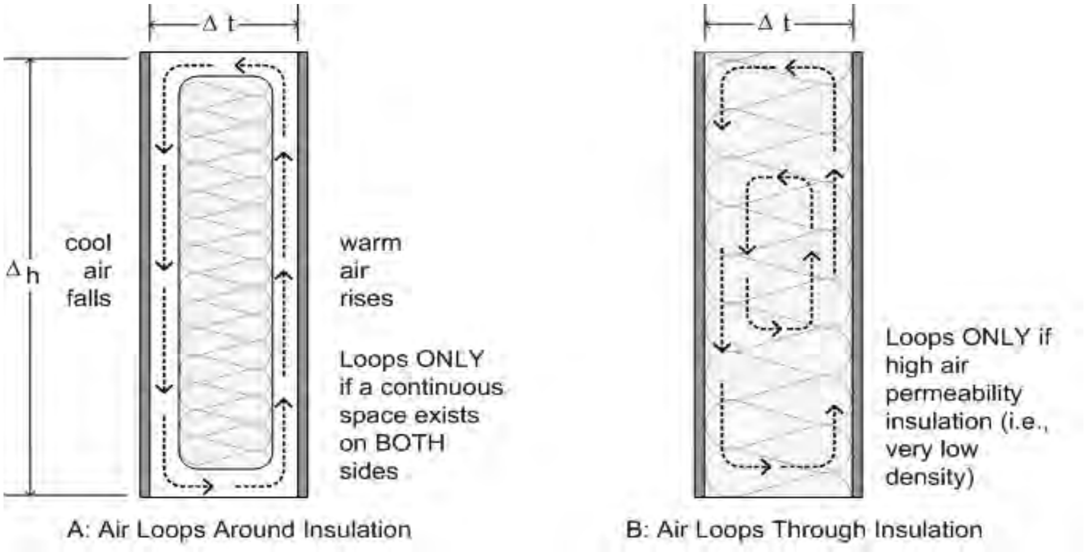

Figure 5: Natural Convection Air Flow Around and Through Insulation

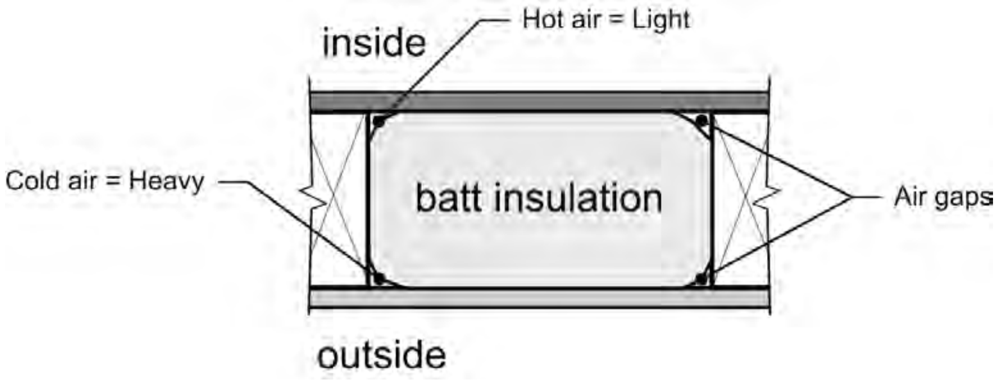

Figure 6: Natural Convection around Batt Insulation (plan view)

Multiple layers of insulation are often specified for low-slope roofs, partly to reduce or eliminate the convective loops that could occur in the small joints that inevitably form between boards. The driving pressure for flow in two independent 2”/ 50 mm high gaps (a typical board thickness) is small enough and the temperature difference is half as much as a single 4” /100 mm layer. The two factors together mean that the pressures driving looping are ¼ as much for two layers as one. An even greater effect is that the flow path from the interior to the exterior is now much more tortuous and low air permeance.

Wind Washing

High velocity air flowing behind the cladding or sheathing can also increase the amount of heat loss by penetrating the structure of low-density fibrous insulations (hence, batt insulation is very vulnerable). This phenomenon is often called wind washing, or *forced convection* and can cause surface condensation in outside corners, increased heat loss and other problems [Timusk et al 1991]. Building corners and parapets are especially susceptible because the wind induces very steep pressure gradients in these areas (Figure 7). Pressure gradients of 100 Pa/m can form, and even small air flow paths can allow excessive air flows with such large pressures.

Air impermeable layers placed outside low-density fibrous insulation can control this form of heat loss. In Scandinavia and Europe, secondary, outer layers of airflow resistance are called wind barriers or convection barriers. To control wind-driven convective heat losses Finnish research [Uvslokk 1988, Ojanen 1995] has recommended limiting the maximum permeability of the wind barrier to between 10 and 25 x 10^{-6} $m^3/(m^2$ Pa s). Some high-density mineral fiber insulations, and rigid foam insulations, housewraps, building paper, and sheathing (all with taped or otherwise secured joints) can provide this level of control.

In-plane air flow resistors provide *compartmentalisation*, which helps to confine air leakage to limited areas of the enclosure, reduces wind washing effects, and can also improve pressure moderation performance. Compartmentalisation should be provided in all assemblies, either provided by tight separators at discrete intervals (e.g., sheet metal) or by the distributed resistance of low-permeance materials (e.g., dense-pack cellulose and foam). Corner separators are often the most useful because of the high pressure gradients acting around corners.

Framing members can also provide resistance to in-plane flow. Wood blocking, or draft stops, have long been used in wood framed construction to prevent the spread of fire and smoke. Wood framing may not be sufficiently airtight at corners because drying shrinkage causes small cracks between the framing and the siding (or drywall). Metal studs tend to have “knock outs” for services which allow unimpeded lateral air flow. In all cases, if air driven by exterior wind pressures enters a stud cavity filled with air permeable insulation, the thermal performance will be seriously degraded.

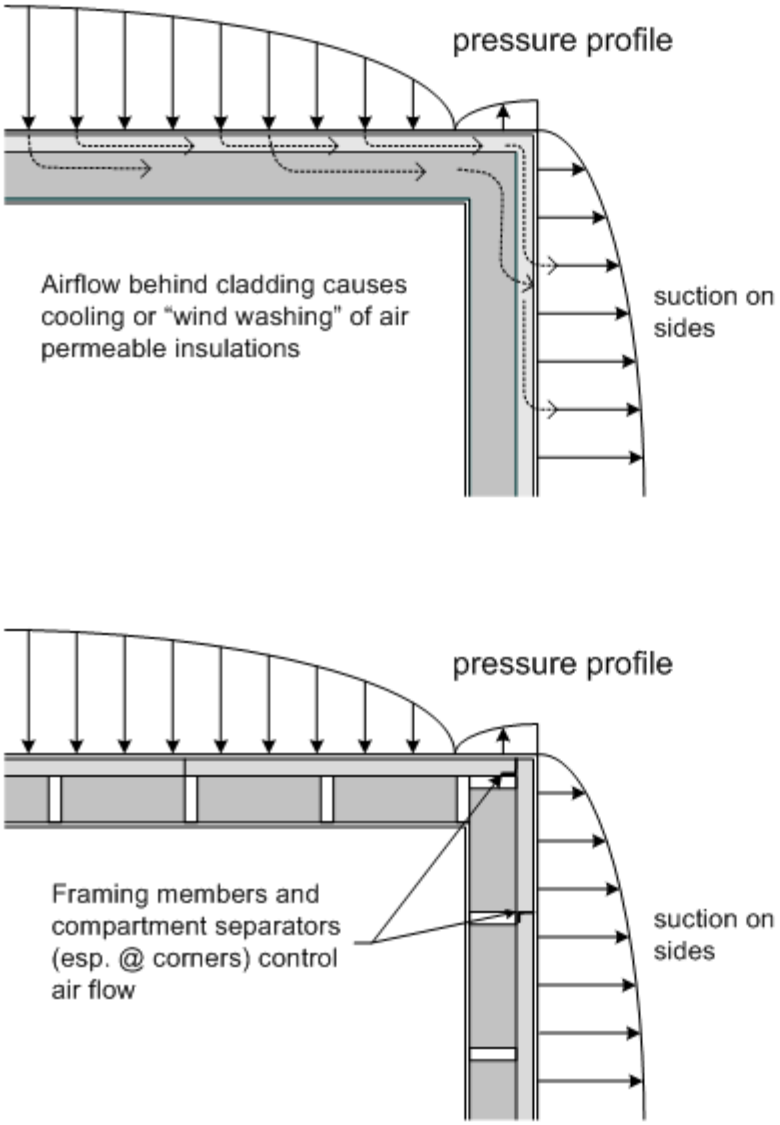

Figure 7: Wind Forced Convection ("Wind Washing")

Practical Solutions To Forced and Natural Convective Flow

Given our current understanding practical advice can be given to designers and builders of high R-value assemblies. There is, however, little quantitative experimental evidence of how the air flow interacts with conduction.

The primary means of controlling convective loops and wind-washing effects are:

- Insulation with low air permeance (foams, or faced fibrous insulation) should be used when exposed to large air pressures such as wind washing.
- Some airtightness in the form of housewraps, taped rigid sheathing etc., should be provided behind cladding and to the exterior of any air permeable fibrous insulations to control wind-washing effects on any enclosure.
- Low air permeance materials (such as foams, and very high density fibrous insulation)

must be placed fully in contact with one airtight surface to avoid looping.

- Good workmanship and inspection must be employed to avoid air gaps around both rigid, semi-rigid and low-density fibrous insulation. Semi-rigid insulation offers the ability to be fitted or pressed to conform to rough surfaces like blockwork and concrete. This may not control convection in low-density batt insulation which must completely fill the space into which it is installed (i.e., no gaps or wrinkles).
- The temperature difference across individual layers of insulation can be reduced by using multiple layers of insulation with non-aligned joints (e.g., insulated sheathing over batt insulation).
- The height of the connected space (h in Eq. 5) can be reduced in roofing details by using multiple layers of insulation.
- The ability of lateral air flow can be reduced by providing air flow resistors around corners and other changes in plan. This can be achieved by compartmentalizing to limit vertical height and horizontal extent, and is especially important at corners and parapets.

Implications for High R-value Assemblies

The influence of airflow within and through building enclosures on heat transfer is significant, much more significant than for standard enclosures. For many high R-value walls, basements, and roofs the proportion of heat flow due to airflow effects increases as R-value increases. For wall and roof assemblies with R-values in the order of 30 to 60, airflow affects can dominate performance, whereas for traditional walls (R-10 to R-15 true r-value) the impacts were small enough they could be ignored.

Higher airtightness standards for both whole buildings and assemblies need to be imposed for high R-value enclosures. Airtightness targets that approach 1.0 l/s/m^2@75 Pa of enclosure area for total building airtightness should be sought for homes that use very high R-value walls and roofs (e.g. R-40/R-60).

The interaction of airflow and heat transfer is poorly understood. There appears to be a real impact, and for accurate assessments heat flow due to conduction and heat flow due to through-enclosure convection cannot simply be added. However, the precise interaction has not been experimentally quantified and is likely in the order of more than 10% impact for high R enclosures.

Airflow within enclosures influence heat flow in all walls. However, small defects and a limited amount of wind washing can be tolerated in enclosures with R-values of 10 to 20 without serious reductions in performance. For high R-value enclosures, even small, perhaps even unavoidable defects, can begin to have a more significant influence on heat flow for high R-value enclosures. Hence, techniques to reduce the impact of these mechanisms need to be implemented. For example, the use of wind washing barriers, multiple layers of insulation and insulation with higher resistance to airflow may be required.

References

Ackerman, M.Y, Dale, D., Wilson, D., Bailey, R. , “Infiltration heat recovery, Part I-field studies in an instrumented test building”, *ASHRAE Transactions*, vol. 112 (2), pp. 597-608, 2006.

Ackerman, M.Y, Dale, D., Wilson, D., Bailey, R. “Infiltration heat recovery, Part II-laboratory studies of two test panel geometries”, *ASHRAE Transactions*, vol. 112 (2), pp. 609-621, 2006.

Baker, P.H., Sharples, S., Ward, I.C., "Air Flow Through Cracks," *Building & Environment*, Vol. 22, No. 4, 1987, pp. 293-304.

Brown, W.C., Bomberg, M.T., Ullet, J.M. and Rasmussen, J. "Measured Thermal Resistance of Frame Walls with Defects in the Installation of Mineral Fibre Insulation"*, J. of Thermal Insulation and Building Envelopes*, Vol 16, April 1993, pp. 318-339.

Computer Simulation of Thermal Impact of Air Infiltration Through Multi-layered Exterior Walls”. *Proc. of Eight International IBPSa Conference*, Eindhoven, Netherlands, August 2003, pp. 155-162.

Garden,G.K., *Control of Air Leakage is Important*. Canadian Building Digest 72, National Research Council of Canada, Ottawa, 1965.

Jones, D. C., Ober, D. G., and Goodrow, J. T., "Thermal Performance Characterization of Residential Wall Systems Using a Calibrated Hot Box with Airflow Induced by Differential Pressures," *Airflow Performance of Building Envelopes, Components, and Systems, ASTM STP 1255,* Mark P. Modera and Andrew K. Persily, Eds., American Society for Testing and Materials, Philadelphia, 1995, pp. 197-228.

Lecompte, J., "Influence of Natural Convection in an Insulated Cavity on the Thermal Performance of a Wall", *Insulation Materials, Testing and Applications, ASTM STP1030*. D.L. McElry and J.F. Kimpflen, Eds., Amercian Society for Tesitng and Materials, Philadelphia, 1990, pp. 397-420.

Lstiburek, Joseph and Carmody, John. *Moisture control handbook : principles and practices for residential and small commercial buildings*. New York : Van Nostrand Reinhold, 1993.

Ojanen, T. and Kohonen, R.,"Hygrothermal Performance Analysis of Wind Barrier Structures", *ASHRAE Transactions, Symposia*, Chicago, 1995, pp. 595-606.

Sherman, M., “The use of Blower Door Data”, Lawrence Berkeley National Labs Publication LBL #35173, March 13, 1998.

Taylor, B.J., Cawthorne, D.A., Ismabi, M.S. “Analytical Investigation of Steady-State Behaviour of Dynamic and Diffusive Bulding Envelopes”, *Bldg and Environment*, Vol. 31, No. 6, pp. 519-525, 1996

TenWolde, A., Carll, C., and Malinauskas, V., “Airflows and Moisture Con- ditions in Walls of Manufactured Homes,” *Airflow Performance of Building Envelopes, Components, and Systems, ASTM STP 1255* Mark P. Modera and Andrew K. Persily, Eds., Amer- ican Society for Testing and Materials, Philadelphia, 1995, pp. 137-155.

Timusk, J, Seskus, A.L., Ary, N. “The Control of Wood Cooling Wood Frame Building Enclosure”, *Jrnl of Thermal Insulation*, Vol. 15, July 1991, pp. 8-19.

Timusk, J. “The dynamic wall”. *Proc. Fourth Conference on Building Science and Technology*, Toromto, 1988.

Uvslokk, S., "The importance of wind barriers for insulated timber frame construction", *J.*

Thermal Insul. and Bldg. Envs., V.20, July, 1996, p.40-62.

Uvsløkk, S., "The Importance of Wind Barriers for Insulated Wood Frame Constructions," *Proc. of Symposium and Day of Building Physics,* Lund University, August 24-27, 1987, Swedish Council for Building Research, 1988, pp. 262-267.

Wilson, A.G., *Air Leakage in Building*. Canadian Building Digest 23, National Research Council of Canada, Ottawa, Dec 1963.

Yarbrough, D.W., Graves, R.S., “The Effect of Airflow on Measured Heat Transport Through Wall Cavity Insulation”. *Proceedings at 2006 ASTM Symposium on Heat, Air, and Moisture Transport in Buildings*, Toronto, Canada.

1.5.2. Heat Losses Below Grade in Low Energy Buildings

by John Straube, December 2009

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John Straube, Ph.D., P.Eng.
Building Science Corporation, Somerville, MA
December 2009

Abstract:

This report documents a literature survey of predictions and measurements of below-grade heat loss through slabs and basement walls, as well as recommend appropriate R-values for these components in cold climates (DOE Climate Zones 5 and higher). Methods of prediction of heat loss through slabs are examined and found to be notoriously inaccurate. Field data from several studies is then reviewed and used to develop a better understanding of below slab soil temperatures. With assumptions based on the reviewed literature, straightforward calculations indicate that, among other recommendations, a sub-slab insulation of level at least R5 should be strongly recommended for all cold climate zones.

Heat Losses Below Grade in Low Energy Buildings

Introduction

The three components of above-grade building enclosures, walls, roofs, and windows, are well studied. Over the last decade, Building Science Corporation has developed and demonstrated technology for delivering high R-value enclosures. Building America teams have used a wide variety of techniques and technologies to achieve high R-value above-grade enclosure components. Much of the research work BSC has conducted to date on basements has involved durability and air quality aspects.

Building codes such as the IECC and ASHRAE 90.1 now require full-height basement insulation of R10 to R15. However most building codes do not require insulation under slabs over the entire area: in many cases, only perimeter insulation is required for slab-on-grade homes and no insulation at all is required below slabs in basements. As such, the slab is the last remaining component of the building enclosure not required to be insulated by code. Given the heightened expectations for energy performance, sub-slab insulation may be an economically sound decision for homes with High R enclosure components in cold climates (Zone 4 and higher).

The investigation below will focus on energy savings. However, insulating below slabs also has the benefit of decoupling the slab temperature from the ground temperature and instead coupling it closely to the interior air temperature. This results in improved radiant and foot comfort and dramatically reduces the chance of condensation and mold growth, particularly below furniture, carpet and boxes.

The goal of this report is to document a literature survey of predictions and measurements of below-grade heat loss through slabs and basement walls, as well as recommend appropriate R-values for these components in cold climates (DOE Climate Zones 5 and higher).

Predicting Heat Loss Through Slabs

The prediction of heat loss through slabs is notoriously inaccurate. A literature survey of measured temperatures and heat loss of slabs and basements was conducted with the goal of collecting cold climate examples of measured heat loss or temperatures through insulated slabs. There are a remarkably few such studies.

Conductive heat flow can be predicted by

$$Q = U \cdot A \cdot \Delta T = 1/R \cdot A \cdot \Delta T \qquad [1]$$

Where U (=1/R) includes the heat transfer coefficient of air to slab. This interior heat flow coefficient for heat flow downward to a cool slab is 6.1 $W/m^2 {}^\circ C$ or R0.93 according to the ASHRAE Handbook of Fundamentals. The thermal resistance of concrete is negligible: for normal density unreinforced concrete, the thermal conductivity ranges from 1.5 to 2.5 W/mK depending on aggregates and moisture content, which translates to a thermal resistance of R0.20 to R0.35 for 3.5” slabs. A value of R0.27 is used below as a mid-range estimate.

Hence, for a standard unfinished and uninsulated slab on grade, the heat flow per unit area (flux) can be estimated as:

$q = 1/R \cdot \Delta T = \Delta T / R = \Delta T / 1.2$ in °F and square feet.

The addition of a carpet can increase the thermal resistance to by R0.5 to R2.0 depending on the nature and thickness of the carpet and underlayment. This small quantity of insulation can result in a significant reduction in heat flow. However, this reduction in heat flow also causes colder slab temperatures, and increases the risk of condensation.

As a first order estimate, if the soil temperature is 55°F and the interior basement air temperature is 70°F, the heat flow through a 1,000 square foot unfinished basement slab would therefore be about 12,500 Btu/hr, or half as much with an R1.2 carpet and underlayment. This is a significant heat loss in a low energy home, as houses with 1,000 to 2,000 sf of above-grade floor area and high R enclosures will have peak design heat losses in the range of 25,000 to 40,000 Btu/hr.   Heat losses through uninsulated slabs are also significant in that the exterior temperature (55°F in the previous example) is essentially constant for months at a time.

The soil temperature below a site varies over the year (Figure 1, from Minneapolis MN). However, at 5 to 10 m (15 to 30 ft) below the surface the temperature is quite stable. Figure 2 shows the range of deep earth temperatures from various sources as it varies across the continental United States. Deep soil temperatures of 40 to 60°F are present across much of DOE Climate Zones 5, 6 and 7.

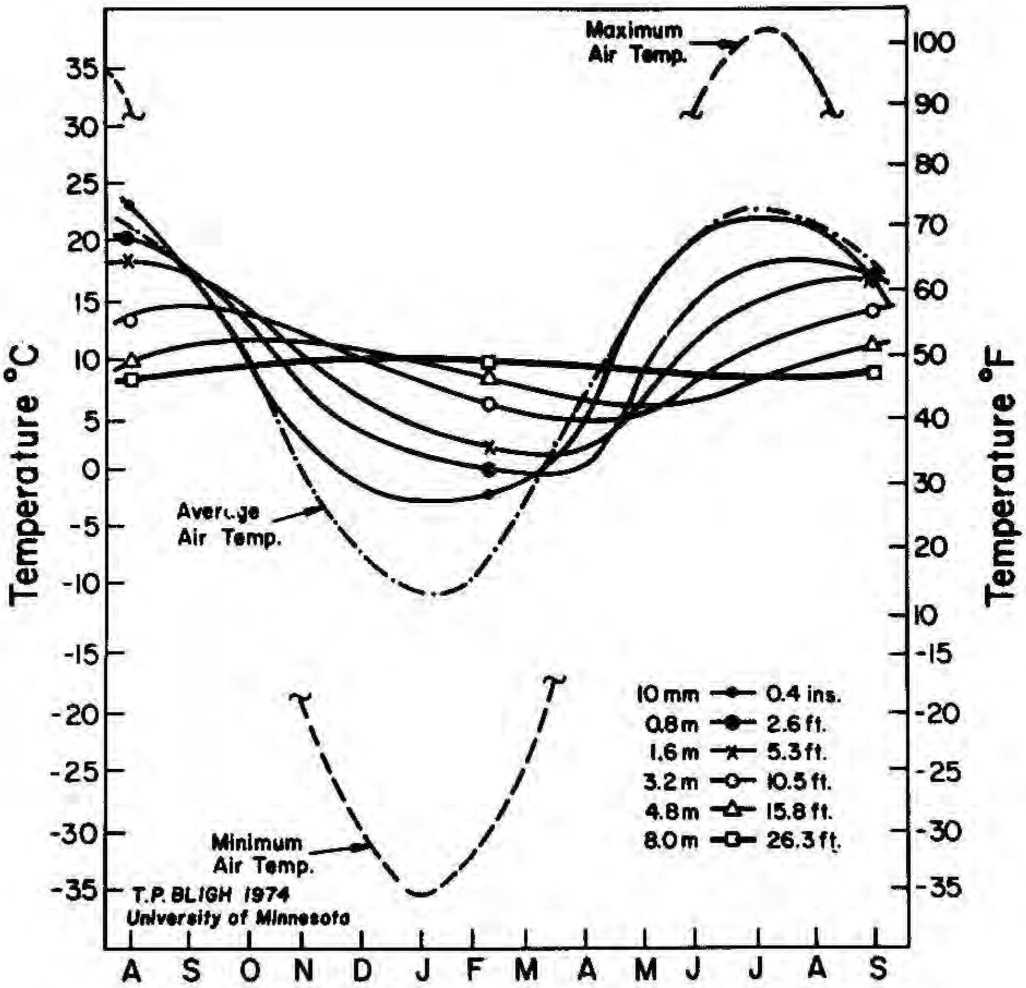


Figure 1: Soil temperature variation (away from any buildings) as a function of depth and time of year

The construction of a building disturbs these temperatures. Heat flows outward from a building heated to 65 or 70°F to the cooler soil (or 40 to 60°F). This heat loss warms the soil in a “bubble” of warmer soil. The actual soil just below the slab will therefore vary with: interior air temperature over the year, the insulation of the slab and basement, the thermal conductivity of the soil (which is influenced by moisture content), the level of the water table, and the shape of the building, among other variables.

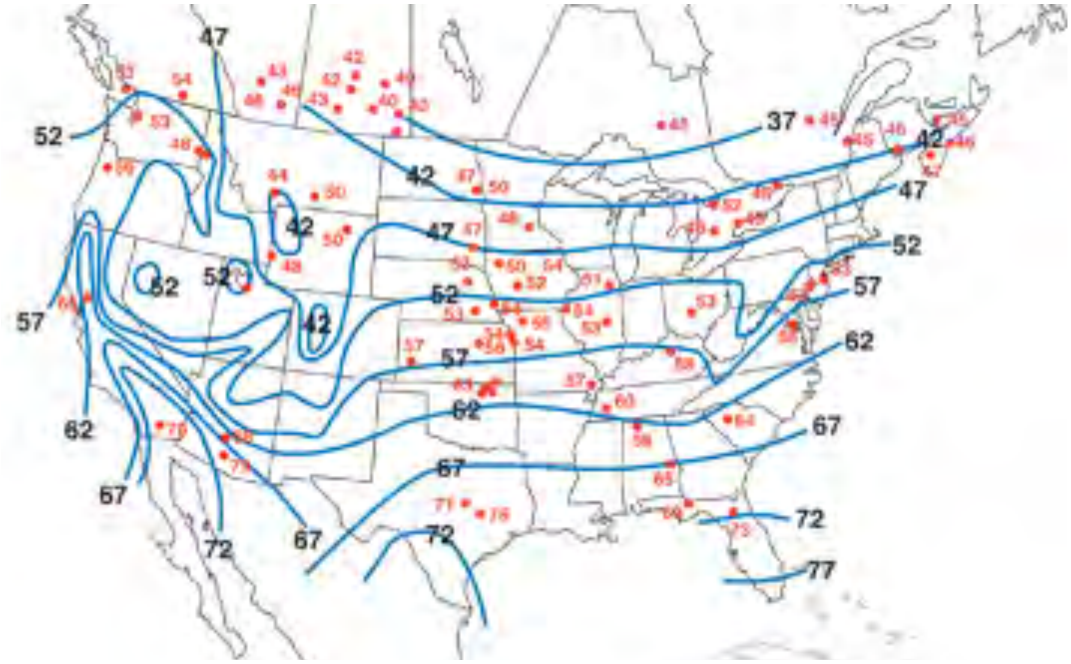


Figure 2: Deep ground annual average soil temperature

The large number of variables make it difficult to predict heat loss as reliably as above-grade models, which can use the air temperature measured at thousands of sites across the country.

To predict heat loss a better understanding of the sub-slab soil temperatures are required, and the deep ground temperature is definitely not the correct temperature: the actual soil temperature under a building will always be warmer.

The most applicable field data found reported the temperatures monitored for a year under a slab-on-grade insulated to R32 in Finland [Rantala 2005], which had an average heating season (6 month) soil temperature of 10-12 °C (50-53 °F). In other work, slabs insulated to R15 [Rantala and Leivo, 2004] exhibited slightly warmer temperatures over 12.5 °C (55 °F).

A more recent paper [Rantala and Leivo 2009], shows even higher temperatures, with averages of 15 °C/60 °F in the winter, except near the edge where they dropped to a minimum of 10 °C/50°F (the overall heating season average temperature was over 15°C/60°F however). They also report, based on numerous of their own measurements, and a review of dozens of models and measurements that: “The average temperature of the fill layer beneath a heated building is relatively high and even throughout the year. This is true especially at the central part of the slab, where the influence of short-term or seasonal fluctuations in the outdoor air temperature is less effective”.

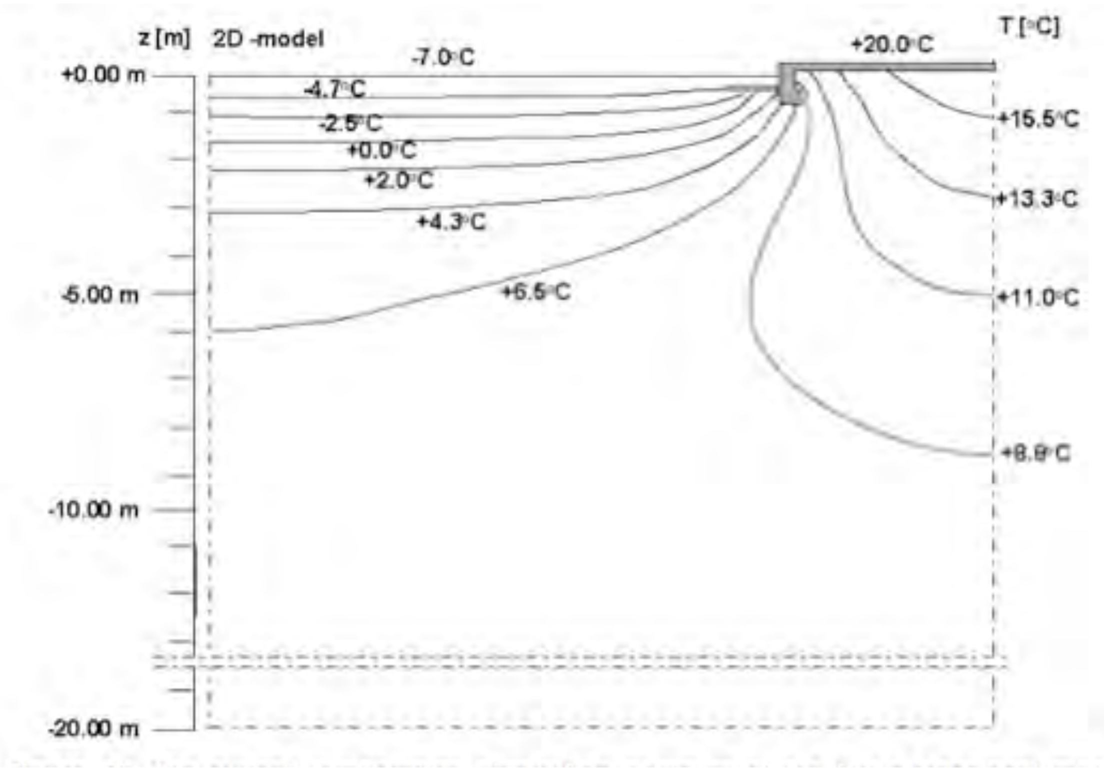


Figure 3: Predicted subsoil temperatures below a R16 slab in a cold climate [Rantala and Leivo 2004].

In Norway, another cold climate country that builds many slabs on grade (due to the prevelance of poor soil and high groundwater conditions), a paper in the 7th Nordic Symposium on Building Physics on slab heat loss [Gunderson 2005] reported "In Norwegian climatic conditions, with a yearly mean soil temperature varying from 2 ~ 7°C, we can use 12±1°C as a default value for the inner zone reference soil temperature". Soil temperatures of 2 to 7°C (36 to 45°F) are equivalent to the colder parts of Zones 6 and 7 deep earth temperatures, and 12°C is 54°F Fahrenheit. It stands to reason that if annual average soil temperatures are higher, in the 40 to 45°F range, design soil temperatures of 55°F would reasonable.

NREL designed a low-energy house for the National Park Service [Balcomb 1999]. The house was carefully measured, modeled, and monitored. Part of the measurement campaign in 1997 included real measurements of the heat loss through the insulated slab on grade floor. The slab on grade was around 1,000 square feet in size, insulated with R10 insulation below the slab and R10 along the perimeter stem walls. The heat loss through the slab was found to be less than the predictions for a number of reasons, but the net effect is that even with only R10, the slab insulation was very effective as only 2.3 MMBtu/yr was lost. Sub-slab temperatures were found to be in the 58-60°F range during the winter period. Appendix A provides more information about this useful project.

Hence, during the heating seasons the average temperature between soil and indoor air is about 15°F. Compare this to an average winter month in Zone 5 and Zone 6, where the average outdoor air temperature is 30°F or 40°F, yielding an average temperature difference of 30°F or 40°F. For example, in Burlington VT, the 6-month heating season's average air temperature is 31°F and that of Minneapolis is 28°F. That is, 2 or 3 times as large a temperature difference acts across the walls windows and roofs as slabs. Since heat loss is a direct function of temperature difference, to reduce heat flux to the same level, one would expect that slab R-values would be 1/2 or 1/3 as much as walls.

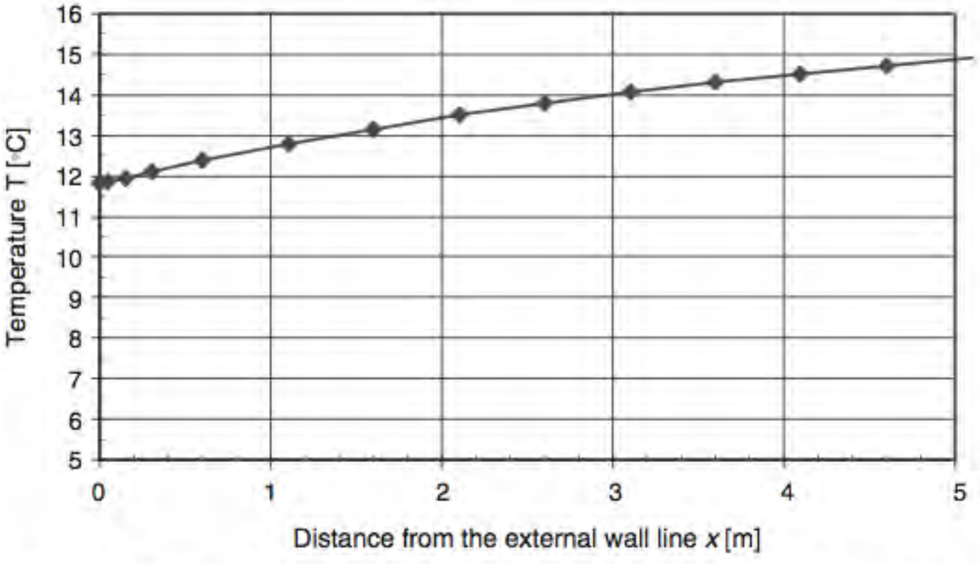


Figure 4: Computer model extrapolation of measured mean annual temperature underneath a 33 ft wide R32 slab-on-grade for a cold Finnish climate with a deep soil temperature of 45° F [from Rantala 2005].

As a rough estimate of heat loss over the year, a comparison can be made to Heating Degree Days (HDD). An average sub-slab soil temperature of around 55°F can be roughly converted to heating degree days (since the temperature is so stable) with a 65F base and a 180 days heating season by

(65-55)*(180 days) = 1800 heating degree days 65°F.

Six months, or 180 days, is a long heating season, and 65°F is a higher than the balance temperature of a well-insulated home, but the comparison to HDD65 climate is reasonably valid. Using this approach, the slab heat loss per unit area over the season would be predicted to be about 1/4 of the above-grade enclosure of the same R-value as a 7200 HDD65 climate (such as Burlington VT) through the walls and roof. More detailed analysis and measurements suggest that this ¼ heat flux ratio is more appropriate for slabs in basements and a 1/3 ratio may be more appropriate for slabs at grade level.

Predicting Below-grade Heat Loss

The DOE 2.1 programming code that underlies many computer models used to predict home energy consumption (such as EnergyGauge USA) uses a simple model which bases the temperature difference between the indoor conditions and monthly, climate specific undisturbed soil temperatures. This approach results in an over estimate of heat loss. Other models result in significant errors in prediction because the ground temperature is assumed to be equal to the average air temperature. This is a rough estimate, but the differences between average air temperature and measured ground temperature are significant. Bahnfleth [1990] showed that using mean air temperature for mean annual ground temperature results in significant (25%) errors. His study considered mostly uninsulated slabs and did not compare model results to real measurements.

EGUSA, a DOE 2.2 model used by many Building America teams, does not even allow the entry of slab insulation and hence does not show the benefits of slab insulation at all.

The most accurate model, based on comparison of measured field energy consumption over a number of years, with numerous houses in a range of cod climates, remains the Mitalas model developed many years ago at the Division of Building Research [Mitalas 1983, 1987]. Ackerman [1987] and Emery [2007] are two further field measurement results that conclude that the Mitalas method is the most accurate method that is simple enough to be general (e.g., it does not require a finite element model with the precise boundary conditions and soil properties).

This model can be implemented with a spreadsheet or with a more sophisticated computer program called BASESIM. The heat loss on a month-by-month basis are produced (see Figure 5), which can then be used to assess the heat loss during the period of the year during which heating is needed in the above-grade portions of the house.

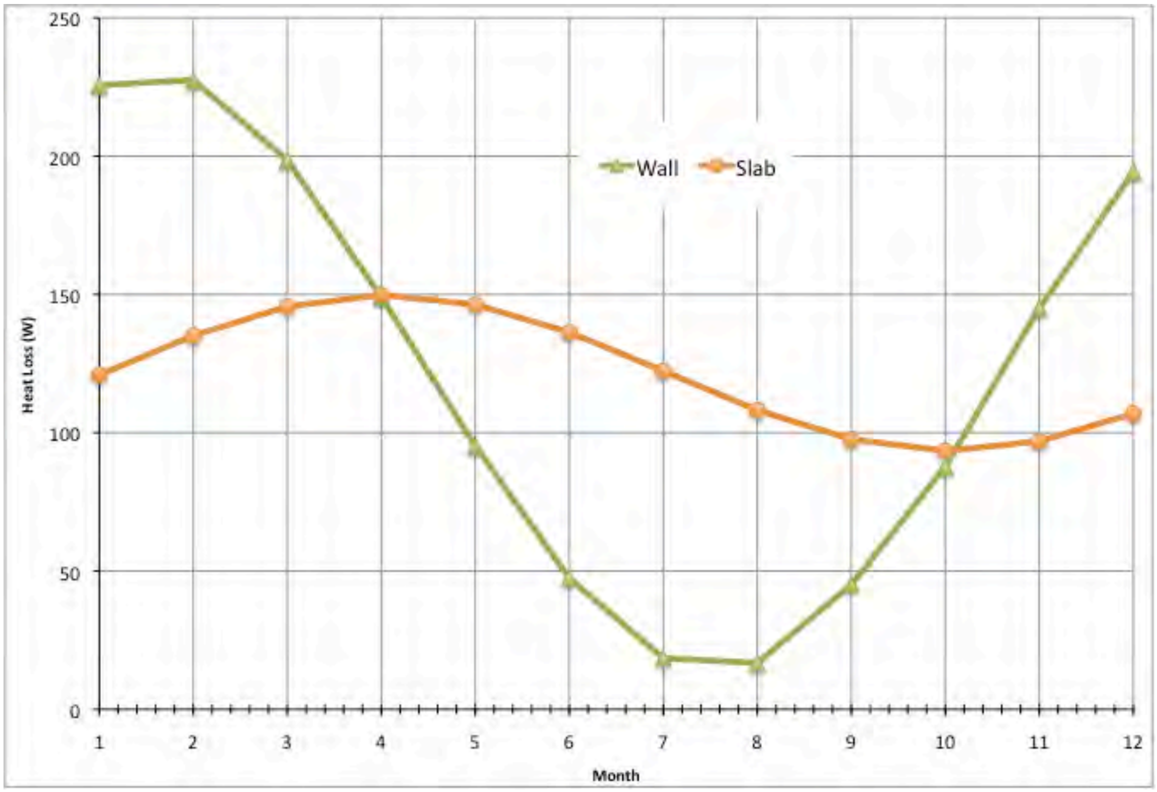


Figure 5: Monthly Average Heat Flow through Basement walls and Slab using the Mitalas model

Results for the standard implementation are shown in Figure 6 for a single-storey 26 x 40 ft house with an 8’ high basement (1’ above grade) and 15% Window-to-Wall ratio. The 6-month heating season heat loss is predicted to be 7.94/4.70/3.94/2.84 MMBtu for R10/R20/R30/R40 basement walls (above grade portions included) and 4.78/3.89/3.29/2.86/2.27 MMBtu for a R5/R10/15/20/30 basement slabs. The total below-grade proportion of the wall heat loss was predicted to be 4.40 MMBtu.

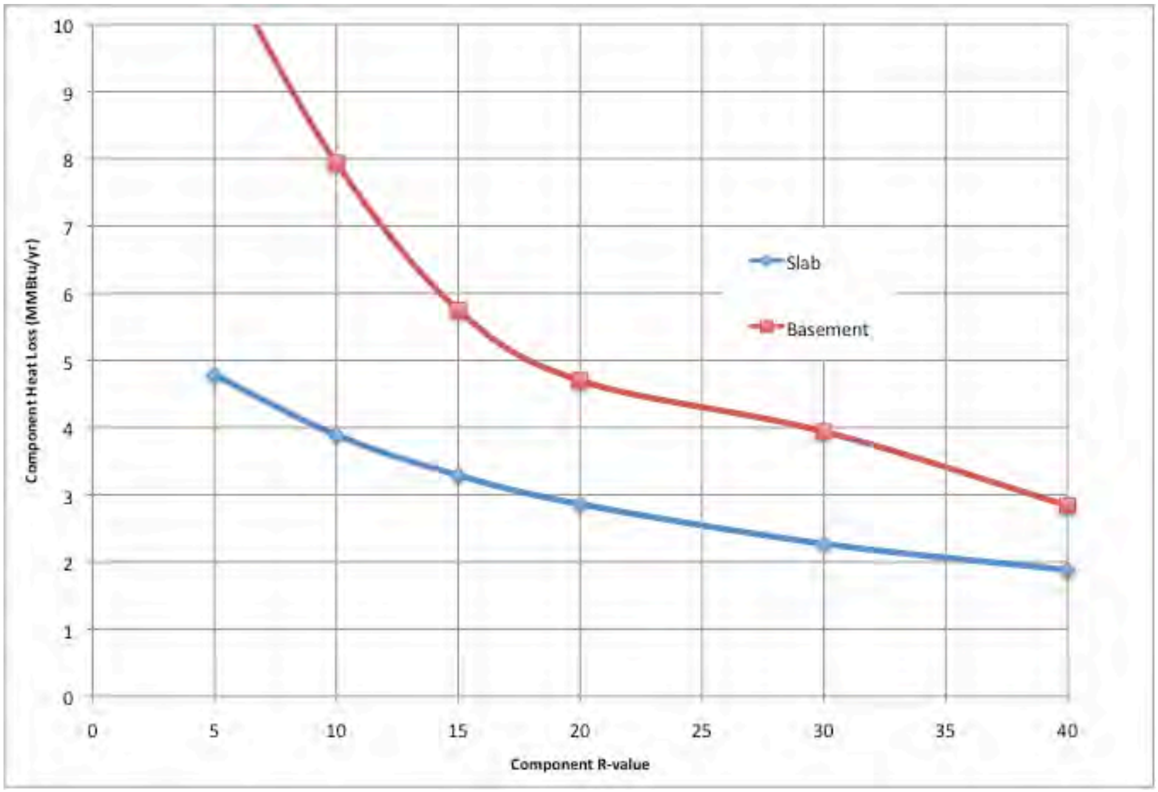


Figure 5: Heating Season Heat Loss as Function of Component R-value for Example Cold-Climate House Basement

Using a simple HDD65 approach to predict heat loss, and assuming a 7200 HDD65 (Zone 6) climate, the heat losses through representative above-grade components can be compared. The total loss is predicted to be 26.6 MMBtu/yr.

These results are representative of a wide range of simulations for Zone 5-7 homes of average size and simple plan shape: by selecting a basement slab basement wall and above-grade wall insulation level in the ratio of 1:2:4, heat loss through each component will be roughly equivalent. Window heat loss can be the largest of all of these components, even if modest areas of triple-glazed R5 windows are specified. Air leakage rates of 2.5ACH@50 Pa would increase this heat loss component to 6.77 MMBtu and make air leakage the dominant heat loss path.

Component	MMBtu	kWh	% of Total
Roof (R60)	3.00	878	11%
Walls (R40)	4.36	1278	16%
Basement wall (R20)	5.13	1504	19%
Basement slab (R10)	3.89	1140	15%
Windows (R5)	6.16	1805	23%
Air Leakage (1.5ACH@50)	4.06	1189	15%
Total	**26.6**	**7794**	**100**

Table 1: Heat Loss over Heating Season for Example House by Component

These conclusions do not take any account of the cost or other performance implications of insulating each of the components.

The cost of insulating below a slab are relatively modest: adding foam insulation to above-grade walls not only costs the increase in foam material, but also the labor, increased fastening, and increased roof area and opening trim costs. Adding insulation below the slab can be relatively inexpensive: currently about 10 cents per R per square foot (i.e., $1/sf for R10). The only other cost increase with thickness (assuming one layer of labor cost is the same regardless of thickness) is the cost of excavation. Excavating an additional depth of 2" or 4" within the area of the floor slab is typically negligible.

Increasing the R-value of walls has other added costs, such as larger window return trim, longer screws, bigger overhangs, more roof area, etc. This is not usually a large premium, but it is a real one. Hence, when one needs to choose between R6/inch polyiso or R4/in expanded polystyrene (EPS), the 50% thicker insulation is one reason polyiso is often chosen, especially for high-R wall with R-30 to R45 insulation levels.

The cost of insulating a ventilated trusses attic with loose fill insulation is much less than either walls or slabs. Loose fill insulation in an attic can be installed at a cost of 2 to 4 cents per R per square foot. The cost of cathedral ceiling insulation is higher: both the need for some more expensive air impermeable insulation and the cost of thicker framing and/or trim makes this component more expensive to insulate than slabs.

Not all of the components can be simply separated. Air leakage through the rim joist area can be a significant heat loss and should be addressed (practically it must be addressed to achieve a 1.5 ACH@50 Pa tightness target). This area can be targeted with spray foam to both insulate and airseal. The cost of the insulation and application (in the order of 15 to 20 cents per R per square foot) should be distributed between energy savings from air sealing and energy saving from insulation.

Practical Implications for High R Assemblies

The slab is the last building enclosure component for which insulation levels are not required by code or installed in practice. The per unit area heat loss through slabs installed at grade level with stem wall insulation can be expected to be about 1/3 that of the above-grade walls. Slabs that are installed deeper in the earth, at floor level of a basement (i.e., 5 to 8 ft below grade), will exhibit a heat loss closer to ¼ that of above grade walls. Sub-slab insulation of at least R5 should be strongly recommended for all cold climate zones.

In general, a slab insulated to R10 has relatively low heat loss compared to other components of a highly insulated building enclosure. In some cases (low cost insulation, expensive renewable energy) it might make sense to increase the floor slab insulation to R20 in a very low energy home. The heat loss would drop from 3.9 to 2.9 MMBtu per year in the example home. This is a rather marginal reduction (about 4% of the total heat loss or 309 kWh/yr), which would cost about $1000 in additional insulation. Given that the cost of providing space heating is currently in the order of 4 to 10 cents per kWh, R20 sub-slab insulation would have an exceptionally long payback period (even assuming a fuel escalation rate of 7% per annum) with no more durability or comfort benefits than R10.

Increasing basement walls insulated from R10 to R20 results in about a 2 MMBtu/yr annual energy saving, and since a cost-effective combination of fibrous (fiberglass, cellulose or rockwool) and foam insulation can be used, the cost of increasing the R-value from 10 to 20 is relatively small. (Note: Other BSC work has shown that a 2x4 stud frame with R12 batt insulation is not moisture safe. A layer of foam insulation is necessary outboard of the wood frame. Hence, adding 2" of XPS to an R13 batt insulated 2x4 stud wall is the upgrade path to an R20 basement wall). A reasonable increase in basement R-value to R30 can be achieved by changing from R13 to R19 batt in 2x6 framing at 24" o.c. framing, and 2" of polyiso insulation (R13) outboard of this. Upgrading to R30 is not a significant cost (perhaps 50 cents per square foot of wall area) and yet results in an almost 2 MMBtu/yr energy savings. Hence, increasing basement wall insulation may be a viable upgrade path, and will usually be significantly more economical than increasing basement slab insulation beyond about R10.

References

Ackerman, M., and J. Dal, . Measurement and prediction of insulated and uninsulated basement wall heat losses in a heating climate. *ASHRAE Transactions* Vol 93(1):897–908, 1987.

Balcomb, J.D., Hancock, C.E. Barker, G., *Design, Construction, and Performance of the Grand Canyon House*. NREL/TP-550-24767, June, 1999.

Bahnfleth, W.P., Amber, JoAnn. *Algorithms for Slab-on-Grade Heat Transfer Calculations*. US Army Corp of Engineers, Technical Report E-90/15, September 1990.

Emery, A.F., Heerwagen, D.R., Kippenhan, C.J. Steele, D.E., "Measured and Predicted Thermal Performance of a Residential Basement",*ASHRAE HVAC & R Research*, January 2007.

Mitalas, G.P. (1983). Calculation of Basement Heat Loss, *ASHRAE Transactions*, 89(1B) 1983, pp. 420–437.

Mitalas, G.P. (1987). Calculation of Below-Grade Residential Heat Loss: Low-rise Residential Building, *ASHRAE Transactions*, 93(1), 1987, pp. 743–784.

Rantala, J., "Estimation of the Mean Temperature Distribution Underneath a Slab-on-ground Structure", *J. of Bldg Phys*, July 2005, pp. 51-68.

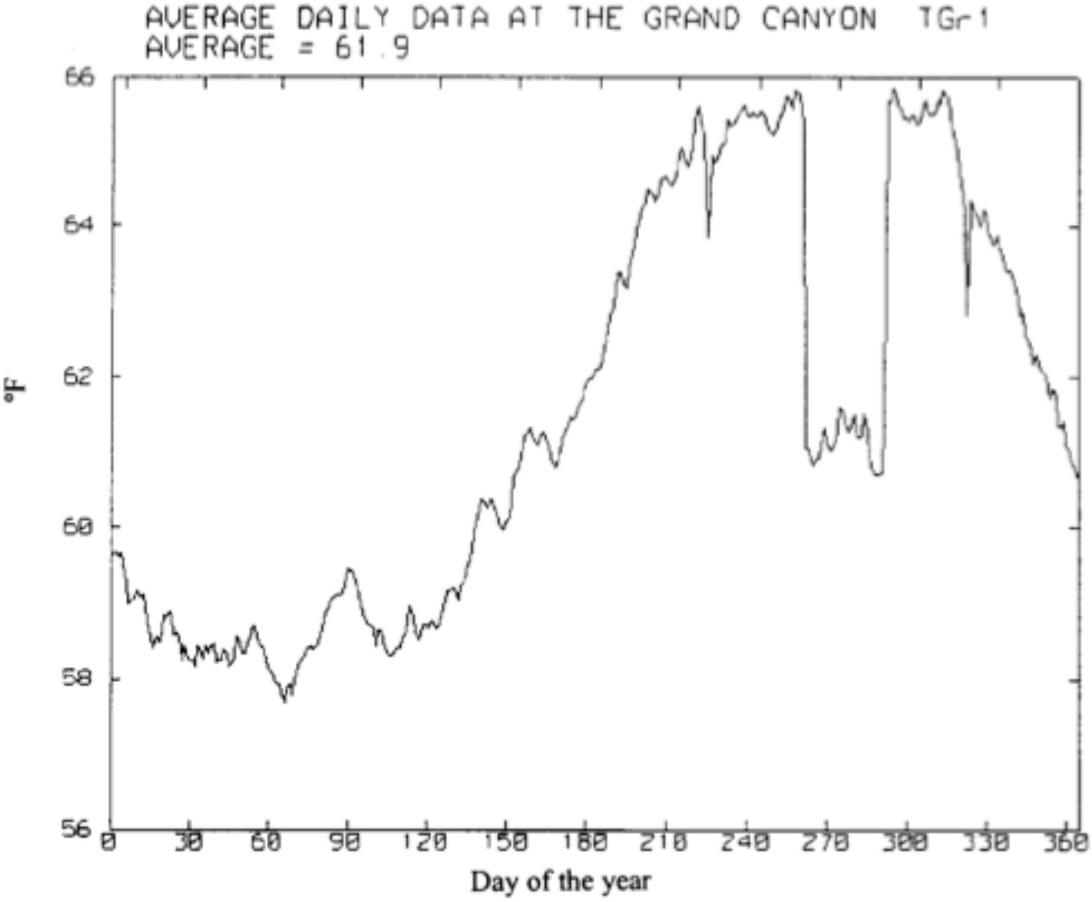
Rantala, J., Leivo, V., "Heat, Air, and Moisture Control in Slab-on-ground Structures", *J. of Bldg Phys*, April 2009, pp. 335-353.

Rantala, J., Leivo, V., "Thermal and Moisture Conditions of Coarse-grained Fill Layer Under a Slab-on-ground Structure in Cold Climate". *J. Bldg Phys* July 2004, pp. 45-62.

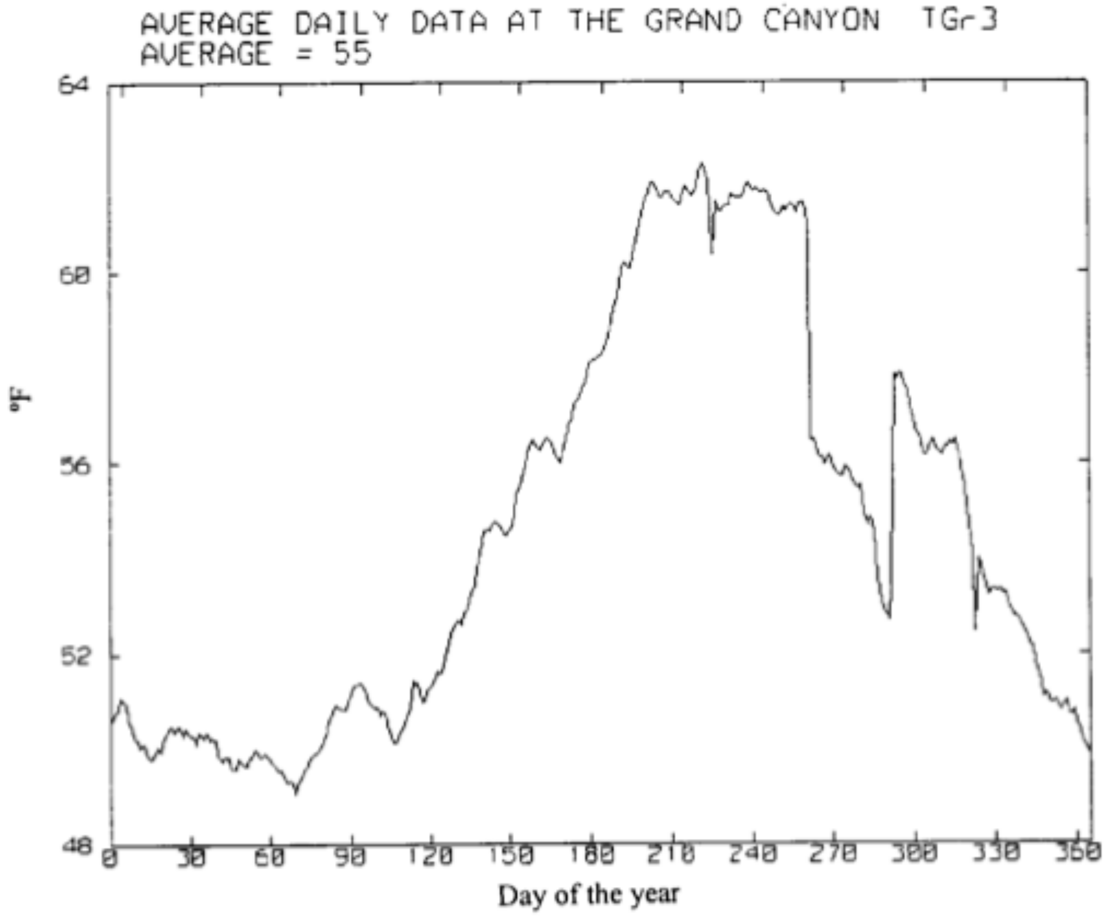
Gunderson, Per., "Slab-on-grade foundation and edge wall element design — frost protection and simplified heat loss calculations", 7th Nordic Symposium on Building Physics, 2005

EN-ISO 13370 "Thermal performance of buildings — Heat transfer via the ground — Calculation methods".

Appendix A: NREL Grand Canyon Research House



Measured Temperature under the Sub-Slab Insulation over the year near the edge of the house



Measured Temperature under the Sub-Slab Insulation over the year near the edge of the house

Floor Heat Loss Estimate

The Grand Canyon house floor is well insulated against heat loss to the ground by 2 in. of rigid foam under the slab and 2-in. perimeter insulation on the exterior of the footings. As a convenient by-product of the under-slab insulation, researchers measure the heat flow to the ground by measuring the temperature difference (ΔT) across the insulation. The floor heat loss is calculated by assuming a conductance value for the 2 in. of rigid foam insulation of 0.1 Btu/h•°F•ft^2, an area of 200 ft^2 for the perimeter floor area and 800 ft^2 for the center floor area (the area of the floor slab is roughly 1000 ft^2).

Tables of monthly average values of the temperatures and ΔTs are given in Appendix C along with plots showing daily variations by month, daily averages for each day of the year, and hourly data for the mid-winter months. Note that although there are large changes in the two ΔTs from month to month, the daily variation is very small. The total floor heat loss is highest in the summer at about 800 Btu/h and lowest in winter at about 400 Btu/h. The reason for this contradictory-sounding statement is that the inside temperature is higher in summer than in winter and the ground temperature does not change much.

The striking result is that the floor loss is small, averaging only 621 Btu/h over the year (182 W). The October-through-March average is 536 Btu/h for a total of 2.3 million Btu or 682 kWh. Researchers concluded that the floor insulation is very effective. The small value of 682 kWh is significant compared to the 2089 kWh of back-up heat required.

The measured winter ground heat loss of 536 kWh is 22% of the value of 2418 kWh predicted by the model. This is not surprising, in retrospect, because (1) the model accounted only for short-term dynamics,[*] (2) the model did not account for annual heat storage in the ground, and (3) it was assumed that the room temperature would be constant (i.e., within the range of thermostat settings) throughout the year. The first assumption is probably not too far from reality; however, the last two assumptions were not realistic.

The most important factor is the variation in inside temperature with seasonal changes. This is a lifestyle issue that would vary from resident to resident. The more complex models, including models that solve for ground heat flow, using finite-element calculations of two- or three-dimensional heat flow, would not be of much help because of the unpredictable variation in house temperature.

1.5.3. High-R Wall Case Study Analysis

by Jonathan Smegal, March 2009, with 2-page Case Studies

building science.com

Building America Special Research Project: High-R Walls Case Study Analysis

Research Report - 0903

March 11, 2009 (rev. 8/7/09)
John Straube and Jonathan Smegal

Abstract:

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. More building codes are being modified to require higher levels of thermal control than ever before. 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 true three-dimensional heat flow and the relative risk of moisture damage.

Building America Special Research Project

High-R Walls Case Study Analysis

2009 08 07

Jonathan Smegal MASc
John Straube, PhD, P.Eng

Building Science Corporation
30 Forest Street
Somerville, MA 02143

www.buildingscience.com

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A. 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. More building codes are being modified to require higher levels of thermal control than ever before. 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 true three-dimensional heat flow and 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.

High R-values for framed wall assemblies are defined here as ranging from approximately R18 to R40 and above depending on the geographic location and climate conditions. A high R-value wall in the south will be considerably less than a high R-value in a cold climate. The analysis in this report includes a summary of historical wall construction types and R-values, current construction strategies, as well as walls that will likely become popular in the future based on considerations such as energy and material availability.

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.

A study currently being conducted by the National Research Council of Canada (NRC) is investigating and developing durable and energy efficient wall assemblies for Northern Canada. In the first stage of the NRC study, meetings with the northern communities and investigations of the houses were conducted. A literature review covering selection criteria for possible envelope assemblies in Northern Canada, current wall systems and systems to consider was written (Saïd 2006). Walls are currently undergoing extreme temperature testing in the NRC laboratory in Ottawa, Canada. All of the walls being tested by the NRC are constructed with a polyethylene air and vapor barrier and none of the walls are constructed with exterior insulation (Rousseau, et al. 2008).

The Cold Climate Housing Research Center (CCHRC) of Alaska has conducted field monitoring tests on different wall systems, specifically to assess the moisture-related performance of high performance wall systems. Several tests were conducted on a test hut at the University of Alaska Southeast, in Juneau AK (8574 HDD65 or 4763 HDD18) (Smegal and Straube 2006), and others were conducted on the CCHRC main office building in Fairbanks Alaska (13980 HDD65 or 7767 HDD18) constructed in 2007. Streaming data and wall drawings can be viewed on the CCHRC website showing the thermal performance of the wall systems (CCHRC 2007). CCHRC also successfully completed construction of a high R-value house as part of the Building American program in Haida, AK, and the report can be found online (BSC 2008).

Some of the walls for this high R-value study were chosen based on the literature review of the NRC report, and references to construction techniques from both the NRC and CCHRC will be made throughout this report. Some walls have been built by niche builders since the early 1980's.

1. OBJECTIVE

The objective of this study is to identify highly-insulated building enclosure wall systems based on selected criteria, resulting in a durable affordable, and resource efficient enclosure that provides a comfortable living environment in different climate zones. This report will present the analysis of different enclosure wall strategies and present their advantages and disadvantages according to several comparison criteria.

2. SCOPE

This study is limited to wall systems for cold climates. Further studies should be conducted to address other components of the building enclosure such as roofs and foundations. In general, only cold climates are considered in this report since enclosures in cold climates benefit the greatest from a highly insulated building enclosure, but important conclusions can also be drawn for other climate zones.

3. APPROACH

This study examines thermal and moisture control, durability, buildability, 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. Minneapolis, MN in IECC climate Zone 6 was used as the representative cold climate for most of the modeling, because of the cold winter weather, and fairly warm and humid summer months. In cold climates, a building's enclosure is often the most important factor limiting heat loss, both in terms of insulation and air tightness.

B. Analysis

1. WALL ASSEMBLIES REVIEWED

Because there are a number of variables possible for each possible wall system depending on the local practices, climate, and architect or general contractor preferences, an attempt was made to choose the most common wall systems and make notes and comments about other alternatives during analysis. This list of chosen systems is explained in more detail in the analysis section for each wall system.

- Case 1a : Standard Construction Practice with 2x6 framing
- Case 1b : Standard Construction Practice with 2x4 framing
- Case 2a : Advanced Framing with 1" of XPS insulated sheathing
- Case 2b : Advanced Framing with 4" of XPS insulated sheathing
- Case 3 : Interior 2x3 horizontal strapping
- Case 4 : Double Stud
- Case 5 : Truss Wall
- Case 6 : Structural Insulated Panel Systems (SIPs)
- Case 7 : Insulated Concrete Forms (ICFs)
- Case 8a : Advanced Framing with low density (0.5 pcf) spray foam
- Case 8b : Advanced Framing with high density (2.0 pcf) spray foam
- Case 9: Hybrid system with high density (2.0 pcf) (Flash and Fill) spray foam and fibrous insulation
- Case 10: Double Stud wall with 2" of high density (2.0 pcf) spray foam and fibrous insulation
- Case 11: Exterior high density (2.0 pcf) (Offset Frame Wall) spray foam with fibrous cavity insulation
- Case 12: Exterior Insulation Finish System (EIFS)

2. 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)	Buildability	Cost	Material Use	Total
Criteria Weighting	1	1	1	1	1	
Case 1: Standard Construction						
Case 2: Advanced Framing with Insulated Shtg						
Case 3: Interior Strapping						
Case 4: Double Stud						
Case 5: Truss Wall						
Case 6: SIPs						
Case 7: ICF						
Case 8: Sprayfoam						
Case 9: Flash and Fill (2" spuf and cell.)						
Case10: Double stud with 2" spray foam and cell.						
Case 11: Offset Framing (ext. Spray foam insul.)						
Case 12: EIFS with fibrous fill in space						

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 wall design. 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 costs of different insulations may be uncertain, fiberglass batt insulation is always less expensive than low density (0.5 pcf) spray foam which is less expensive than high density (2.0 pcf) spray foam, so these systems can be ranked accordingly regardless of the actual costs.

2.1 Heat flow analysis

Two 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. 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 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 in (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, wall/floor, wall/door, and wall/window 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 with a weighted average.

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 92 inches.

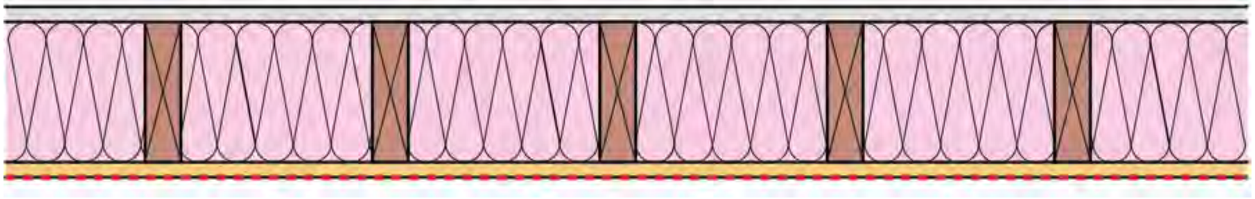


Figure 1 : Plan view of wall section for Therm simulation

The top plate was simulated in section view to assess the importance of the thermal bridging of the top plate(s). This section was eight inches in height since the thermal effect of the top plate will influence the effectiveness of the cavity insulation in its vicinity. The R-value of this detail was calculated over the entire height as indicated by the red dashed line in Figure 2.

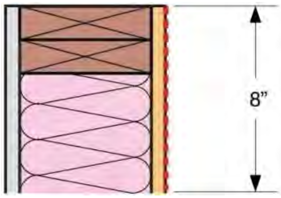


Figure 2: Top plate simulation with 8” of wall

The rim joist was also simulated in a vertical section to take into account the thermal bridging effects of the bottom plate, sill plate, floor sheathing and rim joist. It was simulated with eight inches of wall above the floor sheathing to take into account any changes in the insulation caused by thermal bridging effects.

The concrete foundation was included beneath the rim joist to determine the effects of the interface between the foundation and wood framing, but the concrete was not included in the R-value calculation as indicated by the red dashed line in Figure 3.

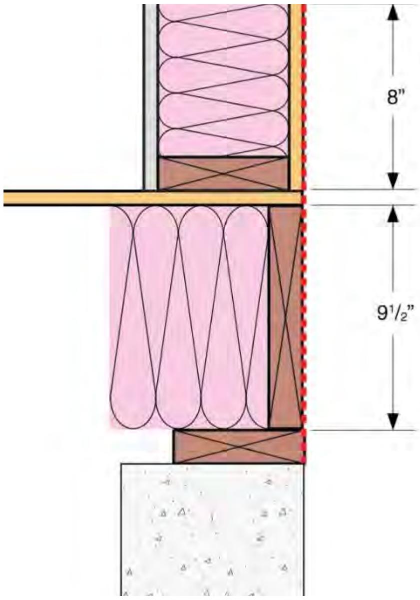


Figure 3 : Rim joist simulation with 8" of wall

Although Therm is a two-dimensional modeling software 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 4), the effective R-value of just this section through the assembly can be determined.

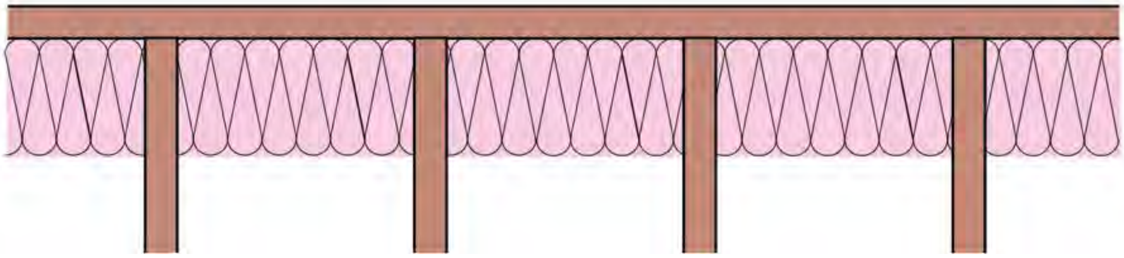


Figure 4 : Plan section of rim joist, floor joists, and fiberglass batt insulation

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 3).

Once the R-values are calculated for all three sections of a wall system, The Whole Wall R-value is calculated by taking the weighted average of the individual components as shown in the equation below. The total wall height from the bottom plate to the top plate is nine feet.

$$\text{Total wall R-value} = \text{R-value top plate x } \frac{\text{height of top plate}}{\text{overall wall height}} + \text{R-value of rim joist x } \frac{\text{height of rim joist}}{\text{overall wall height}} +$$

$$\text{R-value of wall section x } \frac{\mathit{height\ of\ wall\ section}}{\text{overall wall height}}$$

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

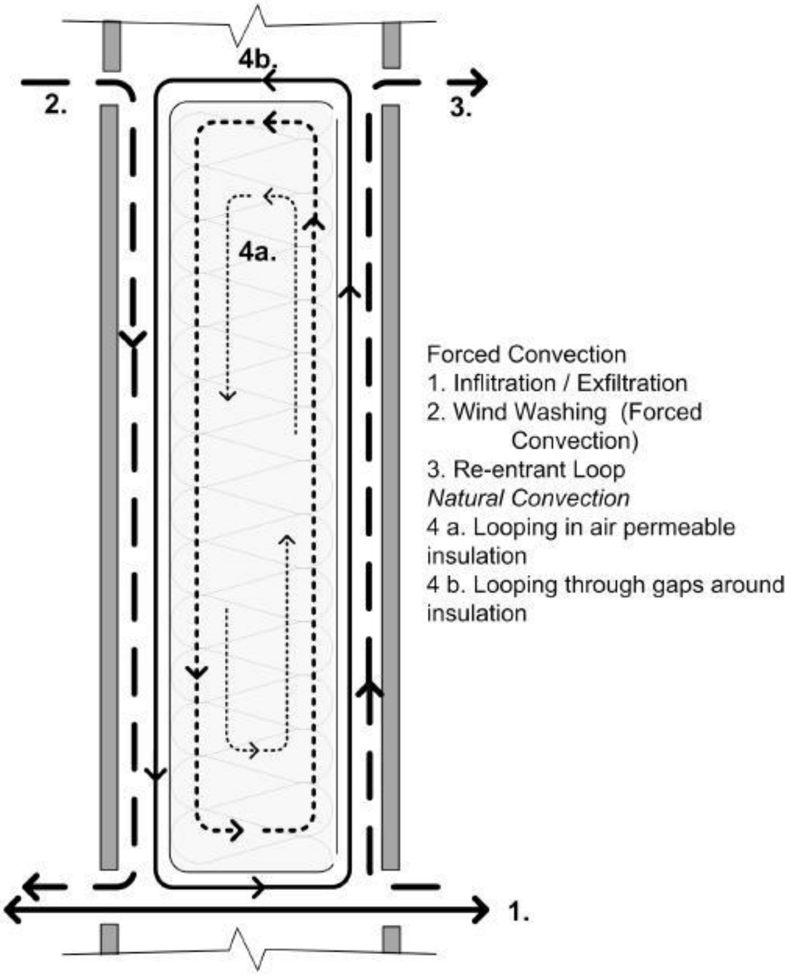


Figure 5 : Common Convective Heat Flow Paths in Enclosures

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 houses 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 pressure difference across the enclosure. Air tightness of the building enclosure has begun to improve in cold climates for the most part to address occupancy comfort issues and contractor call-backs.

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 result in higher installed 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 as well as poorly insulated locations resulting in cold spots around obstacles that could increase the risk of moisture condensation.

Cellulose installation 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 is 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 the fiberglass batt insulation cannot be fully appreciated using this analysis.

All of the Therm analysis were conducted with an interior temperature of 20°C (68°F) and an exterior temperature of -20°C (-4°F) 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	Thermal Conductivity k [W/mK]	R-value per inch [hr·°F·ft^2/Btu]
R8 Fiberglass Batt (2.5")	0.045	3.1
R13 Fiberglass Batt (3.5")	0.039	3.7
R19 Fiberglass Batt (5.5")	0.042	3.4
Extruded Polystyrene (XPS)	0.029	4.9
Expanded Polystyrene (EPS)	0.038	3.7
Framing lumber	0.140	1.0
Cellulose Insulation	0.040	3.5
0.5 pcf spray foam	0.037	3.8
2.0 pcf spray foam	0.025	5.7
OSB	0.140	1.0

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 2x4 stud spacing in a typical wall system is sixteen inches (405 mm) on centre. 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.

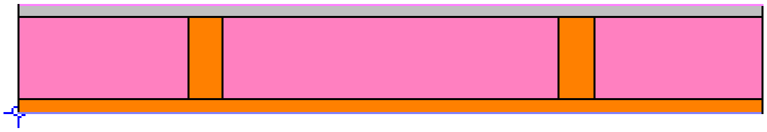


Figure 6 : Typical framing 16"o.c. - 9% framing factor

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). Modeling was conducted to investigate the impact on effective R-value for a wall system with 23% (Figure 7) framing factor and with 9% framing factor. It was found that the Clear Wall R-value of a wall section insulated with R13 fiberglass batt decreased from R12.6 to R10.1 when a more realistic 25% framing factor was used. This results in a Whole Wall R-value decrease from R12 to R10 when the more realistic 25% framing factor was used. The reason that neither wall section achieved a Clear wall or Whole Wall R13 is because of the thermal bridging effects of the studs, one of the underlying issues in using Installed Insulation R-values to describe enclosure systems.

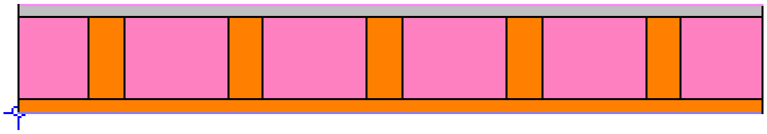


Figure 7 : Actual average framing factor of 23% in standard construction

Most of the framed walls in this analysis were proposed with advanced framing techniques (also described as Optimum Value Engineering, OVE) that include 2x6 framing, 24" o.c., and single top plates. Field studies have also been conducted on advanced framed walls, and it was found that the average framing factor is approximately 16%. For comparison purposes, all of the standard wood framed wall sections were simulated with a framing factor of 25% and advanced framed walls were modeled with 16% framing factor.

Table 3 shows all of the Whole Wall R-values calculated using Therm simulations. The thermal performance is further discussed for each wall system in the following sections.

Table 3 : R-values for analyzed wall systems

Case	Description	Whole Wall R-value	Rim Joist	Clear Wall R-value	Top Plate	Framing Fraction
1a	2x6 AF, 24"oc, R19FG + OSB	**15.2**	12.3	16.1	12.5	16%
1aii	2x6, 16"oc, R19FG + OSB (25%ff)	**13.7**	12.3	14.1	12.5	25%
1b	2x4 AF, 24"oc, R13FG + OSB	**11.1**	9.8	11.5	9.8	16%
1bii	2x4, 16"oc, R13FG + OSB (25%ff)	**10.0**	9.8	10.1	9.8	25%
2a	2x6 AF, 24"oc R19FG + 1" R5 XPS	**20.2**	18.5	20.6	20.3	16%
2b	2x6 AF, 24"oc R19FG + 4" R20 XPS	**34.5**	29.0	35.6	35.4	16%
3	2x6 AF, 24"oc, 2x3 R19+R8 FG	**21.5**	13.4	23.5	18.4	16%
4	Double stud wall 9.5" R34 cellulose	**30.1**	14.4	33.5	28.8	
5	Truss wall 12" R43 cellulose	**36.5**	18.6	40.5	34.4	
6a	SIPs (3.5" EPS)	**14.1**	12.3	14.5	10.6	
6b	SIPs (11.25" EPS)	**36.2**	14	41.6	28.2	
7a	ICF - 8" foam ICF (4" EPS)	**16.4**		16.4		
7b	ICF - 15" foam ICF (5" EPS)	**20.6**		20.6		
7c	ICF - 14" cement woodfiber ICF with Rockwool	**17.4**		17.4		
8a	2x6 AF, 24" o.c., 5" 2 pcf R29 SPF, OSB	**19.1**	13.6	20.3	19.5	16%
8b	2x6 AF, 24" o.c., 5.5" R21 0.5 pcf SPF, OSB	**16.5**	13.1	17.2	16.6	16%
9	2x6 AF, 24"oc, 2" SPF and 3.5" cellulose	**17.5**	13.2	18.4	17.7	16%
10	Double stud with 2" 2.0 pcf foam, 7.5" cell.	**32.4**	15.9	36.2	28.5	
11	Offset frame wall with ext. spray foam	**37.1**	18.8	40.6	41.9	16%
12	2x6 AF, 24"oc, EIFS - 4" EPS	**30.1**	23.8	31.4	31.1	16%

*AF - Advanced Framing

2.2 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.

Vinyl siding was chosen as the cladding system for the analysis as it is the most widely used residential cladding system in North America, and it can be found in almost any geographic area.

Minneapolis MN was chosen as the climate to compare all of the chosen wall systems. Minneapolis is in DOE climate zone 6, which experiences cold wintertime temperatures as well as some warm humid summer temperatures.

A Class I or II vapor retarder is required according to the International Residential Building Code (IRC) on the interior of the framing in zones 5,6,7,8 and marine 4. This will control vapor condensation on the sheathing in the winter months as shown in Figure 9. The RH at the sheathing did not reach elevated levels in Case 1 (framed walls with OSB sheathing) with the Class I vapor retarder in WUFI®. There are some exceptions to the interior vapor control layer if a sufficient amount of insulation and vapor control is installed on the exterior.

Often times, the 6-mil polyethylene vapor barrier is also used as the air barrier. This is very difficult to detail correctly, and because it may not be air tight, there is a considerable risk to air leakage condensation on the sheathing should interior air leak into the enclosure.

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.

2.2.1. Moisture Balance

Assessing moisture related durability risks involves three different moisture processes; wetting, drying and moisture redistribution. These three processes in combination with the safe storage capacity 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, vapour condensation, plumbing leaks and built in construction moisture. Minimizing these sources with good design details for shedding rain, air tightness, and vapour control will help decrease the risk of moisture related durability failure.

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 of the building enclosure
2. Decreasing the permeability of the linings that we put on the interior and exterior of the enclosure
3. Increasing the mould 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.

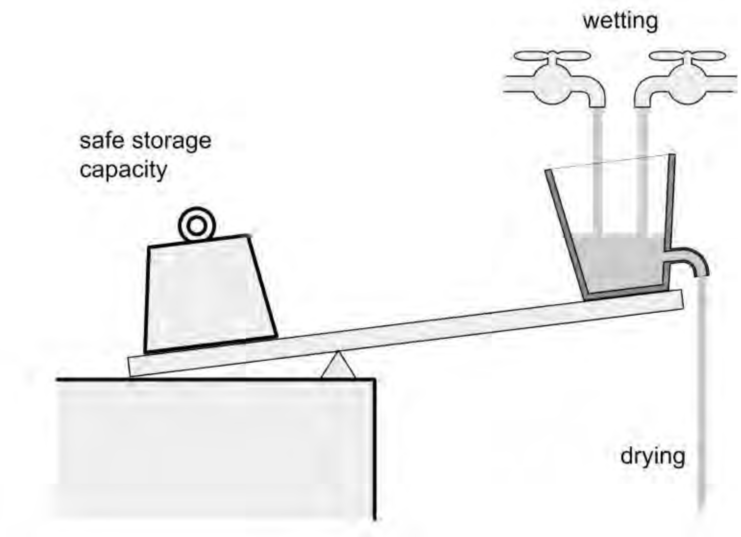


Figure 8 : Moisture balance

2.2.2. Wintertime Condensation

Wintertime diffusion and air leakage condensation potential was determined for each case. The diffusion condensation potential was determined by analyzing the relative humidity at the interior surface of the sheathing (or other condensation plane) during the cold winter months. The interior relative humidity for these simulations was sinusoidal condition varying from a minimum of 30% 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 relative humidity in a cold climate will decrease to between 20% and 30% 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.

In the 2007 supplement to the International residential code, three classes of vapor control were defined for enclosure systems (1 US perm = 57.4 ng/(s·m^2·Pa))

- Class I: 0.1 perm or less (eg. sheet polyethylene)
- Class II: 0.1 < perm ≤ 1.0 perm (eg. kraft faced fiberglass batts , some vapor barrier paints)
- Class III: 1.0 < perm ≤ 10 perm (latex paint)

Class I or II vapor retarders are required on the interior side of framed walls in Zones 5, 6, 7, 8 and marine 4 (IRC N1102.5). Under some conditions, such as vented claddings or insulated sheathings, a Class III vapor retarder is allowed by the code (IRC Table N1102.5.1).

Figure 9 shows a comparison of the relative humidity caused by vapor diffusion at the sheathing for Case 1, standard construction, and Case 2, advanced framing with insulated sheathing. A polyethylene vapor barrier is installed on the interior of the framing in Case 1, vapor barrier paint is used for Case 2 with 1" of XPS insulated sheathing, and latex paint is used for Case 2 with 4" of XPS insulated sheathing. Table 4 shows the vapor control strategies and permeance values for all four walls compared in Figure 9.

Table 4 : Vapor control strategies and permeance values for Case 1 and 2

Case	Description	Vapor Control	Permeance	
			[US perms]	[ng/(s•m^2•Pa)
1a	2x6 AF, 24"oc, R19FG + OSB	poly	0.07	4.0
1b	2x4, 16"oc, R13FG + OSB	poly	0.07	4.0
2a	2x6 AF, 24"oc R19FG + 1" R5 XPS	vapor retarder paint	1.0	57.8
2b	2x6 AF, 24"oc R19FG + 4" R20 XPS	latex paint	10.7	616.7

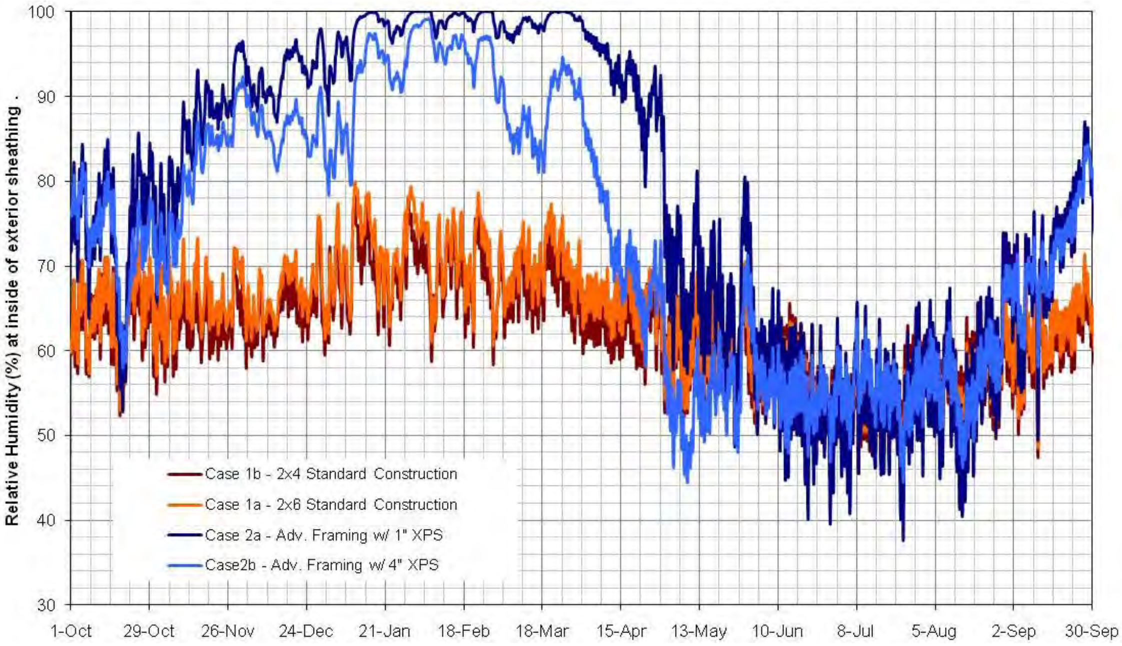


Figure 9 : Winter time sheathing relative humidity for Case 1 and Case 2

The advanced framing wall (Case 2) with 1” of XPS was modeled with the minimum amount of vapor control required (Class II vapor retarder - 1 perm or 57 ng/Pa•s•m2) according to the IRC. The elevated moisture levels during the winter months are only a small concern, since the XPS is not moisture sensitive, and temperatures are quite low in the winter months, minimizing moisture related risks. The advanced framing wall with 4” of XPS insulated sheathing does not require any extra vapor control layers according to the IRC because it qualifies as having more than R-11.25 insulated exterior sheathing over 2x6 wood framing.

Figure 10 shows the potential for air leakage condensation for Case 1 and Case 2. This analysis shows the dewpoint of the interior air and the temperature of the sheathing for both Case 1 and Case 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.

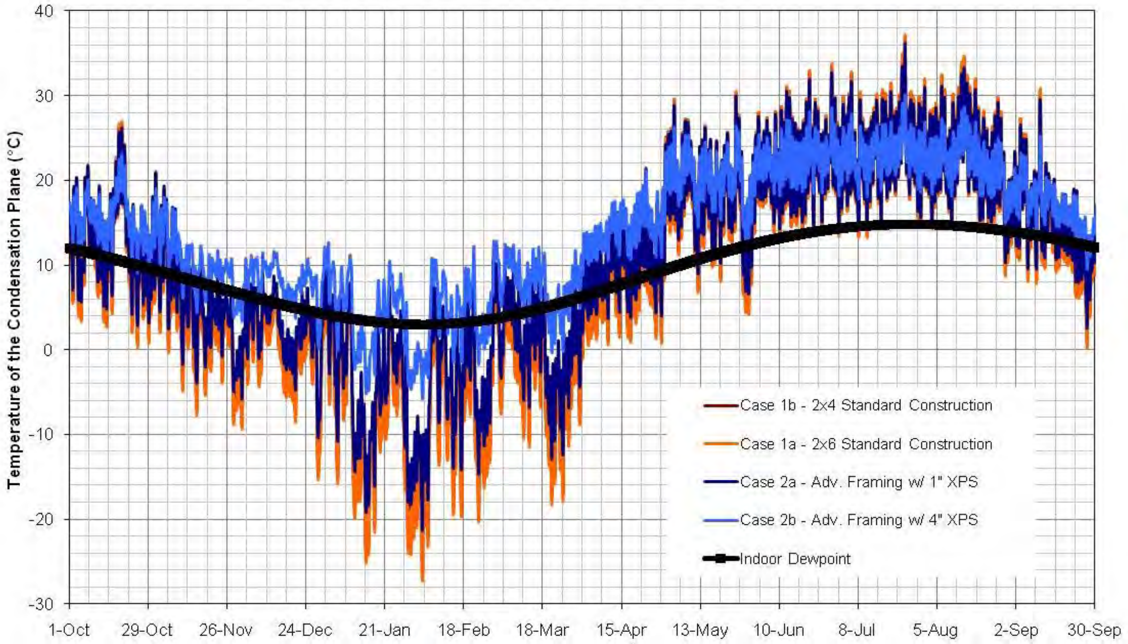


Figure 10 : Winter air leakage condensation potential for Case 1 and Case 2

The risk of air leakage condensation is greatest on the standard construction walls, and slightly improved on the advanced framing wall with 1” of XPS. The wall with 4” of insulated sheathing has the least risk of moisture related durability issues from air leakage condensation because of the short periods of time the interior face of the sheathing is below the dewpoint. When the hours of potential condensation are added together over the entire year, Case 1 with 2x4 construction and 2x6 construction have approximately 4400 and 4500 hours respectively of potential condensation. Case 2 with 1” of insulated sheathing experiences approximately 3800 hours of potential condensation and Case 2 with 4” of insulated sheathing only experiences 1200 hours of potential air leakage condensation.

One method of improving the risk of air leakage condensation in standard construction is by using a hybrid wall system (Case 9). In our analysis a hybrid wall system consists of advanced framing (2x6 24”oc) with OSB sheathing and 2” of high density (2.0 pcf) spray foam installed against the interior of the sheathing. This spray foam can be an excellent air barrier if installed properly and because it is vapor semi-impermeable, the temperature of the condensation plane increases (Figure 11). Two inches of high density spray foam was chosen because it is reported as being the maximum thickness that can be sprayed in one pass on any surface. This hybrid wall has approximately the same amount of condensation potential as Case 2 with 4” of exterior XPS and will be significantly less expensive than Case 8 with 5” of high density spray foam. Unfortunately, it also has much less R-value, and still suffers from thermal bridging.

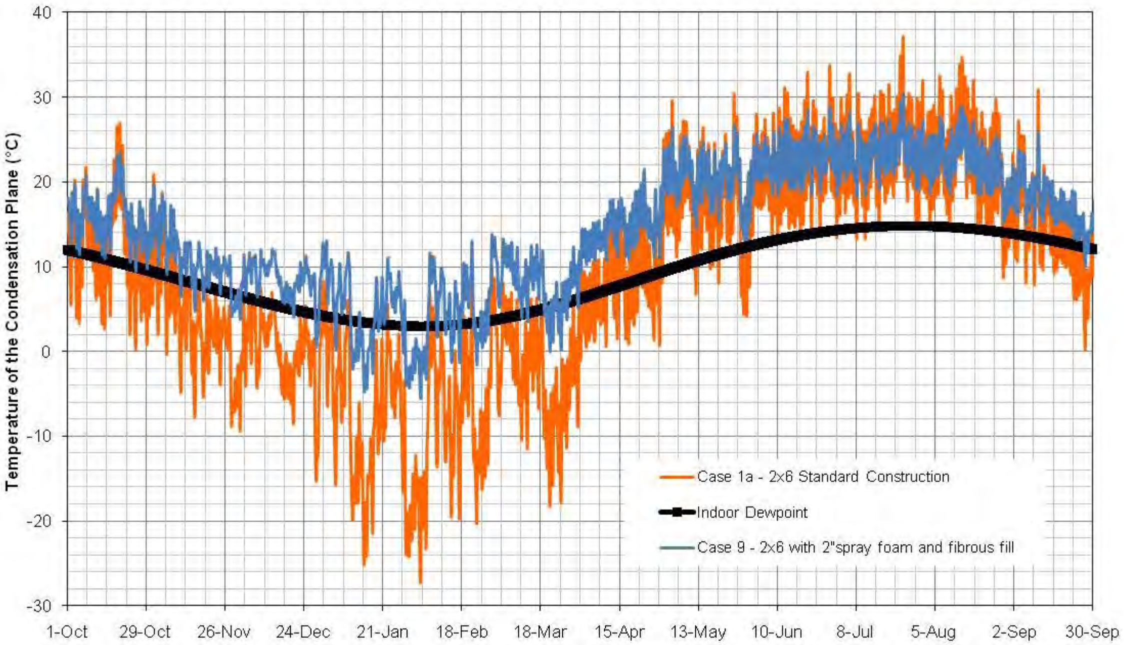


Figure 11 : Winter air leakage condensation potential for Case 1 and Case 9

The winter time sheathing relative humidities for Cases 3, 4, and 5 without air leakage are shown in Figure 12. Constructing these walls with a Class I - 6-mil polyethylene vapor control layer, there is no risk to moisture related issues on the sheathing from vapor diffusion in the winter.

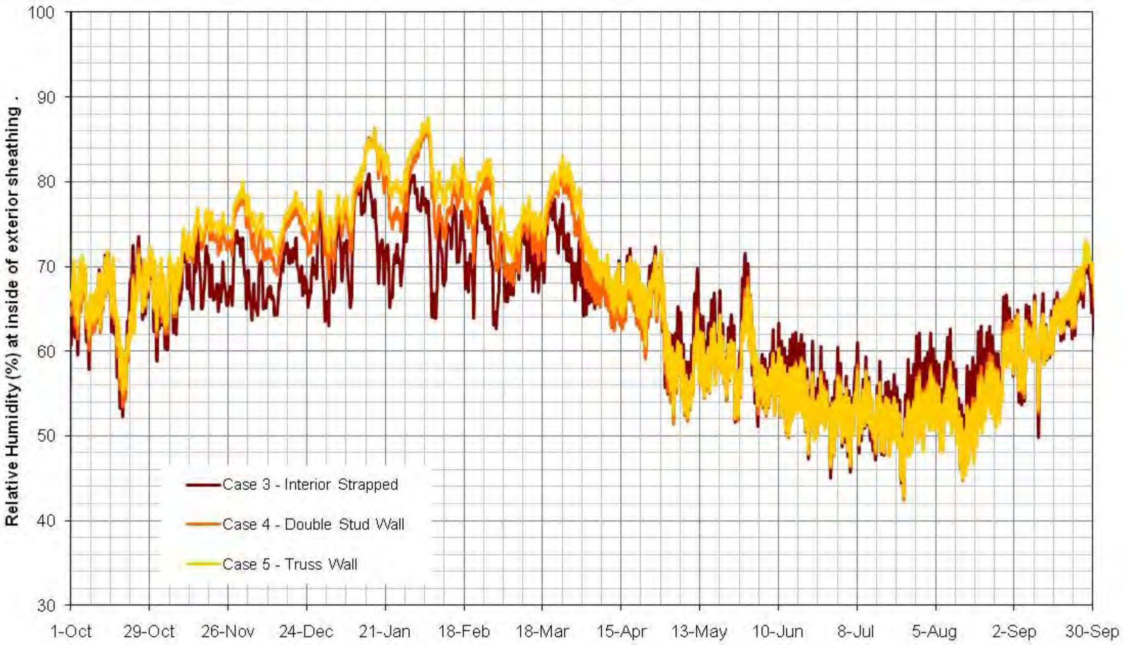


Figure 12 : Winter time sheathing relative humidity for Case 3, Case 4, and Case 5

Winter time air leakage condensation potential for Cases 3, 4, and 5 are shown in Figure 13. The sheathing temperatures of all three of the walls spend a significant portion of the year below the dew point of the interior air because of the increased thermal resistance of the wall system. This means that considerable care must be given to all air tightness details, or there will be a high risk of moisture related durability issues from air leakage.

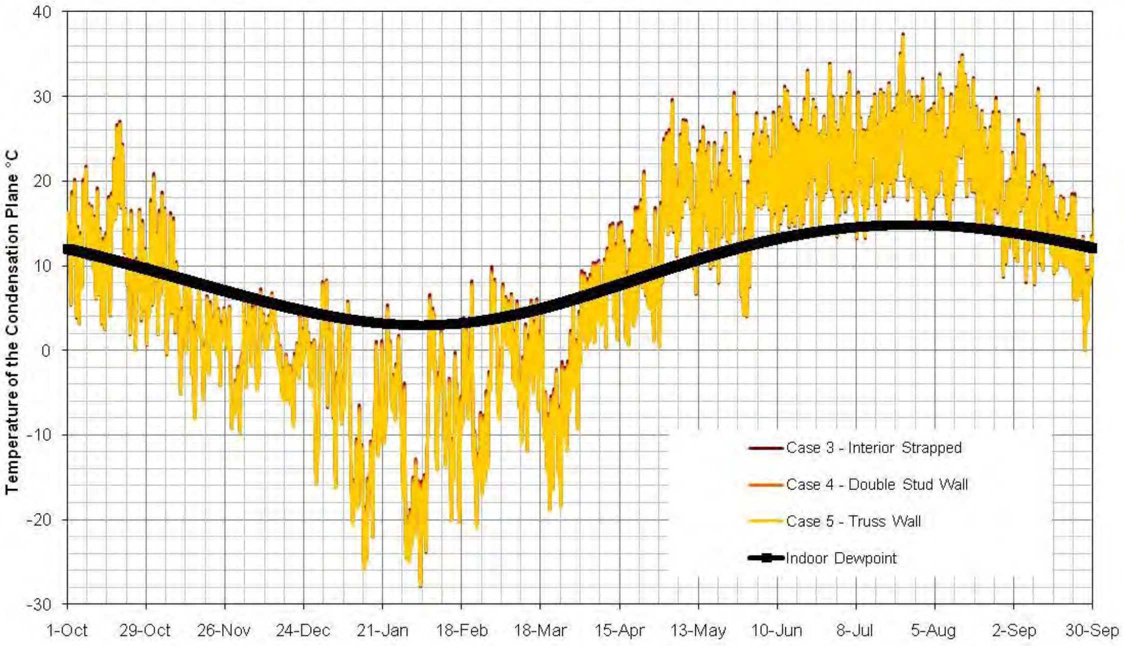


Figure 13 : Winter air leakage condensation potential for Case 3, Case 4, and Case 5

Increasing the temperature of the condensation plane can be done by adding spray foam to the interior surface of the exterior sheathing. Case 10 is a double stud wall with 2” of high density foam sprayed against the sheathing from the interior. Increased vapor resistant insulation raises the temperature of both the diffusion and air leakage condensation planes. Analysis showed that the condensation plane temperature was increased throughout the winter months but that there was still a risk of condensation related damage to the enclosure if air leakage occurs. Figure 14 shows that in Minneapolis (DOE climate zone 6) 2” of high density spray foam may not be enough to reduce the potential condensation risk to a satisfactory level.

Case 10 with 2” of spray foam spends considerably more time below the interior dewpoint compared to Case 9 (hybrid wall) which also has 2” of high density spray foam. The difference in condensation potential is caused by the ratio of the insulation amounts on the interior and exterior of the condensation plane. The remaining 3.5” of the stud space can be filled with an R19 FG batt or cellulose. The increased convection suppression of cellulose insulation is not as critical to this enclosure assembly because of the air tightness of the two inches of spray foam insulation, but will still do a better job of reducing gaps around services, and other places that fiberglass batt is prone to convective looping. The increased thermal resistance of the double stud wall ensures that the condensation plane is kept much cooler. This is a critical consideration to designing a wall enclosure for a specific climate. The double stud walls with 2” of high density spray foam would likely work successfully with little risk in a Climate zone 6 or lower. Alternately, open cell foam could be used to fill the double stud wall although a vapour retarding coating would be needed in cold climates. A mid-density foam, with moderate vapor permeance could also be used as a full fill.

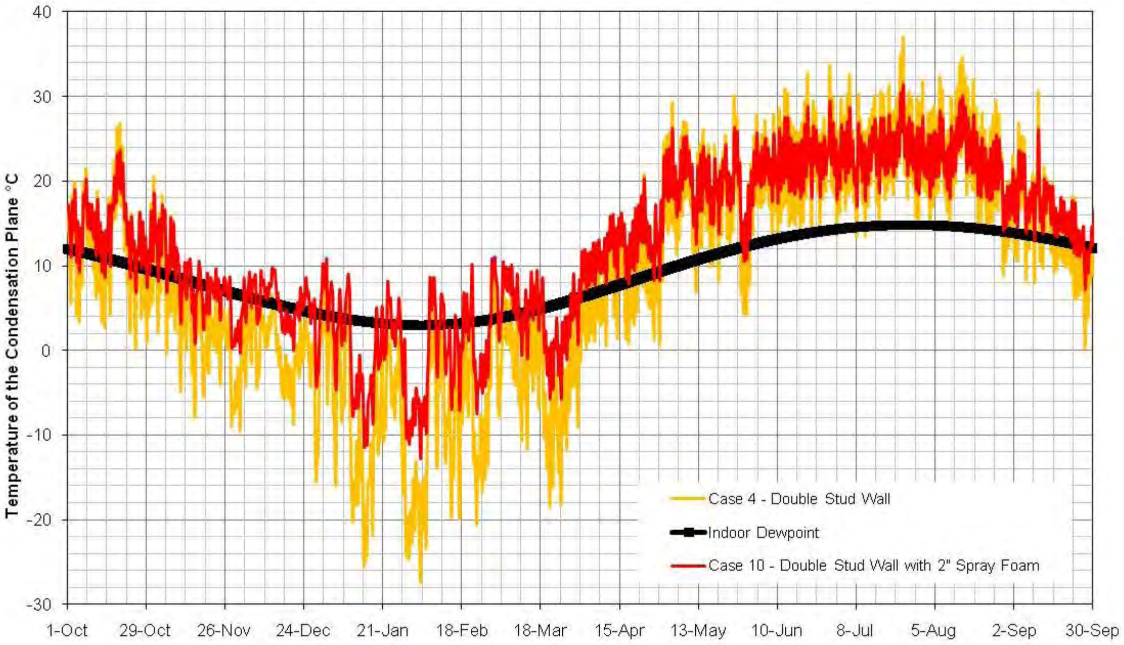


Figure 14 : Winter air leakage condensation potential for Case 4 and Case 10

One wall system becoming more popular in cold climates is a wall constructed with exterior foam insulation, sometimes referred to as an Offset frame wall. This has many advantages over traditional wall construction techniques, and can be used for both new construction and retrofits. Figure 15 shows high density spray foam being installed over the existing exterior sheathing during a retrofit. The surface of the foam becomes the drainage plane, air barrier and vapor barrier of the enclosure. Cladding can be attached directly to the exterior framing that tie back to the framing of the house, and are very stiff and supportive once the foam has been installed.

In this case, the exterior framing was attached with 8" spikes using a spacer to ensure that the exterior framing was the correct distance from the sheathing. Because of the strength and rigidity of the high density spray foam insulation, no additional support is needed for fiber cement siding.

Figure 15 : Installation of high density spray foam in an Offset Framed Wall in a cold climate

In the case of new construction, wood sheathing may not be necessary on the exterior of the structural wall framing to support the spray foam. Removing the sheathing would decrease the cost and work considerably. Other membranes, such as housewraps may be used to support the foam during installation, but more analysis and research may be required before installing spray foam directly on housewraps.

Analysis of the possible wintertime condensation for a Truss Wall constructed with 12" cellulose insulation (Case 5) and constructed with 4.5" of exterior high density foam and 5.5" of fibrous fill in the stud cavity (Case 11) is shown in Figure 16. The sheathing (or foam supporting membrane) never reaches the interior dew point temperature in DOE climate zone 6. In a very extreme cold climate, more foam could be added to the outside or the stud space insulation could be removed which would also decrease the condensation potential.

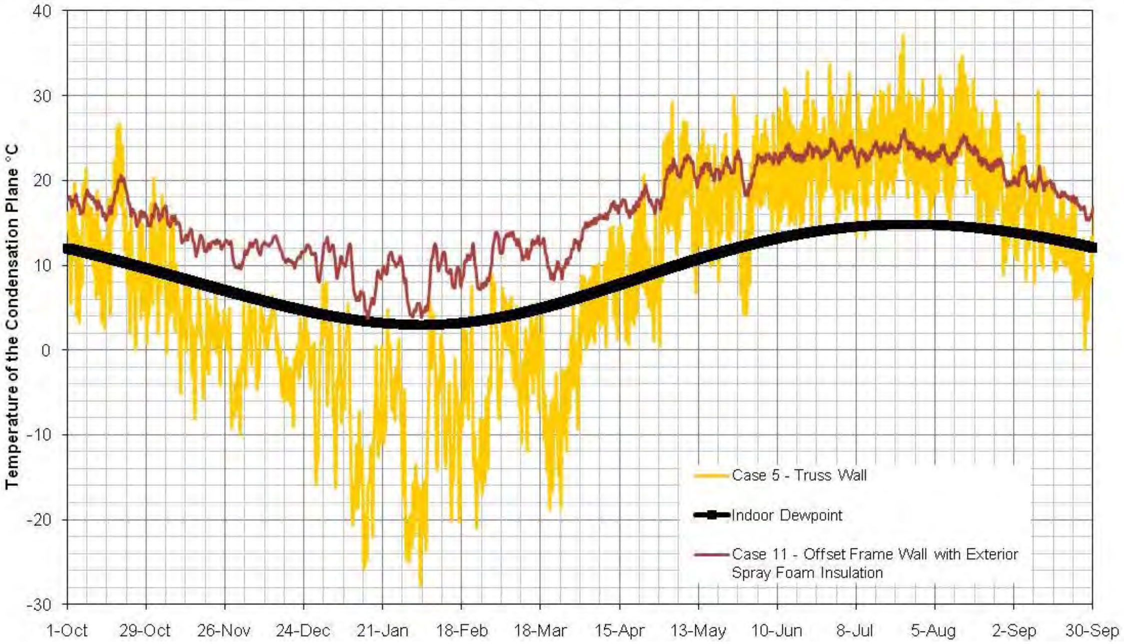


Figure 16 : Winter time air leakage condensation potential for Case 5 and Case 11

There are other advantages to an offset frame wall with exterior foam besides the decreased risk for condensation potential in the enclosure. A house can be dried in very quickly with exterior spray foam insulation, which means that the house is weather proof against rain and snow. This is very important in arctic regions with a very short construction season. Once the foam is installed on the exterior, interior work such as insulation, drywall and finishes can be finished as desired.

There were complaints from the remote areas of Northern Canada (according to the NRC) that when foam board was shipped to be used as exterior insulation, it always arrived broken, which is why they preferred not to use it. High density spray foam is shipped as two liquid components that are combined during the foam installation process. Many more board feet of spray foam can be shipped on the same truck than the equivalent board feet of EPS or XPS board foam insulation. This application is ideal for remote climates.

The sheathing relative humidities for Case 8, the spray foam wall, is shown below in Figure 17. The sheathing relative humidities with high density foam, and low density foam with a vapor barrier show no risks of moisture related issues caused by vapor diffusion. The wall system with low density foam and no vapor control layer may experience some risk to moisture related durability issues depending on the climate.

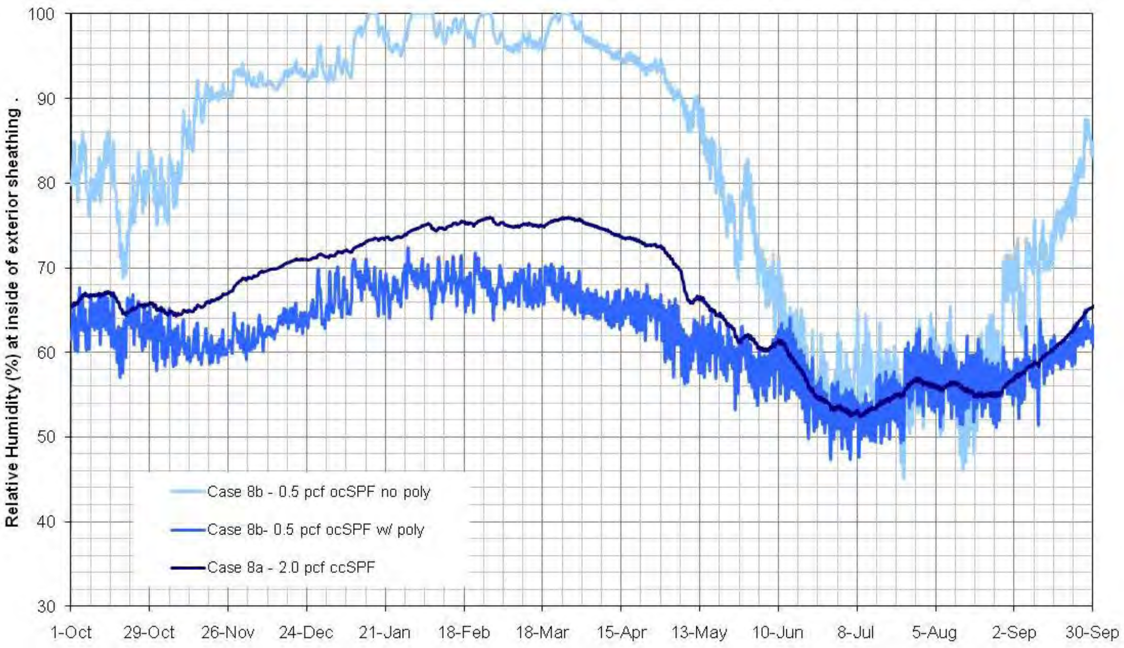


Figure 17 : Winter time sheathing relative humidity for Case 8

A vapor control layer should be used with low-density foam in climate zone 6 based on this hygrothermal analysis. More analysis is required to determine what level of vapor control is required to minimize risk. It may be possible to use a Class II vapor barrier (IBC 2007 supplement). In climate zones warmer than climate zone 6, it may be possible to use 0.5 pcf spray foam with much less risk of moisture related durability issues. More analysis should be conducted on this specific case in different climate zones before design recommendations can be made.

Air leakage condensation potential of Case 8 is shown in Figure 18. Because both low and high density spray foams form an air barrier when installed properly, interior air will not pass the interior surface of the foam. There is no risk of any moisture related durability issues in the walls insulated with spray foam in this analysis.

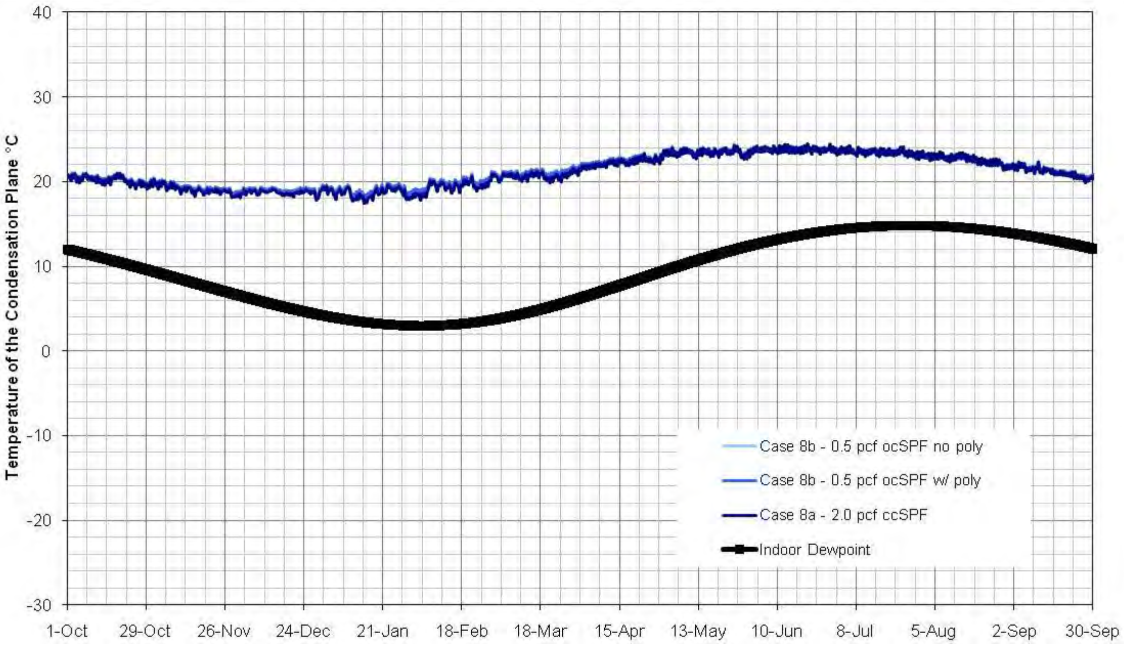


Figure 18 : Winter air leakage condensation potential for Case 8

2.2.3. 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, adhered stone veneer and concrete, 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 polyethylene vapor barrier and may run down the polyethylene to the bottom plate if enough water condenses.

Inward vapor drives were compared in this analysis using vinyl siding as the cladding. This type of cladding does not stress the wall systems from an inward vapor drive perspective but still gives a basis for comparison of the different wall systems. More analysis should be done in the future to more accurately predict the amount of inward vapor drive in cold climates using reservoir claddings (masonry, stucco, adhered stone etc.).

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

Figure 19 shows the comparison of Case 1, standard construction, Case 2, advanced framing with insulated sheathing, and Case 9 hybrid wall. Standard construction experiences higher relative humidities at peak times because of the polyethylene vapor barrier, and lack of vapor control on the exterior. The advanced framing with insulated sheathing walls have some vapor control at the exterior surface of the wall system, and no polyethylene vapor barrier to limit drying to the interior. The advanced framing wall with 1" of XPS has a slightly elevated relative humidity when compared to the wall with 4" of XPS because of the 1 perm (57 ng/Pa•s•m2) paint layer on the drywall slowing drying to the interior, and less vapor control at the exterior surface. The hybrid wall performs very similarly to the advanced framing with 4" of XPS

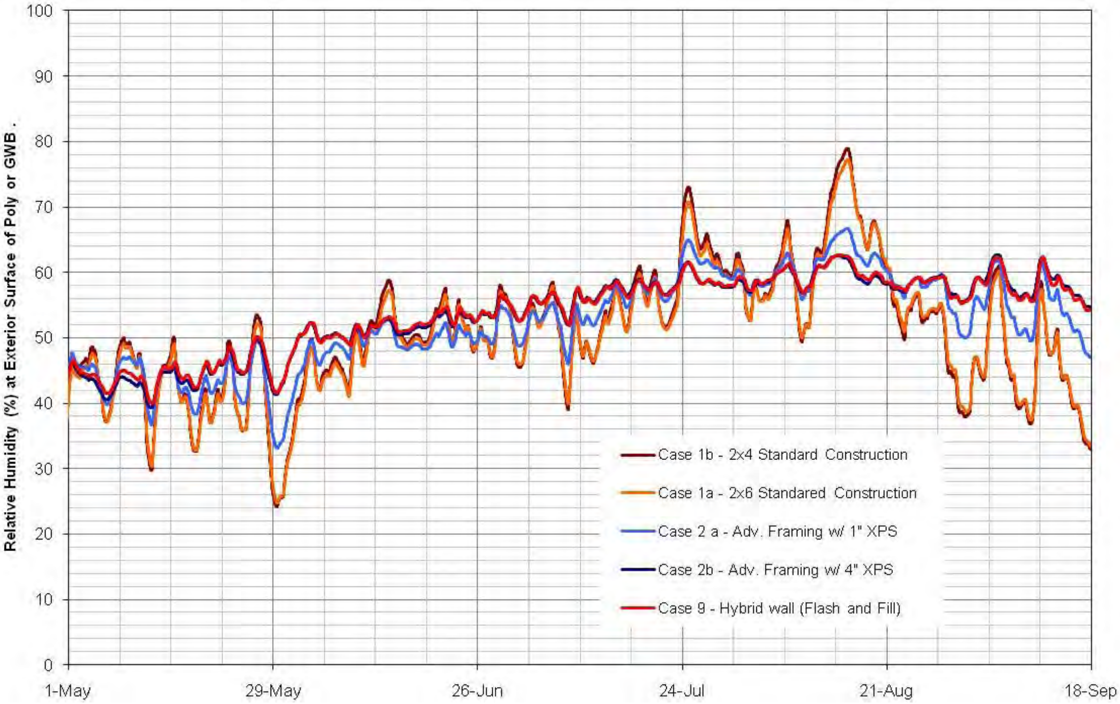


Figure 19 : Inward vapor drive relative humidity of poly or GWB for Case 1, Case 2, and Case 9

Inward vapor drives of Cases 3, 4, and 5(Figure 20) show there is very little performance difference between the test walls, and none of the walls experience any moisture related durability issues caused by inward vapor drives. Case 4, double stud construction, and Case 5, truss wall, experience slightly lower relative humidities because of the moisture buffering effect of the cellulose insulation.

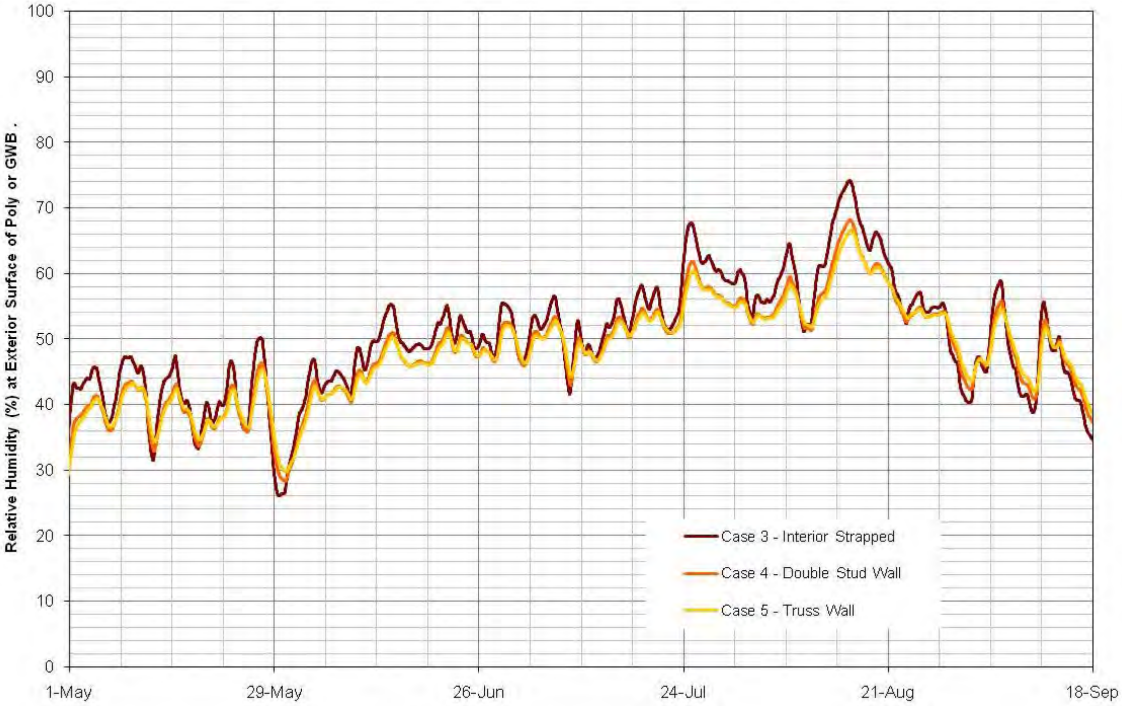


Figure 20 : Inward vapor drive relative humidity of poly or GWB for Case 3, Case 4, and Case 5

A double stud wall with 2" of high density foam (Case 10) with and without an interior vapor barrier was compared to Case 4, a double stud wall filled with cellulose in Figure 21. There was an improvement in performance when two inches of foam were used on the exterior and an interior vapor barrier was installed. The foam restricted the inward vapor drive, and the poly controlled vapor from the interior environment. Although this wall showed lower relative humidities with respect to summer inward vapor drives, it is never recommended to have a high level of vapor control on both sides of the wall system. This substantially increases the risk of moisture related durability issues, should any water get into the wall cavity. This could be improved by adding more foam to the exterior surface, and less vapor control to the interior, with a Class II or III vapor control layer depending on climate. More specific analysis is required before design recommendations can be determined.

Case 10 without an interior vapor barrier experiences slightly elevated relative humidity levels, likely due to the interior relative humidity. In a more severe testing condition for summer inward vapor drives, this wall would likely have lower relative humidity to Case 4, the standard double stud wall.

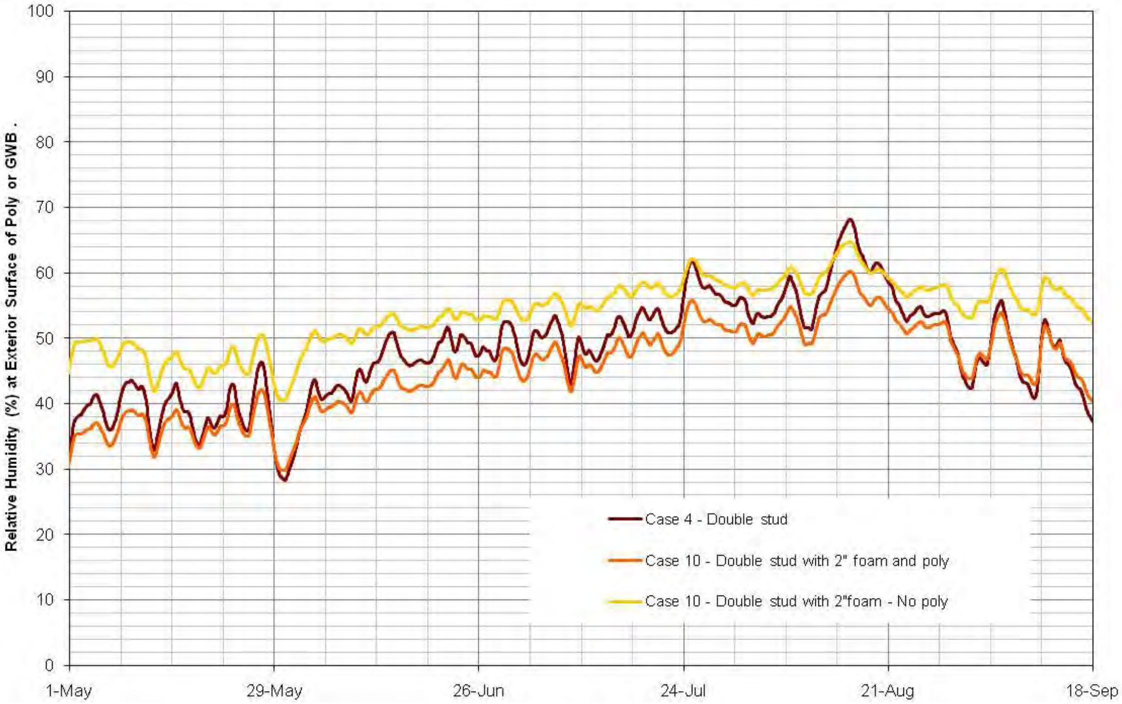


Figure 21 : Inward vapor drive relative humidity of poly or GWB for Case 4, and Case 10

Analysis of inward vapor drives on the spray foam walls shows that the walls without polyethylene vapor barrier dry adequately to the interior, but the low density spray foam wall with poly has elevated relative humidities because of the vapor control layer (Figure 22).

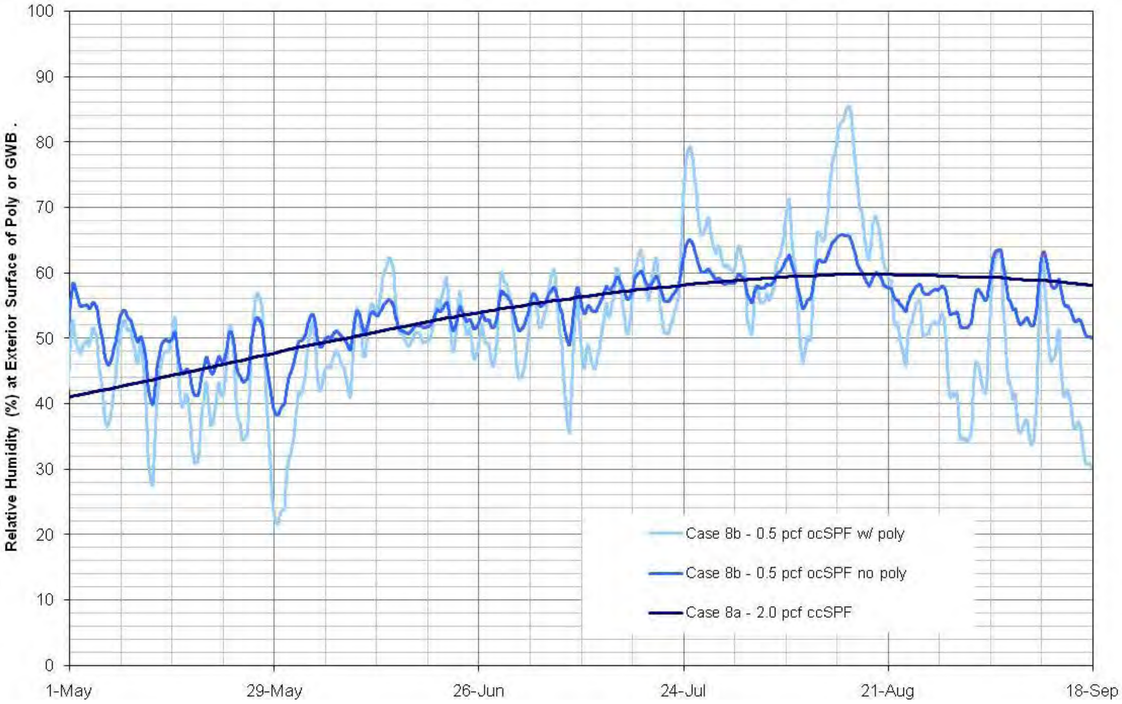


Figure 22 : Inward vapor drive relative humidity of poly or GWB for Case 8

The inward vapor drive for the offset frame wall (Case 11) with exterior foam insulation was compared to Case 3, a truss wall with only cellulose insulation, and Case 8 with 5 ½" of high density spray foam in the cavity space in Figure 23.

Both Case 8 and Case 11 perform very similarly, with slightly higher relative humidities than Case 4, although there is no risk of moisture related damage from inward vapor drives in of the walls (Figure 23). Had the cladding been a moisture storage cladding, it is suspected that both Case 8 with spray foam in the stud space, and Case 11 with exterior foam would have much lower relative humidities than Case 5 because of the vapor control of the high density spray foam.

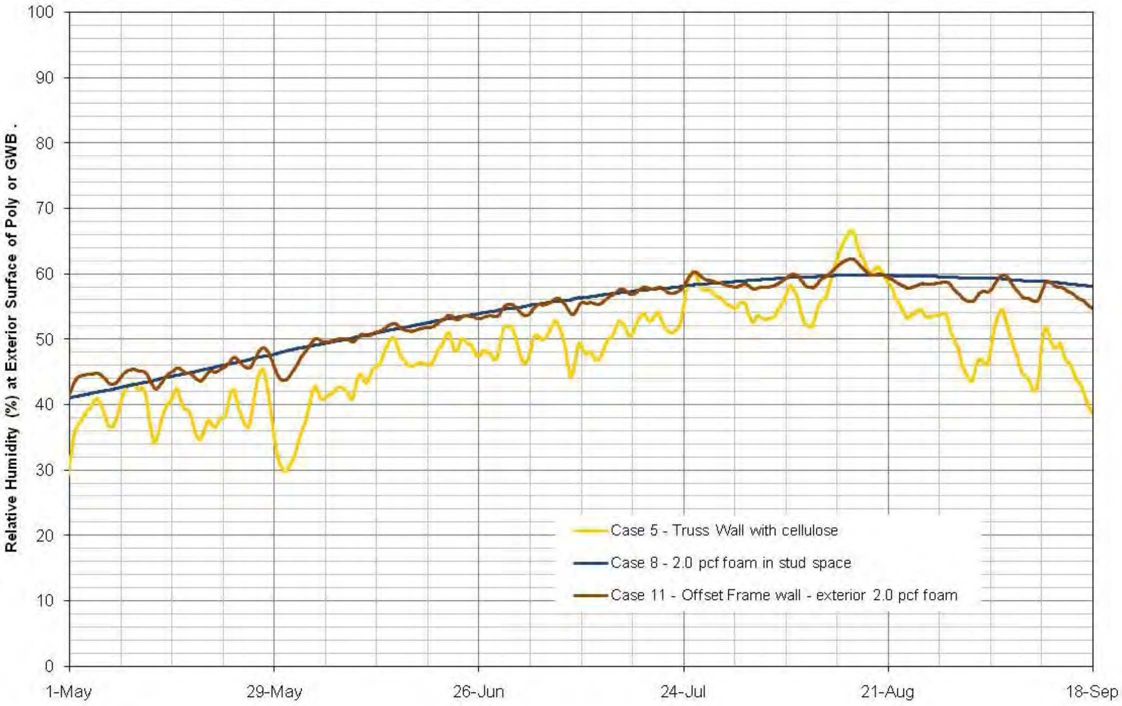


Figure 23 : Inward vapor drive relative humidity of poly or GWB for Cases 5, 8, and 11

2.2.4. 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 elevated sheathing moisture content (250 kg/m3) in the wall systems and observing the drying curve of the wetted layer. In walls without OSB sheathing a wetting layer was applied between the insulated sheathing and fiberglass batt insulation with similar physical properties to fiberglass insulation. 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 try adequately, it can experience some wetting without any long-term durability risks.

The drying curves of Case 1 (standard construction), and Case 2 (advanced framing with insulated sheathing) are shown in Figure 24. The slowest drying wall is the advanced framing with 1" of exterior insulation and interior vapor control paint because there are lower permeance layers on both the interior and exterior of the enclosure. The OSB in the standard construction walls dry only marginally quicker than advanced framing with insulated sheathing, which is likely insignificant in the field. In the advanced framing wall, the wetting layer is immediately interior of the XPS sheathing, and drying is predominantly to the interior.

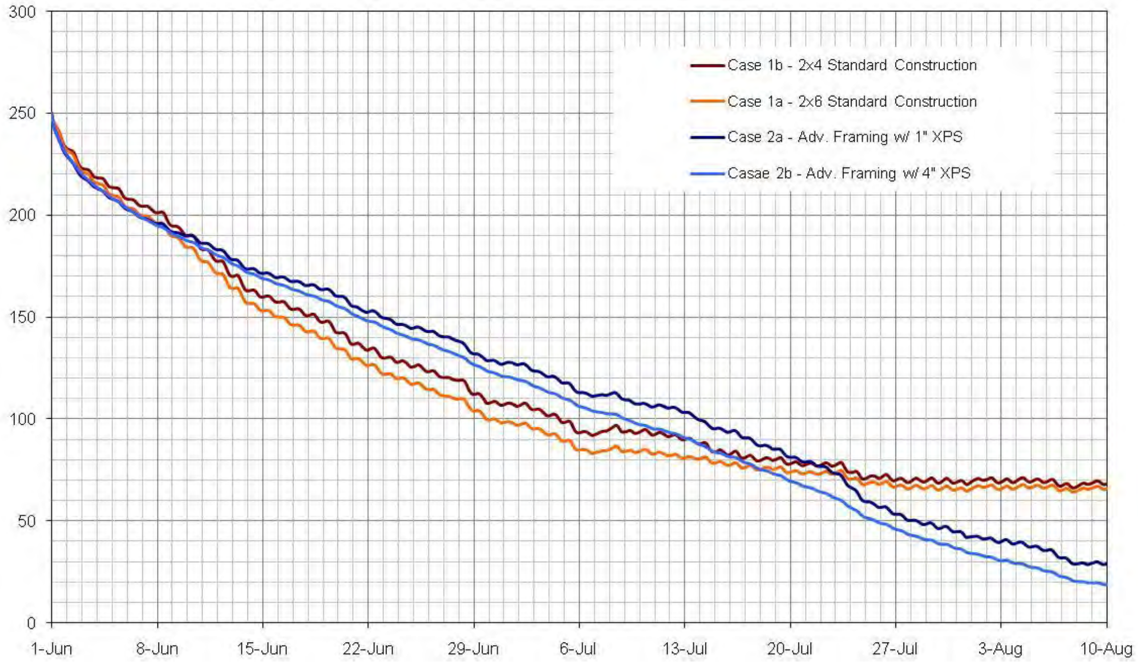


Figure 24 : Drying Curves for Case 1 and Case 2

Figure 25 shows that the drying curves of the interior strapped wall, the double stud wall, and the truss wall are all very similar, with no significant differences. These three walls perform very similarly to the standard construction walls in Figure 24.

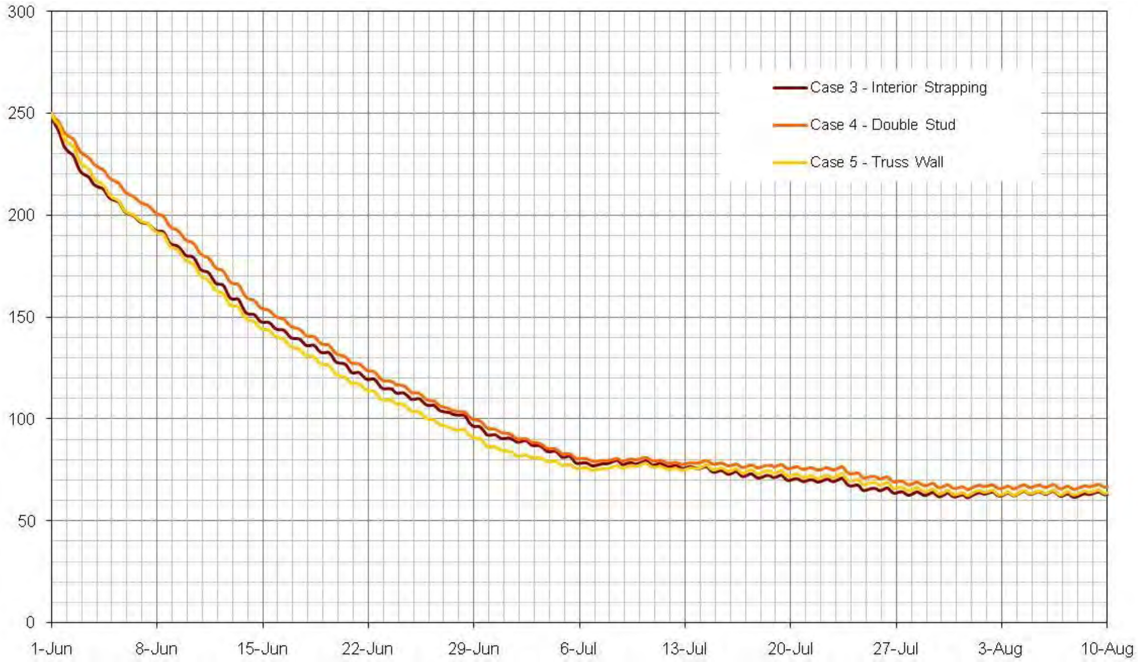


Figure 25 : Drying curves for Case 3, Case 4, and Case 5

The drying curves for spray foam insulated walls, Case 8, are shown in Figure 26. The quickest drying wall is the low density spray foam without a poly vapor barrier. Both the high density spray foam and the low density spray form with poly both dry more slowly because of the decreased permeance of the building enclosure and inhibited drying

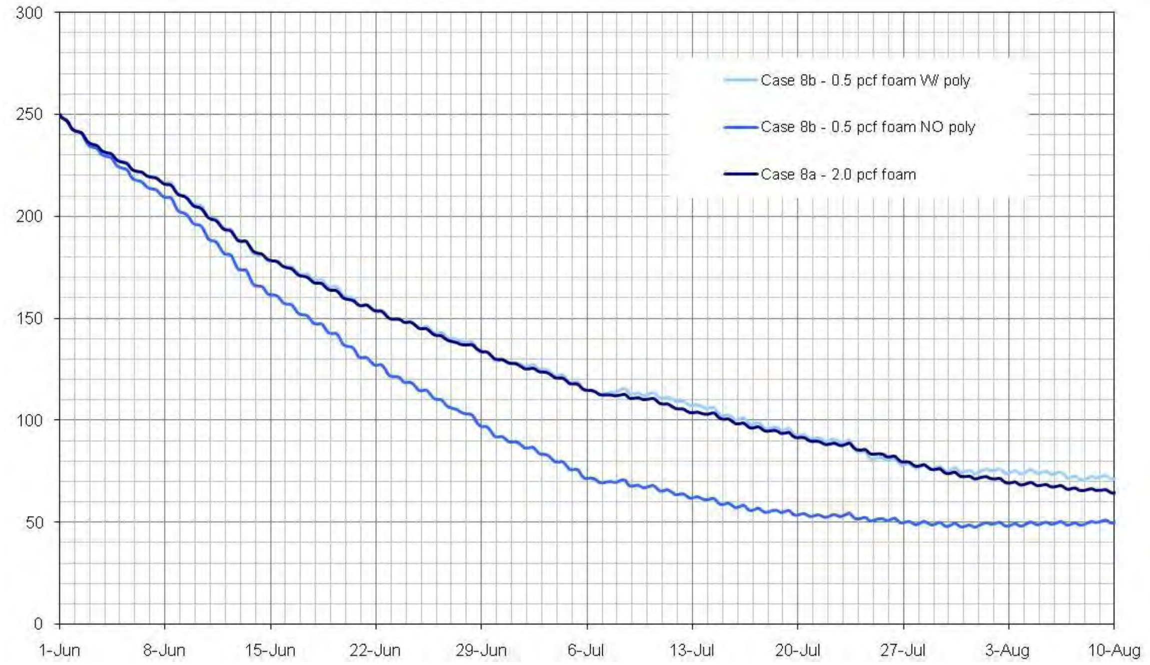


Figure 26 : Drying curves for Case 8

Comparing the double stud wall with cellulose insulation (Case 4) with the double stud wall with spray foam and cellulose (Case 10), Case 4 dried more quickly than Case 10 both with and without a interior polyethylene vapor barrier. With 12" of moisture buffering cellulose insulation in Case 4, it appears that the wall is able to quickly buffer and redistribute the moisture of a single wetting event and then release it slowly, mostly to the exterior of the OSB. Neither wall would suffer moisture related durability issues following a single wetting event but repeated wetting events to the OSB will increase the risk of moisture related durability issues.

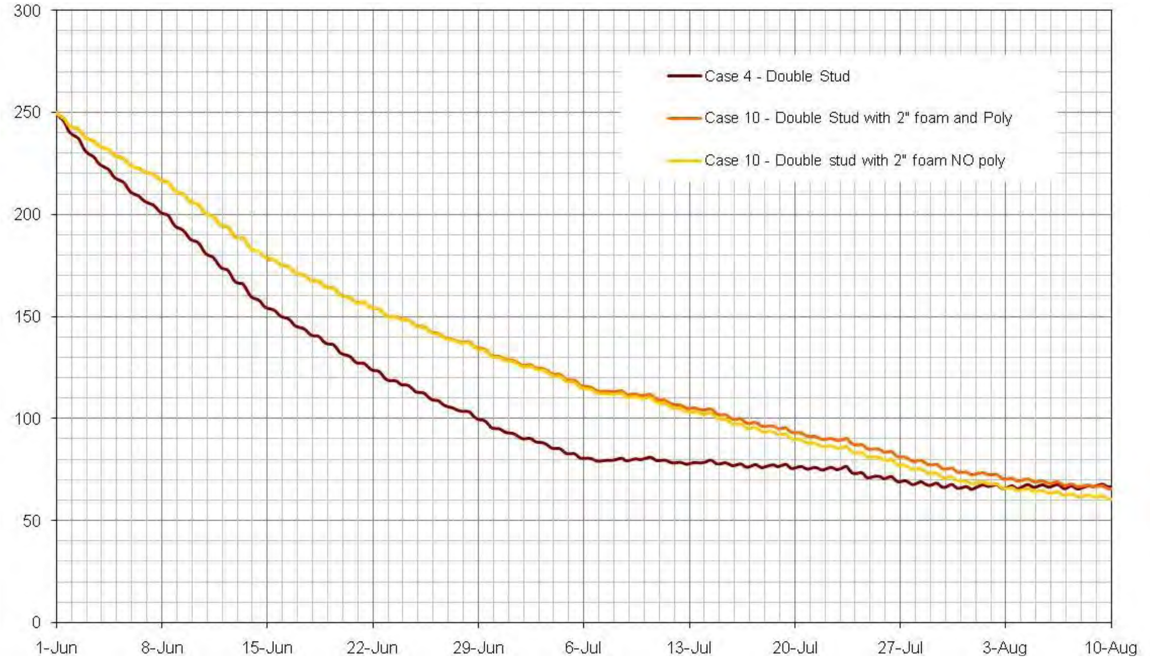


Figure 27 : Drying Curves for Case 4, and Case 10 with and without a poly vapor barrier

The offset wall enclosure with exterior spray foam dried very slowly compared to the truss wall of Case 5 with cellulose insulation. The wall system with exterior high density spray foam is unable to dry to the exterior due to the vapor control of the spray foam. The interior relative humidity is elevated in the spring and summer months which would also affect the vapor pressure gradient and drying potential. The sheathing in Case 11 is not significantly affected by the solar energy of the sun and the warm summer temperatures, nor is it in contact with cellulose insulation to buffer the wetting event.

In Case 5, with cellulose insulation against the wet OSB sheathing, the cellulose absorbed and redistributed the moisture, helping the OSB dry more quickly. Installing fiberglass batt insulation against the sheathing does not redistribute moisture and the OSB will stay wetter longer. Cellulose insulation is more susceptible to repeated wetting events because of its organic nature than fiberglass batt. Both of these wall systems would be at risk for moisture related damage if they were wetted repeatability and both walls are able to handle rare wetting events.

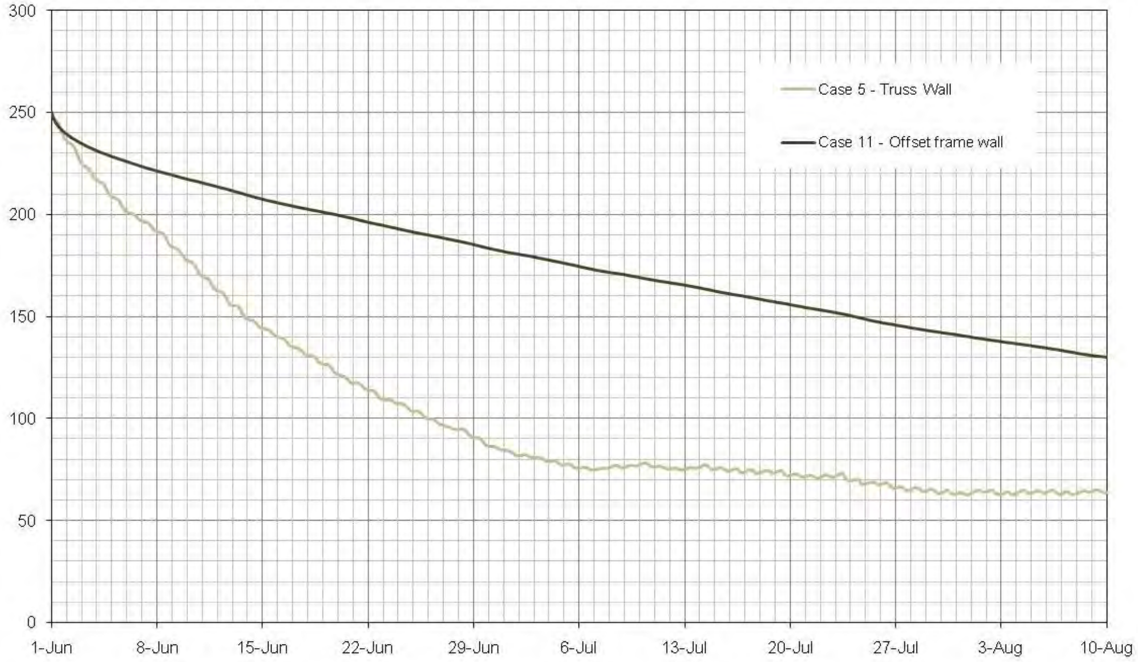


Figure 28 : Drying Curves for Case 5 and Case 11

2.3 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, air leakage 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..

2.4 Buildability

Buildability is a key 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 buildability.

2.5 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 insulation.

2.6 Cost

The factor which generally has the greatest influence on implementation of a building enclosure strategy, particularly for production builders, 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. For example, it's accepted that R19 fiberglass batt is less expensive than low-density (0.5 pcf) spray foam, which is less expensive than high density (2.0 pcf) spray foam. The strategy of a comparison matrix for the test wall assemblies is able to use relative values for cost rather than exact costs.

C. Results

1. CASE 1: STANDARD CONSTRUCTION PRACTICE

For this analysis, standard construction practice includes OSB sheathing, 2x4 or 2x6 framing 16" oc, fiberglass batt insulation, a 6-mil polyethylene vapor barrier and taped and painted ½" drywall. (Figure 29) Historically, this has been used for residential wall construction in most areas of North America.

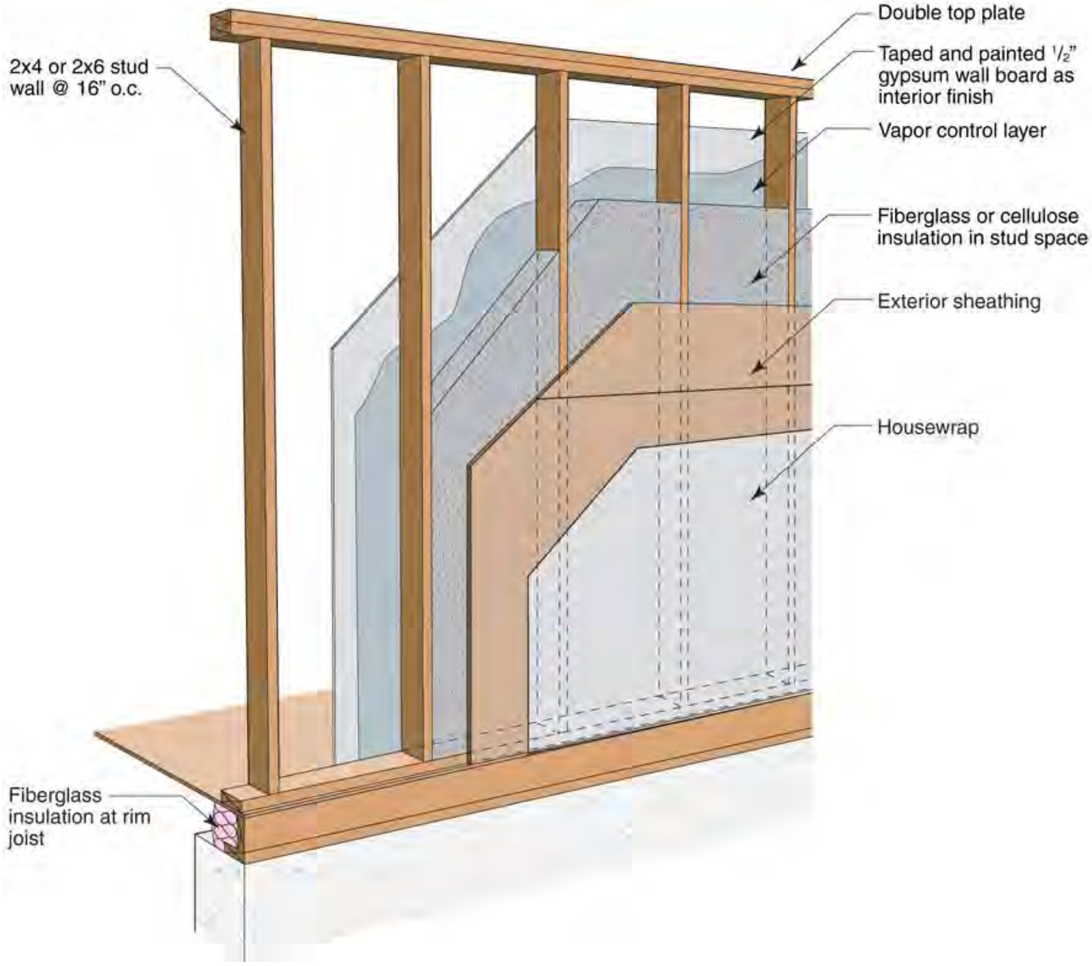


Figure 29 : Standard construction practice

1.1.1. Thermal Control

Fiberglass batt installed in a 2x4 wall system has an installed insulation value of R13, and fiberglass batt in a 2x6 wall system has an installed insulation value of R19. There are several different densities that can be used to provide slightly different R-values (e.g., 3.5" thick batts are available in R11, R12, R13 and R15 ratings). Other insulations that could be used in this assembly include densepack or spray applied cellulose, spray applied fiberglass, and spray foam (Case 8). 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 30 shows the vertical and horizontal wall sections used in Therm to determine the whole wall R-values for standard construction practices.

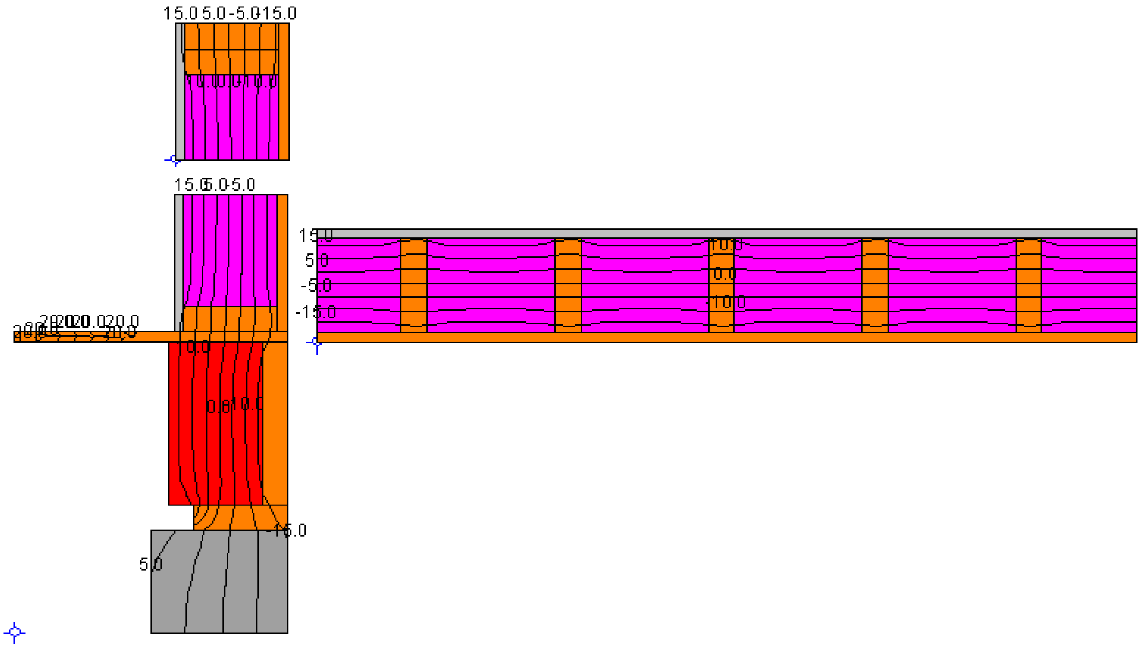


Figure 30 : Therm modeling of Case 1 - 2x6 construction

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 comparison between the different cases, framing factors of 16% were used to limit the variables and determine the effects of other variables.

Table 5 shows a summary of the R-values calculated for the three different components of both the 2x4 and the 2x6 standard construction practice. These insulation values are not considered high-R wall systems in cold climates.

Table 5 : Summary of R-value results from Therm modeling for Case 1

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
1a	2x6 AF, 24"oc, R19FG + OSB	**15.2**	12.3	16.1	12.5
1aii	2x6, 16"oc, R19FG + OSB (25%ff)	**13.7**	12.3	14.1	12.5
1b	2x4 AF, 24"oc, R13FG + OSB	**11.1**	9.8	11.5	9.8
1bii	2x4, 16"oc, R13FG + OSB (25%ff)	**10.0**	9.8	10.1	9.8

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.

1.1.2. Moisture Control

Analysis of the air leakage condensation potential from a poorly detailed air barrier results in approximately 4400 and 4500 hours of potential condensation for the 2x4 and 2x6 standard construction walls respectively when the temperature of the exterior sheathing is less than the dew point of the interior air. (Figure 10)

These walls are unable to dry to the interior, but generally are able to dry fairly well to the exterior depending on the cladding type. WUFI® showed that with a ventilated cladding like vinyl siding, the sheathing in both of the standard construction walls decreased from 250 kg/m3 to 100 kg/m3 in 29-34 days (Figure 24).

1.1.3. Constructability and Cost

Generally speaking, all of the trades and construction industry are very familiar with building the Case 1 wall system. Cladding attachment is straightforward, and the only education necessary may be air tightness details to increase the overall building performance.

1.1.4. Other Considerations

The amount of material used in this type of construction is the standard against what other walls will be compared since it has been the standard of construction in many places of many years. Standard construction uses less framing and wood sheathing than a double stud wall construction (Case 4), 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.

1.2 Case 2: Advanced framing with insulated sheathing

Advanced framing techniques are becoming more popular for residential construction because of several advantages. These practices have been adopted by some smaller builders, but not on many large scale production developments. The main difference with advanced framing is 2x6 framing lumber on 24" o.c. with a single top plate. The idea of advanced framing is to reduce the framing factor of the wall system in the areas by good design, such as corners and penetrations. A single top plate is 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. In many cases of advanced framing, insulated sheathing is used either in place of or in combination with wood sheathing. This is important for thermal performance to minimize thermal bridging effects.

For this analysis, 1" and 4" insulated sheathing is considered (Figure 31). 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.

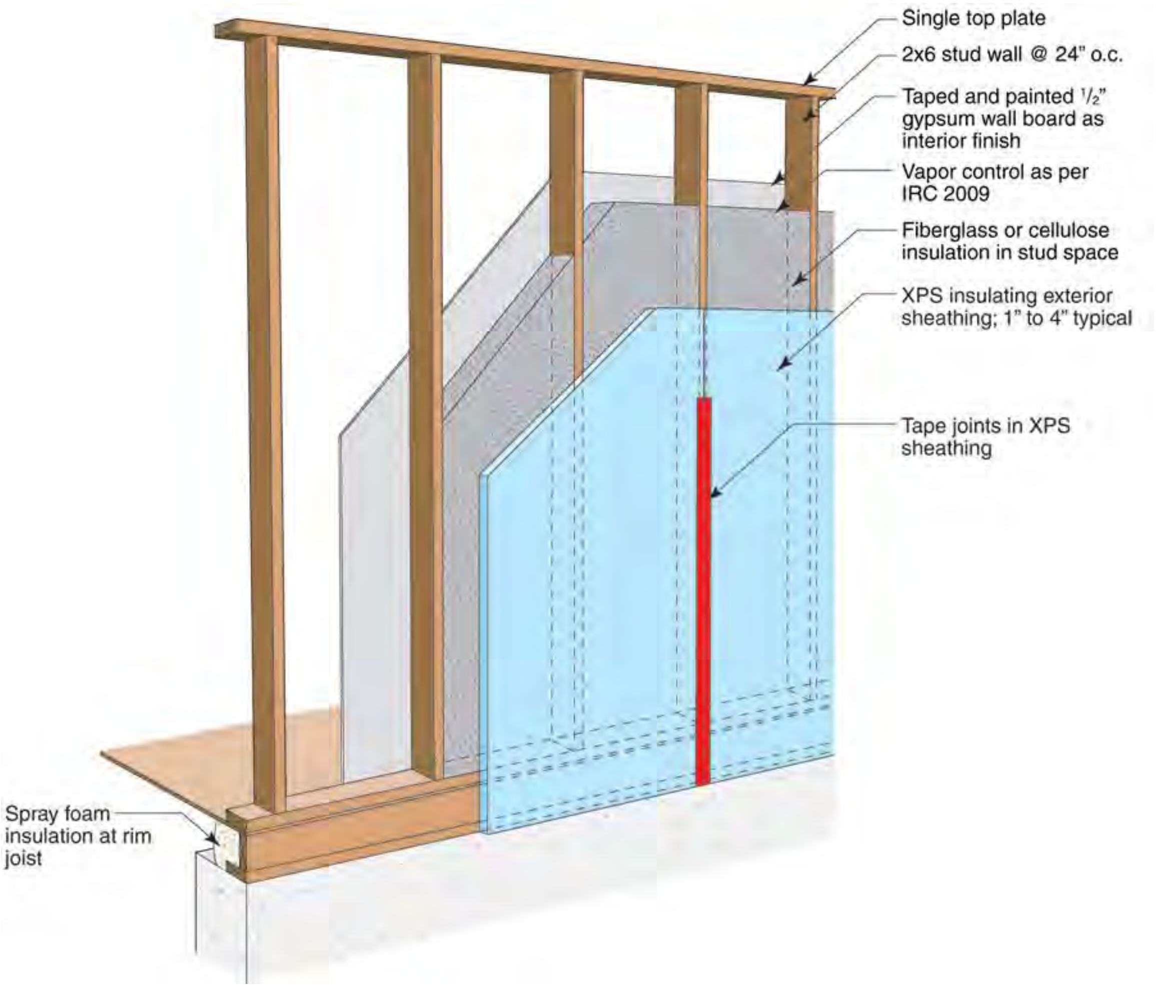


Figure 31 : Advanced framing construction

1.2.1. Thermal Control

Thermal control is improved over standard construction practices by adding insulating sheathing to the exterior of the framing in place of OSB. 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. 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.

Drawings from Therm show the vertical and horizontal sections which indicate increased thermal protection at both the rim joist and top plate, decreasing heat flow through the thermal bridges.

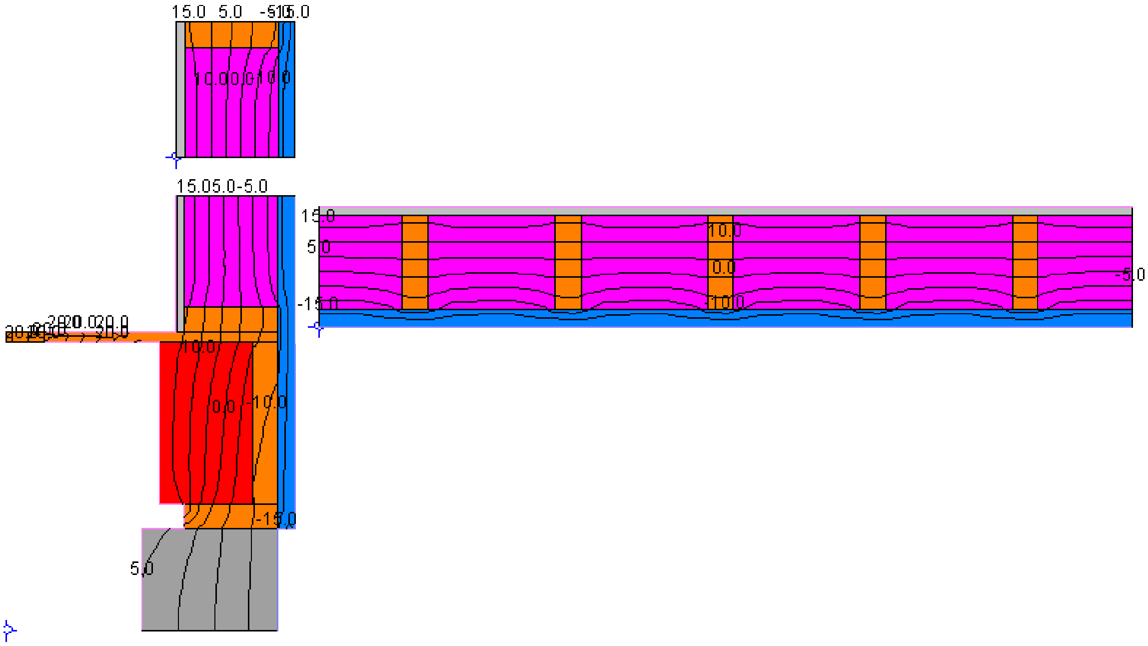


Figure 32 : Therm modeling of Case 2 advanced framing with 1" XPS insulated sheathing

Analysis shows that when substituting 1" of XPS (R5) for the OSB in a standard 2x6 wall with a 16% framing factor, the clear wall R-value increases from R16.1 to R20.6, an increase of R4.5. Since the OSB was removed from the standard construction wall, this is actually a difference of R5.1, which is greater than the R-value of the insulation that was added. 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. For example, increasing the conductivity of the studs by an order of magnitude results in an increase of R6.5 for 1" of R5 XPS sheathing over standard construction. This is an example of the importance of reducing the thermal bridging through the enclosure.

The calculated R-values for both of the advanced framing walls are shown in Table 6.

Table 6 : Summary of R-value results from Therm modeling for Case 2

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
2a	2x6 AF, 24"oc R19FG + 1" R5 XPS	**20.2**	18.5	20.6	20.3
2b	2x6 AF, 24"oc R19FG + 4" R20 XPS	**34.5**	29.0	35.6	35.4

1.2.2. Moisture Control

The Therm results show that the interior surface of the foam is at a higher temperature than the standard construction wall which will decrease the potential for both vapor diffusion condensation and air leakage condensation. According to the IRC, a Class I or II vapor retarder is still required depending on the R- value of the insulated sheathing and the wall framing used. Table N1102.5.1 from the IRC shows that for climate Zone 6, with insulating sheathing R>= 11.25 on a 2x6 wall, only a Class III vapor retarder is required.

There is some risk of winter time condensation from vapor diffusion depending on the level of vapor retarder and the interior temperature and relative humidity conditions. Figure 9 shows that with 1" of XPS some condensation is possible on the surface of the insulated sheathing. Since the XPS is not moisture sensitive, some condensation will not affect the durability of the wall system.

Air leakage condensation may still be a concern, although not as great as with standard construction. There are approximately 3800 hours and 1200 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 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 (Figure 24).

There is less inward vapor drives in the advanced framing walls with insulated sheathing than the standard construction since vapor is slowed at the sheathing, and allowed to dry more readily to the interior (Figure 19). The relative humidity peaks are considerably higher in the standard construction walls than the advanced framing walls.

1.2.3. Constructability and Cost

There is some education and training required for the successful construction of advanced framing walls with insulated sheathing. The changes are very minimal for insulated sheathing thicknesses of 1.5" and less, but for insulating sheathing thicknesses of 2" and greater, special details are required for cladding attachment and window and door installation.

Some solutions have been found for cladding attachment directly to 3/4" strapping anchored to the framing members, but in some areas, building code officials require letters from the specific building materials companies before allowing construction.

1.2.4. Other Considerations

The 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.

1.3 Case 3: Interior 2x3 horizontal strapping

Horizontal interior strapping is a method of reducing the thermal bridging through the wall framing, protecting the vapor barrier against penetrations, and adding more insulation.

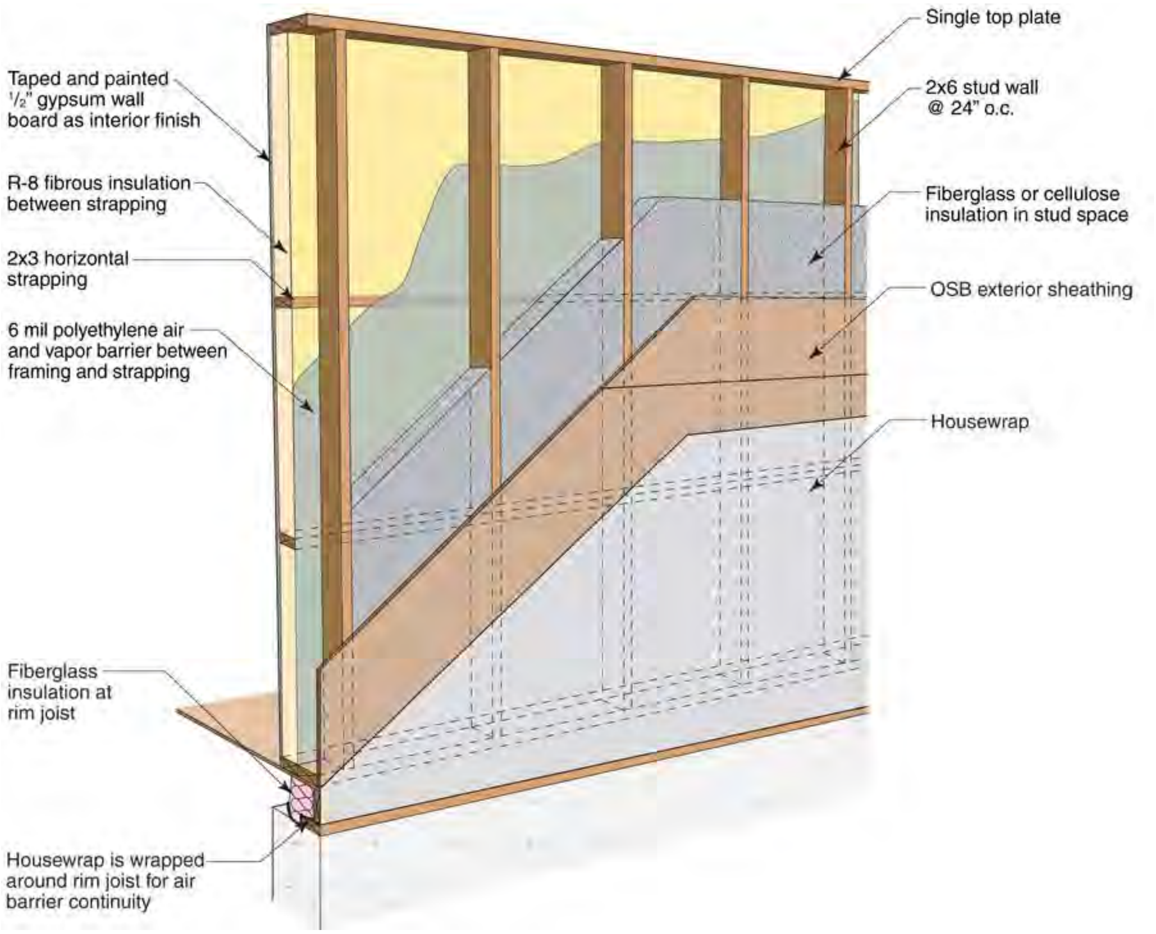


Figure 33 : 2x6 wall construction with interior strapping

1.3.1. Thermal Control

The horizontal strapping added to the wall allows for an extra 2.5" of insulation. This is commonly in the form of R8 fiberglass, which totals an installed insulation R-value of R27 for the wall assembly. For the Therm simulation four interior strapping elements were used as shown in the drawing.

Thermal bridging is decreased through the vertical studs but there is still thermal bridging at the top and bottom plates. Thermal losses due to air leakage are likely been minimized by installing the polyethylene vapor barrier against the wall framing. This means fewer penetrations are required for services and wiring resulting in greater air tightness than standard construction.

Therm was used to determine the whole wall R-value of the interior strapping wall. Figure 34 shows the horizontal and vertical sections from the Therm analysis.

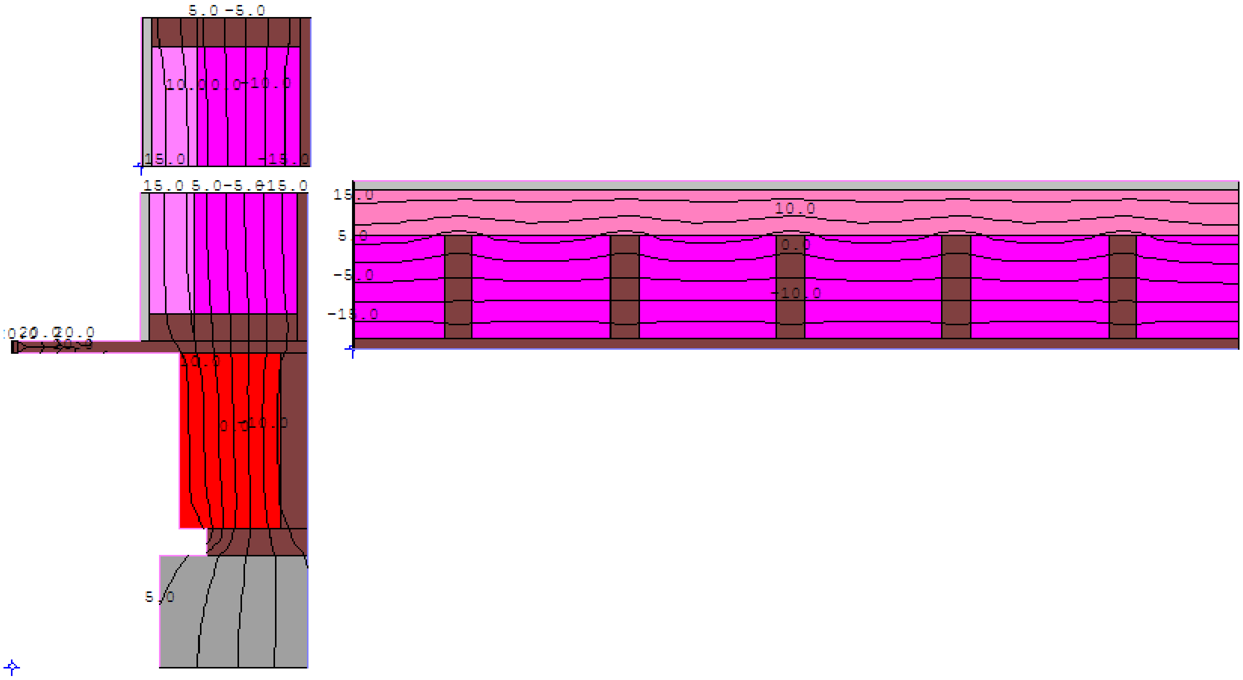


Figure 34 : Therm analysis of horizontally strapped wall

The Whole wall R-value of the wall assembly was determined to be R21.5 (Table 7). This means that even by adding R8 to the standard 2x6 wall, this results in an increase of R6.3 because of the thermal bridging that is not addressed. The rim joist R-value can be improved with more insulation, and better airtightness.

Table 7 : Calculated R-value of an interior horizontal strapped wall

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
3	2x6 AF, 24"oc, 2x3 R19+R8 FG	**21.5**	13.4	23.5	18.4

1.3.2. Moisture Control

The control of both vapor diffusion condensation and air leakage condensation is increased since there are fewer penetrations in the air/vapor barrier of the wall assembly.

The potential for vapor diffusion condensation is very similar to the standard construction assemblies (Figure 12). The temperature of the sheathing is kept only slightly colder because of the increased insulation beyond standard construction which results in a small increase in the potential intensity of air leakage condensation. There does not appear to be any risk of moisture related durability from vapor diffusion assuming the vapor barrier is adequately installed.

Air leakage condensation potential is slightly increased from the standard construction walls with a total of approximately 4600 hours of potential condensation through the winter.

Analysis of the summertime inward vapor drives shows very similar results between the standard construction practices in Case 1 and the interior strapped wall.

Drying of the interior strapped wall shows slightly improved performance over the standard construction practice, by a few days for the OSB to reach 100 kg/m3.

The interior strapped wall performed very similarly to the standard construction practice in terms of moisture control.

1.3.3. Constructability and Cost

Constructing a wall with interior horizontal strapping is not a normal construction technique in most places. It would require some education and training in the design details, such as window installation, but cladding attachment is the same, and the wall system would be less susceptible to workmanship issues on the vapor barrier, since there are far fewer penetrations required through the air/vapor barrier. Additional costs would be incurred due to the addition of both horizontal strapping and the installation of additional batt insulation as well as some more installation time. The mechanical and electrical services should see a reduction in cost since that the horizontal framing does not require as much drilling or modification to distribute the services. The mechanical and electrical trades would also not have to take the time to seal as many locations as in standard vapor and air barrier practices.

1.3.4. Other Considerations

It would be possible to use cellulose insulation between the polyethylene vapor barrier and the exterior sheathing, which would increase the fire resistance, and decrease the embodied energy. There is more framing required to construct these walls, and the tradeoff in adding insulation is not quite made up in the overall R-value of the assembly.

1.4 Case 4: Double Stud

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.

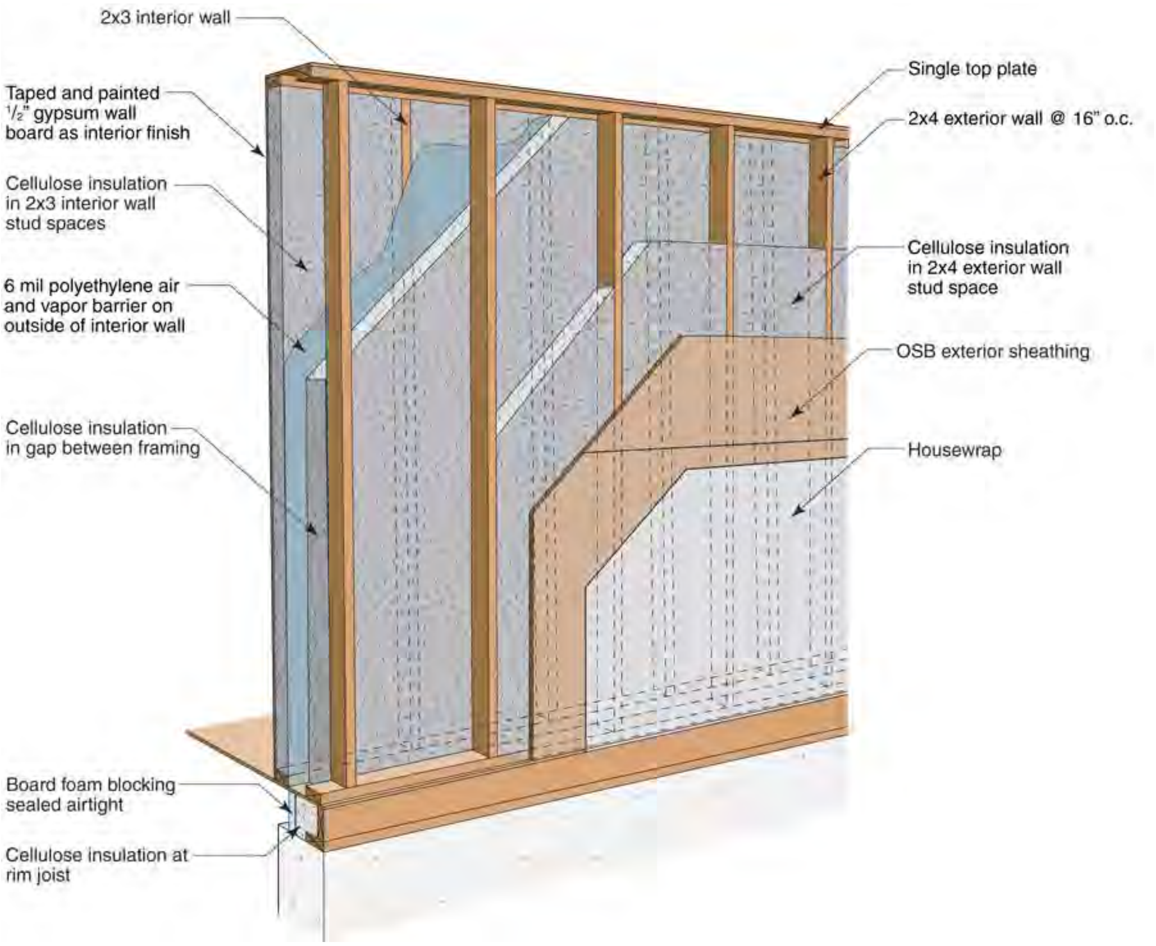


Figure 35 : Double stud wall

1.4.1. Thermal Control

This wall is typically built with an exterior 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"o.c. and the interior framed wall used to support the drywall and insulation was spaced at 24"o.c. 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. It is possible to install the 6-mil polyethylene Class I vapor barrier on the back of the interior wall by installing the plastic when the wall is on the floor, and then lifting the wall into place and securing, making sure to seal the plastic at the top and bottom. This produces a more continuous air/vapor barrier since fewer penetrations are needed for services when compared to the standard framing methods although this may increase the perceived complexity to an unsatisfactory level for some builders.

One advantage observed in the field of installing the air/vapor barrier on the interior framing is one large cavity space that is easier and quicker to insulate with cellulose insulation.

The gap between the two walls can be varied, and produces a much more effective thermal bridge between the two rows of framing than the horizontal interior strapping in Case 3. Often 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 36) 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. Therm analysis shows that with the existing thermal bridging and rim joist, the whole wall R-value of the system is approximately R30 which is only a slight reduction from the clear wall R-value. The R-value can be improved by improving the rim joist detail: more insulation, better airtightness, and better insulation of the concrete foundation.

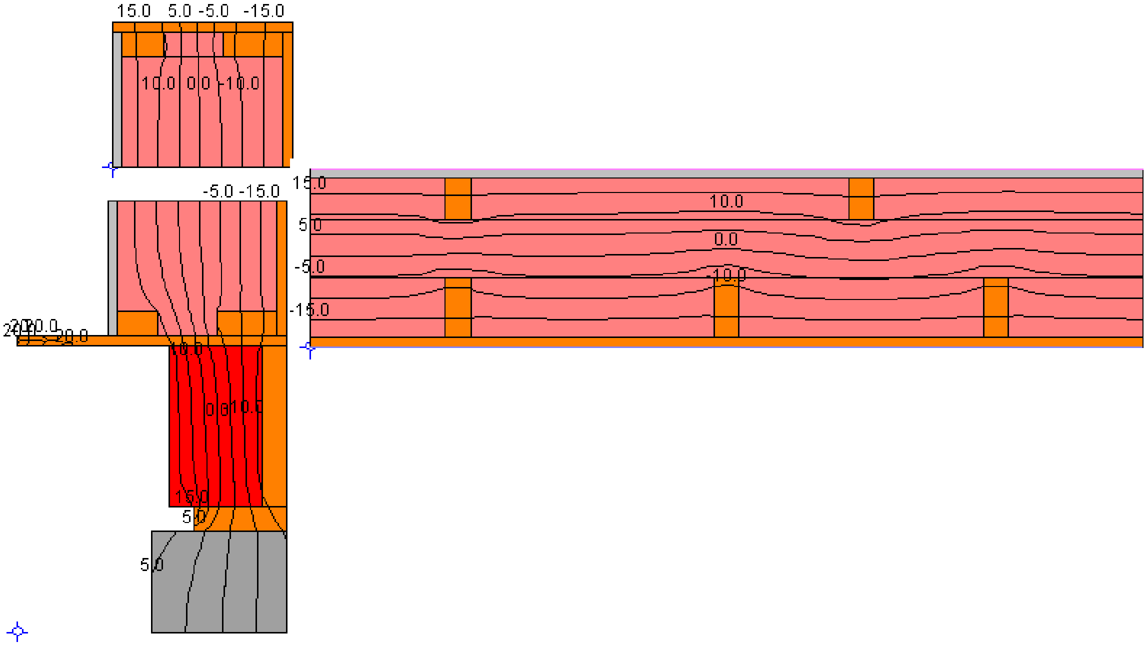


Figure 36 : Therm model of the double stud wall

Table 8 : Calculated R-value of a double stud wall

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
4	Double stud wall 9.5" R34 cellulose	**30.1**	14.4	33.5	28.8

1.4.2. Moisture Control

Moisture control in the form of air leakage condensation and vapor diffusion condensation is controlled with a 6-mil polyethylene vapor barrier that can be installed on the back side of the interior wall or directly behind the drywall. Installing the poly on the back side of the interior wall, if possible, helps reduce the amount of air leakage condensation because fewer penetrations are needed and the air barrier can be more continuous.

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 4600 hours of potential wintertime condensation hours, similar to Case 3 with interior horizontal strapping but because the temperature of the sheathing is colder, the amount of condensation would increase for the same amount of air leakage (Figure 13).

In the summer time the potential inward driven moisture condensation is slightly less than the standard construction walls (Figure 20). This is because the cellulose in the insulation cavity has some buffering effect of moisture, so with a non-reservoir cladding such as vinyl siding, the buffering capacity is not overcome. The outcome may be different with a cladding such as stucco or adhered stone veneer.

In the drying analysis, the double stud wall performs very similarly to the standard construction practice as well as the interior strapped wall drying to 100 kg/m3 in 28 days (Figure 25).

1.4.3. Constructability and Cost

There is some education and training required with this construction technique, mostly with the window boxes and window installation. In any construction where the wall is much thicker than standard construction, window bucks (plywood boxes) are required for window installation. The cladding attachment is the same as normal construction practices.

1.4.4. 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.

1.5 Case 5: Truss Wall

The truss wall is a construction technology that is not as widely known as the other cases being considered. It provides a great deal of insulation space, minimizes thermal bridging through the wall by using plywood gusset plates, and covers the rim joist with insulation (the rim joist is generally a location of significant air leakage and thermal bridging). Also, unlike the double stud wall, the increased wall width is to the exterior of the structural wall, which does not compromise indoor floor area.

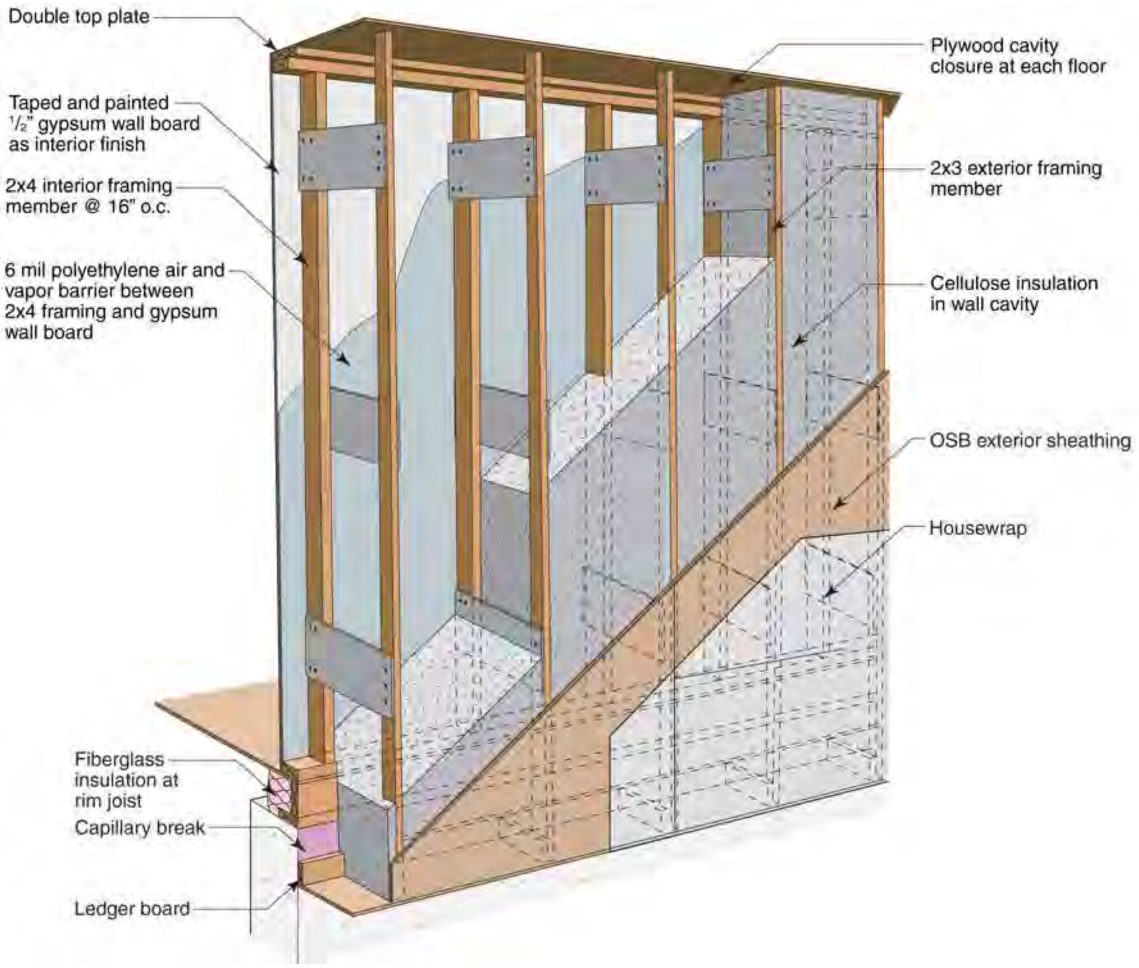


Figure 37 : Truss wall construction

1.5.1. Thermal Control

The goal of this wall is to provide as much space as possible for insulation to increase the thermal performance. In this analysis, an insulation cavity of 12 inches was constructed through the wall system. This was filled with cellulose to achieve a nominal R-value of R43, the highest R-value of any of the walls analyzed.

Therm was used to predict the whole wall R-value of this high-R assembly (Figure 38), and a value of R36.5 was calculated. Looking at the three individual components, the clear wall R-value is R40, but both the top plate and rim joist exhibited lower values. It is likely that a high heel truss with wide overhangs would be utilized for the attic and the attic space insulation would extend out over the top plate creating continuous insulation over the plates reducing the thermal bridging. This is not a commonly constructed wall but it was felt that a double top plate is more likely to be used than a single top plate for construction. It is possible to construct the same wall with a single top plate instead.

The wall schematic in Figure 37 shows that every structural wall stud has a corresponding exterior framing member for cladding attachment. In practice this is unlikely to happen because of extra framing studs commonly used for construction. It is more likely that there will be some structural wall members without a corresponding exterior framing member as was simulated in Therm (Figure 38). Similar to the double stud wall, the actual number and spacing of structural members has little influence on the whole wall R-value because of the significant thermal break of the insulation between the interior and exterior framing members.

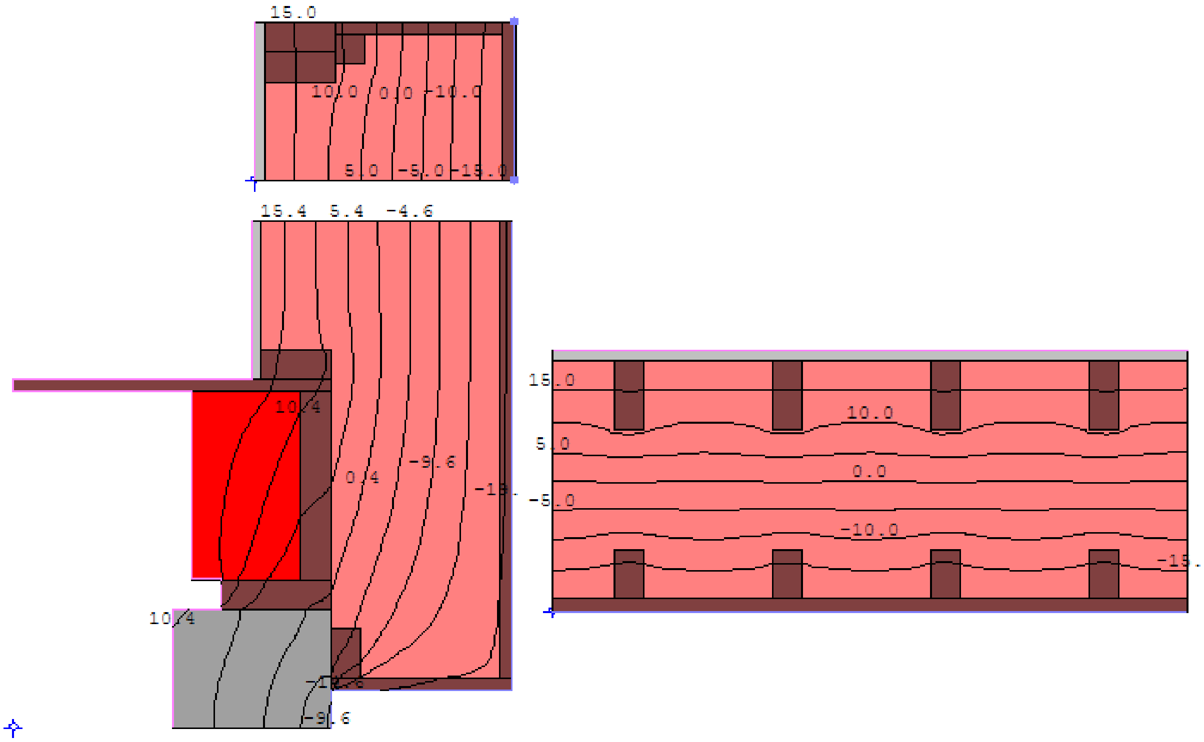


Figure 38 : Therm results of the truss wall

Table 9 : Calculated R-value for truss wall

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
5	Truss wall 12" R43 cellulose	**36.5**	18.6	40.5	34.4

1.5.2. Moisture Control

Vapor diffusion control and air leakage control are particularly important in this assembly since it has the greatest insulation value and the coldest winter sheathing temperatures. The truss wall has similar winter sheathing relative humidities to the double stud wall, but the relative humidities are slightly higher because of the lower sheathing temperature. There are approximately 4600 hours of potential winter time condensation, but the intensity of condensation is slightly greater than the double stud wall, again, because of the lower sheathing temperature (Figure 13).

The truss wall is very similar to the double stud wall although slightly lower in summertime inward vapor drive relative humidity at the vapor barrier (Figure 20). This is likely because of the increased moisture distribution and buffering from the increased amount of cellulose insulation in the truss wall.

Analysis of the drying results shows that the truss wall dries two or three days faster than both the double stud wall and the interior strapping wall (Figure 25) which is also because of the greater redistribution and buffering of moisture.

There is an increased risk of problems with the vapor control layer in the truss wall than both the double stud wall and the interior strapping wall, since the polyethylene vapor barrier will have penetrations for services and wiring. If the polyethylene sheet is also being relied on as the air barrier, which is common, this could lead to the highest risk of moisture related durability issues in all three similar test walls.

1.5.3. Constructability and Cost

The truss wall appears to require more time and energy to construct than the double stud wall. This strategy would likely not be considered by a production builder under normal conditions. Cladding attachment will be the same as the traditional construction. This wall appears to be highly dependent on good workmanship (even more so than the double stud Case 4 and interior strapping Case 3), as holes in the air barrier could result in serious moisture related durability issues from air leakage condensation. If a proper airtight drywall approach is used, this could help resolve any issues with holes in the polyethylene air and vapor barrier.

1.5.4. Other Considerations

This system seems both energy and work intensive, constructing gussets, and installing the exterior framing wall and is unlikely to be used except possibly in the coldest of locations where extremely high R-values are required. There are other alternatives that may have more appeal and less risk such as Cases 10 and 11 further in this report.

1.6 Case 6: Structural Insulated Panel Systems (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.

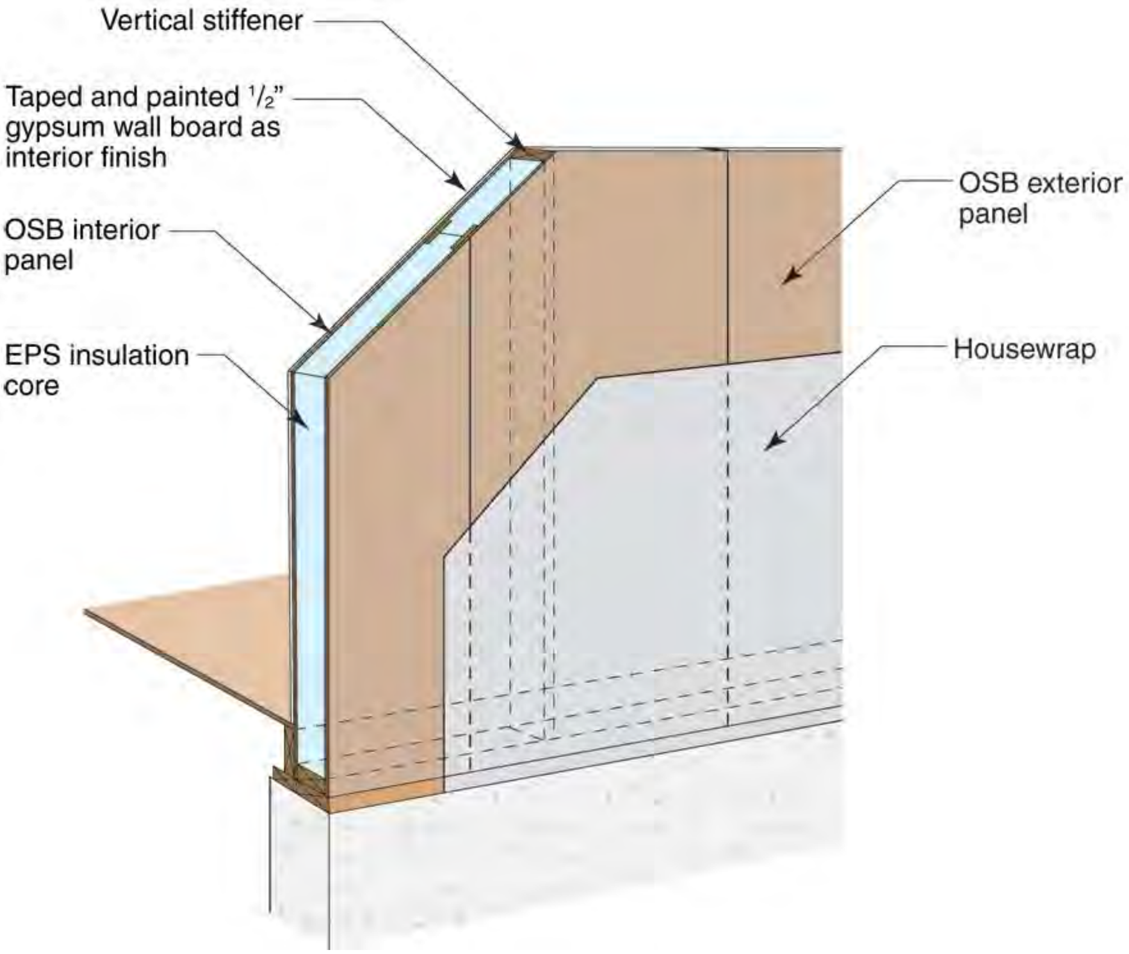


Figure 39 : SIPs wall construction

1.6.1. 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", 7.5"). 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.

The nominal value of this SIPs panel is R13, but because of a lack of thermal bridging through the wall (Figure 39), the calculated clear wall R-value of the wall is approximately R14.5 when the OSB and air films are taken into account. The whole wall R-value is approximately 13.6 when the top and bottom plate thermal bridges are accounted for (Table 10), which is actually higher than the installed insulation R-value.

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.

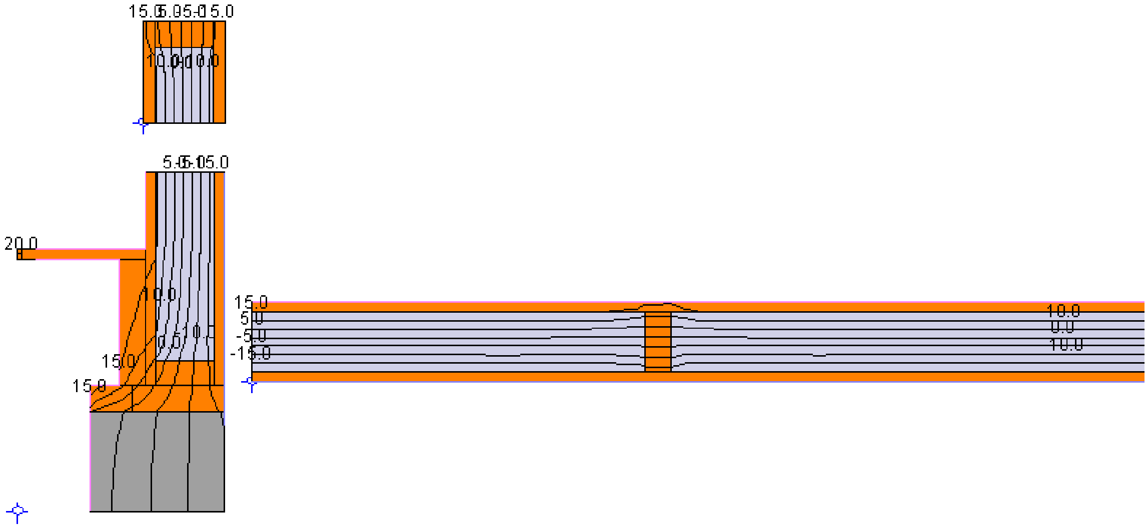


Figure 40 : Therm results of SIPs panel analysis

Table 10 : Calculated R-value for a Sips wall system

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
6a	SIPs (3.5" EPS)	**14.1**	12.3	14.5	10.6
6b	SIPs (11.25" EPS)	**36.2**	14	41.6	28.2

1.6.2. 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.

1.6.3. Constructability and Cost

Construction with SIPs panels requires training and education about construction techniques and design details. Generally, houses built from SIPs panels have very simple layouts and roof designs to help simplify the design of details at SIPs joints and roof-wall interfaces.

1.6.4. 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.

The 3.5” SIPs panel is not considered a High-R wall system, but as the thickness level, and insulation are increased, this system could be considered for more extreme cold climates.

1.7 Case 7: Insulated Concrete Forms (ICFs)

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.

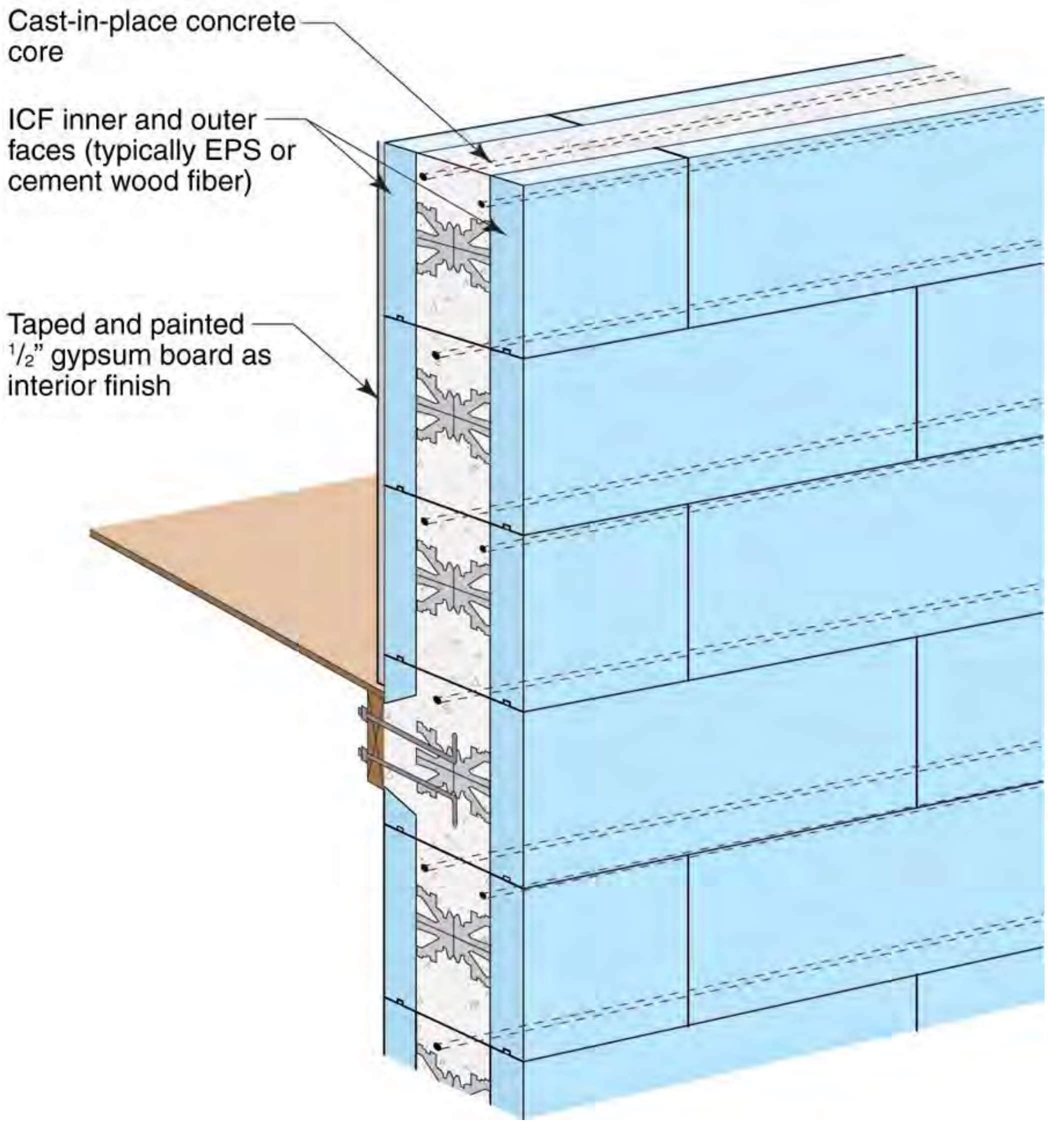


Figure 41 : ICF wall construction

1.7.1. 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 two different ICF systems. Figure 42 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. In comparison a 15" foam ICF with 5 total inches of EPS has an R-value of 20.6

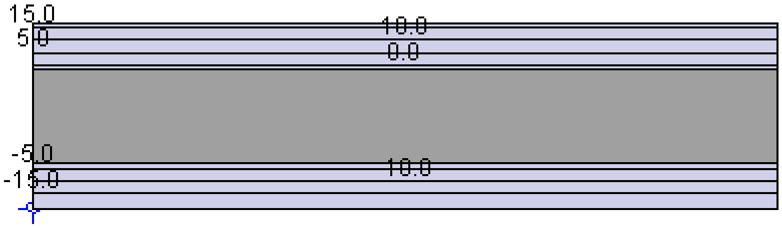


Figure 42 : Eight inch foam ICF with four inches of EPS

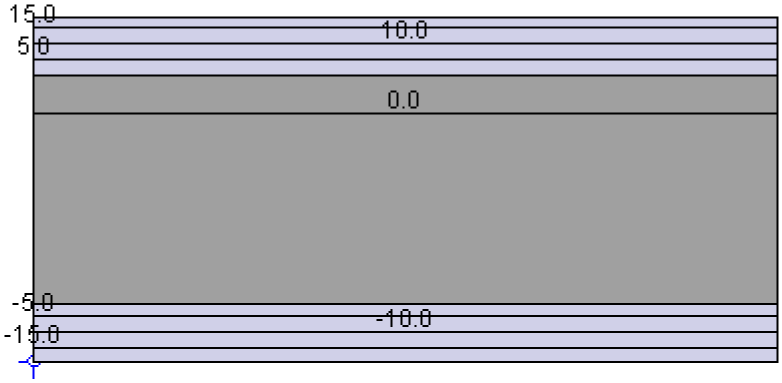


Figure 43 : Fifteen inch foam ICF with five inches of EPS

Neither of these ICF strategies would be considered a high-R enclosure in a cold climate, but these 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.

1.7.2. 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.

1.7.3. Constructability and Cost

ICFs are generally easy to use with some training on where and how to use steel reinforcement if necessary and installing services. Blocks are simply stacked on top of each other and concrete is poured into the centre. There have been reported issues with 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 perfectly flat substrate for drywall installation, but all of these problems can be dealt with by better training and quality control.

1.7.4. 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 alternative 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 mould if installed incorrectly.

1.8 Case 8: Advanced framing with spray foam

Polyurethane spray foam can be used in the stud cavity instead of fiberglass or cellulose insulation. Spray foam forms a very good air barrier when installed correctly and can be installed as low density (0.5 pcf) or high density (2.0 pcf) foam.

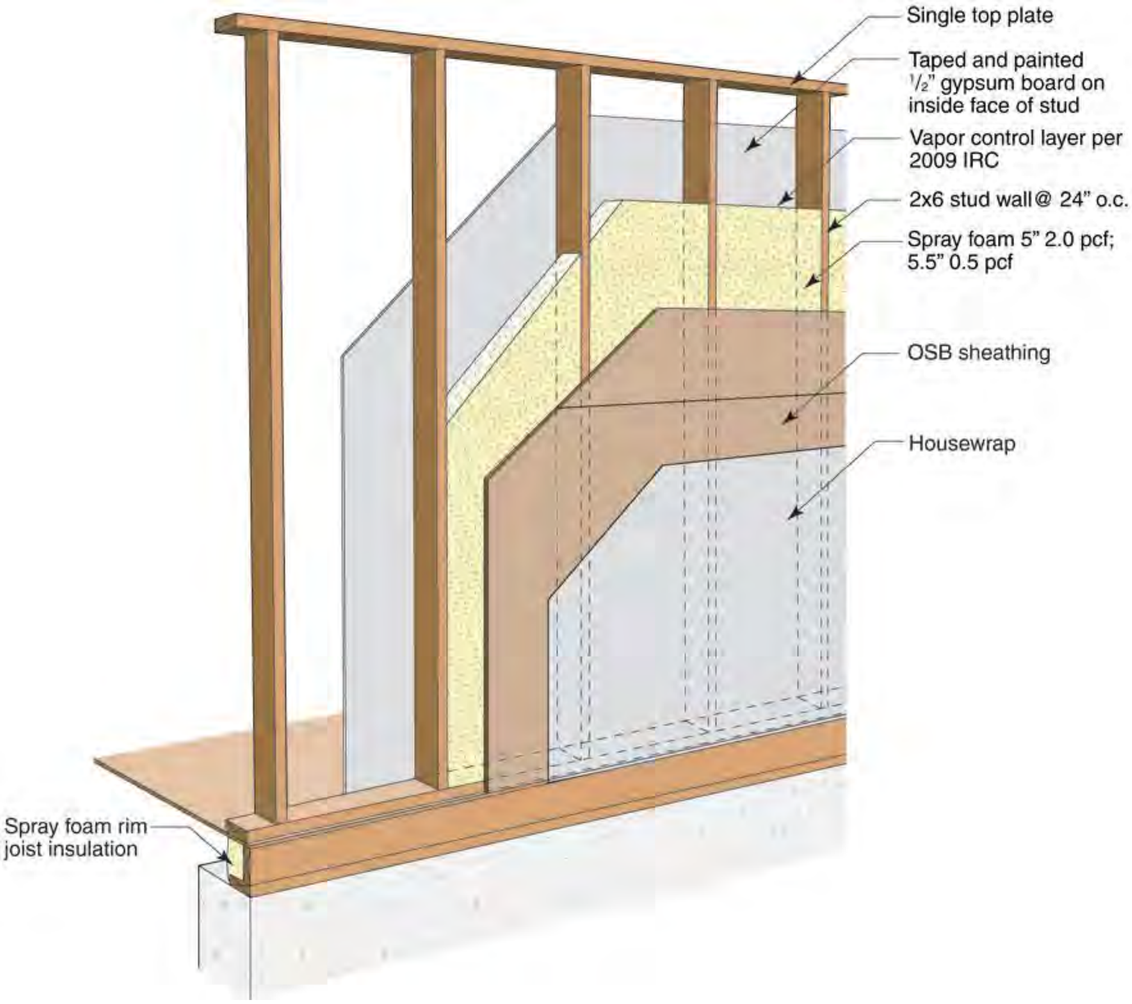


Figure 44 : 2x6 wall construction with spray foam insulation

1.8.1. Thermal Control

Using Therm to model different wall enclosure strategies does not accurate represent the benefits of spray foam insulation. Properly installed spray foam insulation completely stops air flow movement through and around the insulation so decreases in R-value associated with air leakage do not occur, either in the stud space or at the rim joist. There are different published R-values for both low and high density insulation but in this analysis for Case 8, 5.5” of R21 low density foam, and 5” of R28 high density foam were used. High density foam is installed short of the edge of the cavity to minimize trimming of the foam, while low density foam is softer, and installed to the edge of the cavity so that the excess can be trimmed flush with the stud wall framing.

Similar to standard construction practices, using spray foam does not address the concern of thermal bridging through the framing material as can be seen in Figure 45.

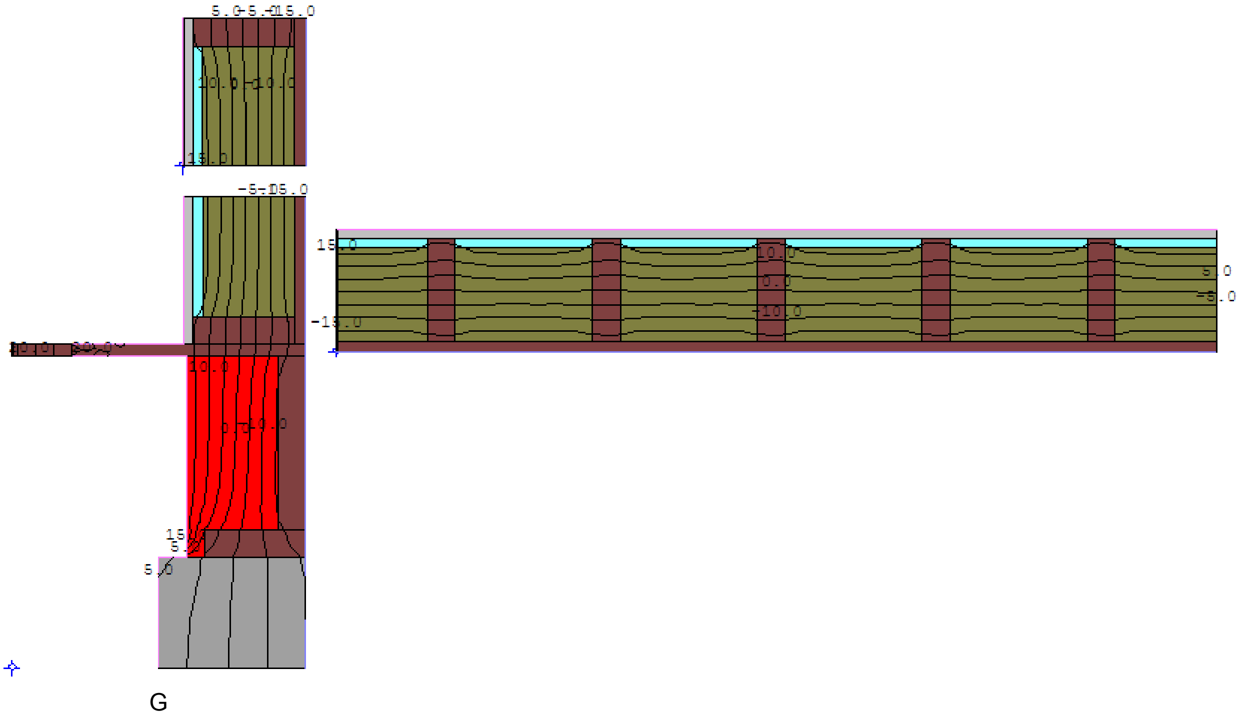


Figure 45 : Therm modeling of spray foam wall and rim joist

Calculating the whole wall R-values for the two spray foam assemblies results in R-values of R19.1 for high density spray foam, and R16.5 for the low density spray foam. The whole wall R-value of low density foam decreased by almost R4.5 versus the installed insulation R-value (from R20.9 to R16.5) because of thermal bridging. The whole wall R-value of the high density foam insulated wall decreased R9 from the installed insulation R-value due to the thermal bridging.

Table 11 : Therm results of spray foam insulation analysis

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
8a	2x6 AF, 24" o.c., 5" 2 pcf R29 SPF, OSB	**19.1**	13.6	20.3	19.5
8b	2x6 AF, 24" o.c., 5.5" R21 0.5 pcf SPF, OSB	**16.5**	13.1	17.2	16.6

1.8.2. Moisture Control

High density spray foam is both an air and vapor barrier. This limits the movement of moisture vapor and air leakage condensation. Low density foam is an air barrier, but it is permeable to water vapor and is susceptible to vapor diffusion condensation. Low density foam was modeled both with and without a class I vapor retarder to determine the performance differences of a class I vapor barrier with low density foam in climate Zone 6.

Both the high density foam and the low density foam with a vapor barrier had some of the lowest sheathing relative humidities in the winter months of all of the tested wall cases. The low density foam without a vapor barrier experienced high sheathing relative humidities sustained above 95% through the winter months (Figure 13).

Analysis of air leakage condensation shows that because the spray foam is an air barrier, there would be no condensation caused by air leakage, since the surface temperature of the interior face of the foam was always warmer than the dew point of the interior air (Figure 14).

Analysis of the summertime inward vapor drive shows that the low density sprayfoam with a poly vapor barrier experienced the highest relative humidity peaks of any of the test walls, approximately 5% higher than standard construction practice.

The high density foam and the low density foam without a vapor barrier experienced some of the lowest relative humidities of test walls because they were allowed to dry very easily to the interior.

Drying results (Figure 21) showed that the low density foam without poly dried to 100 kg/m3 in approximately 28 days similar to some of the other test walls, but the high density foam and low density foam with a vapor barrier took approximately 43 days to dry to 100 kg/m3.

1.8.3. Constructability and Cost

This wall is easier to build than a standard construction wall, since no care is required at installing fiberglass batts. The costs can be perceived as prohibitively expensive which is why sprayfoam is often only used where a perfect air barrier is required, and may be difficult to install, such as garage-house interface and rim joists.

1.8.4. Other Considerations

With the new era of environmentally friendly products, many spray foam companies are marketing green spray foams that are less or harmful to the environment. In most cases, spray foam may need to be protected with a fire rated material according to the code.

1.9 Case 9: Hybrid Wall Insulation – Flash and Fill

In this analysis, hybrid walls consist of two inches of 2.0 pcf closed cell foam sprayed against the interior surface of the exterior sheathing, and three and a half inches of fiberglass. Instead of fiberglass batt, cellulose or sprayed fiberglass could also be used. Flash and Fill or Flash and Batt is often used to describe the combination of spray foam and cellulose, or spray foam and fiberglass batt respectively. The framing strategy used is advanced framing with 2x6s 24" on centre with a single top plate. Spray foam insulation helps considerably with the air tightness of the wall assembly and will increase the temperature of the potential wintertime condensation plane. Two inches of high density spray foam in the cavity also decreases the need for an interior vapor control layer which simplifies construction.

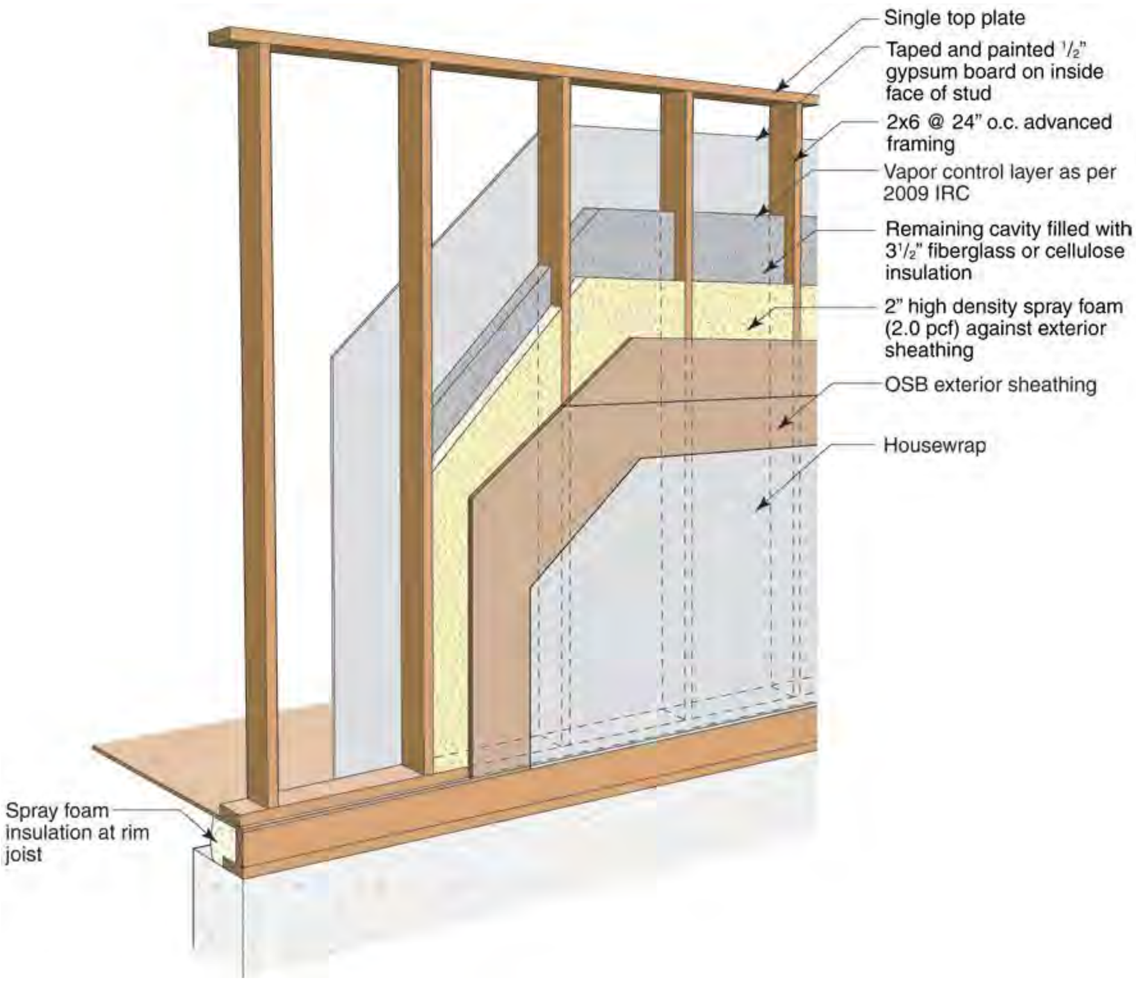


Figure 46 : Hybrid wall construction with 2" spray foam and fibrous fill

1.9.1. Thermal Control

The hybrid wall 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 true R-value. The whole wall R-value increases from R15.2 to R17.5 when comparing the same framing strategy with only fiberglass insulation (Case 1a) to Case 9. 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 and human comfort.

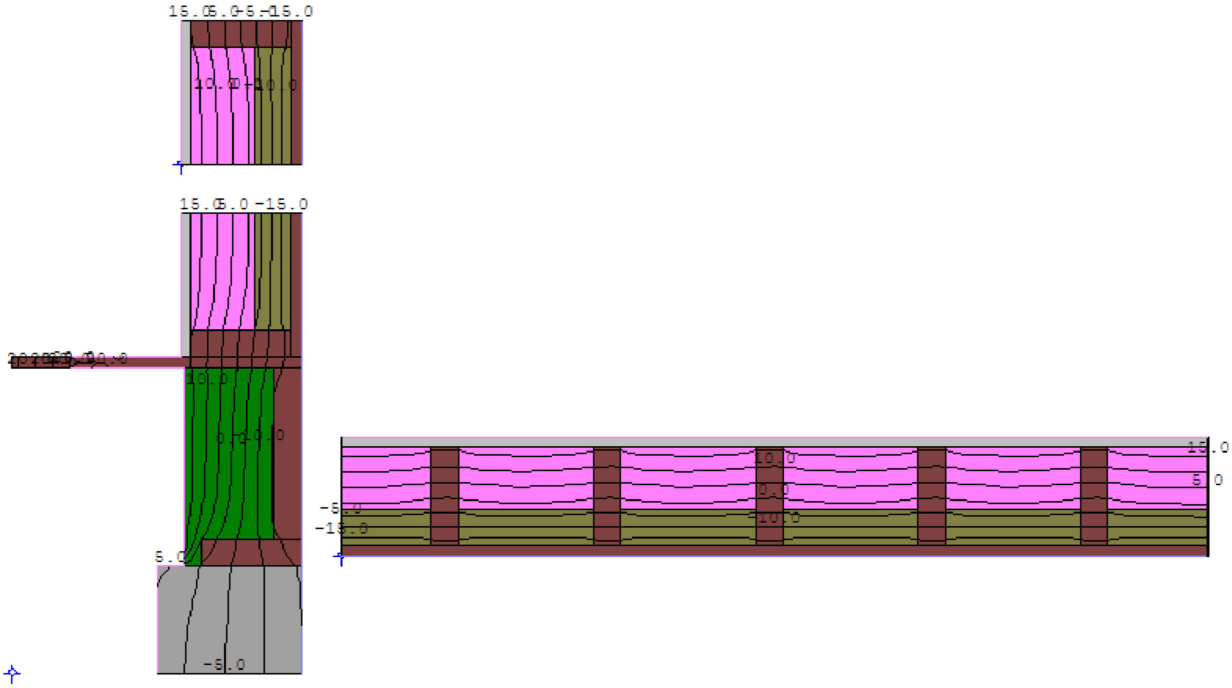


Figure 47 : Therm analysis of hybrid wall system

Table 12 : Calculated R-value for a hybrid wall system

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
9	2x6 AF, 24"oc, 2" SPF and 3.5" fibrous fill	**17.5**	13.2	18.4	17.7

1.9.2. Moisture Control

This wall performs very similarly to the Case 2 with 4" of exterior insulation with respect to summer inward vapor drives as shown in Figure 19.

During the winter months, there is a significant improvement in the potential air leakage condensation on the condensation plane in the hybrid wall, from the standard construction wall, as shown in Figure 11 because the condensation plane is kept warmer by the vapor impermeable spray foam insulation.

One disadvantage of this wall system over advanced framing with exterior insulation (Case 2) is that the sheathing is kept much colder in Case 9. Keeping enclosure materials warm and dry with exterior insulation has been known to increase enclosure durability since the 1960s (Hutcheon 1964).

1.9.3. Constructability and Cost

The constructability of this system is as easy as standard construction but the cost of construction is higher than using exclusively fiberglass insulation. This wall system is not as prone to air leakage moisture related damage as standard construction walls.

1.9.4. 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.

1.10 Case 10: Double Stud Wall with Spray Foam

Case 10 with spray foam insulation was chosen to try and improve the moisture related durability of the double stud wall in Case 4 which used cellulose insulation in the cavity space. The thermal performance of Case 4 was quite good, but the air leakage condensation potential could lead to premature enclosure failure. Case 10 analysis was conducted with two inches of spray foam since that is usually the maximum thickness that is sprayed in one pass during 2.0 pcf foam installation. This should increase the temperature of the condensation plane, thus increasing the moisture durability of the wall system. Depending on the climate zone for construction, more spray foam could be used to further decrease the risk of moisture related damage. Analyzing different thicknesses of spray foam for this single wall system are beyond the scope of this analysis report, but should be considered before this wall is constructed.

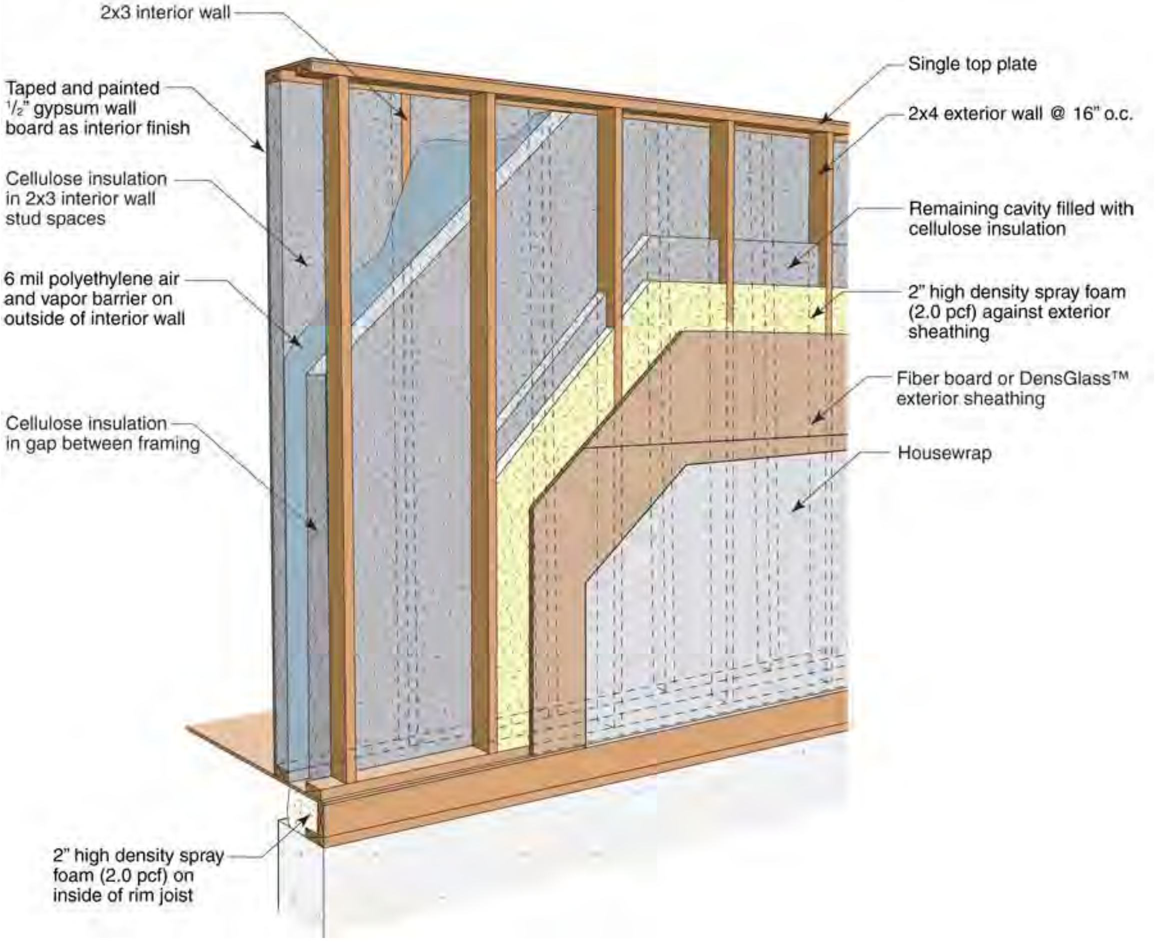


Figure 48 : Double stud wall with 2" of spray foam and cellulose fill

1.10.1. Thermal Control

This wall system has a slight improvement in whole wall R-value over Case 4, without spray foam insulation increasing from R30.1 to R32.4. This is only a minimal increase in the calculated whole wall R-value, but as in all cases with spray foam, there are improvements to the true R-value due to decreasing the air leakage through the wall and rim joist.

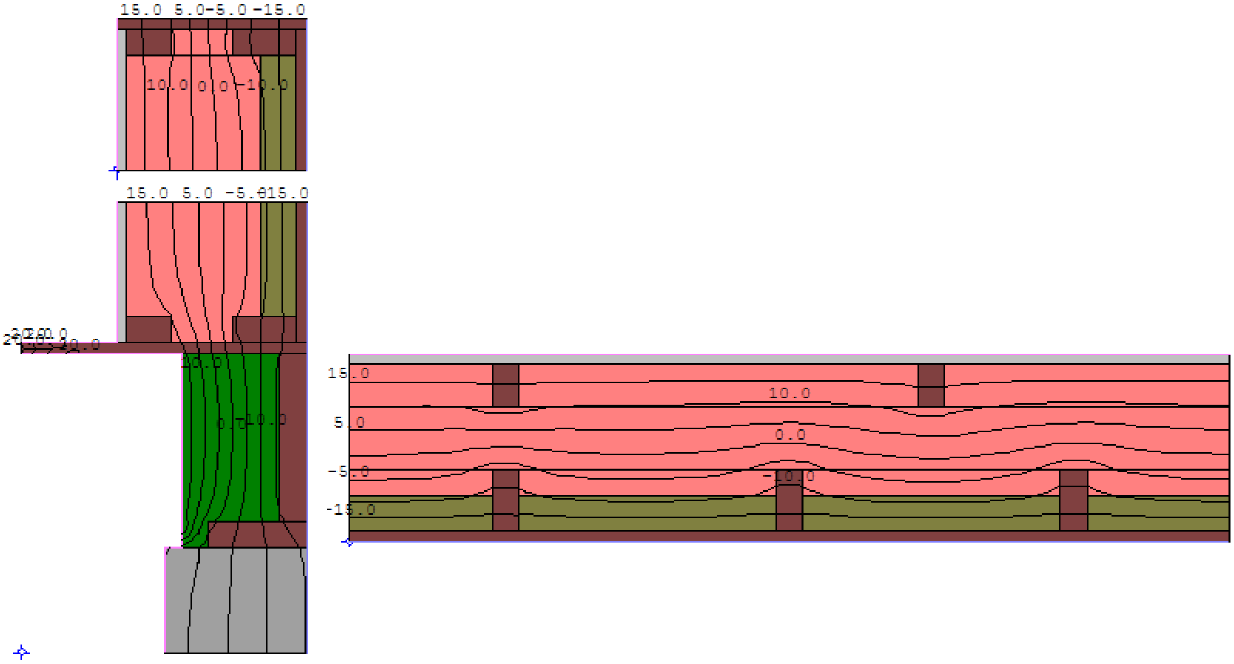


Figure 49 : Therm analysis of double stud wall construction with spray foam

Table 13 : Calculated whole wall R-value for a double stud wall system with 2" spray foam

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
10	Double stud with 2" 2.0 pcf foam, 7.5" cell.	**32.4**	15.9	36.2	28.5

1.10.2. Moisture Control

The most evident improvement to adding spray foam was shown in Figure 14 with less wintertime condensation potential. There are still periods of wintertime condensation risk in climate zone 6, the risks have been improved, and more spray foam would decrease the risk even further in climate zone 6 and should likely be required in colder areas. The hours of potential wintertime condensation decreased from approximately 4600 hours for Case 4 to approximately 2300 for Case 10 with spray foam insulation.

There is very little change to the drying results when comparing the double stud wall with and without spray foam insulation. The sheathing retains its moisture longer in Case 10 because the moisture can only dry to the exterior and is not buffered at all on the interior surface by the cellulose insulation (Figure 27). There are no significant changes to the summertime inward vapor drive by adding 2" of high density spray foam to the sheathing of the double stud wall (Figure 21). If a moisture storage cladding was used for simulations, adding the spray foam may reduce the inward vapor drive because of the vapor resistance of the spray foam.

1.10.3. Constructability and Cost

This wall system uses more framing material than most of the other test wall assemblies. The cost of this wall system is high relative to most of the other options, but does provide very high thermal resistance.

1.10.4. Other Considerations

The majority of the insulation is cellulose which is the lowest embodied energy insulation and readily available. The ratio of cellulose to spray foam insulation can be changed depending on the climate zone for construction to limit the potential winter time condensation.

Spray foam will burn, and therefore should always be protected by fire rated material, which in this case is the cellulose insulation.

1.11 Case 11: Offset Frame Wall with Exterior Spray Foam

Case 11 was included because of the increasing need for a retrofit solution that saves energy, increases durability and does not affect the interior space. This strategy also has several advantages as a new construction strategy as well, especially in extreme climates with a short construction season.

Standing lumber off of the sheathing using plywood trusses allows the cladding to be directly attached without requiring more exterior sheathing. High density foam acts as the drainage plane, air barrier, vapor barrier, and thermal control layer. Using plywood gusseted trusses can be a little work intensive since they all need to be made to identical dimensions.

An alternative solution to the traditional truss wall is shown in Figure 15. This method is less energy intensive in preparation. It uses large nails or spikes to support the framing lumber for the cladding installation. A spacer was used between the sheathing and the framing lumber to ensure even spacing and then was removed after the nails were installed. Even though this method does not appear to be strong enough to support cladding, it has supported approximately 200 lbs on a single truss prior to installing the foam, and is considerably stronger following the installation of the spray foam. An alternative method proposed for spacing the lumber off of the sheathing is to use plastic sleeves (possibly PVC pipe) which are cut to a constant length and used to set the depth of the nails that attach the lumber by driving the nails through the centre of them.

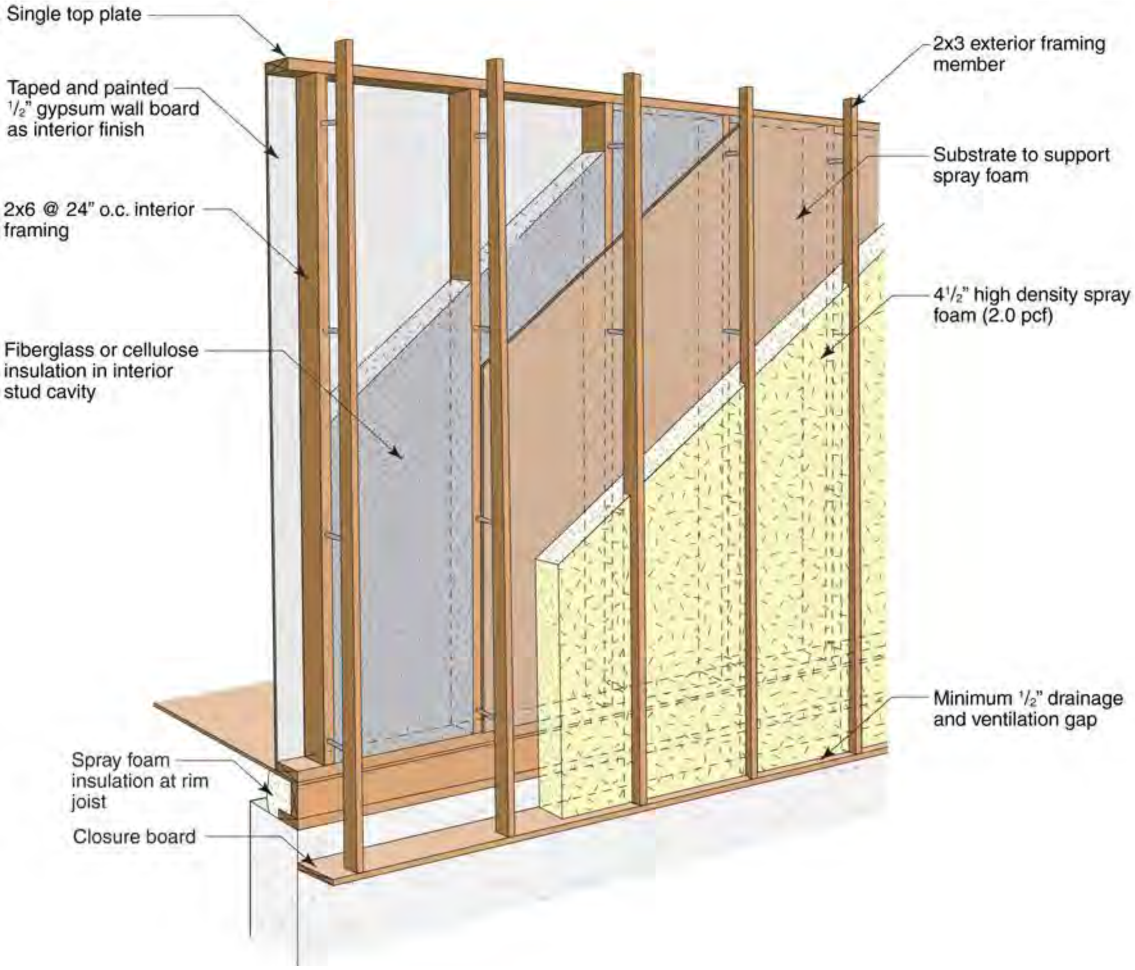


Figure 50 : Offset frame wall construction with exterior spray foam

1.11.1. Thermal Control

This wall with 4.5 inches of high density spray foam and 5.5 inches of fibrous insulation has a whole wall R-value of approximately R37, the highest total wall R-value of all walls analyzed which is, in part, because of the lack of thermal bridges through the entire system. Spray foam is installed over the rim joist, over the exterior of the wall, and up to the soffit, where ideally, it meets with the spray foam in the attic.

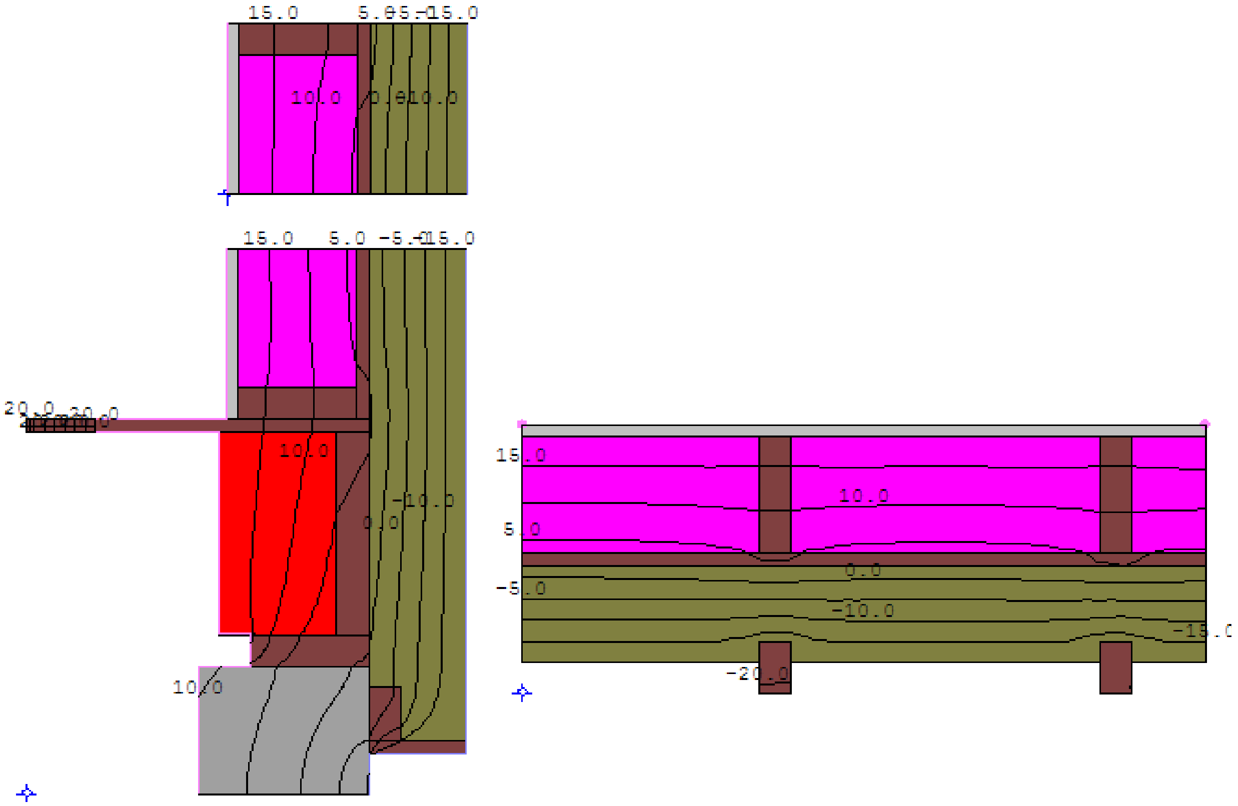


Figure 51 : Therm analysis of an offset truss wall with exterior spray foam

Table 14 : Calculated whole wall R-value for an offset framed wall with exterior spray foam

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
11	Offset frame wall with ext. spray foam	**37.1**	18.8	40.6	41.9

1.11.2. Moisture Control

Because of the high level of vapor control in the exterior spray foam insulation, a vapor barrier is not required on the interior of the wall assembly. This allows any necessary drying to occur to the interior. In Minneapolis, (climate zone 6) there is no risk of winter time condensation on the interior of the exterior sheathing (Figure 16).

The summer time inward vapor drive sheathing relative humidity does not change significantly with the addition of the exterior foam (Figure 23). The relative humidity increases slightly in Case 11 because of the higher interior relative humidity, the low solar inward vapor drive load, and the inability for the exterior spray foam wall to dry to the outside.

The sheathing remains wet during the drying test significantly longer with exterior insulation than without since there is no moisture buffering capacity in the fiberglass batt in Case 11, and there is significant moisture buffering capacity of the cellulose insulation in Case 5 (Figure 28).

1.11.3. Constructability and Cost

High density spray foam is a relatively expensive choice for an insulation strategy. In this case, it provides great thermal resistance, reduced thermal bridging, and minimal air leakage. Some of these benefits will result into operating energy costs savings, but other benefits can not be easily quantified such as greater occupant comfort, and quite possibly higher resale value in an uncertain energy future.

1.11.4. Other Considerations

This method could be used as a retrofit without greatly affecting the interior, or for new construction. It is a very quick, high quality method of sealing the exterior and drying in the interior during construction, so that care can be taken with the interior work including wiring, plumbing and HVAC. This is ideal for locations with short construction seasons. Since the foam is transported in liquid phase, more board feet of foam (and R-value) can be transported on a transport truck than any other type of insulation

1.12 Case 12: Exterior Insulation Finish System (EIFS)

Using an exterior insulation finish system (EIFS) is a valid option for cladding in almost every climate zone. The thickness of the exterior insulation can be varied to provide the thermal resistance required in combination with the stud space insulation. EIFs was one of the cladding strategies used on the CCHRC head office in Fairbanks AK (13980 HDD65 or 7767 HDD18) which is considered to be an extremely cold climate.

There is a stigma attached to EIFS because of the large number of failures in various climates in the past. Field and laboratory observations and testing have shown that this cladding technique is an effective and durable wall assembly, if drainage and water management details are constructed correctly. In most cases, during failures, water was trapped behind the EIFS due to poor water management details which eventually rotted the sheathing, causing corrosion and rot of the wall assembly. A properly detailed continuous drainage plane will ensure that this is a successful cladding technique in any climate zone.

Fiberglass-faced gypsum board exterior sheathing was used instead of OSB in the simulation because it is generally used underneath EIFS cladding systems due to its moisture tolerance.

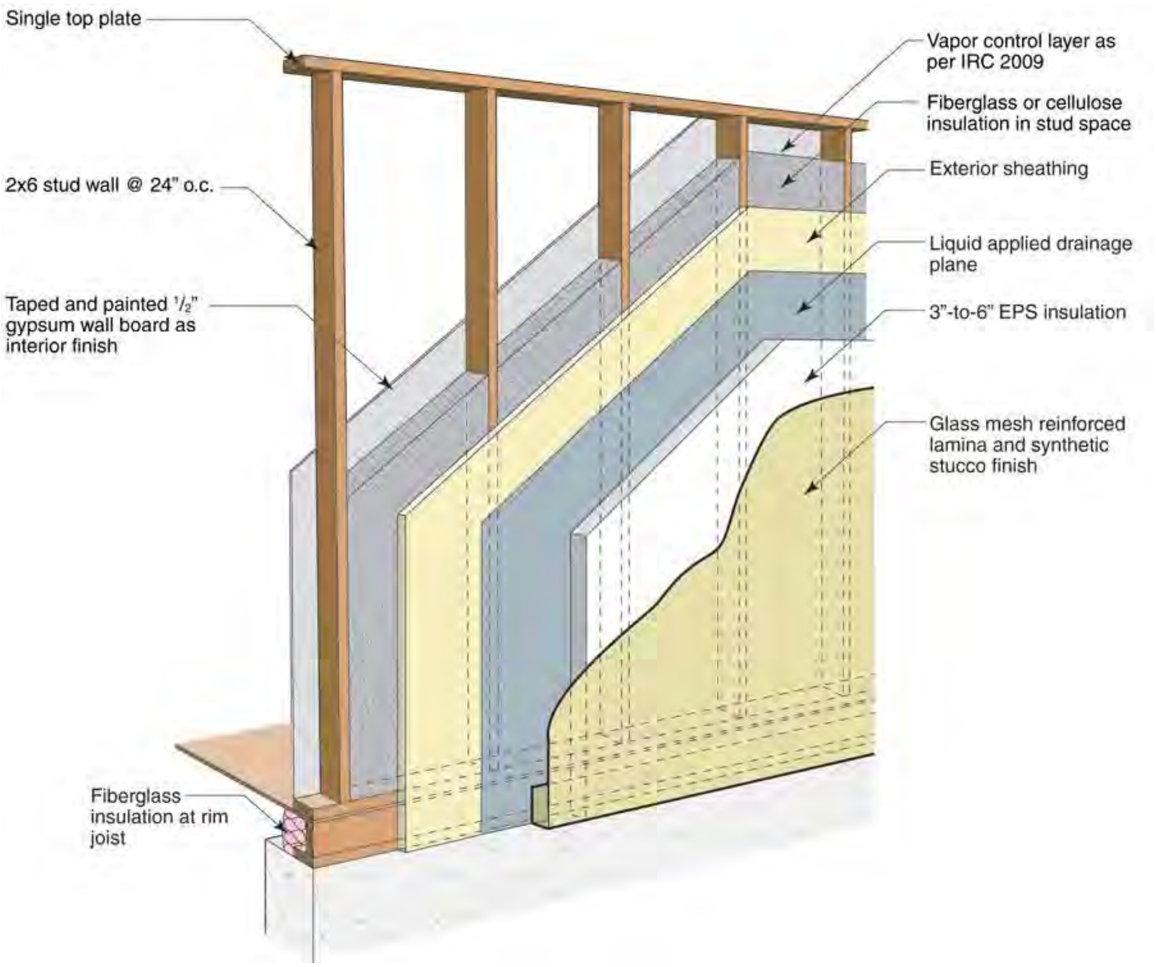


Figure 52 : Wall construction using the EIFS cladding system

1.12.1. Thermal Control

The amount of insulation installed on the exterior of the advanced framing will determine the thermal control of the assembly. In this analysis we used four inches of EPS board foam insulation, and achieved a whole wall R-value of R30. This strategy addresses the thermal bridging of both the framing and the rim joist and is very similar to advanced framing with four inches of XPS insulation in Case 2.

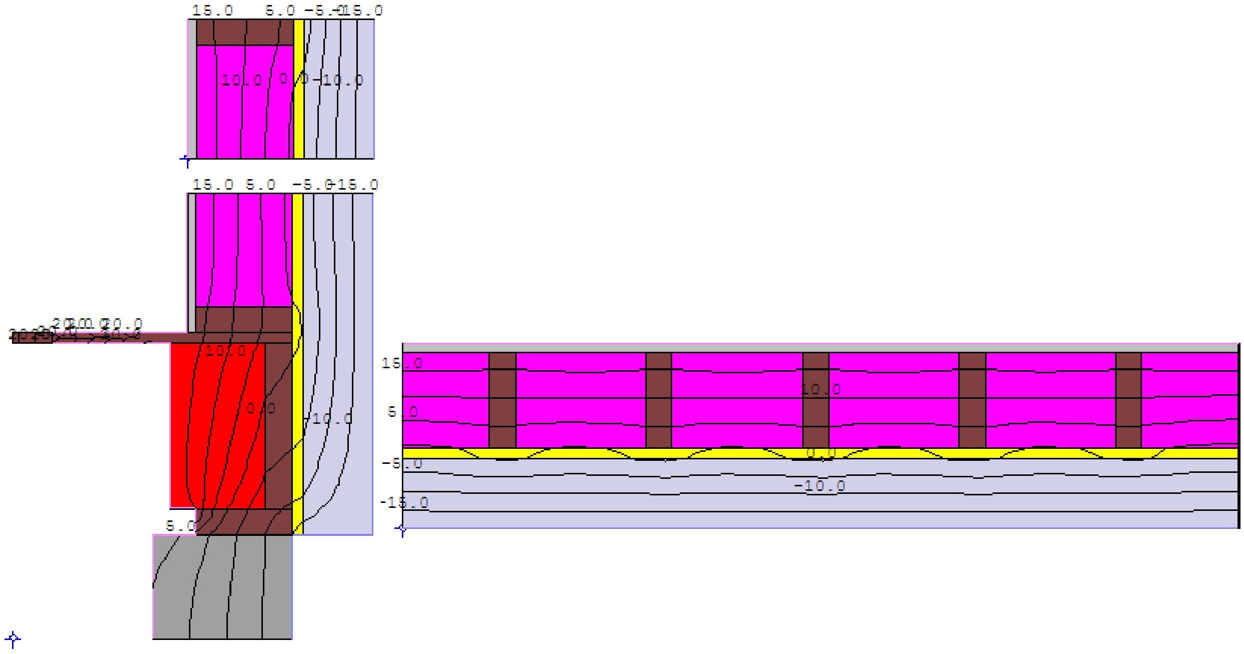


Figure 53 : Thermal analysis of an EIFS wall system

Table 15 : Calculated whole wall R-value for a EIFS wall system with 4” of EPS

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
12	2x6 AF, 24"oc, EIFS - 4" EPS	**30.1**	23.8	31.4	31.1

1.12.2. Moisture Control

The moisture management details for this cladding type can be challenging but EIFS companies generally provide good documentation and design details with their product. For example, both Sto Corp and Dryvit Systems provide many details for all of their products on their websites to help builders and designers with moisture management details.

The performance of this wall system was nearly identical in winter time condensation, drying and summer time inward vapor drives to Case 2 with 4” of XPS insulation. EPS is more vapor permeable than XPS insulation, but laminate coating applied to the EPS insulation is usually less than 1 US perm.

1.12.3. Constructability and Cost

Because of the stucco appearance of this cladding system, it can be more expensive depending on the architectural detailing. EIFS is generally only done if the appearance of stucco is specifically desired. It is approximately the same performance and cost to use advanced framing with four inches of XPS insulation and cladding.

1.12.4. Other Considerations

EIFS are generally chosen when the owner or architect wants a stucco finish on a building. There are no significant performance differences between EIFS and the advanced framing with exterior insulation shown in Case 2. Both strategies minimize thermal bridging, and increase the temperature of the potential wintertime air leakage condensation plane. The main differences are the appearance of the finished cladding surface and water drainage details.

D. Conclusions

Whole wall R-values for all of the assemblies were calculated using Therm and the summary is shown in Table 16 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.

Table 16 : Summary of all calculated R-values

Case	Description	Whole Wall R-value	Rim Joist	Clear Wall R-value	Top Plate
1bii	2x4, 16"oc, R13FG + OSB (25%ff)	**10.0**	9.8	10.1	9.8
1b	2x4 AF, 24"oc, R13FG + OSB	**11.1**	9.8	11.5	9.8
1aii	2x6, 16"oc, R19FG + OSB (25%ff)	**13.7**	12.3	14.1	12.5
6a	SIPs (3.5" EPS)	**14.1**	12.3	14.5	10.6
1a	2x6 AF, 24"oc, R19FG + OSB	**15.2**	12.3	16.1	12.5
7a	ICF - 8" foam ICF (4" EPS)	**16.4**		16.4	
8b	2x6 AF, 24" o.c., 5.5" R21 0.5 pcf SPF, OSB	**16.5**	13.1	17.2	16.6
7c	ICF - 14" cement woodfiber ICF with Rockwool	**17.4**		17.4	
9	2x6 AF, 24"oc, 2" SPF and 3.5" cellulose	**17.5**	13.2	18.4	17.7
8a	2x6 AF, 24" o.c., 5" 2 pcf R29 SPF, OSB	**19.1**	13.6	20.3	19.5
2a	2x6 AF, 24"oc R19FG + 1" R5 XPS	**20.2**	18.5	20.6	20.3
7b	ICF - 15" foam ICF (5" EPS)	**20.6**		20.6	
3	2x6 AF, 24"oc, 2x3 R19+R8 FG	**21.5**	13.4	23.5	18.4
4	Double stud wall 9.5" R34 cellulose	**30.1**	14.4	33.5	28.8
12	2x6 AF, 24"oc, EIFS - 4" EPS	**30.1**	23.8	31.4	31.1
10	Double stud with 2" 2.0 pcf foam, 7.5" cell.	**32.4**	15.9	36.2	28.5
2b	2x6 AF, 24"oc R19FG + 4" R20 XPS	**34.5**	29.0	35.6	35.4
6b	SIPs (11.25" EPS)	**36.2**	14	41.6	28.2
5	Truss wall 12" R43 cellulose	**36.5**	18.6	40.5	34.4
11	Offset frame wall with ext. spray foam	**37.1**	18.8	40.6	41.9

*AF - Advanced Framing

The walls analyzed in this report can be grouped into three groups based on their calculated whole wall R-values. The first group have whole wall R-values less than approximately R20. These walls are not considered High-R wall systems for cold climates.

The second group of walls have whole wall R-values of approximately R-20. According to the IECC, the requirement for climate zones 7 and 8 is an installed R-value of R21. This report has shown that the whole R-value is less than the installed insulation R-value in almost every case, which means that often, the walls that the IECC allow in extremely cold climates are actually performing at a whole wall R-value of between R15 and R20. This is unacceptable in the future of uncertain oil reserves, increasing energy costs, and decreasing environmental health.

The third group of walls have whole wall R-values greater than R30. This is what the construction industry has been achieving in very small numbers, such as Building America prototype homes, and small custom home builders. The R-value of walls in the category can be modified easily by either decreasing or increasing the amount of insulation depending on the specific construction conditions. All of the walls in category three have minimized thermal bridging which increases the effectiveness of insulation.

The potential for wintertime air leakage was compared for all test walls, and the summary of the results are shown in Table 17. The walls were ranked from the least hours of potential condensation to the greatest. This potential condensation is only an issue if the airtightness details aren't constructed properly, but should still be used to assess the potential risk of a wall system, considering that field observations show the air barrier detailing is rarely perfect.

Table 17 : Hours of potential winter time air leakage condensation

Case	Description	Hours of Potential Condensation
8b	2x6 AF, 24" o.c., 5.5" R21 0.5 pcf SPF, OSB	0
8a	2x6 AF, 24" o.c., 5" 2 pcf R29 SPF, OSB	0
11	Offset frame wall with ext. spray foam	0
9	2x6 AF, 24"oc, 2" SPF and 3.5" cell or FG	934
2b	2x6 AF, 24"oc R19FG + 4" R20 XPS	1189
12	2x6 AF, 24"oc, EIFS - 4" EPS	1532
10	Double stud with 2" 2.0 pcf foam, 7.5" cell.	2284
2a	2x6 AF, 24"oc R19FG + 1" R5 XPS	3813
1a	2x6 AF, 24"oc, R19FG + OSB	4379
1b	2x4 AF, 24"oc, R13FG + OSB	4503
4	Double stud wall 9.5" R34 cellulose	4576
3	2x6 AF, 24"oc, 2x3 R19+R8 FG	4594
5	Truss wall 12" R43 cellulose	4622

*AF - Advanced Framing

The comparison matrix explained in the introduction was completed according to the analysis of each wall section in this report (Table 18), and it was found that three walls achieved the highest score of 20 out of a possible 25 points. The advanced framing wall (Case 2), sprayfoam insulation wall (Case 8) and EIFS wall (Case 12) achieved scores of 20 using an even weighting system of all selection criteria.

The main issue with most of the wood framed walls without exterior insulation is the probability of wintertime air leakage condensation depending on the quality of workmanship and the attention to detail. Inspections of production builder 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.

Table 18 : Wall Comparison Chart

	Thermal Control	Durability (wetting/drying)	Buildability	Cost	Material Use	Total
Criteria Weighting	1	1	1	1	1	
Case 1: Standard Construction	1	3	5	5	3	17
Case 2: Advanced Framing with Insulated Shtg	4	4	4	4	4	20
Case 3: Interior Strapping	3	3	3	4	4	17
Case 4: Double Stud	4	3	3	3	2	15
Case 5: Truss Wall	4	3	2	3	3	15
Case 6: SIPs	4	4	3	3	3	17
Case 7: ICF	4	5	4	2	3	18
Case 8: Sprayfoam	5	5	4	2	4	20
Case 9: Flash and Fill (2" spuf and cell.)	4	4	4	3	4	19
Case10: Double stud with 2" spray foam and cell.	5	4	3	3	3	18
Case 11: Offset Framing (ext. Spray foam insul.)	5	5	4	3	2	19
Case 12: EIFS with fibrous fill in space	5	5	4	3	3	20

Adding exterior insulation to most wall systems has many durability and energy benefits. Two dimensional heat flow modeling has shown that exterior insulation is very effective at minimizing the thermal bridging losses of wall framing, and hygrothermal modeling showed reduced condensation potential in the wall from vapor diffusion and air leakage, as well as increased drying potential to the interior with reasonable interior relative humidities. Adding exterior insulation was shown to increase the effectiveness of the fiberglass batt insulation in the stud space and increase the clear wall R-value greater than the amount of insulation added. This becomes even more important with higher thermal bridging such as a high framing factor or steel studs. Adding exterior insulation greater than approximately R5, the installed insulation R-value can be added directly to the clear wall R-value and is approximately equal to the increase in whole wall R-value since most of the thermal bridging is addressed.

Hygrothermal modeling showed that traditional double stud walls, truss walls and interior strapped walls, are at a greater risk of air leakage condensation because of the air permeable insulation, and cold exterior surface. Hybrid walls are a good strategy to help overcome this problem by using vapor impermeable spray foam insulation against the exterior, which increases the temperature of the condensation plane. The amount of spray foam required in a hybrid system is dependent on the climate zone for construction, but it may be difficult to get a high enough R value or thermal bridge control in cold climates for net zero housing.

ICF and SIPS walls both have insulation integral to the system, but require more insulation for a High R value wall assembly. Experience and modeling indicate that both of these techniques are susceptible to moisture issues if the details are not done correctly. SIPS are particularly susceptible to air leakage at the panel joints, and ICF walls need well designed penetrations, to avoid water ingress.

In extreme cold climates, and remote areas, high density spray foam appears to address most of the concerns that have been reported by NRC during visits and interviews with local residents. High density spray foam is easy to ship and install, not subject to damage during transit, and allows some variations in construction quality levels since it is both an air and vapor barrier. High density spray foam can be used in different wall construction strategies as demonstrated in this report, either on its own or as part of an insulation strategy with other insulations types. An offset frame wall with high density spray foam has the added advantage of drying in a house very quickly in the short construction season so that work can be done on the interior during inclement weather.

E. Works Cited

BSC. "BSP-035: Designs that Work: Very Cold Climate (Juneau, AK)." *buildingscience.com information.* 2008. http://www.buildingscience.com/documents/primers/bsp-035-designs-that-work-very-cold-climate-juneau-ak/section-2-the-basic-very-cold-climate-house/view?searchterm=haida%20house.

Carpenter, S C, and C J Schumacher. "Characterization of Framing Factors for Wood-Framed Low-Rise Residential Buildings." *ASHRAE Transactions v 109, Pt 1.*, 2003.

CCHRC. "Cold Climate Housing Research Center." *Research and Testing Faciility.* 2007. http://www.cchrc.org/research+_+testing+facility.aspx.

Christian, J E, and J Kosny. "Towards a National Opaque Wall Rating Label." *U.S. DOE VI Thermal Envelope Conference.* 1995.

Hutcheon, N B. "CBD-50. Principles Applied to an Insulated Masonry Wall." *Canadian Building Digest*, 1964.

Kosny, Jan, David Yarbrough, Phillip Childs, and Syed Azam Mohiuddin. "How the Same Wall Can Have Several Different R-Values: Relations Between Amount of Framing and Overall Thermal Performance in Wood and Steel-Framed Walls." *Buildings X.* ASHRAE, 2007.

Lstiburek, J. *YouTube.* May 3, 2007. http://www.youtube.com/watch?v=D_IrtDR3p0c&feature=channel_page (accessed March 6, 2009).

Niemz, Peter. "Untersuchungen zur Warmeleitfahigkeit ausgewahlter einheimischer und fremdlandischer Holzarten." *Verlag fur Architektur und technische Wissenschaften*, Bauphysik 29 (2007): 311-312.

Rousseau, M.Z., S.M. Cornick, M.N. Said, W Maref, and M.M. Manning. *PERD 079 Project - Report Task 4 - Review of Work Plan & Selection of Wall Assemblies.* Ottawa, Canada: National Research Council Canada, 2008.

Saïd, M.N.A. *Task 2: Literature Review: Building Envelope, Heathing, and Ventilating Practices and Technologies for Extreme Climates.* Ottawa, Canada: National Research Council Canada, 2006.

Simpson, William, and Anton TenWolde. "Physical Properties and Moisture Relations of Wood." In *Wood Handbook*, 3-1 - 3-24. Madison, WI: Forest Products Laboratory, 1999.

SIPA. "SIPA Report on the Juneau, Alaska Roof Issue." *Structural Insulated Panel Association.* February 2002. http://www.sips.org/content/technical/index.cfm?PageId=161 (accessed 03 10, 2009).

Smegal, Jonathan, and John Straube. *CCHRC Test Trailer at University of Alaska Southeast.* Waterloo, Canada: Balanced Solutions Inc., 2006.

Straube, John, and Eric Burnett. *Building Science for Building Enclosures.* Westford: Building Science Press, 2005.

About this Report

This report was prepared with the cooperation of the U.S. Department of Energy's, Building America Program.

Direct all correspondence to: Building Science Corporation, 30 Forest Street, Somerville, MA 02143.

Limits of Liability and Disclaimer of Warranty:

STANDARD WALL CONSTRUCTION

STANDARD WALL CONSTRUCTION DETAILS (*Walls 1A and 1B*)[1]

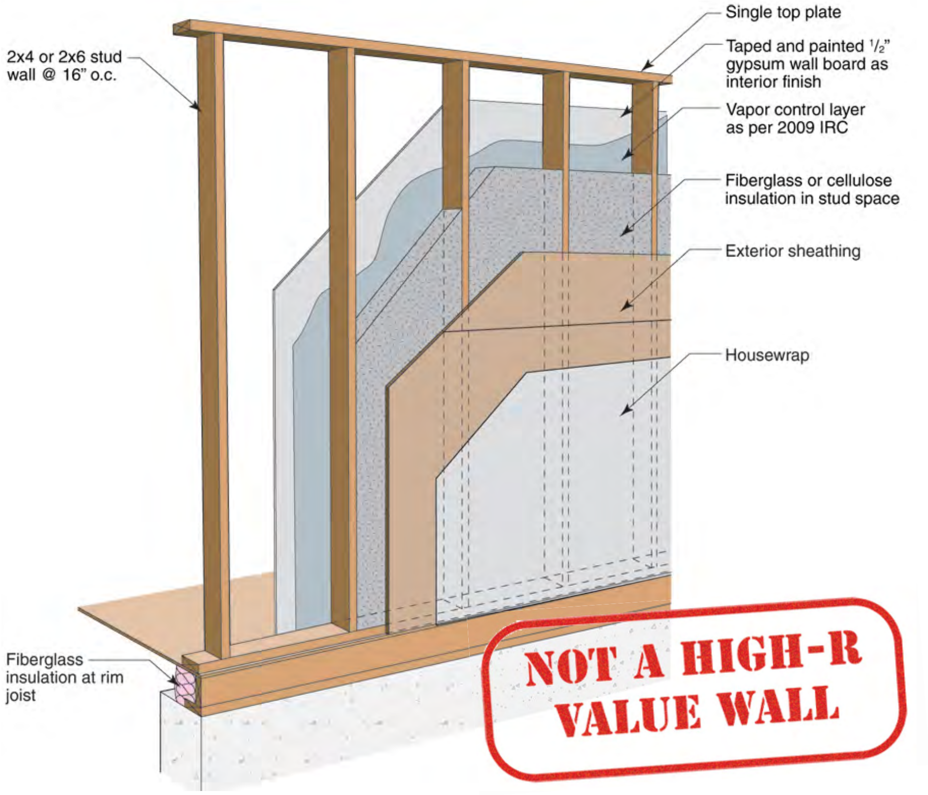
- 2x4 or 2x6 framing
- Fiberglass or cellulose cavity insulation in stud space
- Exterior sheathing
- Housewrap

SCORING: HOW IT RATES

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	1
Durability	3
Buildability	5
Cost	5
Material Use	4
Total	**18**

This wall has been the standard of construction for many years in many places but no longer meets the energy code requirements for insulation in some climates. Many higher performance designs exist.



INTRODUCTION

This two page summary briefly summarizes standard wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

THERMAL CONTROL

Installed Insulation R-value: There is a range of installed insulation R-values in commercially available fiberglass batts. The installed insulation R-value for 2x4 fiberglass batt ranges between R-11 and R-15 and for 2x6 the range is between R-19 and R-22. When blown or sprayed cellulose insulation is used, the R-values are typically R-13 for 2x4 and R-20 for 2x6 walls.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors, a 2x4 wall with R-14 studspace insulation has a whole-wall R-value of R-9. Similarly a 2x6 wall with R-19 stud space insulation has a whole wall R-value of R-11.[1] The framing factor used for standard construction framing 16 inches on center is 25%.[2] These whole wall R-values could decrease even further if there is significant air leakage or convective looping, or increased framing factor.

Air Leakage Control: Fiberglass batt, and both blown and sprayed cellulose are air permeable materials allowing possible air paths between the interior and exterior as well as convective looping in the insulation. Although densepack cellulose has less air permeance it does not control air leakage.

Building America U.S. Department of Energy
Research Toward Zero Energy Homes

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Building Science Corporation
30 Forest Street
Somerville, MA 02143
www.buildingscience.com

Typical Insulation Products: Fiberglass batt, blown fiberglass, blown cellulose, sprayed cellulose

DURABILITY

Rain Control: Rain leakage into the enclosure is the leading cause of premature building enclosure failure. Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). Intersections, windows, doors and other penetrations must be drained and/or detailed to prevent the penetration of rain water beyond the drainage plane.[3]

Air Leakage Control: Air leakage condensation is the second largest cause of premature building enclosure failure with this type of wall construction. It is very important to control air leakage to minimize air leakage condensation durability issues. An air barrier is required in this wall system to ensure that through-wall air leakage is eliminated (ideally) or at least minimized. An air barrier should be stiff and strong enough to resist wind forces, continuous, durable, and air impermeable.[4]

Air need not leak straight through an assembly to cause moisture problems; it can also leak from the inside, through the wall, and back to the inside; or it can leak from the outside, through the wall, and back to the outside. Condensation within the studspace is possible if this type of airflow occurs, depending on the weather conditions. Hence, wall designs should control airflow into the studspace.[5]

Vapor Control: Fiberglass and cellulose are highly vapor permeable materials, so a separate vapor control strategy must be employed to ensure that vapor diffusion does not result in condensation on, or damaging moisture accumulation in, moisture sensitive materials. The permeance and location of vapor control is dependent on the climate zone. Installing the vapor control layer in the incorrect location can lead to building enclosure failure.[6] The IRC building code should be consulted.

Drying: Cellulose and fiberglass insulation allow drying to occur relatively easily, so drying is controlled by other more vapor impermeable enclosure components such as the vapor barrier and OSB sheathing. Installing vapor control on both sides will seal any moisture into the stud space, resulting in low drying potential, and possibly resulting in moisture-related durability risks. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before close in. Cellulose is often sprayed in damp, and manufacturers recommend drying before close in and moisture content limits. Because of the polyethylene vapor barrier required in many climates, and relatively vapor impermeable OSB sheathing, drying could be slow if built-in moisture is present.

Durability Summary: The primary durability risks associated with these wall assemblies involve moisture damage related to rain water penetration or condensation (most likely the result of air leakage, but also potentially the result of vapor diffusion).

Cellulose insulated walls are slightly more durable because cellulose insulation is capable of storing and redistributing small amounts of moisture. Cellulose insulation is typically treated with borates that have been shown to protect itself and neighboring wood material from mold growth and decay. Cellulose insulation also has decreased flame spread potential relative to other insulation materials.

BUILDABILITY

Wood-framed walls with OSB exterior sheathing and fiberglass or cellulose insulation represent the most common wall assembly used in the construction of low-rise residential buildings in North America. Designers, trades and supply chains are well equipped to produce these walls and education is primarily needed to improve durability through better rainwater control and thermal performance through better air tightness and insulating practices.

COST

The cost to build this type of wall is well accepted, and is used as a baseline. Costs vary tremendously from region to region.

MATERIAL USE

This wall design contains redundant wood framing and wood sheathing. Framing lumber could be minimized further if advanced framing was used. In most of America, much of the sheathing could be removed. Cellulose has a significantly lower embodied energy than fiberglass or rockwool.

TOTAL SCORE

This wall has been the standard of construction for many years in many places. This wall no longer meets the energy code requirements for insulation in many climates, and thermal control requirements will only continue to increase. This wall system is difficult to air seal adequately and prone to air leakage related condensation and energy losses. Using advanced framing will reduce framing materials, and the cost of framing. Although this construction technique is usually allowed by code, many higher performance designs exist.

REFERENCES

1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis*. Retrieved from buildingscience.com.

2 Carpenter, S C, and C J Schumacher. "Characterization of Framing Factors for Wood Framed Low Rise Residential Buildings." *ASHRAE Transactions v 109, Pt 1.*, 2003

3 Lstiburek, J. W. (2006). *Water Management Guide.* Westford: Building Science Press Inc.

4 Lstiburek, J. (2008, 08 20). *BSD-104: Understanding Air Barriers*. Retrieved from buildingscience.com.

5 Straube, J. (2009, 04 22). *BSD-014 Air Flow Control in Buildings.* Retrieved from buildingscience.com.

6 Lstiburek, J. (2008, 10 17). *BSD-106 Understanding Vapor Barriers.* Retrieved from buildingscience.com.

2x6 ADVANCED FRAME WALL CONSTRUCTION

2x6 ADVANCED FRAME WALL CONSTRUCTION DETAILS

(Walls 2A and 2B)[1]

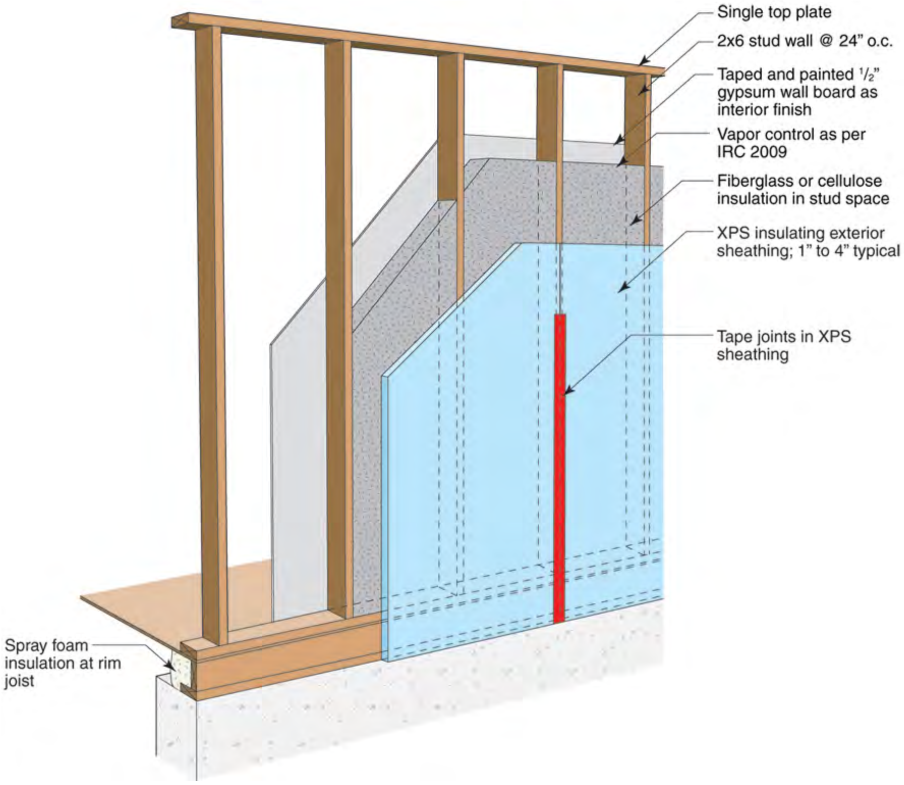
- 2x6 framing
- XPS insulating sheathing
- Fiberglass or cellulose cavity insulation in stud space

SCORING: HOW IT RATES

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	4
Durability	4
Buildability	4
Cost	4
Material Use	4
Total	**20**

Advanced framing with insulated sheathing significantly reduces the thermal bridging through the enclosure and improves the thermal efficiency of the fiberglass batt in the stud space. Using insulated sheathing decreases the potential for both wintertime condensation, and summer inward vapor drives, and helps mitigate issues caused by poor construction practices.



INTRODUCTION

This two page summary briefly summarizes 2x6 advanced frame wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

THERMAL CONTROL

Installed Insulation R-value: There is a range of installed insulation R-values in commercially available fiberglass batts for the stud space insulation in this wall system. The installed insulation R-value for 2x4 fiberglass batt ranges between R-11 and R-15 and for 2x6 the range is R-19 and R-22. When blown or sprayed cellulose insulation is used, the R-values are typically R-13 for 2x4 walls and R-20 for 2x6 walls.

Exterior insulating sheathing is typically added as expanded Ppolystyrene (EPS) at R-4/inch, extruded polystyrene (XPS) at R-5/inch or foil-faced polyisocyanurate at R-6.5/inch.

Whole-wall R-value: Two-dimensional heat flow analysis with thermal bridging effects and average framing factors (16%) shows increases the R-value of the assembly and improvements to the efficiency of the fiberglass batt in the stud space by decreasing the thermal bridging effects. Advanced framing walls with 1" and 4" of XPS insulated sheathing have whole wall R-values of R-20 and R-34 respectively.[1]

Air Leakage Control: Fiberglass, blown and sprayed cellulose are air permeable materials used in the stud space of the wall allowing possible air paths between the interior and exterior as well as convective looping in the insulation. Densepack cellulose has less air permeance but does not control air leakage. Insulating sheathing (EPS, XPS and foil-faced polyisocyanurate board foam) products are air impermeable. When joints between panels of insulation and the insulation and framing are properly sealed with tape, mastic, caulk, etc., an effective air barrier system can be created at the exterior sheathing.

Typical Insulation Products: Fiberglass batt, blown cellulose, sprayed cellulose, and sprayed fiberglass are typically used to insulate the stud space. Expanded polystyrene (EPS), extruded polystyrene (XPS) and foil-faced polyisocyanurate (PIC) board foam are used as the exterior insulating sheathing. Spray foam is used at the rim joist to control air leaks.

DURABILITY

Rain Control: Rain leakage into the enclosure is the leading cause of premature building enclosure failure. Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). It is possible to use insulated sheathing as the drainage plane if all the intersections, windows, doors and other penetrations are connected to the surface of the insulated sheathing in a watertight manner, and the seams of the insulation are taped or flashed to avoid water penetration.[2]

Air Leakage Control: Air leakage condensation is the second largest cause of premature building enclosure failure with this type of wall construction. It is very important to control air leakage to minimize air leakage condensation durability issues. Using insulating sheathing decreases the risk of air leakage condensation by increasing the temperature of the condensation plane, but condensation is still possible with insulated sheathing in cold climates. An air barrier is required in this wall system to ensure that through-wall air leakage is eliminated (ideally) or at least minimized.[3] An air barrier should be stiff and strong enough to resist wind forces, continuous, durable, and air impermeable.[4]

Vapor Control: Fiberglass or cellulose in the stud cavity are vapor permeable, while EPS, XPS and PIR are moderately permeable, moderately impermeable and completely impermeable respectively.

Insulated sheathing reduces the risk of wintertime condensation by increasing the temperature of the condensation plane, and reduces the risk of summer time inward vapor drives by slowing the vapor movement into the enclosure from storage claddings such as masonry or stucco. The level of vapor control in insulated sheathing walls is determined in the IRC and should be consulted as installing the incorrect vapor control layer or installing the vapor control layer in the incorrect location can lead to building enclosure failure.[5]

Drying: Insulating sheathing limits the drying to the exterior, and the wall must be able to dry to the interior. Poly vapor barriers are typically avoided so that this drying can occur. The minimum level of vapor control on the interior surface is determined by the IRC. Installing vapor control on both sides of the enclosure will seal any moisture into the stud space, resulting in low drying potential, and possibly resulting in moisture-related durability risks. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before close in. Cellulose is often sprayed in damp, and manufacturers recommend drying before close in and moisture content limits.

Durability Summary: The primary durability risks associated with these wall assemblies involve moisture damage related to rain water penetration. Condensation (most likely the result of air leakage, but also potentially the result of vapor diffusion) is decreased with insulated sheathing but may still occur, although the insulating sheathing is less susceptible to moisture related risks than structural OSB sheathing.

BUILDABILITY

Exterior insulation up to 1.5” requires minimal changes to standard enclosure construction practices. Exterior insulation in excess of 1.5” requires changes to window and wall construction and detailing which requires training and monitoring during the initial implementation.

Cladding can be easily attached to the studs directly through 1” of insulated sheathing. Thicker levels of insulation (>2”) require strapping or furring strips)anchored to the framing with long fasteners. Some cladding manufacturers allow their cladding to be fastened to the strapping directly.

COST

Advanced framing wall construction decreases the cost required for framing. There is a slight increase in cost for the insulating sheathing to replace most of the structural wood sheathing, but there are measureable cost benefits of saving energy, as well as improvements to comfort, which is difficult to quantify.

MATERIAL USE

If advanced framing is applied correctly (single top plates, correctly sized headers, two stud corners, etc.) the redundant wood framing from standard construction is removed, and the amount of framing will decrease. Using insulated sheathing instead of structural wood sheathing may require using structural panels or bracing in some locations.

TOTAL SCORE

Advanced framing with insulating sheathing is a logical choice as the minimum level of construction in most climates considering the more demanding insulation levels required for new construction in many climates. Using insulated sheathing can decrease the potential for both wintertime condensation, and summer inward vapor drives, and help mitigate issues caused by poor construction practices.

REFERENCES

1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis*. Retrieved from buildingscience.com.

2 Lstiburek, J. W. (2006). *Water Management Guide.* Westford: Building Science Press Inc.

3 Lstiburek, J. (2008, 08 20). *BSD-104: Understanding Air Barriers*. Retrieved from buildingscience.com.

4 Straube, J. (2009, 04 22). *BSD-014 Air Flow Control in Buildings.* Retrieved from buildingscience.com.

5 Lstiburek, J. (2008, 10 17). *BSD-106 Understanding Vapor Barriers*. Retrieved from buildingscience.com.

INTERIOR STRAPPING WALL CONSTRUCTION

INTERIOR STRAPPING WALL CONSTRUCTION DETAILS (*Wall 3*)[1]

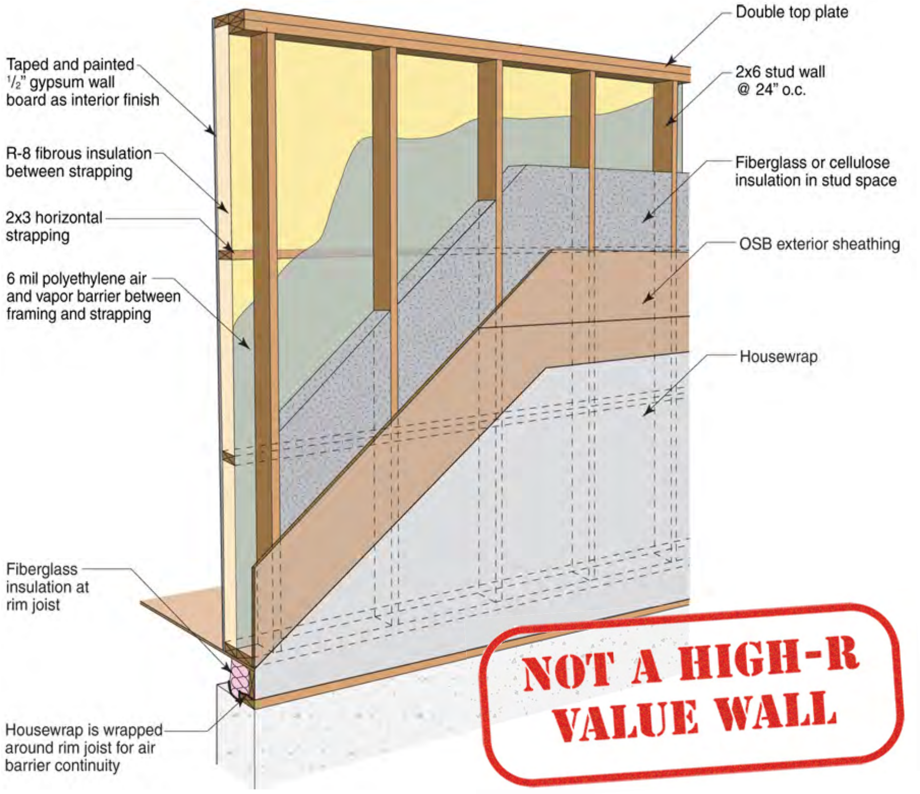
- 2x6 advanced framing
- 2x3 horizontal strapping
- Fibrous insulation between strapping
- 6 mil polyethylene air & vapor barrier
- Fiberglass or cellulose cavity insulation in stud space
- OSB exterior sheathing
- Housewrap

SCORING: HOW IT RATES

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	3
Durability	3
Buildability	3
Cost	4
Material Use	3
Total	**16**

Interior strapping in wall construction does increase the R-value over standard construction, but does not address thermal bridges at the rim joist, top plate or bottom plate. The minimal increases in whole wall R-value over standard construction may not be justified by the increased materials, cost and complexity of this wall system.



INTRODUCTION

This two page summary briefly summarizes interior strapping wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

THERMAL CONTROL

Installed Insulation R-value: There is a range of installed insulation R-values in commercially available fiberglass batts. The installed insulation R-value for 2x6 fiberglass batt ranges between R-19 and R-22 for the framed portion of this wall, the strapped interior section is typically R-8 fiberglass insulation, and for 2x6 the range is between R-19 and R-22. When blown or sprayed cellulose insulation is used, the R-value is typically R-20 for 2x6 walls.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors, this wall construction achieves a whole wall R-value of approximately R-21.5.[1] Adding horizontal strapping to the interior surface helps minimize the thermal bridges through the stud wall, but there are still thermal bridges at the top plate, bottom plate and rim joist that decrease the installed insulation R-value.

Air Leakage Control: Fiberglass batt, and both blown and sprayed cellulose are air permeable materials allowing possible air paths between the interior and exterior as well as convective looping in the insulation. Although densepack cellulose has less air permeance it does not control air leakage.[2]

This summary has been prepared by Building Science Corporation for the Department of Energy's Building America Program, a private/public partnership that develops energy solutions for new and existing homes. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

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30 Forest Street
Somerville, MA 02143
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Typical Insulation Products: Fiberglass batt, blown fiberglass, blown cellulose, sprayed cellulose.

DURABILITY

Rain Control: Rain leakage into the enclosure is the leading cause of premature building enclosure failure. Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). Intersections, windows, doors and other penetrations must be drained and/or detailed to prevent the penetration of rain water beyond the drainage plane.[3]

Air Leakage Control: Air leakage condensation is the second largest cause of premature building enclosure failure with this type of wall construction. It is very important to control air leakage to minimize air leakage condensation durability issues. An air barrier is required in this wall system to ensure that through-wall air leakage is eliminated (ideally) or at least minimized. An air barrier should be stiff and strong enough to resist wind forces, continuous, durable, and air impermeable.[4]

Often the polyethylene vapor barrier will be constructed as the air barrier even though it is not stiff or strong enough to resist wind forces. If the polyethylene is installed between the stud wall and the interior strapping, there will be fewer holes made for electrical and plumbing services, and can be made more airtight than in standard construction.

Air need not leak straight through an assembly to cause moisture problems; it can also leak from the inside, through the wall, and back to the inside; or it can leak from the outside, through the wall, and back to the outside. Condensation within the studspace is possible if this type of airflow occurs, depending on the weather conditions. Hence, wall designs should control airflow into the studspace.[5]

Vapor Control: Fiberglass and cellulose are highly vapor permeable materials, so a separate vapor control strategy must be employed to ensure that vapor diffusion does not result in condensation on, or damaging moisture accumulation in, moisture sensitive materials. The permeance and location of vapor control is dependent on the climate zone. Installing the vapor control layer in the incorrect location can lead to building enclosure failure.[6] The IRC building code should be consulted.

Drying: Cellulose and fiberglass insulation allow drying to occur relatively easily, so drying is controlled by other more vapor impermeable enclosure components such as the vapor barrier and OSB sheathing. Installing vapor control on both sides will seal any moisture into the stud space, resulting in low drying potential, and possibly resulting in moisture-related durability risks. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before close in. Cellulose is often sprayed in damp, and manufacturers recommend drying before close in and moisture content limits. Because of the polyethylene vapor barrier required in many climates, and relatively vapor impermeable OSB sheathing, drying could be slow if built-in moisture is present.

Durability Summary: The primary durability risks associated with these wall assemblies involve moisture damage related to rain water penetration or condensation (most likely the result of air leakage, but also potentially the result of vapor diffusion).

Cellulose insulated walls are slightly more durable because cellulose insulation is capable of storing and redistributing small amounts of moisture. Cellulose insulation is typically treated with borates which have been shown to protect itself and neighbouring wood material from mold growth and decay. Cellulose insulation also has decreased flame spread potential relative to other insulation materials.

BUILDABILITY

This type of construction is a modification of standard construction, but is not common, and construction trades may have difficulty with some of the detailing. All window and door penetrations will require plywood box frames to pass through both the interior strapping and exterior framing. If the poly is installed properly between the stud wall and interior strapping, there is decreased risk of moisture related durability issues often caused by penetrations such as electrical and plumbing.

COST

There will be increased costs over standard construction due to an increase in framing material, and complexity for construction, since this is not a standard construction technique. Costs vary tremendously from region to region.

MATERIAL USE

Using sdvanced framing will reduce redundant wood framing in the wall, but overall framing still increases for the interior strapping. Cellulose has a significantly lower embodied energy than fiberglass or rockwool.

TOTAL SCORE

Interior strapping in wall construction does increase the R-value over standard construction, but does not address thermal bridges at the rim joist, top plate or bottom plate. The minimal increases in whole wall R-value over standard construction may not be justified by the increased materials, cost and complexity of this wall system. Many higher performance designs for wall construction exist.

REFERENCES

1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis.* Retrieved from buildingscience.com.

2 FINAS. *Determination of the air permeability, the short term water absorption by partial immersion, and the water vapour permeatbility of the blown losse-fill cellulose thermal insulation.* Test Report VTT-S-039880-08, VTT Technical Research Centre of Finland, 2008.

3 Lstiburek, J. W. (2006). *Water Management Guide.* Westford: Building Science Press Inc.

4 Lstiburek, J. (2008, 08 20). *BSD-104: Understanding Air Barriers.* Retrieved from buildingscience.com.

5 Straube, J. (2009, 04 22). *BSD-014 Air Flow Control in Buildings.* Retrieved from buildingscience.com.

6 Lstiburek, J. (2008, 10 17). *BSD-106 Understanding Vapor Barriers.* Retrieved from buildingscience.com.

HIGH R-VALUE ENCLOSURE REPORT CASE STUDY

DOUBLE STUD WALL CONSTRUCTION

DOUBLE STUD WALL CONSTRUCTION DETAILS (*Wall 4*)[1]

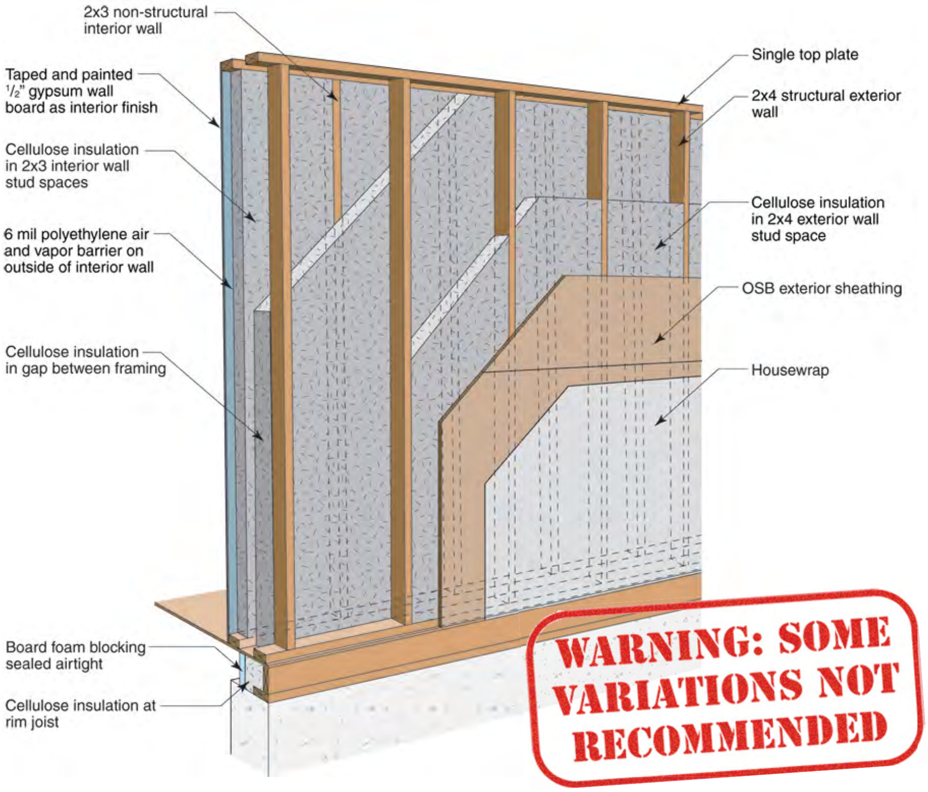
- 2x4 structural exterior wall with cellulose cavity insulation
- 2x3 non-structural interior wall with cellulose cavity insulation
- 6 mil polyethylene vapor barrier
- Cellulose insulation in gap
- OSB exterior sheathing
- Housewrap

SCORING: HOW IT RATES

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	4
Durability	3
Buildability	3
Cost	3
Material Use	2
Total	**15**

This is a highly insulated wall system that will work in extreme climates, but still has significant risks to moisture related durability issues and premature enclosure failure. This wall system decreases the interior floor area of a fixed floorplan and may experience thermal and moisture issues at the rim joist unless it's detailed correctly.



WARNING: SOME VARIATIONS NOT RECOMMENDED

INTRODUCTION

This two page summary briefly summarizes double stud wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

THERMAL CONTROL

Installed Insulation R-value: The thickness of double stud walls varies, however, walls with overall insulation thickness of 9.5" appear to be most common. The insulation can be of either fiberglass batt (R-3.5/inch) or blown cellulose insulation (R-3.7/inch) resulting in overall installed insulation R-values of R-33 and 35 respectively.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors demonstrates that adding an interior framed wall with a insulation filled gap greatly reduces the thermal breaks through the stud wall and can increases the Clear wall R-value to R-34 depending on the thickness of insulation. However, because of the significant thermal losses at the rim joist, the whole-wall R-value is closer to R-30.[1]

Air Leakage Control: Fiberglass batt, and both blown and sprayed cellulose are air permeable materials allowing possible air paths between the interior and exterior as well as convective looping in the insulation. Although densepack cellulose has less air permeance it does not control air leakage.

Typical Insulation Products: Fiberglass batt, or blown cellulose; blown fiberglass is another option, but not too common.

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For more information about Building America go to www.buildingamerica.gov.

DURABILITY

Rain Control: Rain leakage into the enclosure is the leading cause of premature building enclosure failure. Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). Intersections, windows, doors and other penetrations must be drained and/or detailed to prevent the penetration of rain water beyond the drainage plane.[2]

Air Leakage Control: Air leakage condensation is the second largest cause of premature building enclosure failure with this type of wall construction. It is very important to control air leakage to minimize air leakage condensation durability issues. An air barrier is required in this wall system to ensure that through-wall air leakage is eliminated (ideally) or at least minimized. An air barrier should be stiff and strong enough to resist wind forces, continuous, durable, and air impermeable.[3]

Air need not leak straight through an assembly to cause moisture problems; it can also leak from the inside, through the wall, and back to the inside; or it can leak from the outside, through the wall, and back to the outside. Condensation within the stud space is possible if this type of airflow occurs, depending on the weather conditions. Hence, wall designs should control airflow into the studspace.[4]

Vapor Control: Fiberglass and cellulose are highly vapor permeable materials, so a separate vapor control strategy must be employed to ensure that vapor diffusion does not result in condensation on, or damaging moisture accumulation in, moisture sensitive materials. The permeance and location of vapor control is dependent on the climate zone. Installing the vapor control layer in the incorrect location can lead to building enclosure failure.[5] The IRC building code should be consulted.

Drying: Cellulose and fiberglass insulation allow drying to occur relatively easily, so drying is controlled by other more vapor impermeable enclosure components such as the vapor barrier and OSB sheathing. Installing vapor control on both sides will seal any moisture into the stud space, resulting in low drying potential, and possibly resulting in moisture-related durability risks. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before close in. Cellulose is often sprayed in damp, and manufacturers recommend drying before close in and moisture content limits. Because of the polyethylene vapor barrier required in many climates, and relatively vapor impermeable OSB sheathing, drying could be slow if built-in moisture is present.

Durability Summary: The primary durability risks associated with these wall assemblies involve moisture damage related to rain water penetration or condensation (most likely the result of air leakage, but also potentially the result of vapor diffusion).

Cellulose insulated walls are slightly more durable because cellulose insulation is capable of storing and redistributing small amounts of moisture. Cellulose insulation is typically treated with borates that have been shown to protect itself and neighboring wood material from mold growth and decay. Cellulose insulation also has decreased flame spread potential relative to other insulation materials.

BUILDABILITY

This type of wall construction is more typically found in party walls of multi unit residential because of its superior sound suppression and fire resistance. This wall construction is not very complicated, but does require custom frames around penetrations such as windows and doors. If polyethylene is used as the air barrier, it is critical to seal it perfectly to avoid wintertime air leakage condensation against the sheathing. This construction generally does not address the thermal losses or air leakage at the rim joist. Because the second framed wall is constructed on the interior of the structural wall, the interior floor space is decreased. This wall is quite susceptible to construction deficiencies in the air and vapor barrier.

COST

The cost of this wall is higher than standard construction, but with a significant increase in thermal performance. This wall construction requires more time and materials for construction.

MATERIAL USE

The wall framing material is increased significantly by building a secondary interior wall. This wall is often not structural, which means the stud spacing can be wider, and smaller framing lumber can be used provided an even surface is constructed to install the gypsum board. There is also an increase in insulation, but the embodied energy of cellulose is relatively small, and results in large increases in R-value.

TOTAL SCORE

This is a highly insulated wall system that will work in extreme climates as part of a high-R enclosure, if the air barrier details are perfect, and the thermal losses at the rim joist are minimized. This construction technique does cost the occupant interior floor space with the thick insulated wall. There is significant risk to moisture related durability issues from wintertime condensation, however, the large amount of cellulose in this wall system will be able to buffer some moisture in the enclosure as long as the safe moisture capacity of the cellulose is not exceeded.

REFERENCES

1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis.* Retrieved from buildingscience.com.

2 Lstiburek, J. W. (2006). *Water Management Guide.* Westford: Building Science Press Inc.

3 Lstiburek, J. (2008, 08 20). *BSD-104: Understanding Air Barriers*. Retrieved from buildingscience.com.

4 Straube, J. (2009, 04 22). *BSD-014 Air Flow Control in Buildings.* Retrieved from buildingscience.com.

5 Lstiburek, J. (2008, 10 17). *BSD-106 Understanding Vapor Barriers.* Retrieved from buildingscience.com.

TRUSS WALL CONSTRUCTION

TRUSS WALL CONSTRUCTION DETAILS *(Wall 5)*[1]

- 2x4 interior framing member
- 2x3 exterior framing member
- 6 mil polyethylene vapor barrier to interior
- Cellulose cavity insulation
- OSB exterior sheathing
- Housewrap

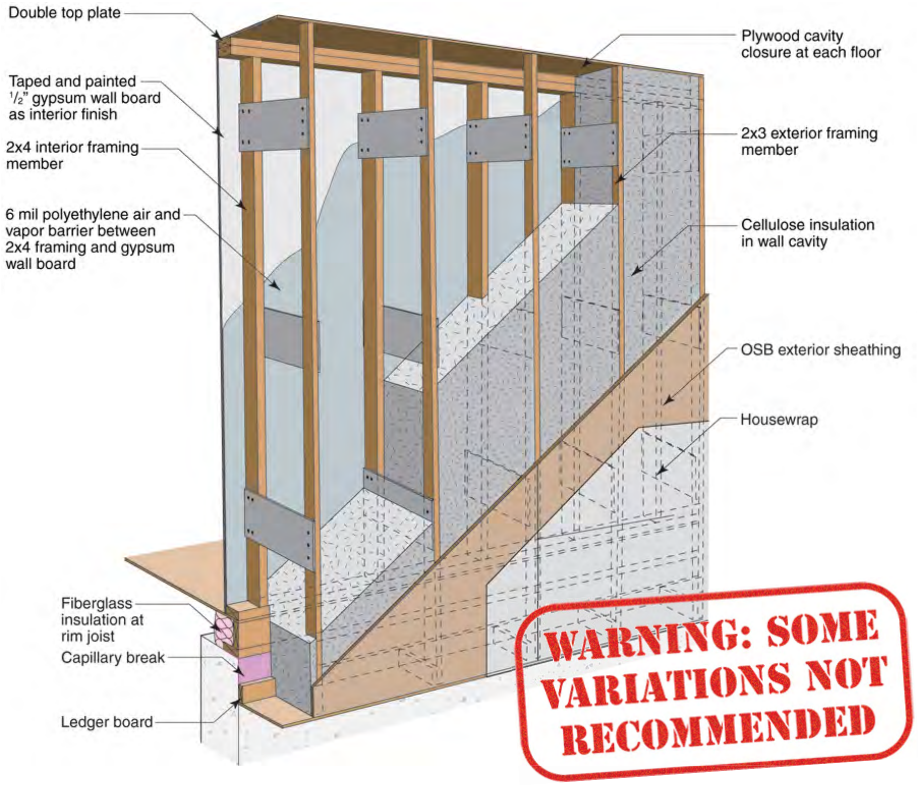
www.builditsolar.com/Projects/SolarHomes/LarsenTruss/LarsenTrussPics.htm

SCORING: HOW IT RATES

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	4
Durability	3
Buildability	2
Cost	3
Material Use	2
Total	**14**

The truss wall system can achieve a very high whole wall R-value with minimal thermal bridging and would be perform well in extreme climates provided the air barrier was detailed perfectly minimizing the high risk of air leakage condensation durability issues. It is time consuming to construct and susceptible to premature enclosure failures resulting from poor construction and detailing.



WARNING: SOME VARIATIONS NOT RECOMMENDED

INTRODUCTION

This two page summary briefly summarizes the truss wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

THERMAL CONTROL

Installed Insulation R-value: The thickness of truss walls varies greatly and because it is not a common wall construction, there does not appear to be a established standard construction insulation thickness. These walls are typically insulated with blown cellulose insulation (R-3.7/inch) or fiberglass batt insulation (R-3.5/inch), and overall installed insulation R-values in excess of 50 are possible.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors shows that adding the insulation to the exterior of the framing addresses the thermal bridge at the rim joist, studs and top plate. There is a large range of R-values possible with this type of construction, but 12” of cellulose provides a whole-wall R-value of approximately R-36.[1]

Air Leakage Control: Cellulose insulation is an air permeable material allowing possible air paths between the interior and exterior as well as convective looping in the insulation. Although densepack cellulose has less air permeance than some other air permeable insulations, it does not control air leakage.

Typical Insulation Products: Blown cellulose.

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DURABILITY

Rain Control: Rain leakage into the enclosure is the leading cause of premature building enclosure failure. Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). Intersections, windows, doors and other penetrations must be drained and/or detailed to prevent the penetration of rainwater beyond the drainage plane.[2]

Air Leakage Control: Air leakage condensation is the second largest cause of premature building enclosure failure with this type of wall construction. It is very important to control air leakage to minimize air leakage condensation durability issues. An air barrier is required in this wall system to ensure that through-wall air leakage is eliminated (ideally) or at least minimized. An air barrier should be stiff and strong enough to resist wind forces, continuous, durable, and air impermeable.[3]

Air need not leak straight through an assembly to cause moisture problems; it can also leak from the inside, through the wall, and back to the inside; or it can leak from the outside, through the wall, and back to the outside. Condensation within the stud space is possible if this type of airflow occurs, depending on the weather conditions. Hence, wall designs should control airflow into the stud space.[4]

The truss wall has a much higher R-value that standard construction, and the exterior sheathing is well insulated from the interior conditions. This wall system has greater risk for severe air leakage condensation since the sheathing is considerably colder than standard construction.

Vapor Control: Fiberglass and cellulose are highly vapor permeable materials, so a separate vapor control strategy must be employed to ensure that vapor diffusion does not result in condensation on, or damaging moisture accumulation in, moisture sensitive materials. The permeance and location of vapor control is dependent on the climate zone. Installing the vapor control layer in the incorrect location can lead to building enclosure failure.[5] The IRC building code should be consulted.

There is a higher risk of vapor diffusion condensation if the vapor barrier is not detailed correctly due to the lower wintertime temperature of the sheathing in the truss wall relative to standard construction.

Drying: Cellulose and fiberglass insulation allow drying to occur relatively easily, so drying is controlled by other more vapor impermeable enclosure components such as the vapor barrier and OSB sheathing. Installing vapor control on both sides will seal any moisture into the stud space, resulting in low drying potential, and possibly resulting in moisture-related durability risks. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before close in. Because of the polyethylene vapor barrier required in many climates, and relatively vapor impermeable OSB sheathing, drying could be slow if built-in moisture is present.

Durability Summary: The primary durability risks associated with these wall assemblies involve moisture damage related to rain water penetration or condensation (most likely the result of air leakage, but also potentially the result of vapor diffusion).

Cellulose insulated walls are slightly more durable than fiberglass insulated walls because cellulose insulation is capable of storing and redistributing small amounts of moisture. Cellulose insulation is typically treated with borates that have been shown to protect itself and neighboring wood material from mold growth and decay. Cellulose insulation also has decreased flame spread potential relative to other insulation materials.

BUILDABILITY

This wall construction is not a standard construction practice. The gussets used to space the exterior framed wall off the structure are time consuming to construct, and require tight tolerances to ensure smooth sheathing and cladding. This wall is highly susceptible to construction workmanship and requires a perfect air barrier in cold climates since the potential for wintertime condensation is high. Penetrations such as windows and doors require plywood boxes be installed through the wall.

COST

This construction requires increases in both time and materials for the enclosure. The wall framing material is essentially doubled, and constructing the exterior wall with gussets is time consuming. The increased thermal performance and decreased thermal bridges may be worth the extra time and money in specific cases.

MATERIAL USE

There is a significant increase to framing since every framing member in the structural wall has a corresponding exterior framing member attached with wood gussets.

TOTAL SCORE

The truss wall system can achieve a very high whole wall R-value with minimal thermal bridging and would be perform well in extreme climates provided the air barrier was detailed perfectly minimizing air leakage condensation durability risks. It is possible to reduce the risk of condensation by using a combination of the truss wall in combination with an air impermeable insulation. One advantage of the truss wall is that it is used in both new construction and retrofit situations to decrease energy consumption, and improve occupant comfort. The truss wall allows the extra insulation to be placed on the exterior of the structural wall that does not affect the interior space, unlike the double stud wall.

REFERENCES

1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis.* Retrieved from buildingscience.com.

2 Lstiburek, J. W. (2006). *Water Management Guide.* Westford: Building Science Press Inc.

3 Lstiburek, J. (2008, 08 20). *BSD-104: Understanding Air Barriers*. Retrieved from buildingscience.com.

4 Straube, J. (2009, 04 22). *BSD-014 Air Flow Control in Buildings.* Retrieved from buildingscience.com.

5 Lstiburek, J. (2008, 10 17). *BSD-106 Understanding Vapor Barriers.* Retrieved from buildingscience.com.

SIPS WALL CONSTRUCTION

SIPS WALL CONSTRUCTION DETAILS *(Wall 6)*[1]

- OSB interior and exterior panels
- EPS insulation core typical
- Housewrap

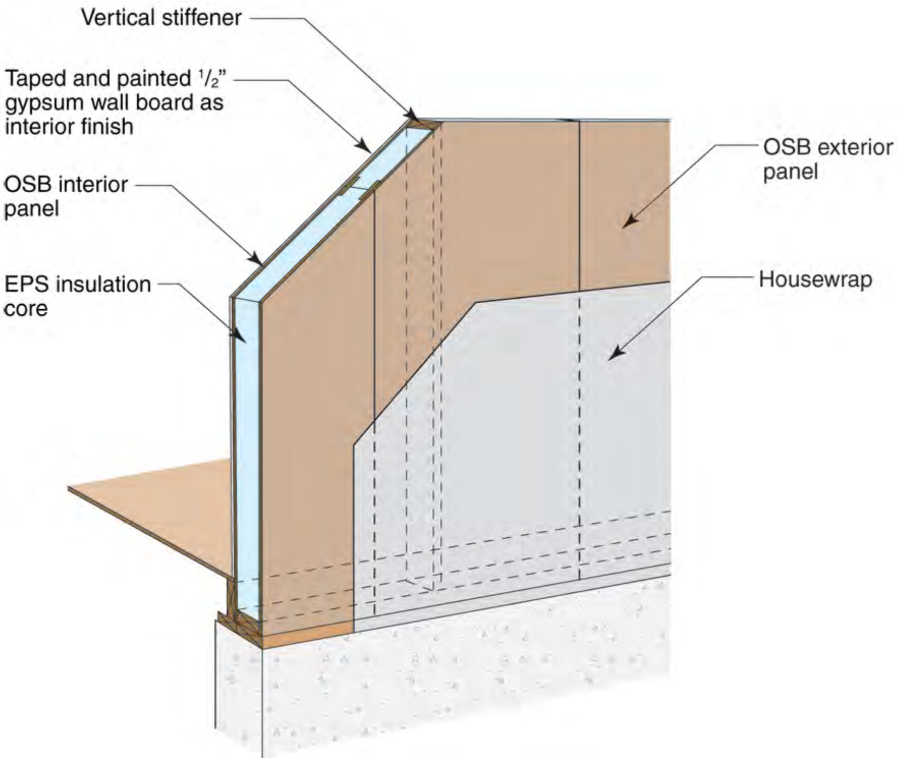

Photo: SIPA

SCORING: HOW IT RATES

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	4
Durability	4
Buildability	3
Cost	3
Material Use	3
Total	**17**

The typical SIPs panels are not constructed with enough insulation to be considered high-R assemblies in heating climates. SIPs installation requires specialized training but is quicker and easier than wood framed construction following training. Historical moisture related durability issues with SIPs have been solved with a better understanding of building science, and airtightness details.



INTRODUCTION

This two page summary briefly summarizes SIPs wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

THERMAL CONTROL

Installed Insulation R-value: Structural Insulated Panels (SIPs) are typically constructed using OSB panels adhered to both sides of an expanded polystyrene (EPS) foam insulation core. The most common SIP insulation thicknesses are 3.5" and 5.5" and are equivalent to R-14 and R-22. It is possible, although not as common, to use different insulation types, and thicker panels to achieve high R wall values.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors, the clear wall R-value with the OSB layers, drywall, cladding, and surface films often has an R-value higher than the installed insulation R-value because of fewer thermal bridges in the wall system. The whole-wall R-value depends on thermal bridging through vertical stiffeners, top and bottom plate, as well as the wood bucks for windows and doors.[1]

Air Leakage Control: Both OSB and EPS foam are air impermeable so there is no air leakage through the centre of the SIPS panels; however it is important to address the air tightness of joints between the panels as well as interfaces with other structural elements (i.e. foundation walls or roofs) and penetrations such as windows, doors and services.[2] It is relatively easy to achieve a high level of airtightness on a SIPs enclosure.

Typical Insulation Products: EPS foam is the most common, but SIPs have also been constructed with XPS and polyisocyanurate foam cores.

DURABILITY

Rain Control: Rain leakage into the enclosure is the leading cause of premature building enclosure failure. Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). Intersections, windows, doors and other penetrations must be drained and/or detailed to prevent the penetration of rainwater beyond the drainage plane.[3]

Air Leakage Control: There is no air leakage through the centre of the panel but there is risk of air leakage at the joints between panels if not detailed correctly. Historically, there were design detail issues with the air tightness of the joints between the panels allowing warm moist interior air to condense on the exterior cold OSB layer.[4] Standards of SIPs construction have improved and following the recommended construction guidelines mitigates nearly all of the risk of moisture related durability issues from air leakage.

Vapor Control: A SIPs panel controls vapor well. There is very minimal risk to vapor related moisture damage in SIPs construction.

Drying: Water on either the interior or exterior of the SIPs will dry easily to the interior or exterior in most climates. In very humid or wet climates with minimal drying potential, the OSB may remain wet for an extended period and could result in moisture related durability issues. If moisture accumulates between the interior and exterior OSB faces, it will be difficult to dry.

Built- in Moisture: Water on the surfaces of the panel during construction should dry easily following completion, any water trapped in the panel joints will dry much more slowly.

Durability Summary: If the SIPs are installed according to best practice, with proper air seals and flashed penetrations, the system is very durable in all climates.

BUILDABILITY

Using SIPs is relatively easy and quick once the training has been completed. Panels are ordered and shipped to site and assembled with a crane. More specific info can be found at www.sips.org. Generally, most of the services are run on interior partition walls, but there are methods of installing services on the interior of a SIPs panel. A SIPs house can be assembled and dried in more quickly than a wood framed house once the panels are on site.

COST

SIPs panels range considerably in price depending on the project details and the required thickness of wall panels. It is more expensive than standard construction and can generally only be used on simple geometries.

MATERIAL USE

SIPs panels require minimal framing lumber but an increase in structural sheathing panels.

TOTAL SCORE

SIPs wall panels are generally not constructed with enough insulation to be considered a high R enclosure system on its own in heating climates. It is possible to use thicker insulation panels or to combine SIPs with another insulation strategy in cold climates. It is relatively quick and easy to build with SIPs following training, and refined standard practice techniques have removed nearly all of the historical risks of air leakage condensation. The cost and simple geometries of SIPs houses are two of the main reasons why this technology is not used more often.

REFERENCES

1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis*. Retrieved from buildingscience.com.

2 Lstiburek, J. W. (2008). *Builder's Guide to Structural Insulated Panels (SIPs) for all Climates.* Westford: Building Science Press Inc.

3 Lstiburek, J. W. (2006). *Water Management Guide.* Westford: Building Science Press Inc.

4 SIPA (n.d.). *Report on the Juneau, Alaska Roof Issue*. Retrieved May 2009 from Structural Insulated panel Association: http://www.sips.org/content/technical/index.cfm?PageId=161.

ICF WALL CONSTRUCTION

ICF WALL CONSTRUCTION DETAILS *(Wall 7)*[1]

- ICF inner and outer faces; typically EPS or cement wood fiber
- Cast-in-place concrete core

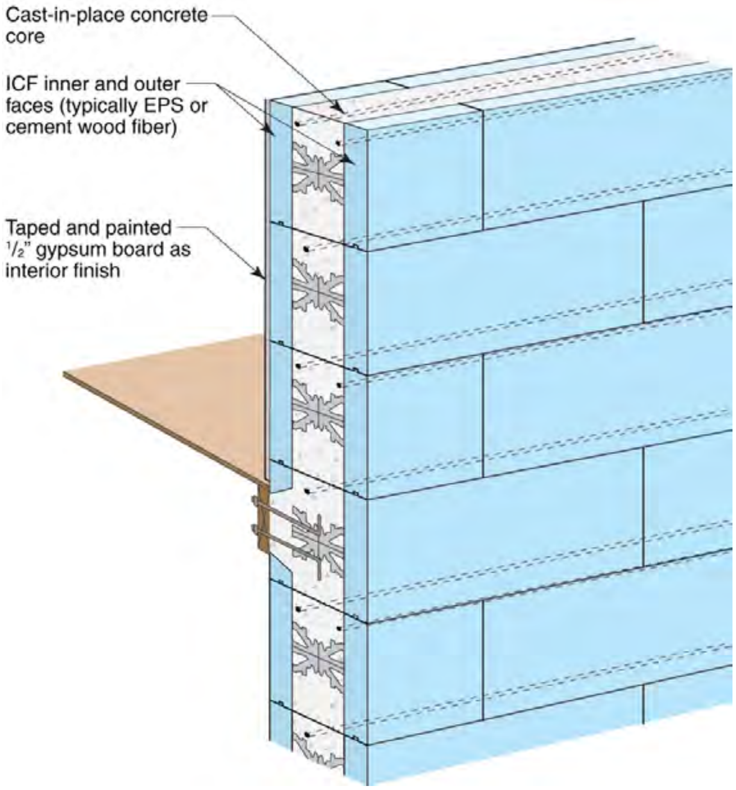

www.silverspurconstruction.com/icfphotogallery.htm

SCORING: HOW IT RATES

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	4
Durability	5
Buildability	4
Cost	2
Material Use	3
Total	**18**

ICF construction is a very durable construction strategy provided the rainwater management details are constructed correctly. Generally, ICF construction alone cannot achieve a high R-value and will require other insulation strategies in combination for cold climates, which is commonly done in practice.



INTRODUCTION

This two page summary briefly summarizes ICF wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

THERMAL CONTROL

Installed Insulation R-value: R-values of Insulated Concrete Form construction vary considerably with the type, and thickness of form. The most common ICF form is constructed of EPS insulation in the range of 2" thick on the interior and exterior. Other ICF materials include cementitious wood based forms, some of which are constructed with an extra layer of insulation (e.g. Rockwool) in the form.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors shows that there are few thermal breaks from the interior to the exterior on an ICF wall. An 8" foam ICF form with 4" of EPS has a whole-wall R-value of approximately R-16.[1]

Air Leakage Control: Many ICF construction strategies form air barriers in the field of the wall. Air leakage will occur at penetrations through the wall if they are not detailed correctly.[2]

Typical Insulation Products: EPS foam insulation forms, or cementitious wood based forms.

DURABILITY

Rain Control: Rain leakage into the enclosure is the leading cause of premature building enclosure failure. Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). Intersections, windows, doors and other penetrations must be drained and/or detailed to prevent the penetration of rainwater beyond the drainage plane.[3] There is little to no moisture buffering capacity of and ICF wall so even a minimal amount of water, undetectable in standard construction, will have durability issues in ICF construction.

Air Leakage Control: ICF construction strategies form air barriers in the field of the wall. All through wall penetrations require air sealing details.[4]

Vapor Control: There are no significant risks to moisture durability from vapor drive in ICF construction.

Drying: ICFs will dry both to the interior and exterior depending on climate and time of year.

Built- in Moisture: Since ICFs are poured concrete walls in forms with relatively low vapor permeance surfaces, the concrete will dry very slowly, and should be allowed to dry to both sides following the completion of the wall system.

Durability Summary: There are very few risks associated with air leakage and vapor condensation of ICF construction. The most common durability issue is from rainwater leakage into the enclosure. ICF forms typically do not have any buffering capacity of leakage, so even a small leak, that may occur undetected with no durability risks in a wood framed wall, may affect the interior of and ICF building. The ICF wall itself is not susceptible to moisture related issues but interior finishes are generally sensitive to moisture.

BUILDABILITY

Generally, building with ICFs is quite easy and straightforward following initial training. Care should be taken to line the surfaces of the forms up to ensure even drywall if it is directly attached. Problems in the past have occurred with air pockets in the forms, as well as bulging and breaking of forms due to the hydrostatic pressure of concrete. These problems are well documented and there are strategies to address these issues.

COST

The cost of ICF construction varies considerably depending on the type of forms chosen, geometry of construction and location. ICF construction is more expensive that standard construction and is usually prohibitively expensive in residential housing.

MATERIAL USE

ICF walls use less concrete than an alternative wall built entirely with concrete, and concrete is very high in embodied energy. The wood framing can be minimized by attaching the drywall directly to the ICF block on the interior.

TOTAL SCORE

ICF construction is a very durable construction strategy provided the rainwater management details are constructed correctly. Generally, ICF construction alone cannot achieve a high R-value and will require other insulation strategies in combination for cold climates, which is commonly done in practice. ICF is generally only used in multifamily and mid rise buildings, and not in residential housing.

REFERENCES

1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis.* Retrieved from buildingscience.com.

2 Straube, J. (2009, 04 22). *BSD-014 Air Flow Control in Buildings.* Retrieved from buildingscience.com.

3 Lstiburek, J. W. (2006). *Water Management Guide.* Westford: Building Science Press Inc.

4 Lstiburek, J. (2008, 08 20). *BSD-104: Understanding Air Barriers.* Retrieved from buildingscience.com.

SPRAY FOAM WALL CONSTRUCTION

SPRAY FOAM WALL CONSTRUCTION DETAILS *(Wall 8a and 8b)*[1]

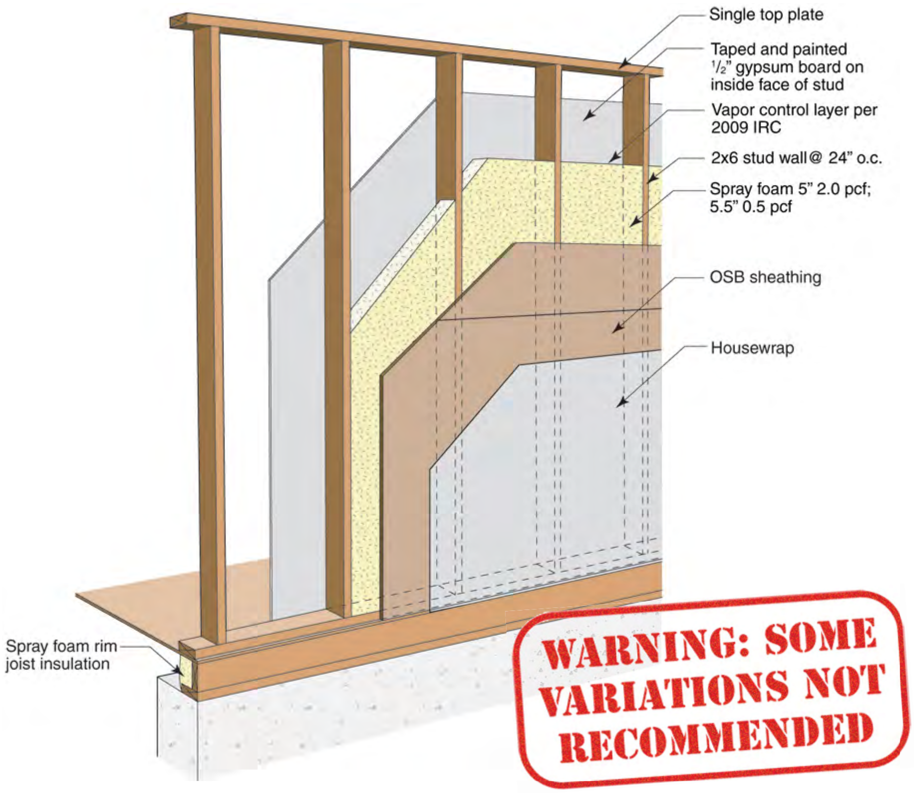
- 2x6 wood frame wall at 24" o.c.
- Spray foam cavity insulation
- OSB sheathing
- Housewrap

SCORING: HOW IT RATES

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	5
Durability	5
Buildability	4
Cost	2
Material Use	4
Total	**20**

Both low and high density foam increase the air tightness of the enclosure and reduce the risks to air leakage related durability risks. The R-values of both the low and high density spray foam are significantly reduced by thermal bridging of the wall framing and rim joist, demonstrating the value of insulated sheathing.



WARNING: SOME VARIATIONS NOT RECOMMENDED

INTRODUCTION

This two page summary briefly summarizes spray foam wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

THERMAL CONTROL

Installed Insulation R-value: The installed insulation R-value depends somewhat on the company and but generally speaking, high density foam (2.0 pcf) ranges between R-5.5 and R-6.5 per inch for the aged R-value, and low density foam (0.5pcf) has an R-value of approximately R-3.6/inch. Since high density foam is generally installed short of the cavity to avoid trimming, the installed insulation R-value is approximately R-30 (using R-6/inch). Low density is generally installed deliberately overflowing the cavity and trimmed off resulting in an R-value of approximately R-21.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors, it is clear that the thermal bridging through the framing, bottom plate, and top plate reduces the effectiveness of the spray foam insulation.[1] The R-value of the high density spray foam wall decreases from an installed R-value of R-30 to approximately R-20, a decrease of R-10 because of thermal bridging. The low density spray foam wall decreases from an installed insulation R-value of 21 to a whole wall R-value of approximately R-16.

Air Leakage Control: Both low density and high density foam form an air barrier decreasing thermal losses through air leakage. Air leakage is still common under the bottom plate and at the rim joist if these areas are not detailed correctly.[2]

Typical Insulation Products: Low density 0.5 pcf foam, or high density 2.0 pcf foam.

Durability

Rain Control: Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). Intersections, windows, doors and other penetrations must be detailed to prevent the penetration of rain water.[3]

Air Leakage Control: Air leakage is significantly minimized by installing spray foam insulation in the stud space since both low density and high density spray foam act as an air barrier. This increases the durability of the wall system considerably over standard construction.[4]

Vapor Control: High density (2.0 pcf) foam forms a vapor control layer reducing vapor movement through the enclosure, minimizing the potential for wintertime vapor condensation and summertime inward vapor drive. Low density foam allows moisture vapor movement through the foam so other methods of vapor control such as poly, kraft paper, or vapor barrier paint may be required based on the geographic location.[5] The IRC building code should be consulted.

Drying: Both of the spray foam walls dry relatively slowly if water enters the enclosure, since they do not experience convective looping and air movement similar to air permeable insulations. Spray foam does not provide any buffering capacity or redistribution. Foam is relatively moisture tolerant and will be able to dry given enough time. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before close in. High density foam will inhibit the drying of wet building materials more than low density vapor permeable foam.

Durability Summary: The primary durability risks associated with these wall assemblies involve moisture damage related to rain water penetration. Both air leakage and vapor diffusion durability is significantly increased with spray foam but some vapor control may be necessary with low density spray foam in cold climates.

Buildability

Using spray foam as the stud space insulation is a very simple modification to the construction technique. Generally, the wall construction is the same as standard or advanced framing construction, and spray foam is sprayed into the cavity. Spray foam significantly reduces risks of poor air tightness detailing of the exterior sheathing or interior drywall.

Cost

Using spray foam will increase construction costs considerably but these increased costs may be outweighed by the benefits to energy efficiency, and occupancy comfort from reduced drafts.

Material Use

Wood framing required for spray foam insulation is the same required for the standard construction, or advanced framed wall depending on the framing strategy used.

Total Score

Both low and high density foam increase the air tightness of the enclosure and reduce the risks to air leakage related durability risks. A vapor control (ie. polyethylene, kraft paper, SVR) with high density foam is generally not required and vapor control with low density spray foam will be climate specific. The R-values of both the low and high density spray foam are significantly reduced by thermal bridging of the wall framing and rim joist, demonstrating the value of insulated sheathing. It may be possible to use spray foam insulation in combination with another insulation strategy to maximize the R-value gained with the spray foam insulation.

References

1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis*. Retrieved from buildingscience.com.

2 Straube, J. (2009, 04 22). *BSD-014 Air Flow Control in Buildings.* Retrieved from buildingscience.com.

3 Lstiburek, J. W. (2006). *Water Management Guide.* Westford: Building Science Press Inc.

4 Lstiburek, J. (2008, 08 20). *BSD-104: Understanding Air Barriers*. Retrieved from buildingscience.com.

5 Lstiburek, J. (2008, 10 17). *BSD-106 Understanding Vapor Barriers.* Retrieved from buildingscience.com.

FLASH-AND-FILL HYBRID WALL CONSTRUCTION

FLASH-AND-FILL HYBRID WALL CONSTRUCTION DETAILS *(Wall 9)*[1]

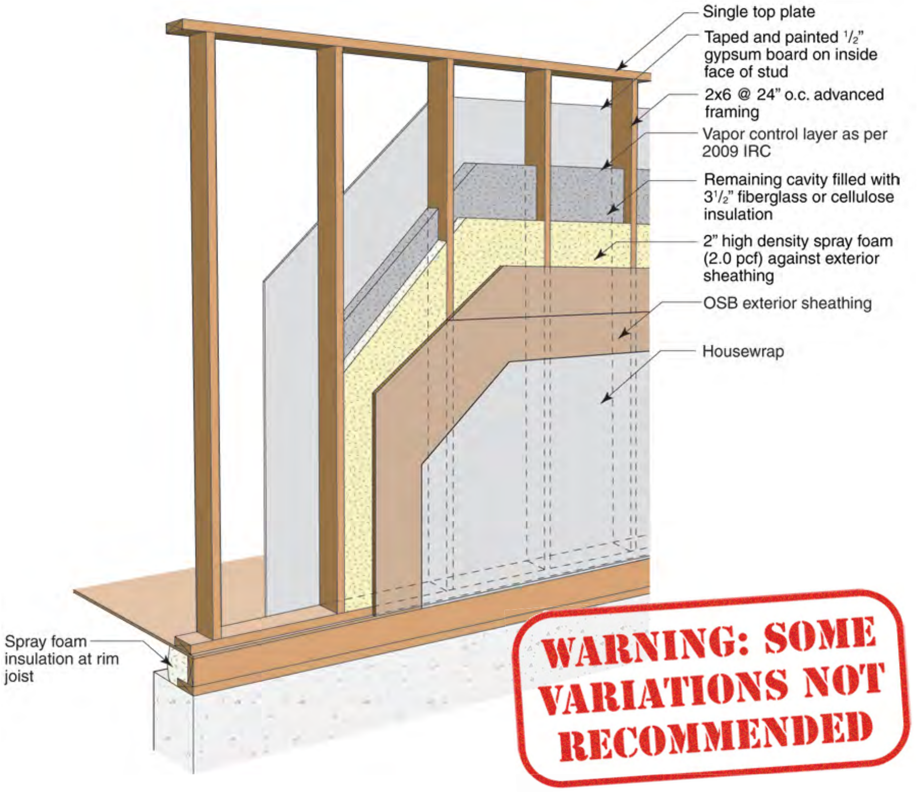
- 2x6 wood frame wall at 24” o.c.
- 2” high density spray foam
- Fiberglass or cellulose cavity insulation
- OSB sheathing
- Housewrap

SCORING: HOW IT RATES

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	4
Durability	4
Buildability	4
Cost	3
Material Use	4
Total	**19**

The hybrid wall system significantly reduces air leakage over standard construction or advanced framing, which conserves energy, and reduces the potential for both air leakage and vapor condensation durability issues. Unfortunately, the added cost of the spray foam insulation only adds a minimal amount to the R-value since the thermal bridging of the wall is not addressed. Addressing the thermal bridges would improve this wall construction.



WARNING: SOME VARIATIONS NOT RECOMMENDED

INTRODUCTION

This two page summary briefly summarizes flash-and-fill hybrid wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

THERMAL CONTROL

Installed Insulation R-value: The installed R-value is approximately R-12 for two inches of high density spray foam (2.0 pcf) and R-13 for three and a half inches of fiberglass batt, totaling R-25.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors, the R-value decreases from an installed insulation R-value of R-25 to whole wall R-value of approximately R-17 for a the hybrid wall construction in this case.[1] The decrease in R-value is due to the thermal bridging of the wall framing, top and bottom plates.

Air Leakage Control: Fiberglass batt, and both blown and sprayed cellulose are air permeable materials allowing possible air paths between the interior and exterior as well as convective looping in the insulation. Although densepack cellulose has less air permeance it does not control air leakage. In the case of the hybrid wall system, the spray foam is used as an air barrier in the stud space to limit the air movement between the interior and exterior so there are fewer energy losses due to air leakage. It is still possible and common to get air leakage

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below the bottom plate if is not sealed.[2] When spray foam is used in the wall system, it is beneficial to also use it in the rim joist which has a high potential for air leakage.

Typical Insulation Products: Spray foam insulation and fiberglass batt, blown fiberglass, blown cellulose, or sprayed cellulose.

DURABILITY

Rain Control: Rain leakage into the enclosure is the leading cause of premature building enclosure failure. Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). Intersections, windows, doors and other penetrations must be drained and/or detailed to prevent the penetration of rainwater beyond the drainage plane.[3]

Air Leakage Control: Air leakage condensation is the second largest cause of premature building enclosure failure with wood framed wall construction. It is very important to control air leakage to minimize air leakage condensation durability issues. An air barrier is required in this wall system to ensure that through-wall air leakage is eliminated (ideally) or at least minimized. An air barrier should be stiff and strong enough to resist wind forces, continuous, durable, and air impermeable.[4]

In the hybrid wall system, two inches of spray foam is used as an air barrier to reduce the air leakage. This also reduces the air leakage condensation against the sheathing in the winter as it significantly warms the condensation plane. Since air leakage from the interior, into the studspace and back into the interior can also cause condensation in some climates, it is still important to detail the interior surface as an air barrier as well.

Vapor Control: Fiberglass and cellulose are vapor permeable materials, but including two inches of high density spray foam acts as a vapor barrier limiting vapor movement to the cold exterior sheathing, and significantly reduces the risk of vapor condensation durability issues. High density spray foam also decreases the summer inward vapor drives. If low density spray foam is used, it is not a vapor barrier, and other vapor control may be required depending on the climate. Calculations should be done to ensure a minimum risk to vapor condensation durability issues.[5] The IRC building code should be consulted.

Drying: Using high density spray foam will slow the movement of moisture across the enclosure. and there is no moisture buffering capacity or redistribution within the spray foam. Some vapor control may still be required at the interior surface in cold climates which slows drying. Proper flashing of all penetrations should help minimize moisture in the enclosure. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before close in. High density spray foam may slow drying across the enclosure since it is a vapor barrier. In geographic regions with reduced drying potential, the moisture content of the sheathing may stay elevated for an extended period due to the inability to dry or redistribute moisture into the wall.

Durability Summary: Hybrid wall construction has a greater resistance to both air leakage condensation and vapor diffusion condensation because of the high density spray foam increasing the dew point of the condensation surface. The primary durability risks associated with these wall assemblies involve moisture damage related to rain water penetration.

BUILDABILITY

Hybrid wall construction is not very different from standard wall construction or advanced framing. By filling the stud space with two inches of spray foam, an R-13 batt can still easily be installed against the foam, or cellulose could be sprayed in the remaining stud space. All other aspects of the construction are the same as standard construction or advanced framing. Using high density spray foam reduces the risks from poor workmanship during construction.

COST

Using spray foam insulation can be costly, and while it reduces the risks of moisture related durability issues, the minimal increase in R-value due to the thermal bridging may not be worth the increased cost of the spray foam insulation.

MATERIAL USE

There is no increase in framing materials from standard construction, but the embodied energy of the system increases with the addition of high density spray foam insulation.

TOTAL SCORE

The hybrid wall system significantly reduces air leakage over standard construction, which conserves energy, and reduces the potential for both air leakage and vapor condensation durability issues. Reducing the air leakage may also increase occupancy comfort by reducing drafts. Unfortunately, the added cost of the spray foam insulation only adds a minimal amount to the R-value since the thermal bridging of the wall is not addressed. This wall is very similar to build as standard construction and less susceptible to poor workmanship during construction. Addressing the thermal bridges would improve this wall construction.

REFERENCES

1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis*. Retrieved from buildingscience.com.

2 Straube, J. (2009, 04 22). *BSD-014 Air Flow Control in Buildings.* Retrieved from buildingscience.com.

3 Lstiburek, J. W. (2006). *Water Management Guide.* Westford: Building Science Press Inc.

4 Lstiburek, J. (2008, 08 20). *BSD-104: Understanding Air Barriers*. Retrieved from buildingscience.com.

5 Lstiburek, J. (2008, 10 17). *BSD-106 Understanding Vapor Barriers.* Retrieved from buildingscience.com.

DOUBLE STUD WITH SPRAY FOAM WALL CONSTRUCTION

DOUBLE STUD WITH SPRAY FOAM WALL CONSTRUCTION DETAILS *(Wall 10)*[1]

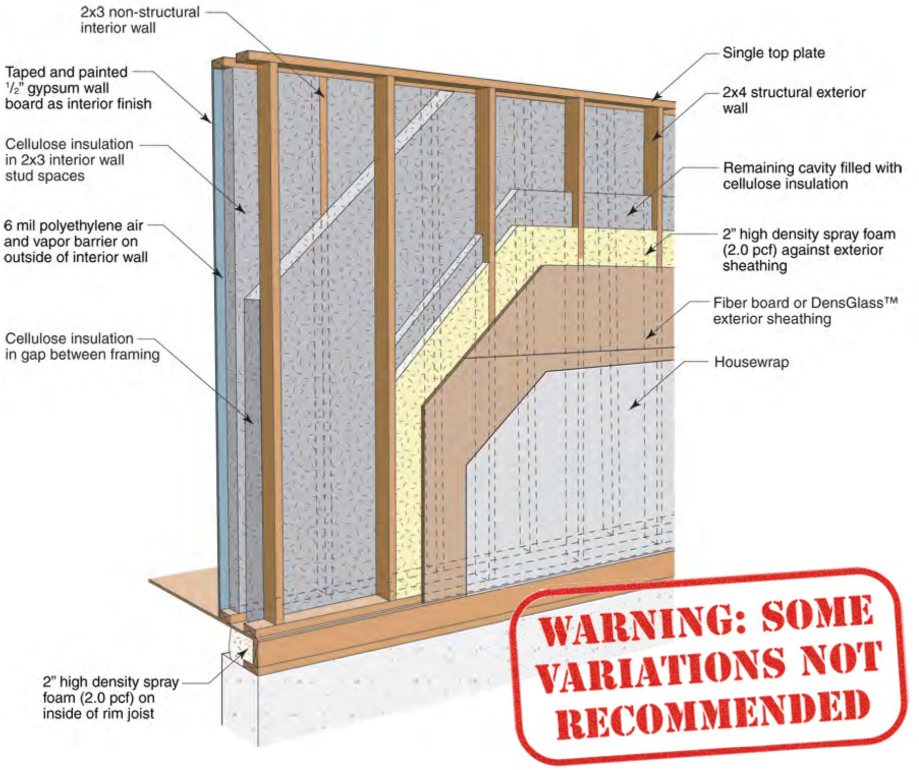
- 2x4 exterior wall framing
- 2” high density spray foam
- Fiberglass or cellulose cavity insulation
- 2x3 interior wall framing
- Fiber board or DensGlass™ sheathing
- Housewrap

SCORING: HOW IT RATES

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	5
Durability	4
Buildability	3
Cost	3
Material Use	3
Total	**18**

This is truly a high-R wall assembly, and with the addition of spray foam, there is a reduction in moisture related durability issues. In some extreme climates, two inches of spray foam may not be enough to sufficiently reduce the risk, which means that more spray foam is required, or an interior air barrier and some form of vapor control, likely a Class II or Class II would be sufficient.



WARNING: SOME VARIATIONS NOT RECOMMENDED

INTRODUCTION

This two page summary briefly summarizes double stud with spray foam wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

THERMAL CONTROL

Installed Insulation R-value: The thickness of double stud walls varies, however walls with overall insulation thickness of 9.5” appear to be most common. The insulation is most commonly cellulose insulation but could also be sprayed fiberglass. In this system with two inches of high density spray foam (R-6/inch) the installed insulation R-value is approximately R-40. This is an increase of R-5 over the same double stud construction insulated only with cellulose.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors shows that adding an interior framed wall with a insulation filled gap greatly reduces the thermal breaks through the stud wall and can increases the Clear wall R-value to R-36 depending on the thickness of insulation. However, because of the thermal losses at the rim joist, the Whole-wall R-value is closer to R-33.[1]

Air Leakage Control: Fiberglass batt, blown and sprayed cellulose are all air permeable materials allowing possible air paths between the interior and exterior as well as convective looping through the material. In this case, the spray foam is used as an air barrier in the stud space to limit the air movement between the interior and exterior so there are fewer energy losses due to air leakage. It is still possible and common to get air leakage below the bottom plate if is

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not sealed.[2] When spray foam is used in the wall system, it is beneficial to also use it in the rim joist that has a high potential for air leakage. Reducing the air leakage with spray foam may also increase occupancy comfort by reducing drafts.

Typical Insulation Products: High density spray foam, blown cellulose, sprayed fiberglass.

DURABILITY

Rain Control: Rain Control – Rain leakage into the enclosure is the leading cause of premature building enclosure failure. Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). Intersections, windows, doors and other penetrations must be drained and/or detailed to prevent the penetration of rainwater beyond the drainage plane.[3]

Air Leakage Control: Since fibrous insulations are air permeable, air leakage condensation may occur if air moves into the stud space from the interior, or the exterior, depending on the climate. An air barrier is required in this wall system to ensure that air leakage is ideally eliminated, but at least minimized. Air leakage condensation is one of the greatest causes of premature building enclosure failure. An air barrier should be stiff, continuous, durable, strong, and impermeable.[4]

Air need not leak straight through an assembly to cause moisture problems; it can also leak from the inside, through the wall, and back to the inside. Condensation within the stud space is possible if this type of airflow occurs, depending on the weather conditions. Hence, wall designs should control airflow into the stud space.

Vapor Control: Fiberglass and cellulose are vapor permeable materials, so a separate vapor control strategy must be employed to ensure that vapor diffusion from does not result in condensation on or damaging moisture accumulation in moisture sensitive materials. In this case, the high density foam acts as a vapor control layer in the assembly. The permeance and location of vapor control is dependent on the climate zone and in cold climates, further vapor control may be required due to the ratio of insulation interior of the vapor control layer. Some level of vapor control may be needed on the interior surface or the amount of spray foam insulation could be increased. Installing the vapor control layer in the incorrect location can lead to building enclosure failure.[5] The IRC building code should be consulted.

Drying: Cellulose and fiberglass insulation allow drying easily, so drying is controlled by other enclosure components such as the high density spray foam and OSB sheathing. Installing vapor control on both sides will seal any moisture into the stud space, resulting in low drying potential, and possibly resulting in moisture-related durability risks. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before close in. Cellulose is often sprayed in damp, and manufacturers recommend drying before close in and moisture content limits. Interior vapor control may be required depending on the climate zone, and with the combination of vapor semi-impermeable foam and OSB, will increase the time required for adequate drying.

Durability Summary: The primary durability risks associated with these wall assemblies involve moisture damage related to rain water penetration or condensation (most likely the result of air leakage, but also potentially the result of vapor diffusion). In some extreme cold climates, two inches of spray foam may not be enough insulation to minimize the risk of air leakage and vapor condensation durability issues because of the ratio of insulation to the interior and exterior of the surface of the spray foam. Increasing the amount of spray foam (the amount of insulation exterior of the condensation plane) will further decrease the risk.

An airtight drywall construction approach will also reduce risks associated with air leakage condensation, and some form of vapor control may be needed (poly, kraft paper or vapor barrier paint depending on climate).

Cellulose insulated walls are slightly more durable because cellulose insulation is capable of storing and redistributing small amounts of moisture. Cellulose insulation is typically treated with borates that have been shown to protect itself and neighboring wood material from mold growth and decay. Cellulose insulation also has decreased flame spread potential relative to other insulation materials.

BUILDABILITY

A double stud wall requires more effort and time to construct properly compared to standard construction practices. The thickness of the wall requires plywood boxes to install all windows and doors in the enclosure. Installing spray foam reduces the risks from poor workmanship but in some climates more than two inches of high density spray foam may be required to completely avoid the risk of air leakage and vapor condensation. Double stud wall construction reduces the interior living space of the building by adding insulation to the interior of the structural framed wall.

COST

There are increased costs in the addition of a secondary interior wall, and spray foam insulation. The benefits of reduced condensation potential may not be worth the cost of adding spray foam since there are only minimal benefits to the R-value of the wall assembly.

MATERIAL USE

A secondary interior framed wall increases the amount of framing material required for wall construction. Spray foam insulation significantly increases the embodied energy over using cellulose insulation with minimal returns in R-value.

TOTAL SCORE

This is truly a high-R wall assembly, and with the addition of spray foam, there is a reduction in moisture related durability issues. In some extreme climates, two inches of spray foam may not be enough to sufficiently reduce the risk, which means that more spray foam is required, or an interior air barrier and some form of vapor control, likely a Class II or Class II would be sufficient. The other disadvantage to this wall system is that it reduces the living space of the building.

REFERENCES

1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis*. Retrieved from buildingscience.com.

2 Straube, J. (2009, 04 22). *BSD-014 Air Flow Control in Buildings.* Retrieved from buildingscience.com.

3 Lstiburek, J. W. (2006). *Water Management Guide.* Westford: Building Science Press Inc.

4 Lstiburek, J. (2008, 08 20). *BSD-104: Understanding Air Barriers*. Retrieved from buildingscience.com.

5 Lstiburek, J. (2008, 10 17). *BSD-106 Understanding Vapor Barriers.* Retrieved from buildingscience.com.

OFFSET FRAME WALL CONSTRUCTION

OFFSET FRAME WALL CONSTRUCTION DETAILS *(Wall 11)*[1]

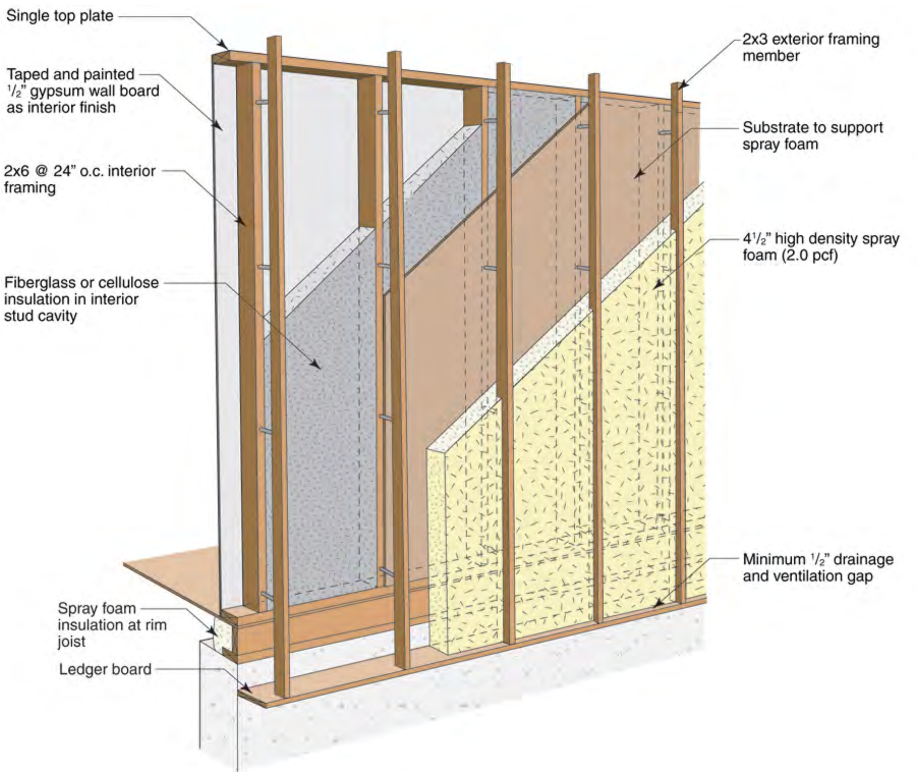
- 2x6 structural framing wall
- 2x3 cantilevered wall
- 4.5” high density spray foam
- Fiberglass or cellulose cavity insulation
- OSB sheathing

SCORING: HOW IT RATES

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	5
Durability	5
Buildability	4
Cost	3
Material Use	2
Total	**19**

The offset frame wall system is ideal in many situations where the cost of high density spray foam is justified. There is very minimal risk to moisture related durability issues from rain penetration or condensation because off the continuous exterior spray foam insulation if the penetrations are detailed correctly. This is a very durable wall system for all climates, and can be built as new construction or a deep retrofit.



INTRODUCTION

This two page summary briefly summarizes the offset frame wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

THERMAL CONTROL

Installed Insulation R-value: The amount of insulation installed in this wall system can be modified quite easily but in this case, 4.5” of high density spray foam (R-6/inch) was used on the exterior, and 5.5” of cellulose (R-3.7/inch) was installed in the stud space for a total installed insulation R-value of R-47. It is possible to install as much or as little spray foam insulation on the exterior as practical in specific cases.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors, the thermal bridging in this wall system is significantly reduced by the uniform layer of spray foam over the exterior covering the rim joist and wall framing. The whole wall R-value for this assembly is approximately R-37.[1]

Air Leakage Control: The exterior spray foam insulation is a perfect air barrier for this enclosure eliminating heat losses by air leakage through the wall. Air still could leak around penetrations such as windows, doors, and services if not detailed correctly.[2]

Typical Insulation Products: High density spray foam and fiberglass batt, blown cellulose, sprayed cellulose, or sprayed fiberglass.

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DURABILITY

Rain Control: For this wall system, the continuous drainage plane will be the exterior surface of the high density foam. Rain screen cladding will be installed directly on the exterior framing, and any moisture that passes through the cladding will drain against the high density spray foam. Intersections, windows, doors and other penetrations must be detailed to prevent the penetration of rainwater.[3]

Air Leakage Control: The continuous layer of high density spray foam prevents all air leakage through the enclosure system. Care should be taken to make sure that penetrations through the enclosure (windows, doors, services) are airtight. There should be no risk of air leakage condensation against the sheathing in most climates with 4.5" of exterior spray foam. In climate zone 8, more spray foam may be required, or the stud space insulation can be removed to ensure that there is no condensation.[4]

Vapor Control: The continuous layer of high density spray foam prevents vapor movement through the enclosure system. There should be no risk of vapor condensation against the sheathing in most climates with 4.5" of exterior spray foam. In climate zone 8, more spray foam may be required, or the stud space insulation can be removed to ensure that there is no condensation.[5]

Drying: This enclosure system will dry both to the interior, if the moisture is in the stud space, and to the exterior, if the moisture is in the cladding. Proper flashing of all penetrations should help minimize moisture in the enclosure. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before closing in. Cellulose is often sprayed in wet, and manufacturer's recommendation is to allow drying before closing in. Because no polyethylene vapor barrier is required, moisture in the stud space will be able to dry quite easily to the interior.

Durability Summary: Provided the minimum amount of spray foam insulation is exceeded for a given climate to keep the condensation plane above the dew point, there is virtually no risk to moisture condensation in the enclosure, and any small amounts of moisture in the enclosure will dry easily.

Cellulose insulation is typically treated with borates that have been shown to protect itself and neighboring wood material from mould and decay. Cellulose insulation also has decreased flame-spread potential.

BUILDABILITY

This wall system does require some attention to detailing, and likely some initial training to install the exterior framing material1, but the risks from poor construction are very minimal. Spray foam insulation is shipped as a liquid in two components and only mixed as it is installed, so shipping is much more efficient and reliable than board foam, which has been reported to arrive on the job site damaged, especially in remote areas. It is very quick and easy to dry in a structure with spray foam insulation to weatherproof it, which is critical in environments with short construction seasons. Interior finishing can be done even in inclement weather. This enclosure system has been used both in new construction and in retrofit situations in cold climates.

COST

In most regions high density spray foam is a relatively expensive method of insulating the enclosure, however the benefits, of a complete air and vapor barrier, occupancy comfort, reduced energy consumption, and reduced risks to contractor errors may be worth the increased cost in some locations and situations.

MATERIAL USE

More framing materials are required for this enclosure assembly, as well as the higher embodied energy high density spray foam. Cellulose in the stud space has very low embodied energy.

TOTAL SCORE

This wall system is ideal in many situations where the cost of high density spray foam is justified. One of the locations where the cost is justified is the extremely cold climates and short construction seasons of the north. Most of the durability related issues are caused by air leakage and vapor condensation on the sheathing causing rot and mold in the enclosure. The common complaints in the remote locations is that the board foam arrives on trucks badly damaged, but with spray foam, the foam is shipped in two liquid components, and more board feet of foam could be shipped on the same truck. The construction season is very short but houses can be dried in during the best weather, and the interior finished later if necessary.

REFERENCES

1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis*. Retrieved from buildingscience.com.

2 Straube, J. (2009, 04 22). *BSD-014 Air Flow Control in Buildings.* Retrieved from buildingscience.com.

3 Lstiburek, J. W. (2006). *Water Management Guide.* Westford: Building Science Press Inc.

4 Lstiburek, J. (2008, 08 20). *BSD-104: Understanding Air Barriers.* Retrieved from buildingscience.com.

5 Lstiburek, J. (2008, 10 17). *BSD-106 Understanding Vapor Barriers.* Retrieved from buildingscience.com.

EXTERIOR INSULATION FINISH SYSTEMS (EIFS) WALL CONSTRUCTION

EXTERIOR INSULATION FINISH SYSTEMS (EIFS) WALL CONSTRUCTION DETAILS

(Wall 12)[1]

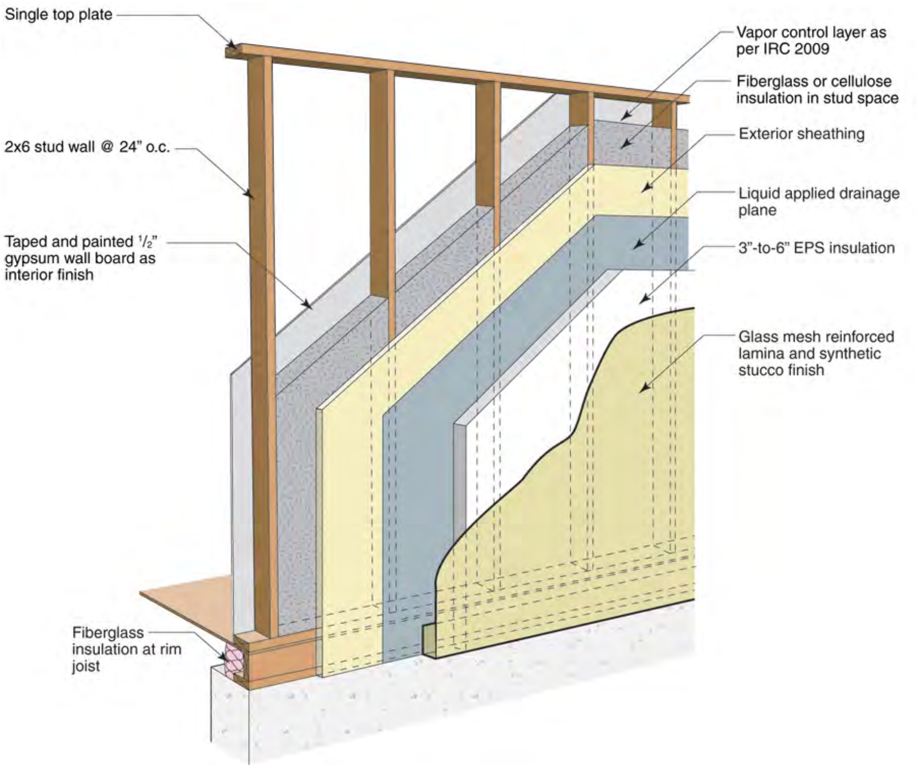
- 2x6 structural framing wall
- Fiberglass or cellulose cavity insulation
- Glass-faced gypsum sheathing
- Exterior EPS insulation
- Stucco finish

SCORING: HOW IT RATES

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	5
Durability	5
Buildability	4
Cost	3
Material Use	3
Total	**20**

This wall system is a durable and reliable choice regardless of the historical failures of this construction strategy. A better understanding of enclosure design and building science with drained and ventilated claddings and better design details have nearly eliminated the historical moisture related issues. This wall system has the appearance of a stucco finish, but with significant energy improvements, which is often the reason for using this construction strategy.



INTRODUCTION

This two page summary briefly summarizes EIFS wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

THERMAL CONTROL

Installed Insulation R-value: The framed portion of this wall assembly typically has an R-value of R-19-20 when insulated with fiberglass batt or cellulose. Exterior insulation for EIFS is typically EPS at R-4/inch.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors demonstrates improvements in the efficiency of the fiberglass batt or cellulose in the stud space by decreasing the thermal bridging effects of the framing and the rim joist. Adding 4" of EPS insulation for a total an increase of R-16 increases the Clear-wall R-value of standard construction by slightly more than R-16 because of thermal bridging of the framing and rim joist. The whole-wall R-value for this system is approximately R-30.[1]

Air Leakage Control: Fiberglass batt, blown and sprayed cellulose are all air permeable materials allowing possible air paths between the interior and exterior as well as convective looping through the material. The air tightness of an EIFS system is typically at the surface of the exterior sheathing (usually glass-faced exterior gypsum) because it is the drainage plane.

Typical Insulation Products: EPS exterior insulation, fiberglass batt, blown cellulose, sprayed cellulose.

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DURABILITY

Rain Control: In the EIFS system, it is critical to correctly detail the drainage plane to adequately handle rain. Historically EIFS were constructed using a face-sealed approach, but this lead to many moisture related durability issues. EIFS can be used as part of a very durable and reliable enclosure system, provided it is drained and ventilated. Intersections, windows, doors and other penetrations must be detailed to prevent the penetration of rain water.[2]

Air Leakage Control: By adding exterior insulation as part of the EIFS construction, the temperature of the sheathing (condensation plane) increases, and the risk of air leakage condensation is reduced. It is always good practice to build airtight enclosure systems, often with both an interior and exterior air barrier to avoid air leakage condensation and windwashing. Air leakage condensation is one of the greatest causes of premature building enclosure failure. An air barrier should be stiff, continuous, durable, strong, and impermeable.[3]

Air need not leak straight through an assembly to cause moisture problems; it can also leak from the inside, through the wall, and back to the inside. Condensation within the stud space is possible if this type of airflow occurs, depending on the weather conditions. Hence, wall designs should control airflow into the studspace.[4]

Vapor Control: By adding exterior insulation as part of the EIFS construction, the temperature of the sheathing (condensation plane) increases, and the risk of moisture vapor condensation is reduced. It may be possible to avoid the use of an interior vapor control layer, or use a higher permeance vapor control layer (Class II or III) depending on the amount of insulation on the exterior and regional building codes. Installing the incorrect vapor control layer or installation in the incorrect location can lead to building enclosure failure.[5] The IRC building code should be consulted.

Drying: Insulating sheathing limits the drying to the exterior, and the wall must be able to dry to the interior. Poly vapor barriers are typically avoided so that this drying can occur. The minimum level of vapor control on the interior surface is determined by the IRC. Installing vapor control on both sides of the enclosure will seal any moisture into the stud space, resulting in low drying potential, and possibly resulting in moisture-related durability risks. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before close in. Cellulose is often sprayed in damp, and manufacturers recommend drying before close in and moisture content limits.

Durability Summary: The primary durability risks associated with these wall assemblies involve moisture damage related to rain water penetration. Insulating sheathings keep the condensation plane temperature elevated so there is less risk of condensation due to air leakage or vapor diffusion. Framing members are also kept warmer so they are exposed to lower relative humidity levels and generally have lower equilibrium moisture contents. Board foam products are typically less moisture sensitive than wood-based structural sheathing products.

Cellulose insulated walls are somewhat more durable because cellulose insulation is capable of storing and redistributing small amounts of moisture. Cellulose insulation is typically treated with borates that have been argued to protect adjacent wood members from mold and decay.

BUILDABILITY

Exterior insulation up to 1.5” requires minimal changes to standard construction practices. Exterior insulation in excess of 1.5” requires minor changes to window and wall construction and detailing which requires training and monitoring during the initial implementation. The EIFS finish system is directly applied to the exterior foam, and requires skilled trades to install. Some EIFS companies produce detail drawings for their products to reduce the risk of construction issues resulting in premature enclosure failure. www.stocorp.com and www.dryvit .ca are two examples that provide detailed drawings on their websites.

COST

There is an increased cost to EIFS wall construction because of the specialized stucco like finish. It is possible to add exterior insulation with a rain screen cladding as an alternative to the stucco appearance finish that may be more cost effective.

MATERIAL USE

Typically, in EIFS construction, structural wood sheathing is exchanged for a more moisture tolerant sheathing such as glass mesh reinforced exterior gypsum board. The addition of EPS foam can usually be sourced locally, and has relatively low embodied energy relative to other board foam insulations.

TOTAL SCORE

This wall system is a durable and reliable choice regardless of the historical failures of this construction strategy. A better understanding of enclosure design and building science with drained and ventilated claddings and better design details have nearly eliminated the historical moisture related issues. This wall system has the appearance of a stucco finish, but with significant energy improvements, which is often the reason for using this construction strategy. It is possible to use exterior insulation with many different cladding options if a stucco appearance is not the desired architectural result.

REFERENCES

1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis*. Retrieved from buildingscience.com.

2 Lstiburek, J. W. (2006). *Water Management Guide.* Westford: Building Science Press Inc.

3 Lstiburek, J. (2008, 08 20). *BSD-104: Understanding Air Barriers*. Retrieved from buildingscience.com.

4 Straube, J. (2009, 04 22). *BSD-014 Air Flow Control in Buildings.* Retrieved from buildingscience.com.

5 Lstiburek, J. (2008, 10 17). *BSD-106 Understanding Vapor Barriers.* Retrieved from buildingscience.com.

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Building America Special Research Project: High-R Walls Case Study Analysis

Research Report - 0903

March 11, 2009 (rev. 8/7/09)
John Straube and Jonathan Smegal

Abstract:

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. More building codes are being modified to require higher levels of thermal control than ever before. 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 true three-dimensional heat flow and the relative risk of moisture damage.

Building America Special Research Project

High-R Walls Case Study Analysis

2009 08 07

Jonathan Smegal MASc
John Straube, PhD, P.Eng

Building Science Corporation
30 Forest Street
Somerville, MA 02143

www.buildingscience.com

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A. 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. More building codes are being modified to require higher levels of thermal control than ever before. 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 true three-dimensional heat flow and 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.

High R-values for framed wall assemblies are defined here as ranging from approximately R18 to R40 and above depending on the geographic location and climate conditions. A high R-value wall in the south will be considerably less than a high R-value in a cold climate. The analysis in this report includes a summary of historical wall construction types and R-values, current construction strategies, as well as walls that will likely become popular in the future based on considerations such as energy and material availability.

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.

A study currently being conducted by the National Research Council of Canada (NRC) is investigating and developing durable and energy efficient wall assemblies for Northern Canada. In the first stage of the NRC study, meetings with the northern communities and investigations of the houses were conducted. A literature review covering selection criteria for possible envelope assemblies in Northern Canada, current wall systems and systems to consider was written (Saïd 2006). Walls are currently undergoing extreme temperature testing in the NRC laboratory in Ottawa, Canada. All of the walls being tested by the NRC are constructed with a polyethylene air and vapor barrier and none of the walls are constructed with exterior insulation (Rousseau, et al. 2008).

The Cold Climate Housing Research Center (CCHRC) of Alaska has conducted field monitoring tests on different wall systems, specifically to assess the moisture-related performance of high performance wall systems. Several tests were conducted on a test hut at the University of Alaska Southeast, in Juneau AK (8574 HDD65 or 4763 HDD18) (Smegal and Straube 2006), and others were conducted on the CCHRC main office building in Fairbanks Alaska (13980 HDD65 or 7767 HDD18) constructed in 2007. Streaming data and wall drawings can be viewed on the CCHRC website showing the thermal performance of the wall systems (CCHRC 2007). CCHRC also successfully completed construction of a high R-value house as part of the Building American program in Haida, AK, and the report can be found online (BSC 2008).

Some of the walls for this high R-value study were chosen based on the literature review of the NRC report, and references to construction techniques from both the NRC and CCHRC will be made throughout this report. Some walls have been built by niche builders since the early 1980's.

1. OBJECTIVE

The objective of this study is to identify highly-insulated building enclosure wall systems based on selected criteria, resulting in a durable affordable, and resource efficient enclosure that provides a comfortable living environment in different climate zones. This report will present the analysis of different enclosure wall strategies and present their advantages and disadvantages according to several comparison criteria.

2. SCOPE

This study is limited to wall systems for cold climates. Further studies should be conducted to address other components of the building enclosure such as roofs and foundations. In general, only cold climates are considered in this report since enclosures in cold climates benefit the greatest from a highly insulated building enclosure, but important conclusions can also be drawn for other climate zones.

3. APPROACH

This study examines thermal and moisture control, durability, buildability, 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. Minneapolis, MN in IECC climate Zone 6 was used as the representative cold climate for most of the modeling, because of the cold winter weather, and fairly warm and humid summer months. In cold climates, a building's enclosure is often the most important factor limiting heat loss, both in terms of insulation and air tightness.

B. Analysis

1. WALL ASSEMBLIES REVIEWED

Because there are a number of variables possible for each possible wall system depending on the local practices, climate, and architect or general contractor preferences, an attempt was made to choose the most common wall systems and make notes and comments about other alternatives during analysis. This list of chosen systems is explained in more detail in the analysis section for each wall system.

- Case 1a : Standard Construction Practice with 2x6 framing
- Case 1b : Standard Construction Practice with 2x4 framing
- Case 2a : Advanced Framing with 1" of XPS insulated sheathing
- Case 2b : Advanced Framing with 4" of XPS insulated sheathing
- Case 3 : Interior 2x3 horizontal strapping
- Case 4 : Double Stud
- Case 5 : Truss Wall
- Case 6 : Structural Insulated Panel Systems (SIPs)
- Case 7 : Insulated Concrete Forms (ICFs)
- Case 8a : Advanced Framing with low density (0.5 pcf) spray foam
- Case 8b : Advanced Framing with high density (2.0 pcf) spray foam
- Case 9: Hybrid system with high density (2.0 pcf) (Flash and Fill) spray foam and fibrous insulation
- Case 10: Double Stud wall with 2" of high density (2.0 pcf) spray foam and fibrous insulation
- Case 11: Exterior high density (2.0 pcf) (Offset Frame Wall) spray foam with fibrous cavity insulation
- Case 12: Exterior Insulation Finish System (EIFS)

2. 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)	Buildability	Cost	Material Use	Total
Criteria Weighting	1	1	1	1	1	
Case 1: Standard Construction						
Case 2: Advanced Framing with Insulated Shtg						
Case 3: Interior Strapping						
Case 4: Double Stud						
Case 5: Truss Wall						
Case 6: SIPs						
Case 7: ICF						
Case 8: Sprayfoam						
Case 9: Flash and Fill (2" spuf and cell.)						
Case10: Double stud with 2" spray foam and cell.						
Case 11: Offset Framing (ext. Spray foam insul.)						
Case 12: EIFS with fibrous fill in space						

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 wall design. 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 costs of different insulations may be uncertain, fiberglass batt insulation is always less expensive than low density (0.5 pcf) spray foam which is less expensive than high density (2.0 pcf) spray foam, so these systems can be ranked accordingly regardless of the actual costs.

2.1 Heat flow analysis

Two 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. 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 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 in (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, wall/floor, wall/door, and wall/window 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 with a weighted average.

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 92 inches.

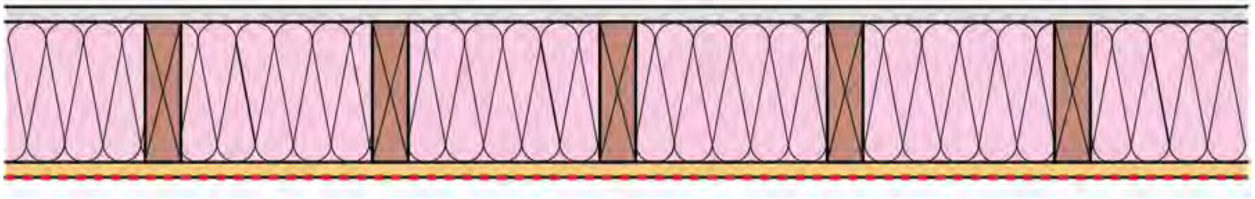


Figure 1 : Plan view of wall section for Therm simulation

The top plate was simulated in section view to assess the importance of the thermal bridging of the top plate(s). This section was eight inches in height since the thermal effect of the top plate will influence the effectiveness of the cavity insulation in its vicinity. The R-value of this detail was calculated over the entire height as indicated by the red dashed line in Figure 2.

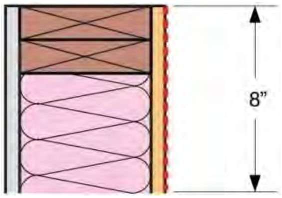


Figure 2: Top plate simulation with 8” of wall

The rim joist was also simulated in a vertical section to take into account the thermal bridging effects of the bottom plate, sill plate, floor sheathing and rim joist. It was simulated with eight inches of wall above the floor sheathing to take into account any changes in the insulation caused by thermal bridging effects.

The concrete foundation was included beneath the rim joist to determine the effects of the interface between the foundation and wood framing, but the concrete was not included in the R-value calculation as indicated by the red dashed line in Figure 3.

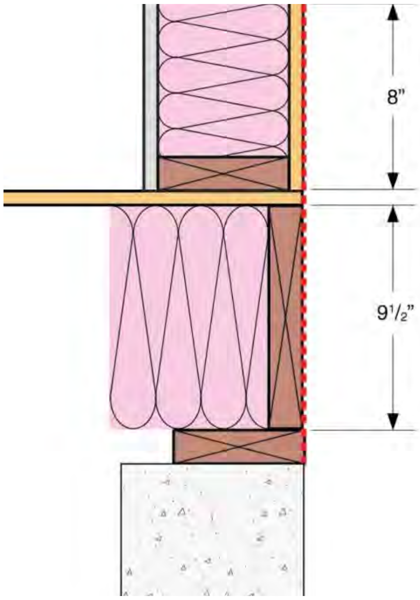


Figure 3 : Rim joist simulation with 8" of wall

Although Therm is a two-dimensional modeling software 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 4), the effective R-value of just this section through the assembly can be determined.

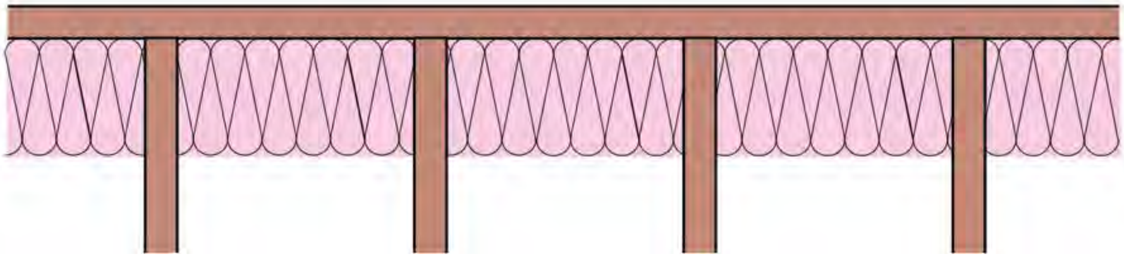


Figure 4 : Plan section of rim joist, floor joists, and fiberglass batt insulation

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 3).

Once the R-values are calculated for all three sections of a wall system, The Whole Wall R-value is calculated by taking the weighted average of the individual components as shown in the equation below. The total wall height from the bottom plate to the top plate is nine feet.

$$\text{Total wall R-value} = \text{R-value top plate x } \frac{\text{height of top plate}}{\text{overall wall height}} + \text{R-value of rim joist x } \frac{\text{height of rim joist}}{\text{overall wall height}} +$$

$$\text{R-value of wall section x } \frac{height\ of\ wall\ section}{\text{overall wall height}}$$

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

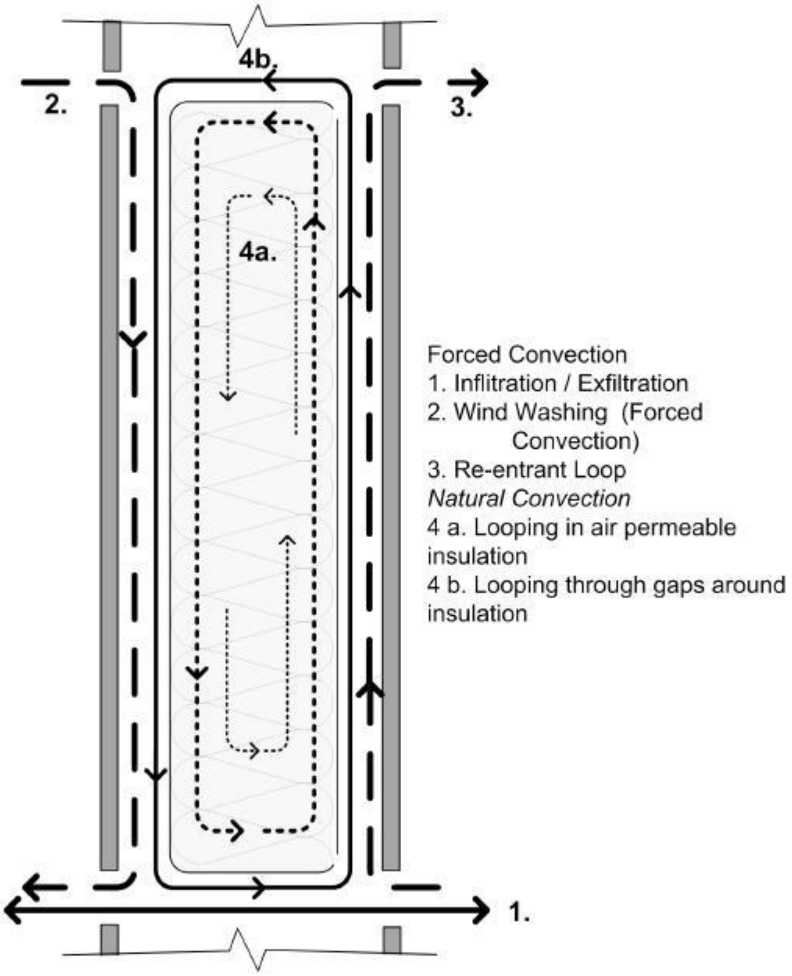


Figure 5 : Common Convective Heat Flow Paths in Enclosures

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 houses 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 pressure difference across the enclosure. Air tightness of the building enclosure has begun to improve in cold climates for the most part to address occupancy comfort issues and contractor call-backs.

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 result in higher installed 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 as well as poorly insulated locations resulting in cold spots around obstacles that could increase the risk of moisture condensation.

Cellulose installation 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 is 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 the fiberglass batt insulation cannot be fully appreciated using this analysis.

All of the Therm analysis were conducted with an interior temperature of 20°C (68°F) and an exterior temperature of -20°C (-4°F) 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	Thermal Conductivity k [W/mK]	R-value per inch [hr·°F·ft^2/Btu]
R8 Fiberglass Batt (2.5")	0.045	3.1
R13 Fiberglass Batt (3.5")	0.039	3.7
R19 Fiberglass Batt (5.5")	0.042	3.4
Extruded Polystyrene (XPS)	0.029	4.9
Expanded Polystyrene (EPS)	0.038	3.7
Framing lumber	0.140	1.0
Cellulose Insulation	0.040	3.5
0.5 pcf spray foam	0.037	3.8
2.0 pcf spray foam	0.025	5.7
OSB	0.140	1.0

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 2x4 stud spacing in a typical wall system is sixteen inches (405 mm) on centre. 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.

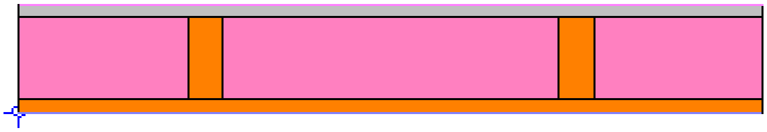


Figure 6 : Typical framing 16" o.c. - 9% framing factor

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). Modeling was conducted to investigate the impact on effective R-value for a wall system with 23% (Figure 7) framing factor and with 9% framing factor. It was found that the Clear Wall R-value of a wall section insulated with R13 fiberglass batt decreased from R12.6 to R10.1 when a more realistic 25% framing factor was used. This results in a Whole Wall R-value decrease from R12 to R10 when the more realistic 25% framing factor was used. The reason that neither wall section achieved a Clear wall or Whole Wall R13 is because of the thermal bridging effects of the studs, one of the underlying issues in using Installed Insulation R-values to describe enclosure systems.

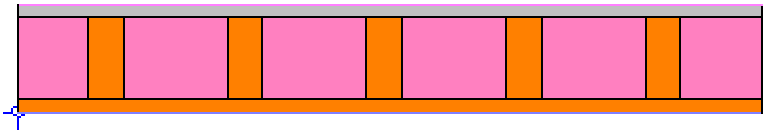


Figure 7 : Actual average framing factor of 23% in standard construction

Most of the framed walls in this analysis were proposed with advanced framing techniques (also described as Optimum Value Engineering, OVE) that include 2x6 framing, 24" o.c., and single top plates. Field studies have also been conducted on advanced framed walls, and it was found that the average framing factor is approximately 16%. For comparison purposes, all of the standard wood framed wall sections were simulated with a framing factor of 25% and advanced framed walls were modeled with 16% framing factor.

Table 3 shows all of the Whole Wall R-values calculated using Therm simulations. The thermal performance is further discussed for each wall system in the following sections.

Table 3 : R-values for analyzed wall systems

Case	Description	Whole Wall R-value	Rim Joist	Clear Wall R-value	Top Plate	Framing Fraction
1a	2x6 AF, 24"oc, R19FG + OSB	**15.2**	12.3	16.1	12.5	16%
1aii	2x6, 16"oc, R19FG + OSB (25%ff)	**13.7**	12.3	14.1	12.5	25%
1b	2x4 AF, 24"oc, R13FG + OSB	**11.1**	9.8	11.5	9.8	16%
1bii	2x4, 16"oc, R13FG + OSB (25%ff)	**10.0**	9.8	10.1	9.8	25%
2a	2x6 AF, 24"oc R19FG + 1" R5 XPS	**20.2**	18.5	20.6	20.3	16%
2b	2x6 AF, 24"oc R19FG + 4" R20 XPS	**34.5**	29.0	35.6	35.4	16%
3	2x6 AF, 24"oc, 2x3 R19+R8 FG	**21.5**	13.4	23.5	18.4	16%
4	Double stud wall 9.5" R34 cellulose	**30.1**	14.4	33.5	28.8	
5	Truss wall 12" R43 cellulose	**36.5**	18.6	40.5	34.4	
6a	SIPs (3.5" EPS)	**14.1**	12.3	14.5	10.6	
6b	SIPs (11.25" EPS)	**36.2**	14	41.6	28.2	
7a	ICF - 8" foam ICF (4" EPS)	**16.4**		16.4		
7b	ICF - 15" foam ICF (5" EPS)	**20.6**		20.6		
7c	ICF - 14" cement woodfiber ICF with Rockwool	**17.4**		17.4		
8a	2x6 AF, 24" o.c., 5" 2 pcf R29 SPF, OSB	**19.1**	13.6	20.3	19.5	16%
8b	2x6 AF, 24" o.c., 5.5" R21 0.5 pcf SPF, OSB	**16.5**	13.1	17.2	16.6	16%
9	2x6 AF, 24"oc, 2" SPF and 3.5" cellulose	**17.5**	13.2	18.4	17.7	16%
10	Double stud with 2" 2.0 pcf foam, 7.5" cell.	**32.4**	15.9	36.2	28.5	
11	Offset frame wall with ext. spray foam	**37.1**	18.8	40.6	41.9	16%
12	2x6 AF, 24"oc, EIFS - 4" EPS	**30.1**	23.8	31.4	31.1	16%

*AF - Advanced Framing

2.2 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.

Vinyl siding was chosen as the cladding system for the analysis as it is the most widely used residential cladding system in North America, and it can be found in almost any geographic area.

Minneapolis MN was chosen as the climate to compare all of the chosen wall systems. Minneapolis is in DOE climate zone 6, which experiences cold wintertime temperatures as well as some warm humid summer temperatures.

A Class I or II vapor retarder is required according to the International Residential Building Code (IRC) on the interior of the framing in zones 5,6,7,8 and marine 4. This will control vapor condensation on the sheathing in the winter months as shown in Figure 9. The RH at the sheathing did not reach elevated levels in Case 1 (framed walls with OSB sheathing) with the Class I vapor retarder in WUFI®. There are some exceptions to the interior vapor control layer if a sufficient amount of insulation and vapor control is installed on the exterior.

Often times, the 6-mil polyethylene vapor barrier is also used as the air barrier. This is very difficult to detail correctly, and because it may not be air tight, there is a considerable risk to air leakage condensation on the sheathing should interior air leak into the enclosure.

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.

2.2.1. Moisture Balance

Assessing moisture related durability risks involves three different moisture processes; wetting, drying and moisture redistribution. These three processes in combination with the safe storage capacity 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, vapour condensation, plumbing leaks and built in construction moisture. Minimizing these sources with good design details for shedding rain, air tightness, and vapour control will help decrease the risk of moisture related durability failure.

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 of the building enclosure
2. Decreasing the permeability of the linings that we put on the interior and exterior of the enclosure
3. Increasing the mould 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.

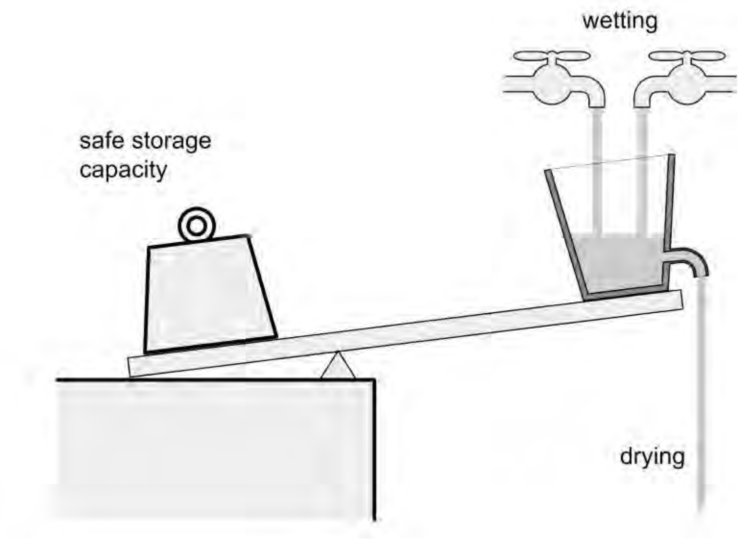


Figure 8 : Moisture balance

2.2.2. Wintertime Condensation

Wintertime diffusion and air leakage condensation potential was determined for each case. The diffusion condensation potential was determined by analyzing the relative humidity at the interior surface of the sheathing (or other condensation plane) during the cold winter months. The interior relative humidity for these simulations was sinusoidal condition varying from a minimum of 30% 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 relative humidity in a cold climate will decrease to between 20% and 30% 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.

In the 2007 supplement to the International residential code, three classes of vapor control were defined for enclosure systems (1 US perm = 57.4 ng/(s·m^2·Pa))

- Class I: 0.1 perm or less (eg. sheet polyethylene)
- Class II: 0.1 < perm ≤ 1.0 perm (eg. kraft faced fiberglass batts , some vapor barrier paints)
- Class III: 1.0 < perm ≤ 10 perm (latex paint)

Class I or II vapor retarders are required on the interior side of framed walls in Zones 5, 6, 7, 8 and marine 4 (IRC N1102.5). Under some conditions, such as vented claddings or insulated sheathings, a Class III vapor retarder is allowed by the code (IRC Table N1102.5.1).

Figure 9 shows a comparison of the relative humidity caused by vapor diffusion at the sheathing for Case 1, standard construction, and Case 2, advanced framing with insulated sheathing. A polyethylene vapor barrier is installed on the interior of the framing in Case 1, vapor barrier paint is used for Case 2 with 1" of XPS insulated sheathing, and latex paint is used for Case 2 with 4" of XPS insulated sheathing. Table 4 shows the vapor control strategies and permeance values for all four walls compared in Figure 9.

Table 4 : Vapor control strategies and permeance values for Case 1 and 2

Case	Description	Vapor Control	Permeance	
			[US perms]	[ng/(s•m^2•Pa)
1a	2x6 AF, 24"oc, R19FG + OSB	poly	0.07	4.0
1b	2x4, 16"oc, R13FG + OSB	poly	0.07	4.0
2a	2x6 AF, 24"oc R19FG + 1" R5 XPS	vapor retarder paint	1.0	57.8
2b	2x6 AF, 24"oc R19FG + 4" R20 XPS	latex paint	10.7	616.7

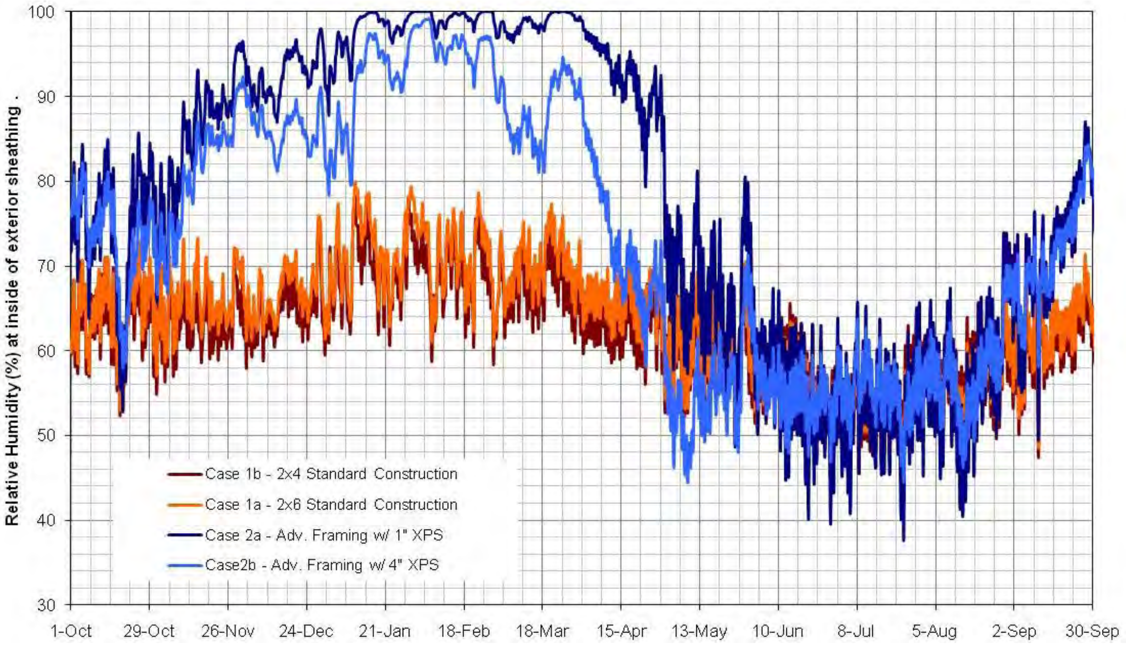


Figure 9 : Winter time sheathing relative humidity for Case 1 and Case 2

The advanced framing wall (Case 2) with 1” of XPS was modeled with the minimum amount of vapor control required (Class II vapor retarder - 1 perm or 57 ng/Pa•s•m2) according to the IRC. The elevated moisture levels during the winter months are only a small concern, since the XPS is not moisture sensitive, and temperatures are quite low in the winter months, minimizing moisture related risks. The advanced framing wall with 4” of XPS insulated sheathing does not require any extra vapor control layers according to the IRC because it qualifies as having more than R-11.25 insulated exterior sheathing over 2x6 wood framing.

Figure 10 shows the potential for air leakage condensation for Case 1 and Case 2. This analysis shows the dewpoint of the interior air and the temperature of the sheathing for both Case 1 and Case 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.

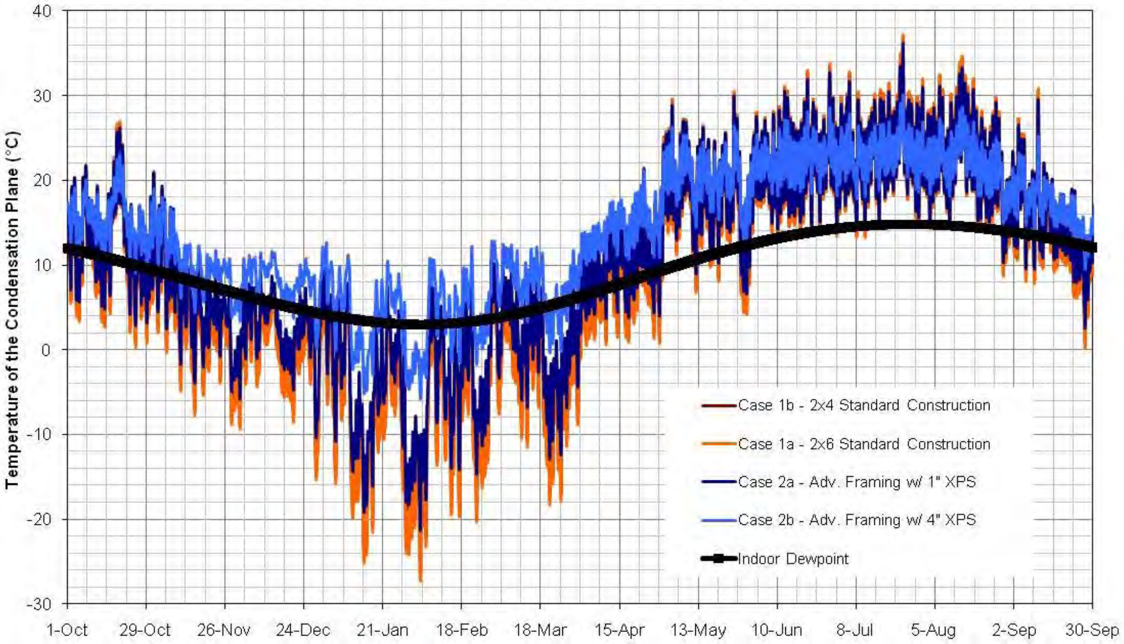


Figure 10 : Winter air leakage condensation potential for Case 1 and Case 2

The risk of air leakage condensation is greatest on the standard construction walls, and slightly improved on the advanced framing wall with 1” of XPS. The wall with 4” of insulated sheathing has the least risk of moisture related durability issues from air leakage condensation because of the short periods of time the interior face of the sheathing is below the dewpoint. When the hours of potential condensation are added together over the entire year, Case 1 with 2x4 construction and 2x6 construction have approximately 4400 and 4500 hours respectively of potential condensation. Case 2 with 1” of insulated sheathing experiences approximately 3800 hours of potential condensation and Case 2 with 4” of insulated sheathing only experiences 1200 hours of potential air leakage condensation.

One method of improving the risk of air leakage condensation in standard construction is by using a hybrid wall system (Case 9). In our analysis a hybrid wall system consists of advanced framing (2x6 24”oc) with OSB sheathing and 2” of high density (2.0 pcf) spray foam installed against the interior of the sheathing. This spray foam can be an excellent air barrier if installed properly and because it is vapor semi-impermeable, the temperature of the condensation plane increases (Figure 11). Two inches of high density spray foam was chosen because it is reported as being the maximum thickness that can be sprayed in one pass on any surface. This hybrid wall has approximately the same amount of condensation potential as Case 2 with 4” of exterior XPS and will be significantly less expensive than Case 8 with 5” of high density spray foam. Unfortunately, it also has much less R-value, and still suffers from thermal bridging.

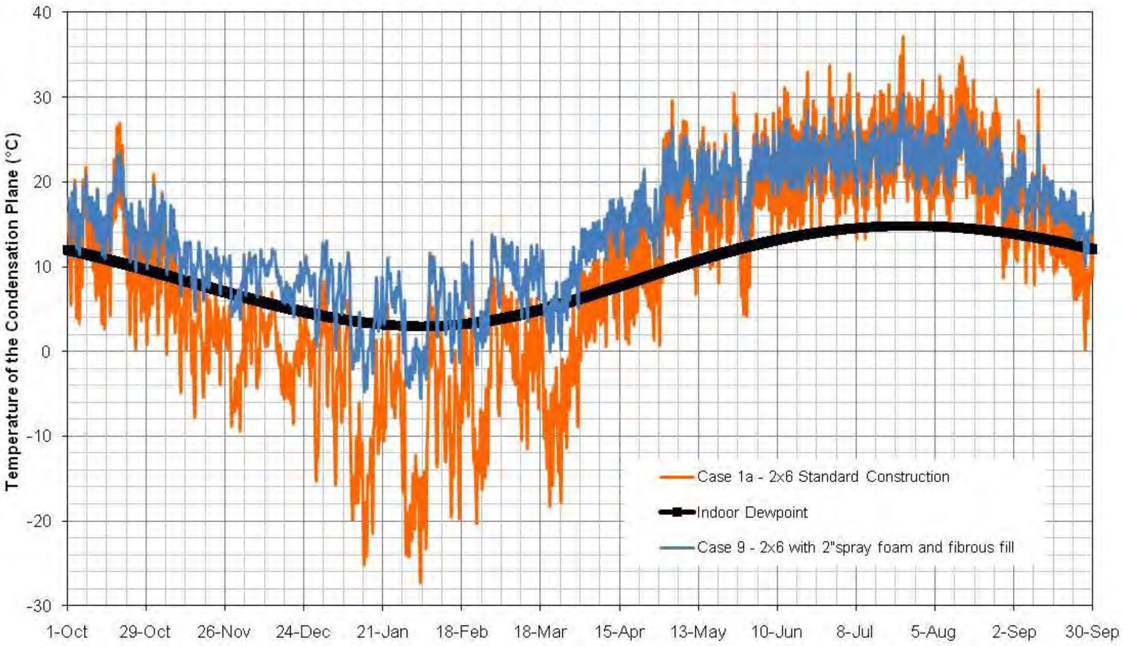


Figure 11 : Winter air leakage condensation potential for Case 1 and Case 9

The winter time sheathing relative humidities for Cases 3, 4, and 5 without air leakage are shown in Figure 12. Constructing these walls with a Class I - 6-mil polyethylene vapor control layer, there is no risk to moisture related issues on the sheathing from vapor diffusion in the winter.

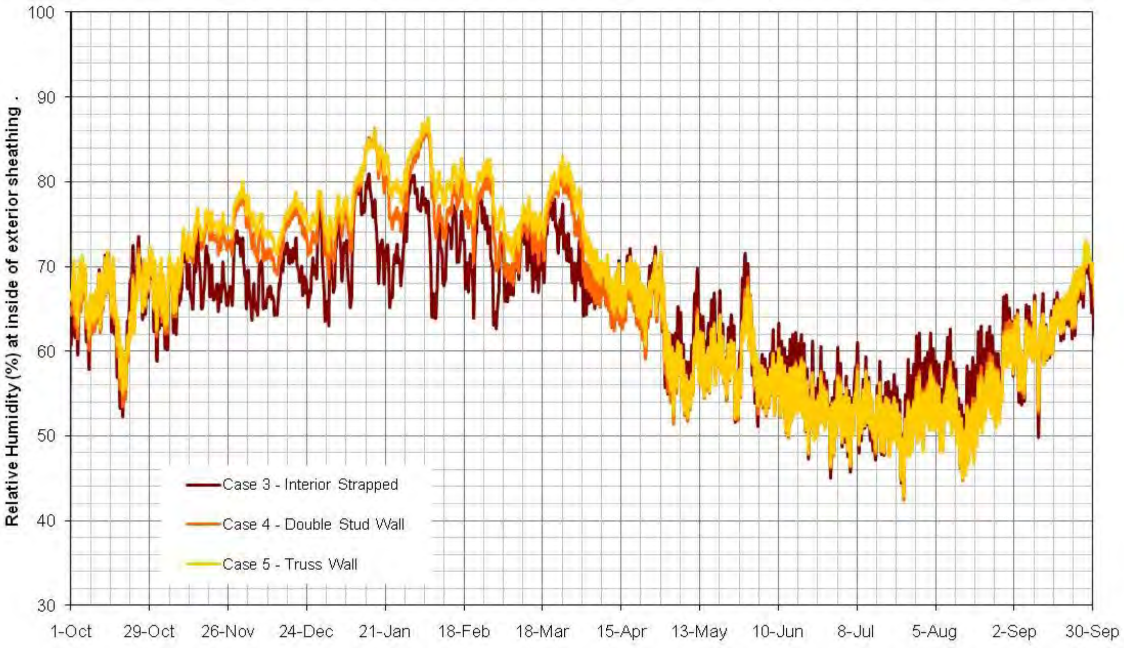


Figure 12 : Winter time sheathing relative humidity for Case 3, Case 4, and Case 5

Winter time air leakage condensation potential for Cases 3, 4, and 5 are shown in Figure 13. The sheathing temperatures of all three of the walls spend a significant portion of the year below the dew point of the interior air because of the increased thermal resistance of the wall system. This means that considerable care must be given to all air tightness details, or there will be a high risk of moisture related durability issues from air leakage.

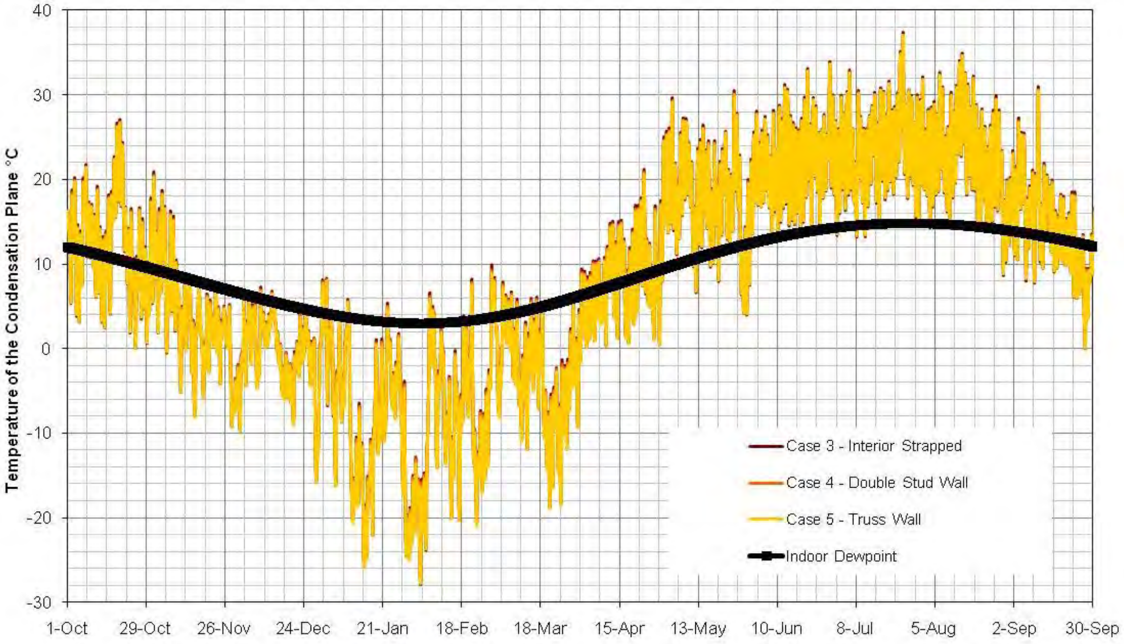


Figure 13 : Winter air leakage condensation potential for Case 3, Case 4, and Case 5

Increasing the temperature of the condensation plane can be done by adding spray foam to the interior surface of the exterior sheathing. Case 10 is a double stud wall with 2" of high density foam sprayed against the sheathing from the interior. Increased vapor resistant insulation raises the temperature of both the diffusion and air leakage condensation planes. Analysis showed that the condensation plane temperature was increased throughout the winter months but that there was still a risk of condensation related damage to the enclosure if air leakage occurs. Figure 14 shows that in Minneapolis (DOE climate zone 6) 2" of high density spray foam may not be enough to reduce the potential condensation risk to a satisfactory level.

Case 10 with 2" of spray foam spends considerably more time below the interior dewpoint compared to Case 9 (hybrid wall) which also has 2" of high density spray foam. The difference in condensation potential is caused by the ratio of the insulation amounts on the interior and exterior of the condensation plane. The remaining 3.5" of the stud space can be filled with an R19 FG batt or cellulose. The increased convection suppression of cellulose insulation is not as critical to this enclosure assembly because of the air tightness of the two inches of spray foam insulation, but will still do a better job of reducing gaps around services, and other places that fiberglass batt is prone to convective looping. The increased thermal resistance of the double stud wall ensures that the condensation plane is kept much cooler. This is a critical consideration to designing a wall enclosure for a specific climate. The double stud walls with 2" of high density spray foam would likely work successfully with little risk in a Climate zone 6 or lower. Alternately, open cell foam could be used to fill the double stud wall although a vapour retarding coating would be needed in cold climates. A mid-density foam, with moderate vapor permeance could also be used as a full fill.

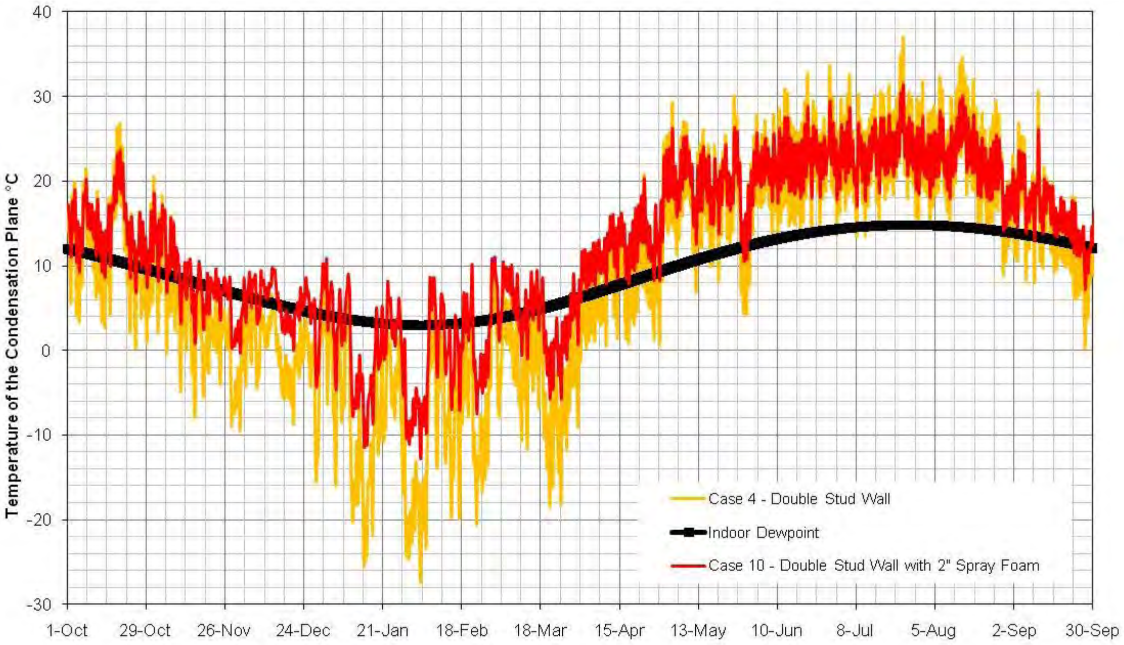


Figure 14 : Winter air leakage condensation potential for Case 4 and Case 10

One wall system becoming more popular in cold climates is a wall constructed with exterior foam insulation, sometimes referred to as an Offset frame wall. This has many advantages over traditional wall construction techniques, and can be used for both new construction and retrofits. Figure 15 shows high density spray foam being installed over the existing exterior sheathing during a retrofit. The surface of the foam becomes the drainage plane, air barrier and vapor barrier of the enclosure. Cladding can be attached directly to the exterior framing that tie back to the framing of the house, and are very stiff and supportive once the foam has been installed.

In this case, the exterior framing was attached with 8" spikes using a spacer to ensure that the exterior framing was the correct distance from the sheathing. Because of the strength and rigidity of the high density spray foam insulation, no additional support is needed for fiber cement siding.

Figure 15 : Installation of high density spray foam in an Offset Framed Wall in a cold climate

In the case of new construction, wood sheathing may not be necessary on the exterior of the structural wall framing to support the spray foam. Removing the sheathing would decrease the cost and work considerably. Other membranes, such as housewraps may be used to support the foam during installation, but more analysis and research may be required before installing spray foam directly on housewraps.

Analysis of the possible wintertime condensation for a Truss Wall constructed with 12” cellulose insulation (Case 5) and constructed with 4.5” of exterior high density foam and 5.5” of fibrous fill in the stud cavity (Case 11) is shown in Figure 16. The sheathing (or foam supporting membrane) never reaches the interior dew point temperature in DOE climate zone 6. In a very extreme cold climate, more foam could be added to the outside or the stud space insulation could be removed which would also decrease the condensation potential.

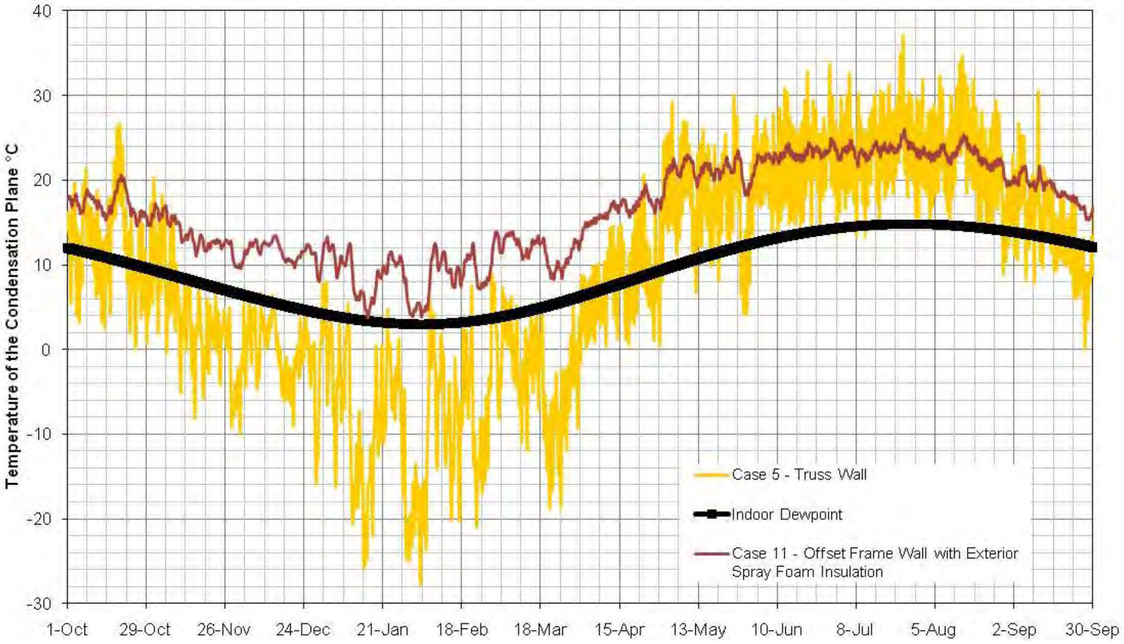


Figure 16 : Winter time air leakage condensation potential for Case 5 and Case 11

There are other advantages to an offset frame wall with exterior foam besides the decreased risk for condensation potential in the enclosure. A house can be dried in very quickly with exterior spray foam insulation, which means that the house is weather proof against rain and snow. This is very important in arctic regions with a very short construction season. Once the foam is installed on the exterior, interior work such as insulation, drywall and finishes can be finished as desired.

There were complaints from the remote areas of Northern Canada (according to the NRC) that when foam board was shipped to be used as exterior insulation, it always arrived broken, which is why they preferred not to use it. High density spray foam is shipped as two liquid components that are combined during the foam installation process. Many more board feet of spray foam can be shipped on the same truck than the equivalent board feet of EPS or XPS board foam insulation. This application is ideal for remote climates.

The sheathing relative humidities for Case 8, the spray foam wall, is shown below in Figure 17. The sheathing relative humidities with high density foam, and low density foam with a vapor barrier show no risks of moisture related issues caused by vapor diffusion. The wall system with low density foam and no vapor control layer may experience some risk to moisture related durability issues depending on the climate.

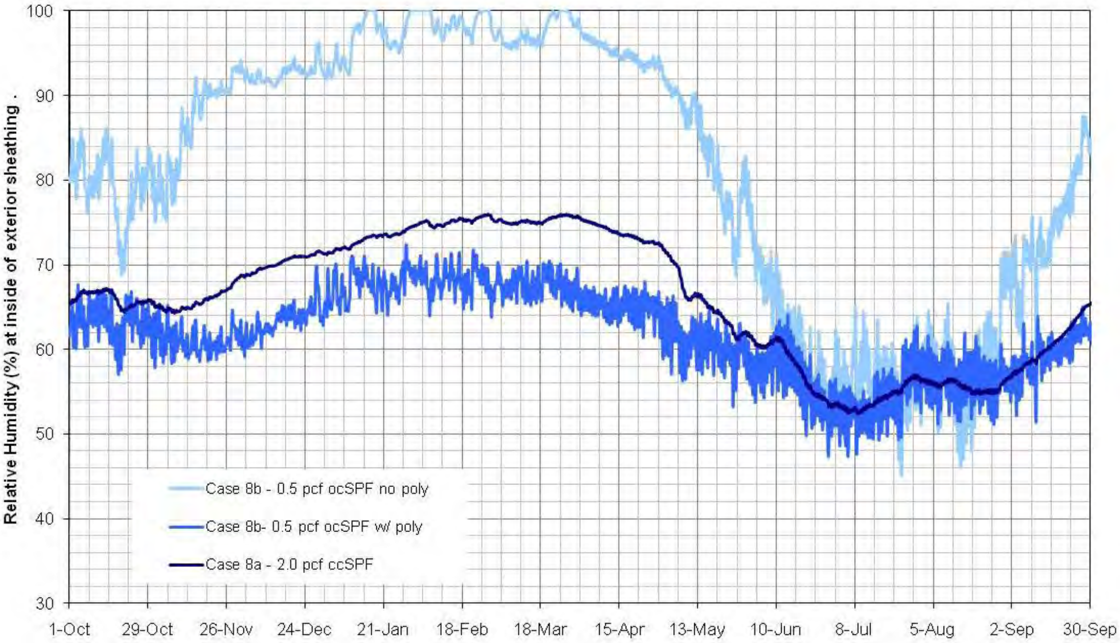


Figure 17 : Winter time sheathing relative humidity for Case 8

A vapor control layer should be used with low-density foam in climate zone 6 based on this hygrothermal analysis. More analysis is required to determine what level of vapor control is required to minimize risk. It may be possible to use a Class II vapor barrier (IBC 2007 supplement). In climate zones warmer than climate zone 6, it may be possible to use 0.5 pcf spray foam with much less risk of moisture related durability issues. More analysis should be conducted on this specific case in different climate zones before design recommendations can be made.

Air leakage condensation potential of Case 8 is shown in Figure 18. Because both low and high density spray foams form an air barrier when installed properly, interior air will not pass the interior surface of the foam. There is no risk of any moisture related durability issues in the walls insulated with spray foam in this analysis.

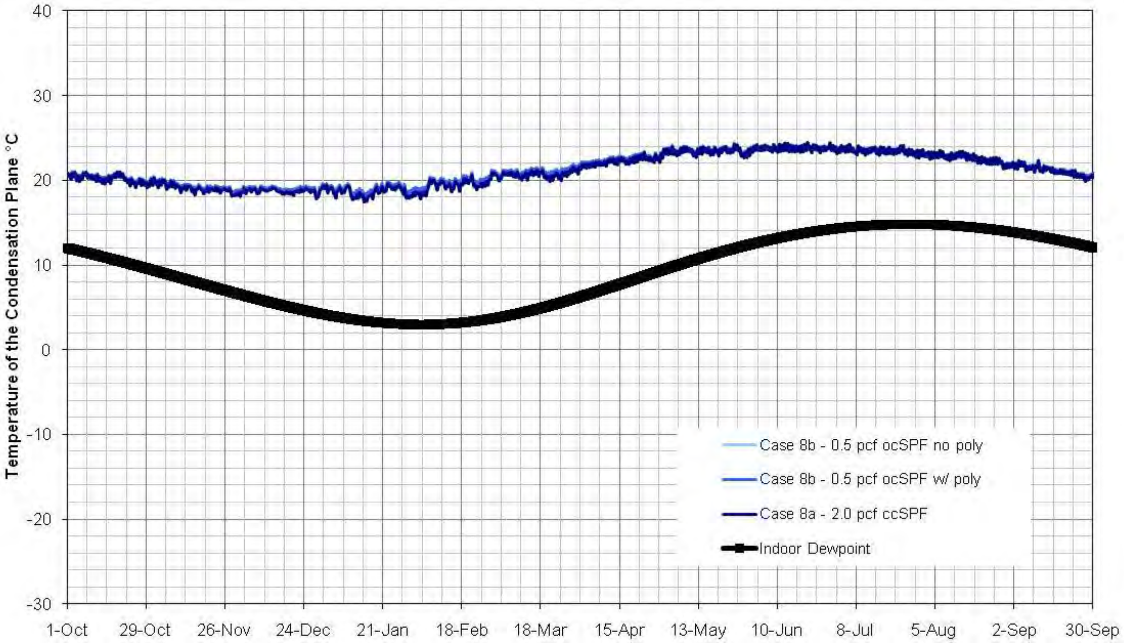


Figure 18 : Winter air leakage condensation potential for Case 8

2.2.3. 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, adhered stone veneer and concrete, 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 polyethylene vapor barrier and may run down the polyethylene to the bottom plate if enough water condenses.

Inward vapor drives were compared in this analysis using vinyl siding as the cladding. This type of cladding does not stress the wall systems from an inward vapor drive perspective but still gives a basis for comparison of the different wall systems. More analysis should be done in the future to more accurately predict the amount of inward vapor drive in cold climates using reservoir claddings (masonry, stucco, adhered stone etc.).

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

Figure 19 shows the comparison of Case 1, standard construction, Case 2, advanced framing with insulated sheathing, and Case 9 hybrid wall. Standard construction experiences higher relative humidities at peak times because of the polyethylene vapor barrier, and lack of vapor control on the exterior. The advanced framing with insulated sheathing walls have some vapor control at the exterior surface of the wall system, and no polyethylene vapor barrier to limit drying to the interior. The advanced framing wall with 1" of XPS has a slightly elevated relative humidity when compared to the wall with 4" of XPS because of the 1 perm (57 ng/Pa•s•m2) paint layer on the drywall slowing drying to the interior, and less vapor control at the exterior surface. The hybrid wall performs very similarly to the advanced framing with 4" of XPS

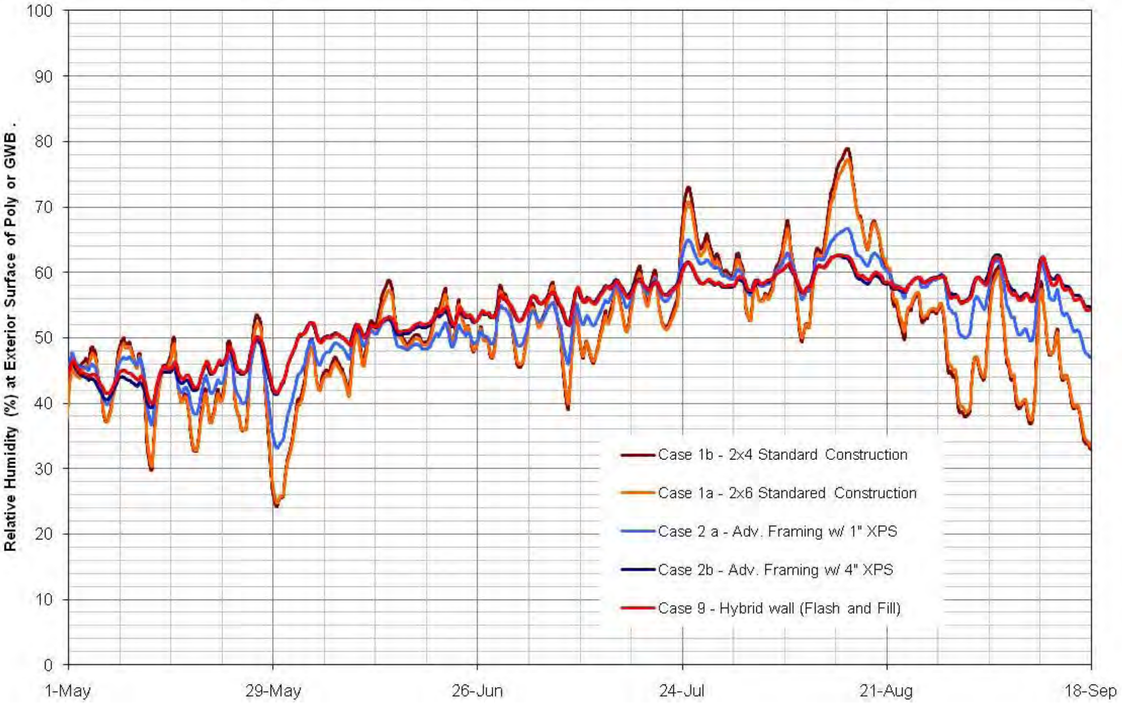


Figure 19 : Inward vapor drive relative humidity of poly or GWB for Case 1, Case 2, and Case 9

Inward vapor drives of Cases 3, 4, and 5(Figure 20) show there is very little performance difference between the test walls, and none of the walls experience any moisture related durability issues caused by inward vapor drives. Case 4, double stud construction, and Case 5, truss wall, experience slightly lower relative humidities because of the moisture buffering effect of the cellulose insulation.

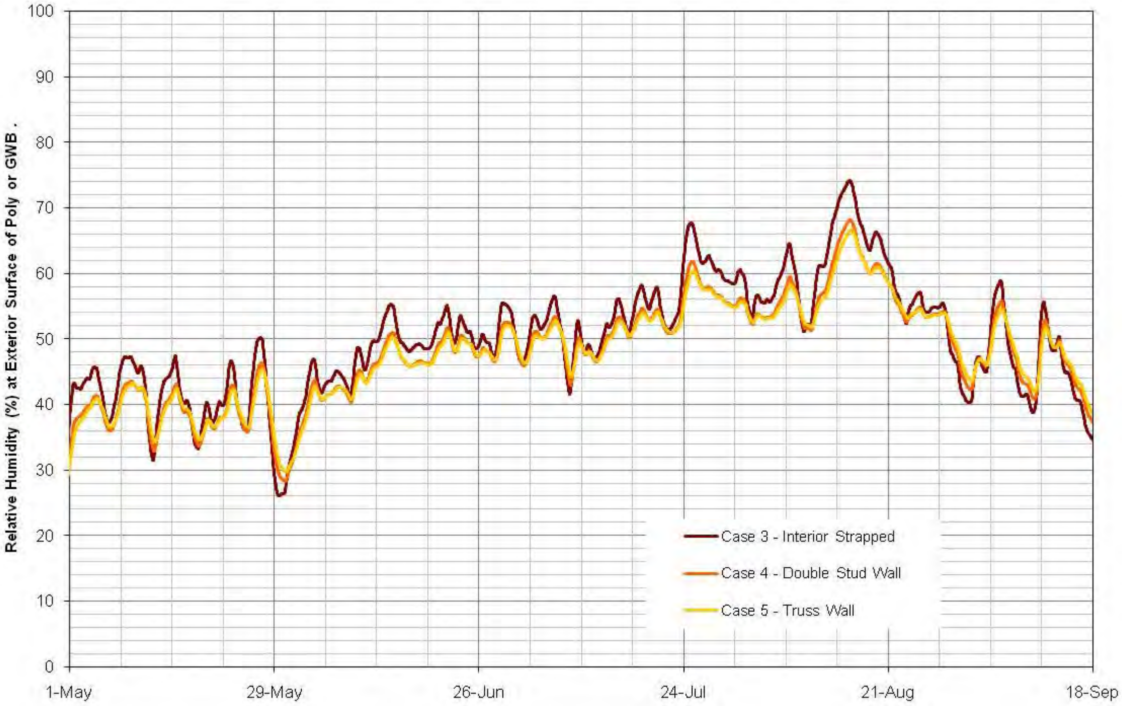


Figure 20 : Inward vapor drive relative humidity of poly or GWB for Case 3, Case 4, and Case 5

A double stud wall with 2" of high density foam (Case 10) with and without an interior vapor barrier was compared to Case 4, a double stud wall filled with cellulose in Figure 21. There was an improvement in performance when two inches of foam were used on the exterior and an interior vapor barrier was installed. The foam restricted the inward vapor drive, and the poly controlled vapor from the interior environment. Although this wall showed lower relative humidities with respect to summer inward vapor drives, it is never recommended to have a high level of vapor control on both sides of the wall system. This substantially increases the risk of moisture related durability issues, should any water get into the wall cavity. This could be improved by adding more foam to the exterior surface, and less vapor control to the interior, with a Class II or III vapor control layer depending on climate. More specific analysis is required before design recommendations can be determined.

Case 10 without an interior vapor barrier experiences slightly elevated relative humidity levels, likely due to the interior relative humidity. In a more severe testing condition for summer inward vapor drives, this wall would likely have lower relative humidity to Case 4, the standard double stud wall.

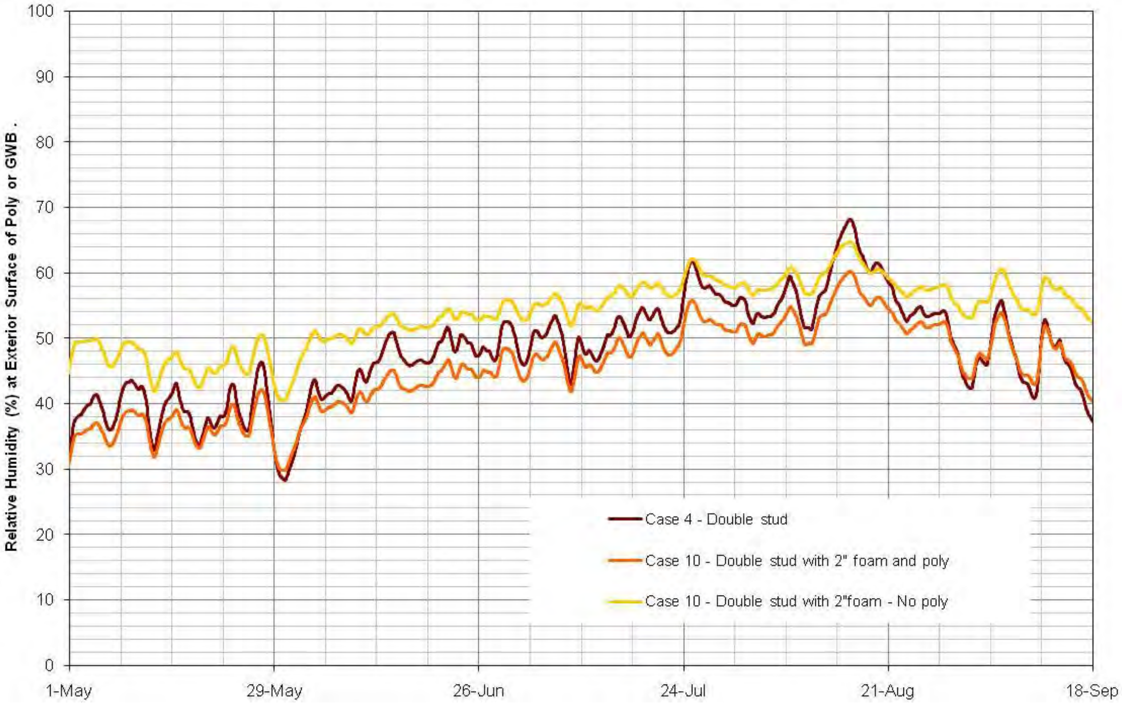


Figure 21 : Inward vapor drive relative humidity of poly or GWB for Case 4, and Case 10

Analysis of inward vapor drives on the spray foam walls shows that the walls without polyethylene vapor barrier dry adequately to the interior, but the low density spray foam wall with poly has elevated relative humidities because of the vapor control layer (Figure 22).

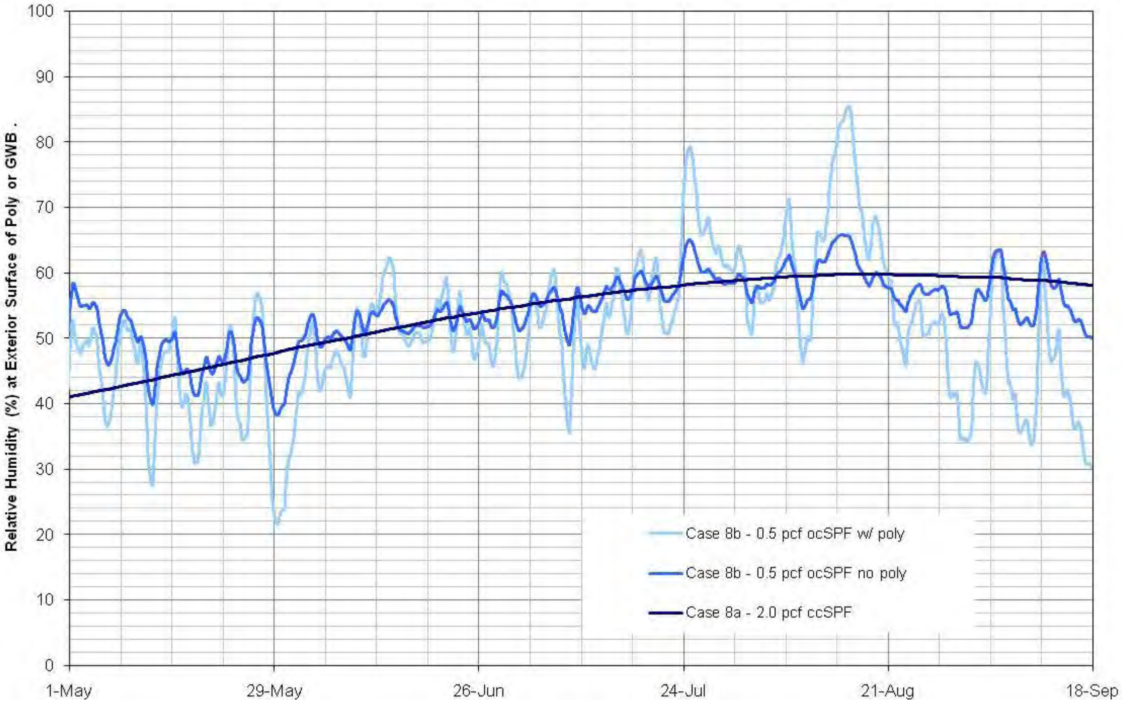


Figure 22 : Inward vapor drive relative humidity of poly or GWB for Case 8

The inward vapor drive for the offset frame wall (Case 11) with exterior foam insulation was compared to Case 3, a truss wall with only cellulose insulation, and Case 8 with 5 ½" of high density spray foam in the cavity space in Figure 23.

Both Case 8 and Case 11 perform very similarly, with slightly higher relative humidities than Case 4, although there is no risk of moisture related damage from inward vapor drives in of the walls (Figure 23). Had the cladding been a moisture storage cladding, it is suspected that both Case 8 with spray foam in the stud space, and Case 11 with exterior foam would have much lower relative humidities than Case 5 because of the vapor control of the high density spray foam.

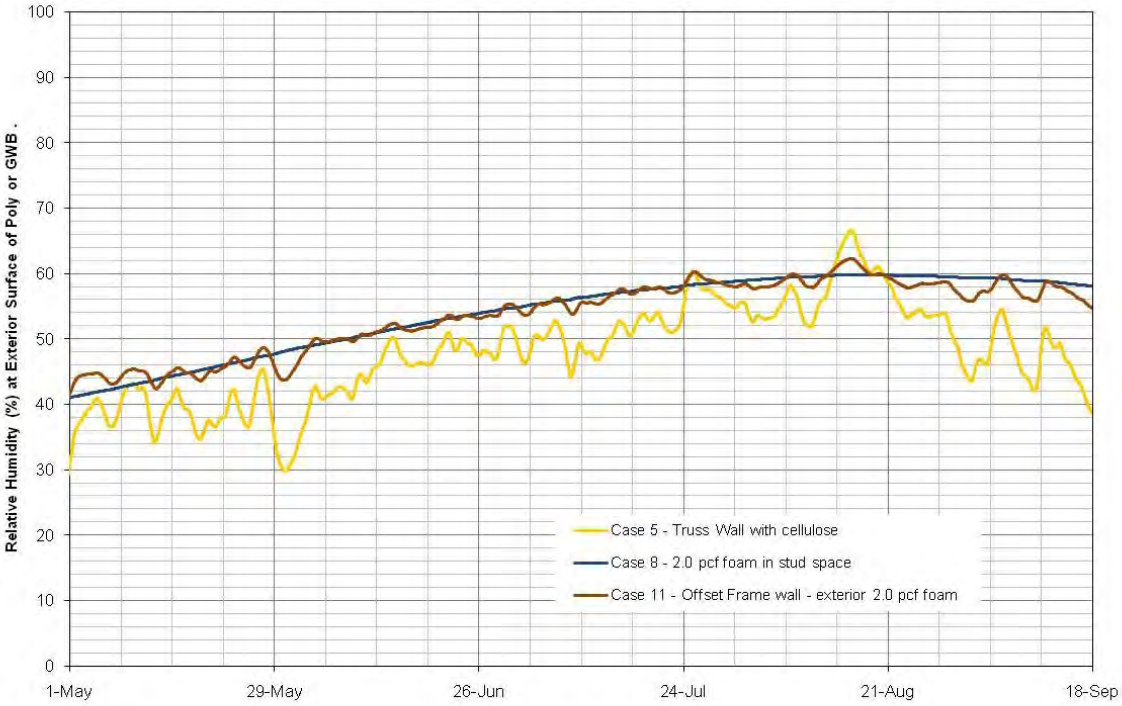


Figure 23 : Inward vapor drive relative humidity of poly or GWB for Cases 5, 8, and 11

2.2.4. 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 elevated sheathing moisture content (250 kg/m3) in the wall systems and observing the drying curve of the wetted layer. In walls without OSB sheathing a wetting layer was applied between the insulated sheathing and fiberglass batt insulation with similar physical properties to fiberglass insulation. 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 try adequately, it can experience some wetting without any long-term durability risks.

The drying curves of Case 1 (standard construction), and Case 2 (advanced framing with insulated sheathing) are shown in Figure 24. The slowest drying wall is the advanced framing with 1" of exterior insulation and interior vapor control paint because there are lower permeance layers on both the interior and exterior of the enclosure. The OSB in the standard construction walls dry only marginally quicker than advanced framing with insulated sheathing, which is likely insignificant in the field. In the advanced framing wall, the wetting layer is immediately interior of the XPS sheathing, and drying is predominantly to the interior.

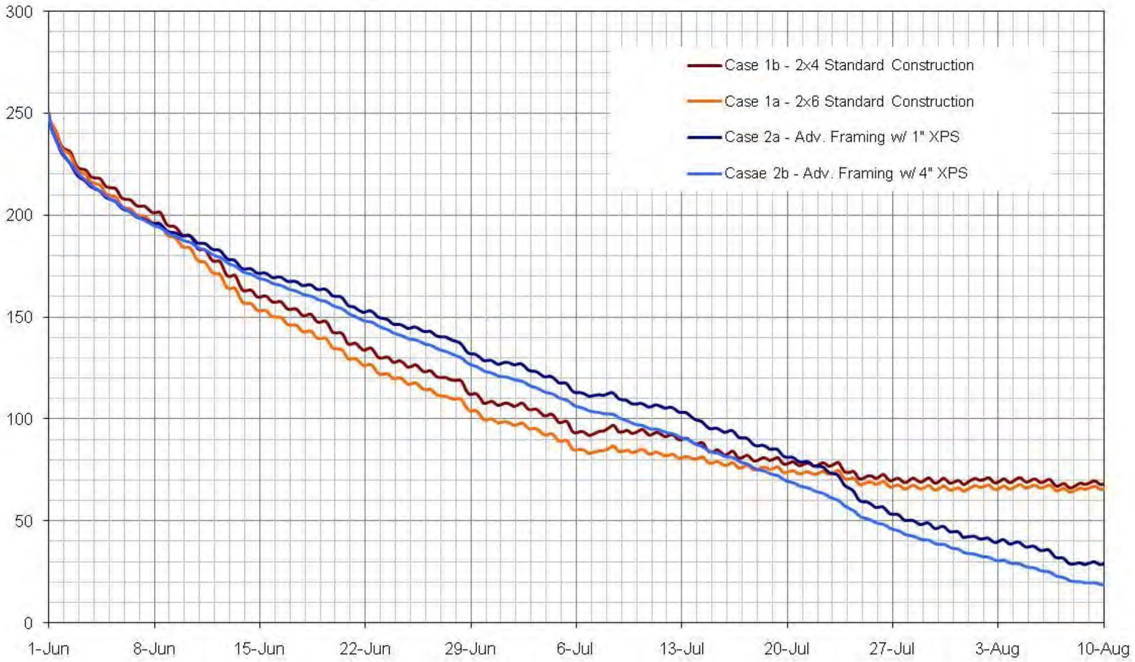


Figure 24 : Drying Curves for Case 1 and Case 2

Figure 25 shows that the drying curves of the interior strapped wall, the double stud wall, and the truss wall are all very similar, with no significant differences. These three walls perform very similarly to the standard construction walls in Figure 24.

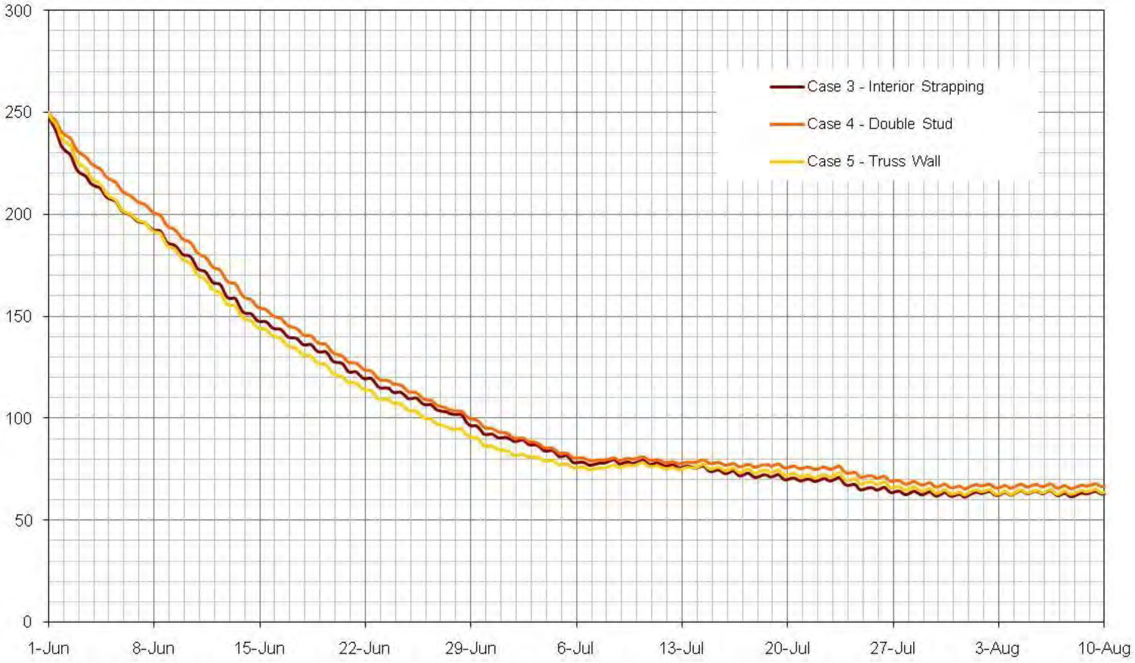


Figure 25 : Drying curves for Case 3, Case 4, and Case 5

The drying curves for spray foam insulated walls, Case 8, are shown in Figure 26. The quickest drying wall is the low density spray foam without a poly vapor barrier. Both the high density spray foam and the low density spray form with poly both dry more slowly because of the decreased permeance of the building enclosure and inhibited drying

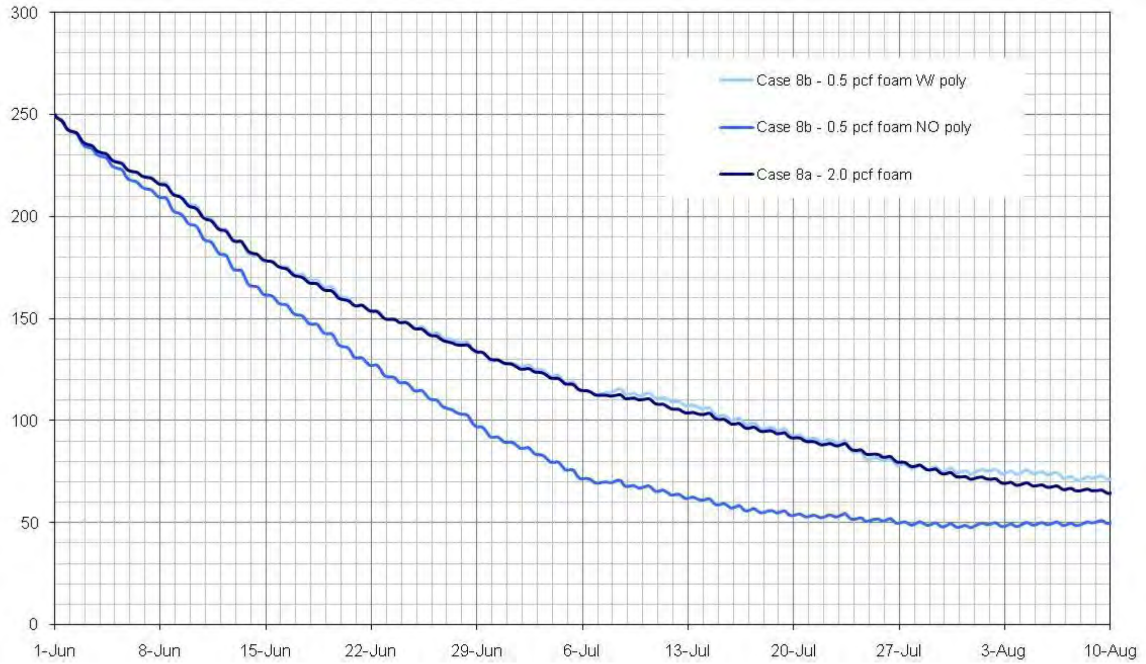


Figure 26 : Drying curves for Case 8

Comparing the double stud wall with cellulose insulation (Case 4) with the double stud wall with spray foam and cellulose (Case 10), Case 4 dried more quickly than Case 10 both with and without a interior polyethylene vapor barrier. With 12" of moisture buffering cellulose insulation in Case 4, it appears that the wall is able to quickly buffer and redistribute the moisture of a single wetting event and then release it slowly, mostly to the exterior of the OSB. Neither wall would suffer moisture related durability issues following a single wetting event but repeated wetting events to the OSB will increase the risk of moisture related durability issues.

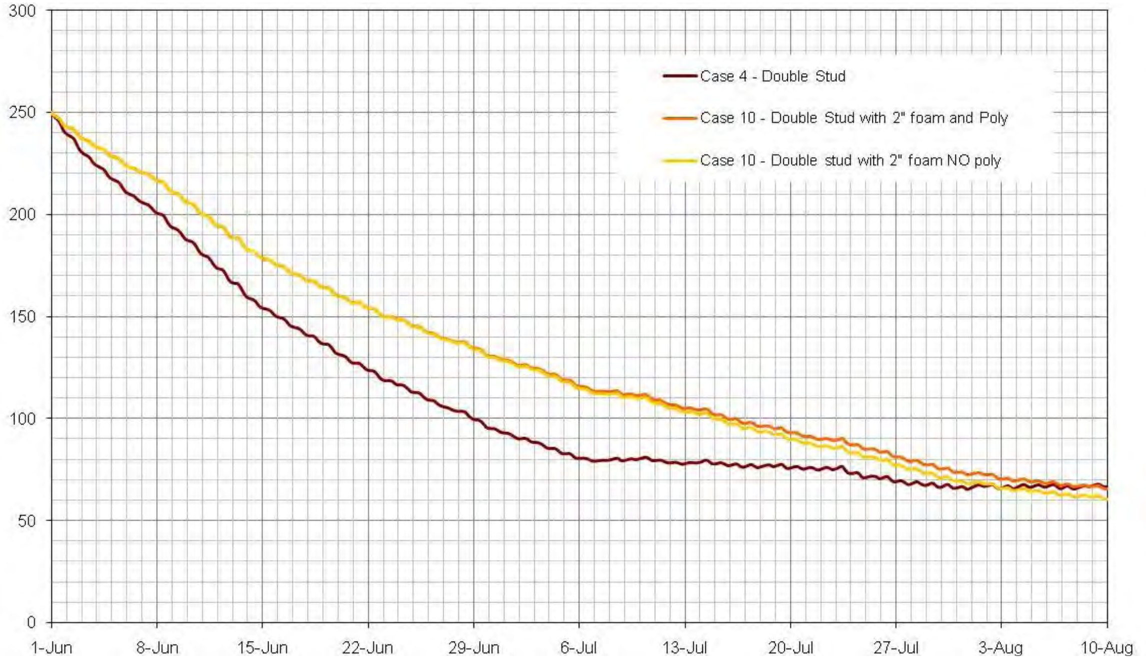


Figure 27 : Drying Curves for Case 4, and Case 10 with and without a poly vapor barrier

The offset wall enclosure with exterior spray foam dried very slowly compared to the truss wall of Case 5 with cellulose insulation. The wall system with exterior high density spray foam is unable to dry to the exterior due to the vapor control of the spray foam. The interior relative humidity is elevated in the spring and summer months which would also affect the vapor pressure gradient and drying potential. The sheathing in Case 11 is not significantly affected by the solar energy of the sun and the warm summer temperatures, nor is it in contact with cellulose insulation to buffer the wetting event.

In Case 5, with cellulose insulation against the wet OSB sheathing, the cellulose absorbed and redistributed the moisture, helping the OSB dry more quickly. Installing fiberglass batt insulation against the sheathing does not redistribute moisture and the OSB will stay wetter longer. Cellulose insulation is more susceptible to repeated wetting events because of its organic nature than fiberglass batt. Both of these wall systems would be at risk for moisture related damage if they were wetted repeatability and both walls are able to handle rare wetting events.

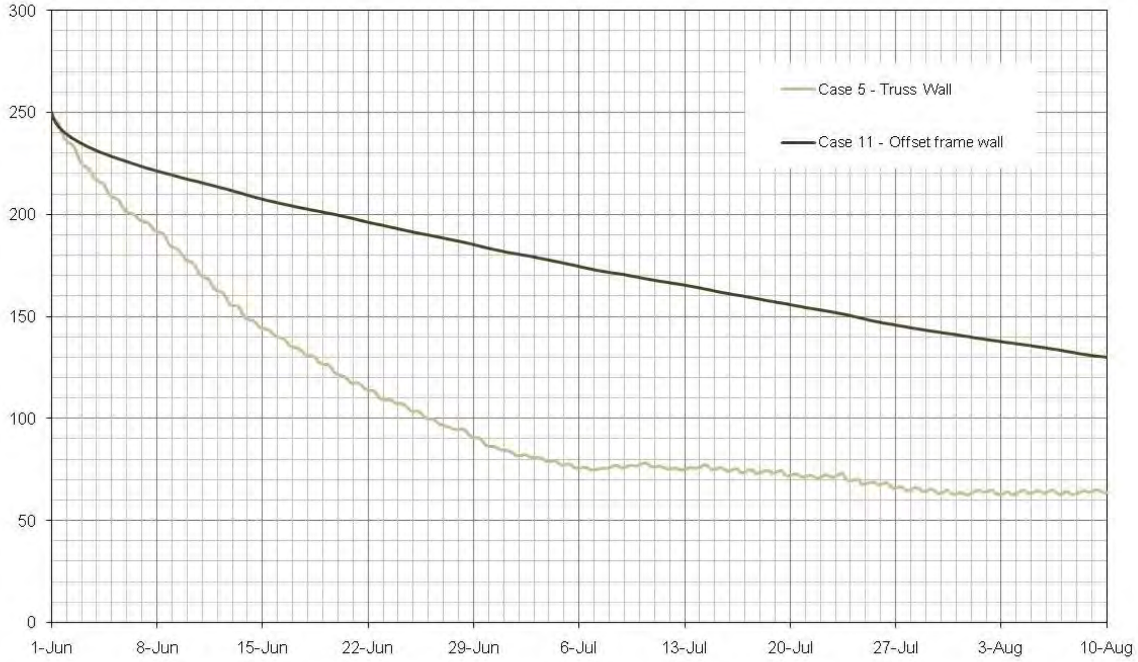


Figure 28 : Drying Curves for Case 5 and Case 11

2.3 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, air leakage 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..

2.4 Buildability

Buildability is a key 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 buildability.

2.5 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 insulation.

2.6 Cost

The factor which generally has the greatest influence on implementation of a building enclosure strategy, particularly for production builders, 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. For example, it's accepted that R19 fiberglass batt is less expensive than low-density (0.5 pcf) spray foam, which is less expensive than high density (2.0 pcf) spray foam. The strategy of a comparison matrix for the test wall assemblies is able to use relative values for cost rather than exact costs.

C. Results

1. CASE 1: STANDARD CONSTRUCTION PRACTICE

For this analysis, standard construction practice includes OSB sheathing, 2x4 or 2x6 framing 16" oc, fiberglass batt insulation, a 6-mil polyethylene vapor barrier and taped and painted ½" drywall. (Figure 29) Historically, this has been used for residential wall construction in most areas of North America.

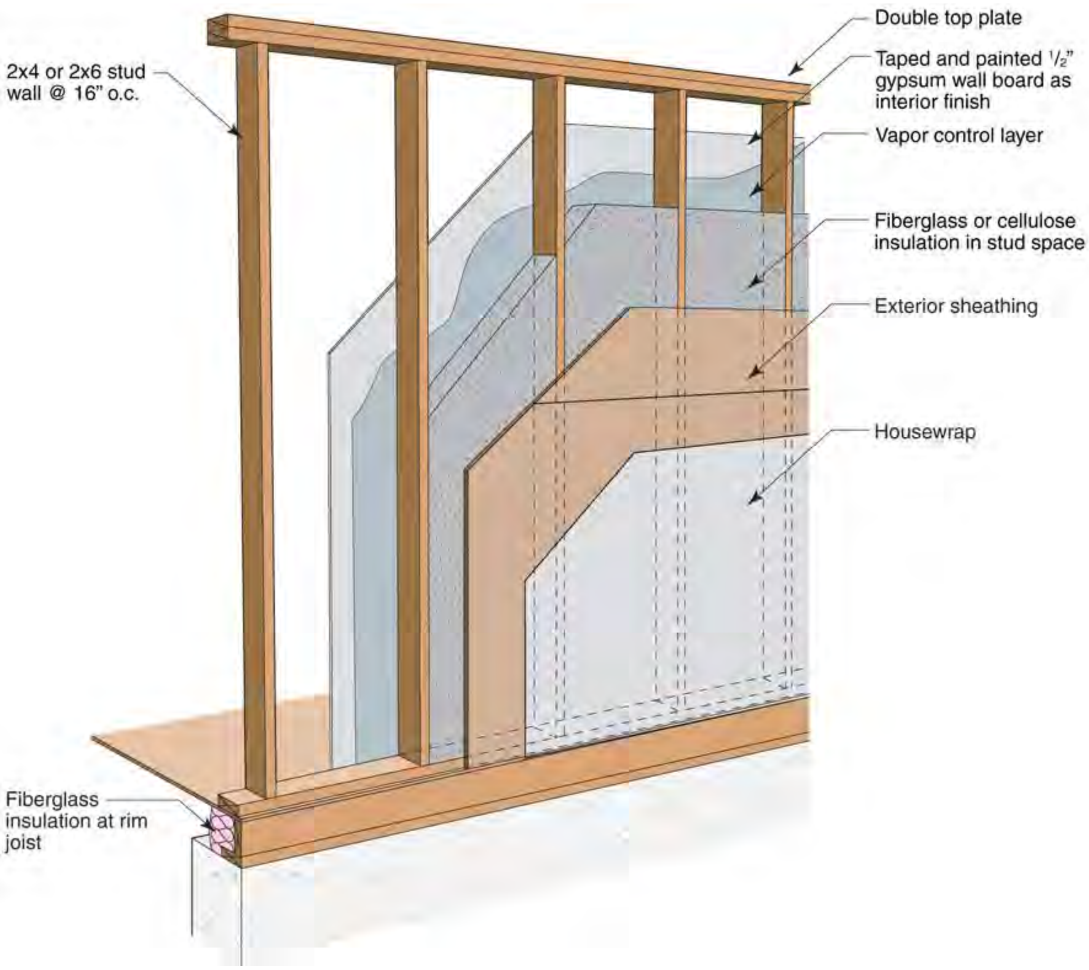


Figure 29 : Standard construction practice

1.1.1. Thermal Control

Fiberglass batt installed in a 2x4 wall system has an installed insulation value of R13, and fiberglass batt in a 2x6 wall system has an installed insulation value of R19. There are several different densities that can be used to provide slightly different R-values (e.g., 3.5" thick batts are available in R11, R12, R13 and R15 ratings). Other insulations that could be used in this assembly include densepack or spray applied cellulose, spray applied fiberglass, and spray foam (Case 8). 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 30 shows the vertical and horizontal wall sections used in Therm to determine the whole wall R-values for standard construction practices.

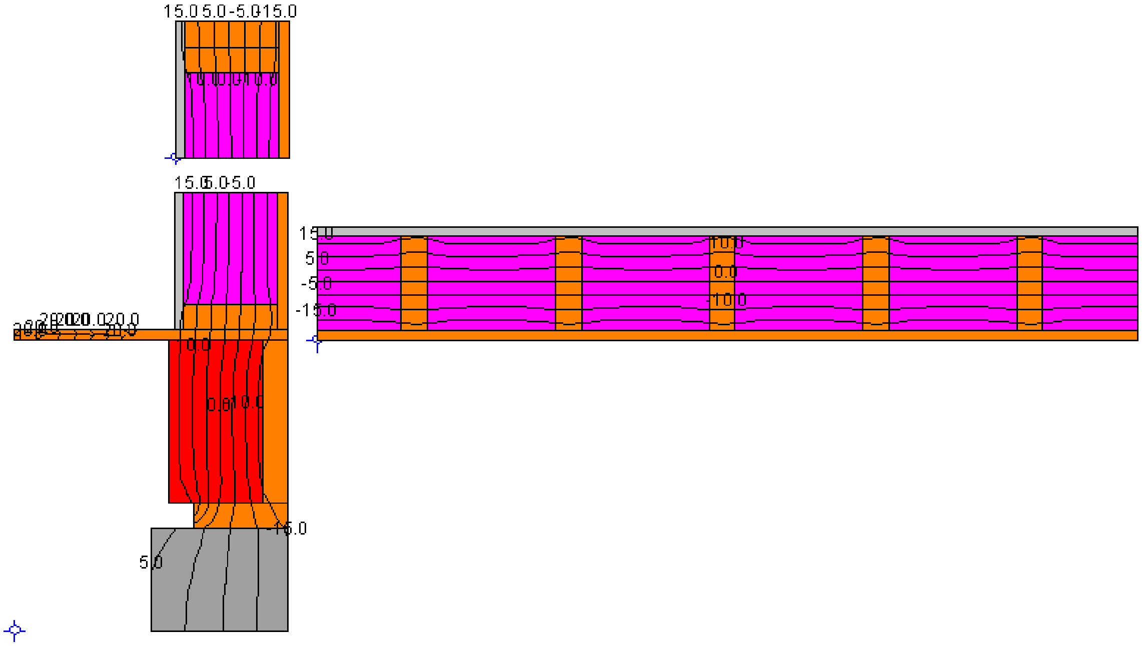


Figure 30 : Therm modeling of Case 1 - 2x6 construction

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 comparison between the different cases, framing factors of 16% were used to limit the variables and determine the effects of other variables.

Table 5 shows a summary of the R-values calculated for the three different components of both the 2x4 and the 2x6 standard construction practice. These insulation values are not considered high-R wall systems in cold climates.

Table 5 : Summary of R-value results from Therm modeling for Case 1

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
1a	2x6 AF, 24"oc, R19FG + OSB	**15.2**	12.3	16.1	12.5
1aii	2x6, 16"oc, R19FG + OSB (25%ff)	**13.7**	12.3	14.1	12.5
1b	2x4 AF, 24"oc, R13FG + OSB	**11.1**	9.8	11.5	9.8
1bii	2x4, 16"oc, R13FG + OSB (25%ff)	**10.0**	9.8	10.1	9.8

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.

1.1.2. Moisture Control

Analysis of the air leakage condensation potential from a poorly detailed air barrier results in approximately 4400 and 4500 hours of potential condensation for the 2x4 and 2x6 standard construction walls respectively when the temperature of the exterior sheathing is less than the dew point of the interior air. (Figure 10)

These walls are unable to dry to the interior, but generally are able to dry fairly well to the exterior depending on the cladding type. WUFI® showed that with a ventilated cladding like vinyl siding, the sheathing in both of the standard construction walls decreased from 250 kg/m3 to 100 kg/m3 in 29-34 days (Figure 24).

1.1.3. Constructability and Cost

Generally speaking, all of the trades and construction industry are very familiar with building the Case 1 wall system. Cladding attachment is straightforward, and the only education necessary may be air tightness details to increase the overall building performance.

1.1.4. Other Considerations

The amount of material used in this type of construction is the standard against what other walls will be compared since it has been the standard of construction in many places of many years. Standard construction uses less framing and wood sheathing than a double stud wall construction (Case 4), 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.

1.2 Case 2: Advanced framing with insulated sheathing

Advanced framing techniques are becoming more popular for residential construction because of several advantages. These practices have been adopted by some smaller builders, but not on many large scale production developments. The main difference with advanced framing is 2x6 framing lumber on 24" o.c. with a single top plate. The idea of advanced framing is to reduce the framing factor of the wall system in the areas by good design, such as corners and penetrations. A single top plate is 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. In many cases of advanced framing, insulated sheathing is used either in place of or in combination with wood sheathing. This is important for thermal performance to minimize thermal bridging effects.

For this analysis, 1" and 4" insulated sheathing is considered (Figure 31). 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.

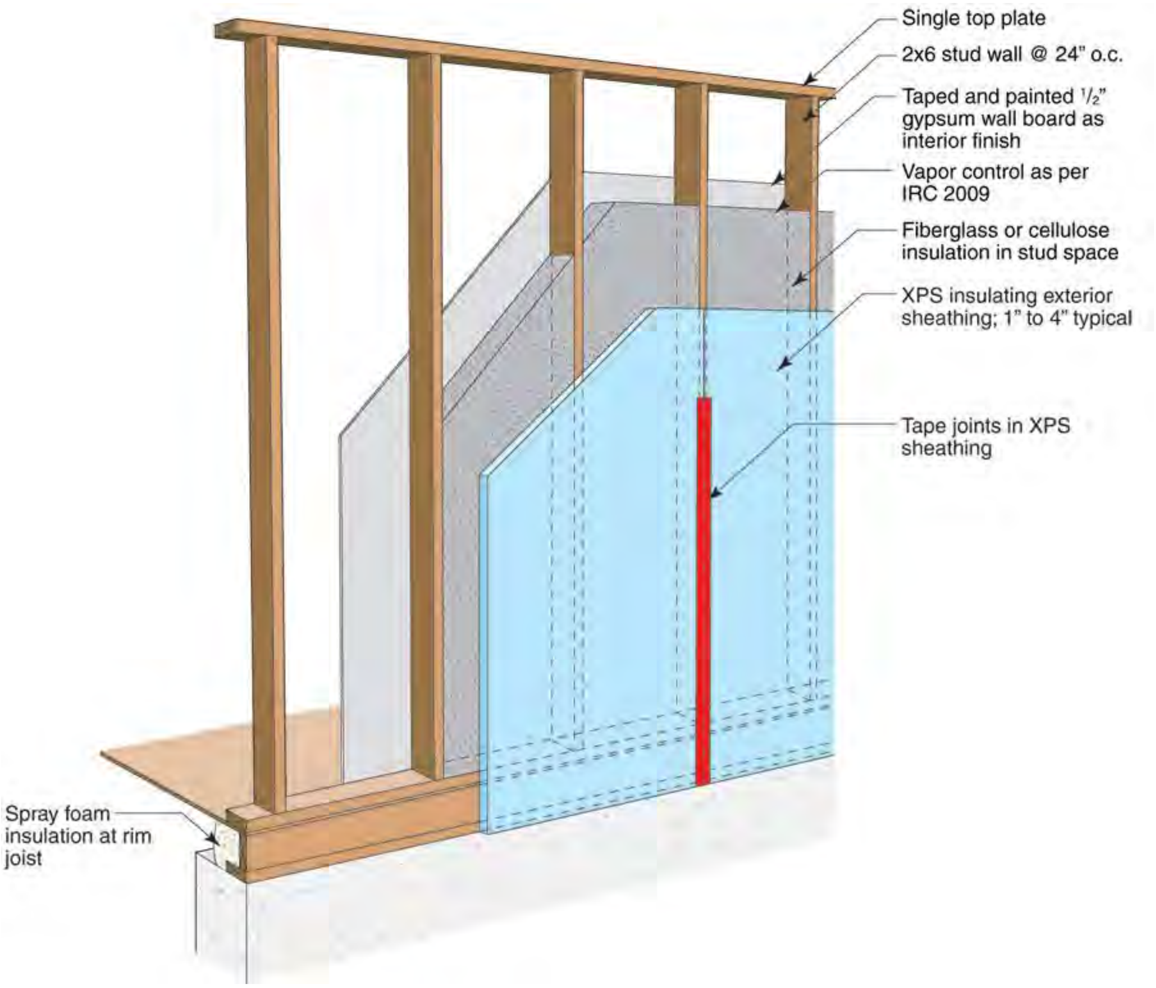


Figure 31 : Advanced framing construction

1.2.1. Thermal Control

Thermal control is improved over standard construction practices by adding insulating sheathing to the exterior of the framing in place of OSB. 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. 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.

Drawings from Therm show the vertical and horizontal sections which indicate increased thermal protection at both the rim joist and top plate, decreasing heat flow through the thermal bridges.

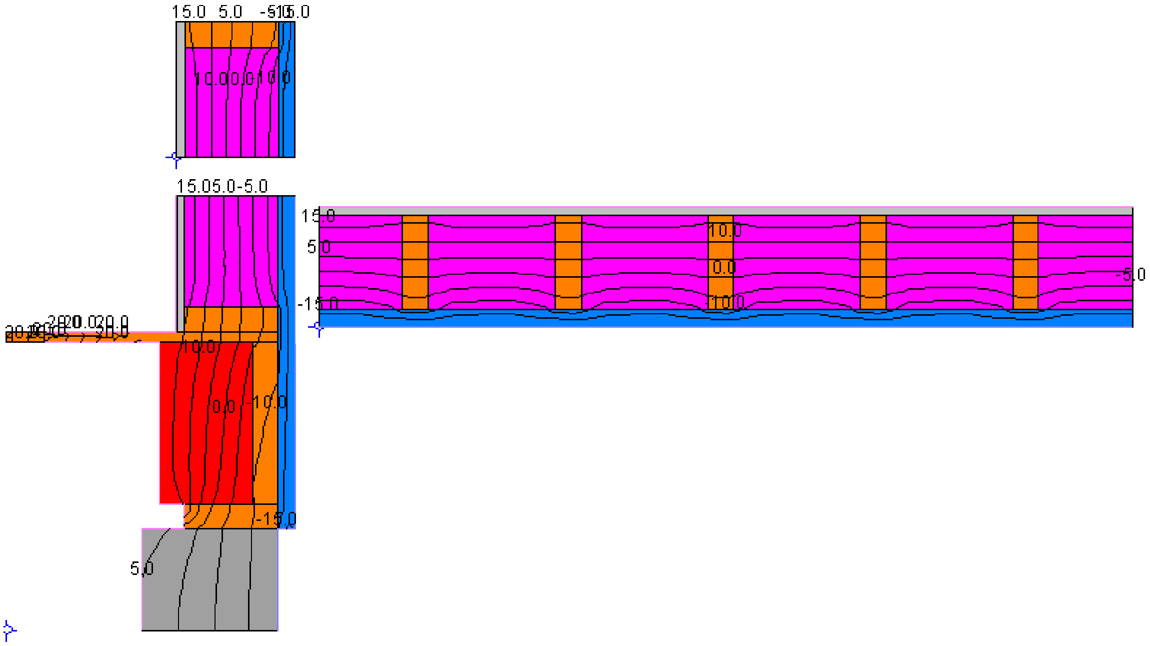


Figure 32 : Therm modeling of Case 2 advanced framing with 1" XPS insulated sheathing

Analysis shows that when substituting 1” of XPS (R5) for the OSB in a standard 2x6 wall with a 16% framing factor, the clear wall R-value increases from R16.1 to R20.6, an increase of R4.5. Since the OSB was removed from the standard construction wall, this is actually a difference of R5.1, which is greater than the R-value of the insulation that was added. 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. For example, increasing the conductivity of the studs by an order of magnitude results in an increase of R6.5 for 1” of R5 XPS sheathing over standard construction. This is an example of the importance of reducing the thermal bridging through the enclosure.

The calculated R-values for both of the advanced framing walls are shown in Table 6.

Table 6 : Summary of R-value results from Therm modeling for Case 2

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
2a	2x6 AF, 24"oc R19FG + 1" R5 XPS	**20.2**	18.5	20.6	20.3
2b	2x6 AF, 24"oc R19FG + 4" R20 XPS	**34.5**	29.0	35.6	35.4

1.2.2. Moisture Control

The Therm results show that the interior surface of the foam is at a higher temperature than the standard construction wall which will decrease the potential for both vapor diffusion condensation and air leakage condensation. According to the IRC, a Class I or II vapor retarder is still required depending on the R- value of the insulated sheathing and the wall framing used. Table N1102.5.1 from the IRC shows that for climate Zone 6, with insulating sheathing R>= 11.25 on a 2x6 wall, only a Class III vapor retarder is required.

There is some risk of winter time condensation from vapor diffusion depending on the level of vapor retarder and the interior temperature and relative humidity conditions. Figure 9 shows that with 1” of XPS some condensation is possible on the surface of the insulated sheathing. Since the XPS is not moisture sensitive, some condensation will not affect the durability of the wall system.

Air leakage condensation may still be a concern, although not as great as with standard construction. There are approximately 3800 hours and 1200 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 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 (Figure 24).

There is less inward vapor drives in the advanced framing walls with insulated sheathing than the standard construction since vapor is slowed at the sheathing, and allowed to dry more readily to the interior (Figure 19). The relative humidity peaks are considerably higher in the standard construction walls than the advanced framing walls.

1.2.3. Constructability and Cost

There is some education and training required for the successful construction of advanced framing walls with insulated sheathing. The changes are very minimal for insulated sheathing thicknesses of 1.5” and less, but for insulating sheathing thicknesses of 2” and greater, special details are required for cladding attachment and window and door installation.

Some solutions have been found for cladding attachment directly to 3/4” strapping anchored to the framing members, but in some areas, building code officials require letters from the specific building materials companies before allowing construction.

1.2.4. Other Considerations

The 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.

1.3 Case 3: Interior 2x3 horizontal strapping

Horizontal interior strapping is a method of reducing the thermal bridging through the wall framing, protecting the vapor barrier against penetrations, and adding more insulation.

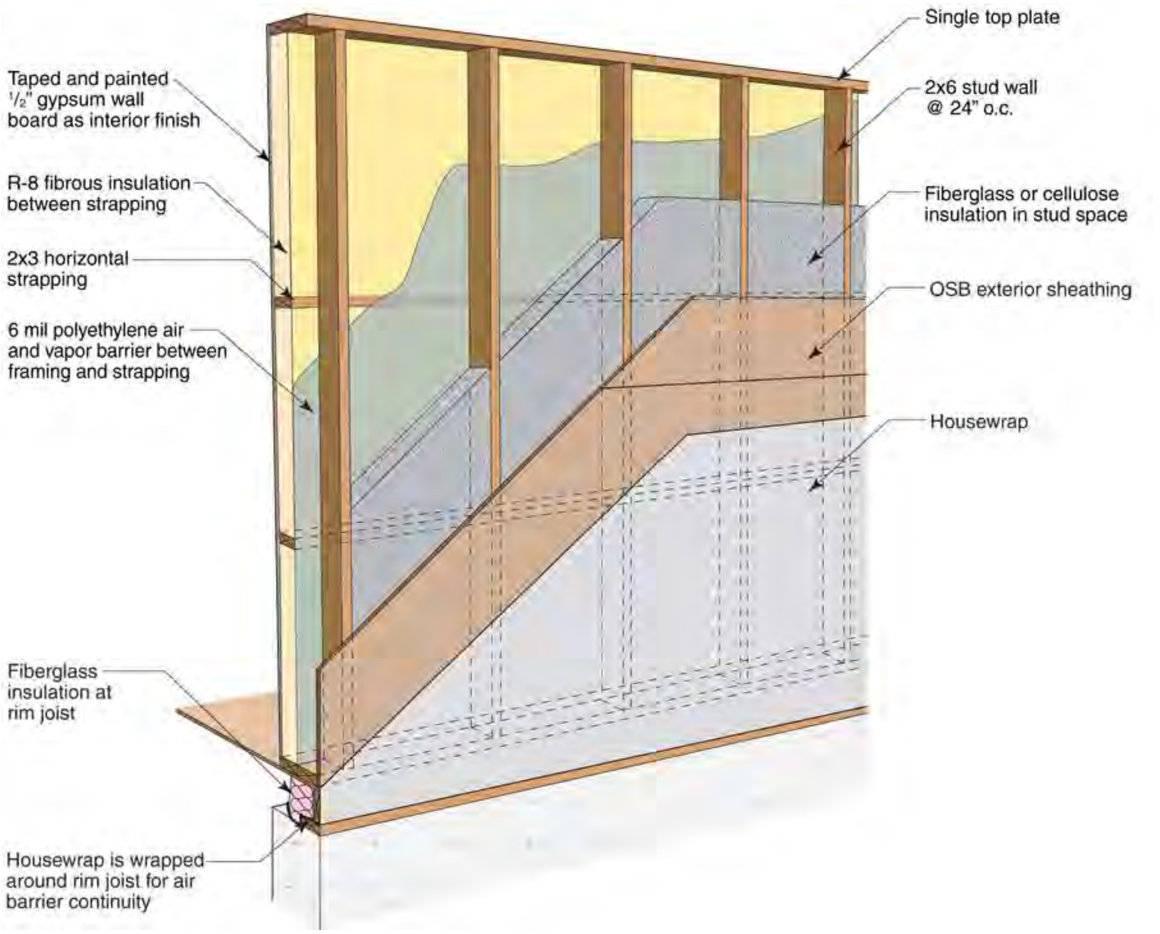


Figure 33 : 2x6 wall construction with interior strapping

1.3.1. Thermal Control

The horizontal strapping added to the wall allows for an extra 2.5" of insulation. This is commonly in the form of R8 fiberglass, which totals an installed insulation R-value of R27 for the wall assembly. For the Therm simulation four interior strapping elements were used as shown in the drawing.

Thermal bridging is decreased through the vertical studs but there is still thermal bridging at the top and bottom plates. Thermal losses due to air leakage are likely been minimized by installing the polyethylene vapor barrier against the wall framing. This means fewer penetrations are required for services and wiring resulting in greater air tightness than standard construction.

Therm was used to determine the whole wall R-value of the interior strapping wall. Figure 34 shows the horizontal and vertical sections from the Therm analysis.

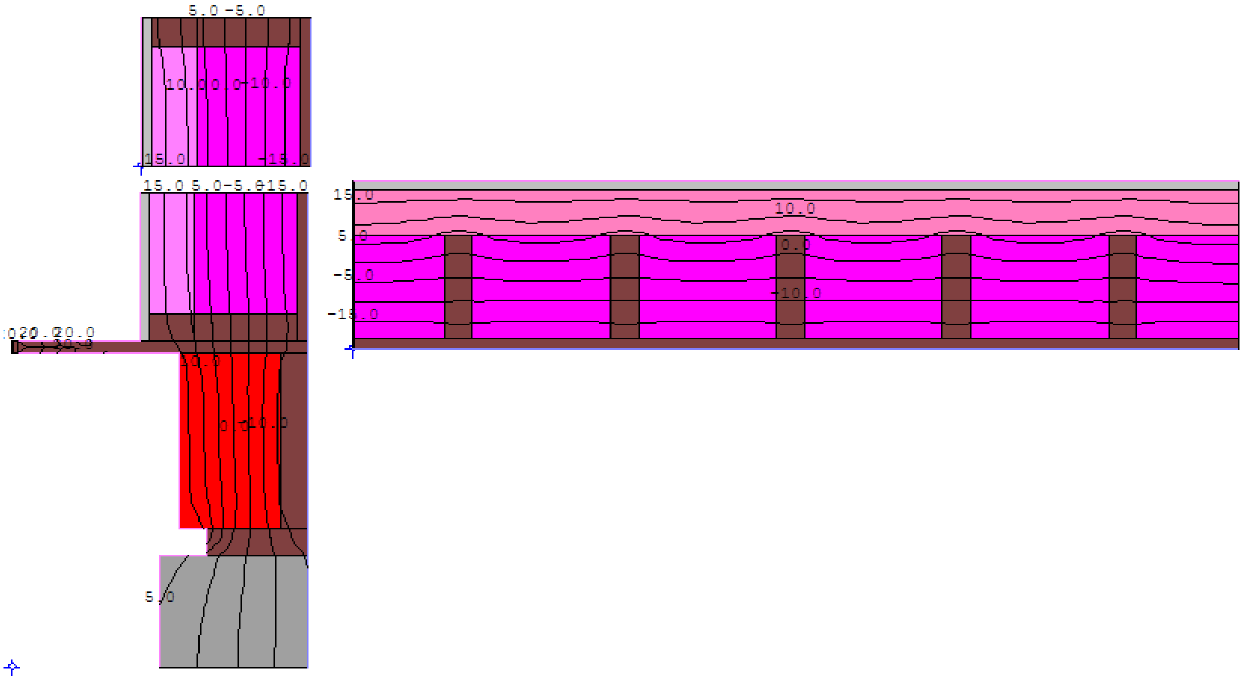


Figure 34 : Therm analysis of horizontally strapped wall

The Whole wall R-value of the wall assembly was determined to be R21.5 (Table 7). This means that even by adding R8 to the standard 2x6 wall, this results in an increase of R6.3 because of the thermal bridging that is not addressed. The rim joist R-value can be improved with more insulation, and better airtightness.

Table 7 : Calculated R-value of an interior horizontal strapped wall

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
3	2x6 AF, 24"oc, 2x3 R19+R8 FG	**21.5**	13.4	23.5	18.4

1.3.2. Moisture Control

The control of both vapor diffusion condensation and air leakage condensation is increased since there are fewer penetrations in the air/vapor barrier of the wall assembly.

The potential for vapor diffusion condensation is very similar to the standard construction assemblies (Figure 12). The temperature of the sheathing is kept only slightly colder because of the increased insulation beyond standard construction which results in a small increase in the potential intensity of air leakage condensation. There does not appear to be any risk of moisture related durability from vapor diffusion assuming the vapor barrier is adequately installed.

Air leakage condensation potential is slightly increased from the standard construction walls with a total of approximately 4600 hours of potential condensation through the winter.

Analysis of the summertime inward vapor drives shows very similar results between the standard construction practices in Case 1 and the interior strapped wall.

Drying of the interior strapped wall shows slightly improved performance over the standard construction practice, by a few days for the OSB to reach 100 kg/m3.

The interior strapped wall performed very similarly to the standard construction practice in terms of moisture control.

1.3.3. Constructability and Cost

Constructing a wall with interior horizontal strapping is not a normal construction technique in most places. It would require some education and training in the design details, such as window installation, but cladding attachment is the same, and the wall system would be less susceptible to workmanship issues on the vapor barrier, since there are far fewer penetrations required through the air/vapor barrier. Additional costs would be incurred due to the addition of both horizontal strapping and the installation of additional batt insulation as well as some more installation time. The mechanical and electrical services should see a reduction in cost since that the horizontal framing does not require as much drilling or modification to distribute the services. The mechanical and electrical trades would also not have to take the time to seal as many locations as in standard vapor and air barrier practices.

1.3.4. Other Considerations

It would be possible to use cellulose insulation between the polyethylene vapor barrier and the exterior sheathing, which would increase the fire resistance, and decrease the embodied energy. There is more framing required to construct these walls, and the tradeoff in adding insulation is not quite made up in the overall R-value of the assembly.

1.4 Case 4: Double Stud

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.

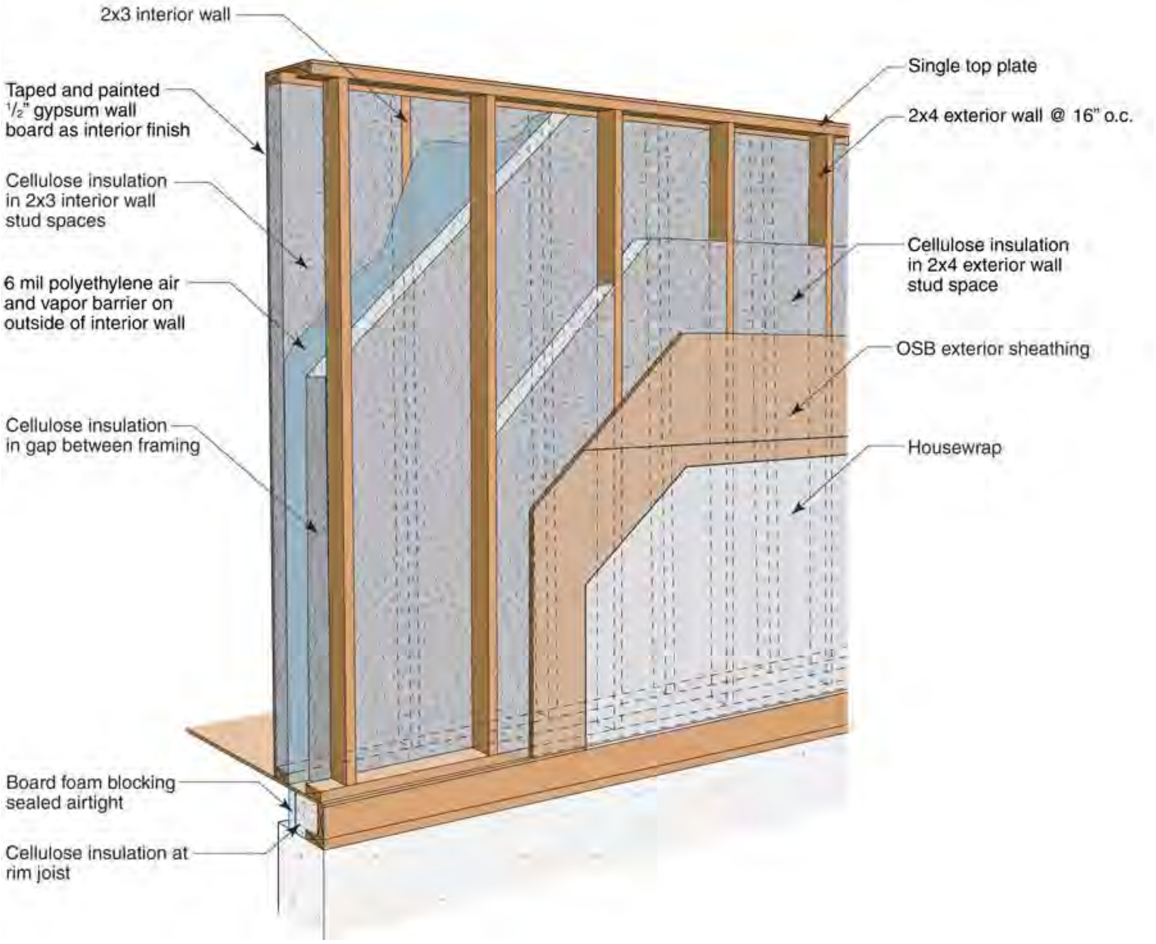


Figure 35 : Double stud wall

1.4.1. Thermal Control

This wall is typically built with an exterior 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"o.c. and the interior framed wall used to support the drywall and insulation was spaced at 24"o.c. 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. It is possible to install the 6-mil polyethylene Class I vapor barrier on the back of the interior wall by installing the plastic when the wall is on the floor, and then lifting the wall into place and securing, making sure to seal the plastic at the top and bottom. This produces a more continuous air/vapor barrier since fewer penetrations are needed for services when compared to the standard framing methods although this may increase the perceived complexity to an unsatisfactory level for some builders.

One advantage observed in the field of installing the air/vapor barrier on the interior framing is one large cavity space that is easier and quicker to insulate with cellulose insulation.

The gap between the two walls can be varied, and produces a much more effective thermal bridge between the two rows of framing than the horizontal interior strapping in Case 3. Often 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 36) 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. Therm analysis shows that with the existing thermal bridging and rim joist, the whole wall R-value of the system is approximately R30 which is only a slight reduction from the clear wall R-value. The R-value can be improved by improving the rim joist detail: more insulation, better airtightness, and better insulation of the concrete foundation.

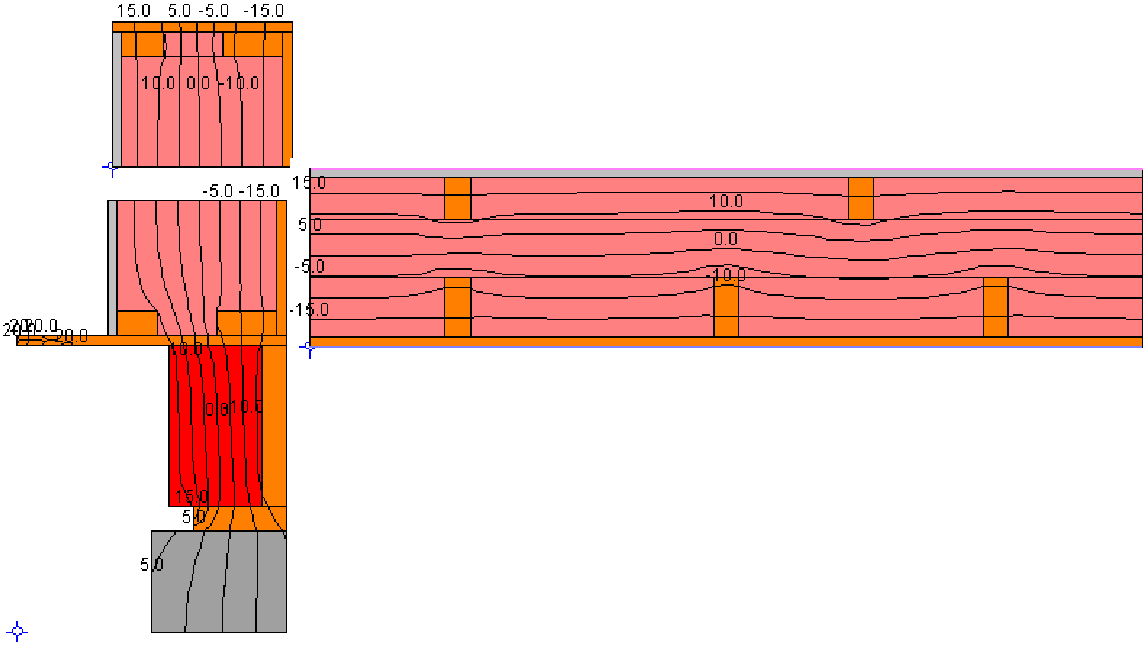


Figure 36 : Therm model of the double stud wall

Table 8 : Calculated R-value of a double stud wall

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
4	Double stud wall 9.5" R34 cellulose	**30.1**	14.4	33.5	28.8

1.4.2. Moisture Control

Moisture control in the form of air leakage condensation and vapor diffusion condensation is controlled with a 6-mil polyethylene vapor barrier that can be installed on the back side of the interior wall or directly behind the drywall. Installing the poly on the back side of the interior wall, if possible, helps reduce the amount of air leakage condensation because fewer penetrations are needed and the air barrier can be more continuous.

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 4600 hours of potential wintertime condensation hours, similar to Case 3 with interior horizontal strapping but because the temperature of the sheathing is colder, the amount of condensation would increase for the same amount of air leakage (Figure 13).

In the summer time the potential inward driven moisture condensation is slightly less than the standard construction walls (Figure 20). This is because the cellulose in the insulation cavity has some buffering effect of moisture, so with a non-reservoir cladding such as vinyl siding, the buffering capacity is not overcome. The outcome may be different with a cladding such as stucco or adhered stone veneer.

In the drying analysis, the double stud wall performs very similarly to the standard construction practice as well as the interior strapped wall drying to 100 kg/m3 in 28 days (Figure 25).

1.4.3. Constructability and Cost

There is some education and training required with this construction technique, mostly with the window boxes and window installation. In any construction where the wall is much thicker than standard construction, window bucks (plywood boxes) are required for window installation. The cladding attachment is the same as normal construction practices.

1.4.4. 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.

1.5 Case 5: Truss Wall

The truss wall is a construction technology that is not as widely known as the other cases being considered. It provides a great deal of insulation space, minimizes thermal bridging through the wall by using plywood gusset plates, and covers the rim joist with insulation (the rim joist is generally a location of significant air leakage and thermal bridging). Also, unlike the double stud wall, the increased wall width is to the exterior of the structural wall, which does not compromise indoor floor area.

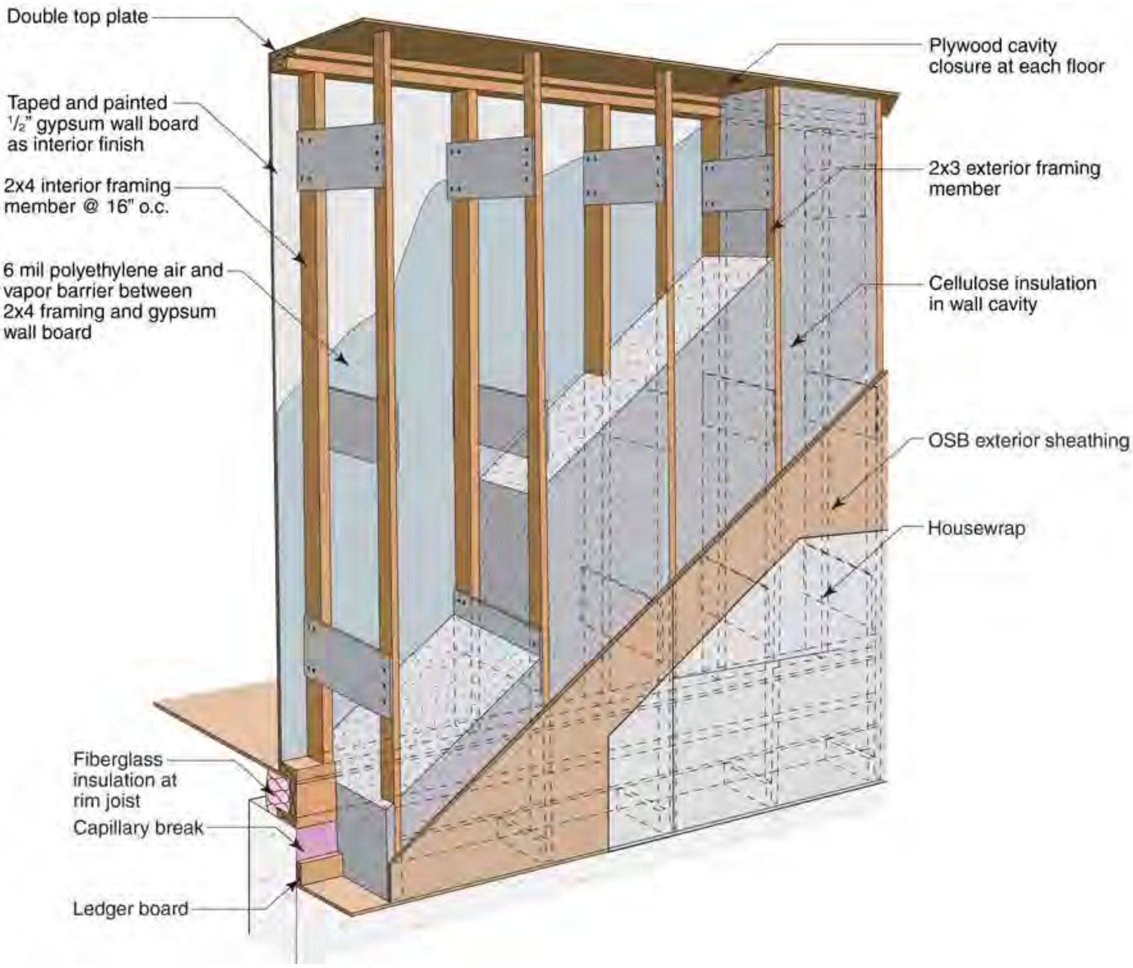


Figure 37 : Truss wall construction

1.5.1. Thermal Control

The goal of this wall is to provide as much space as possible for insulation to increase the thermal performance. In this analysis, an insulation cavity of 12 inches was constructed through the wall system. This was filled with cellulose to achieve a nominal R-value of R43, the highest R-value of any of the walls analyzed.

Therm was used to predict the whole wall R-value of this high-R assembly (Figure 38), and a value of R36.5 was calculated. Looking at the three individual components, the clear wall R-value is R40, but both the top plate and rim joist exhibited lower values. It is likely that a high heel truss with wide overhangs would be utilized for the attic and the attic space insulation would extend out over the top plate creating continuous insulation over the plates reducing the thermal bridging. This is not a commonly constructed wall but it was felt that a double top plate is more likely to be used than a single top plate for construction. It is possible to construct the same wall with a single top plate instead.

The wall schematic in Figure 37 shows that every structural wall stud has a corresponding exterior framing member for cladding attachment. In practice this is unlikely to happen because of extra framing studs commonly used for construction. It is more likely that there will be some structural wall members without a corresponding exterior framing member as was simulated in Therm (Figure 38). Similar to the double stud wall, the actual number and spacing of structural members has little influence on the whole wall R-value because of the significant thermal break of the insulation between the interior and exterior framing members.

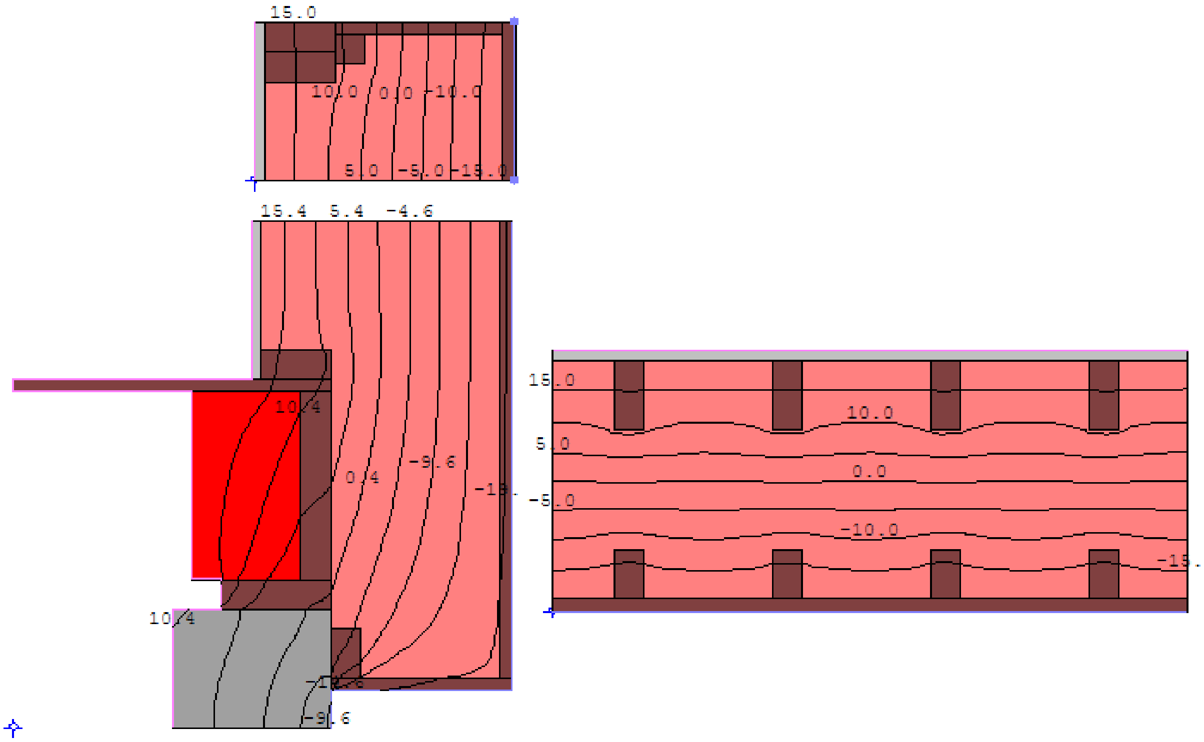


Figure 38 : Therm results of the truss wall

Table 9 : Calculated R-value for truss wall

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
5	Truss wall 12" R43 cellulose	**36.5**	18.6	40.5	34.4

1.5.2. Moisture Control

Vapor diffusion control and air leakage control are particularly important in this assembly since it has the greatest insulation value and the coldest winter sheathing temperatures. The truss wall has similar winter sheathing relative humidities to the double stud wall, but the relative humidities are slightly higher because of the lower sheathing temperature. There are approximately 4600 hours of potential winter time condensation, but the intensity of condensation is slightly greater than the double stud wall, again, because of the lower sheathing temperature (Figure 13).

The truss wall is very similar to the double stud wall although slightly lower in summertime inward vapor drive relative humidity at the vapor barrier (Figure 20). This is likely because of the increased moisture distribution and buffering from the increased amount of cellulose insulation in the truss wall.

Analysis of the drying results shows that the truss wall dries two or three days faster than both the double stud wall and the interior strapping wall (Figure 25) which is also because of the greater redistribution and buffering of moisture.

There is an increased risk of problems with the vapor control layer in the truss wall than both the double stud wall and the interior strapping wall, since the polyethylene vapor barrier will have penetrations for services and wiring. If the polyethylene sheet is also being relied on as the air barrier, which is common, this could lead to the highest risk of moisture related durability issues in all three similar test walls.

1.5.3. Constructability and Cost

The truss wall appears to require more time and energy to construct than the double stud wall. This strategy would likely not be considered by a production builder under normal conditions. Cladding attachment will be the same as the traditional construction. This wall appears to be highly dependent on good workmanship (even more so than the double stud Case 4 and interior strapping Case 3), as holes in the air barrier could result in serious moisture related durability issues from air leakage condensation. If a proper airtight drywall approach is used, this could help resolve any issues with holes in the polyethylene air and vapor barrier.

1.5.4. Other Considerations

This system seems both energy and work intensive, constructing gussets, and installing the exterior framing wall and is unlikely to be used except possibly in the coldest of locations where extremely high R-values are required. There are other alternatives that may have more appeal and less risk such as Cases 10 and 11 further in this report.

1.6 Case 6: Structural Insulated Panel Systems (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.

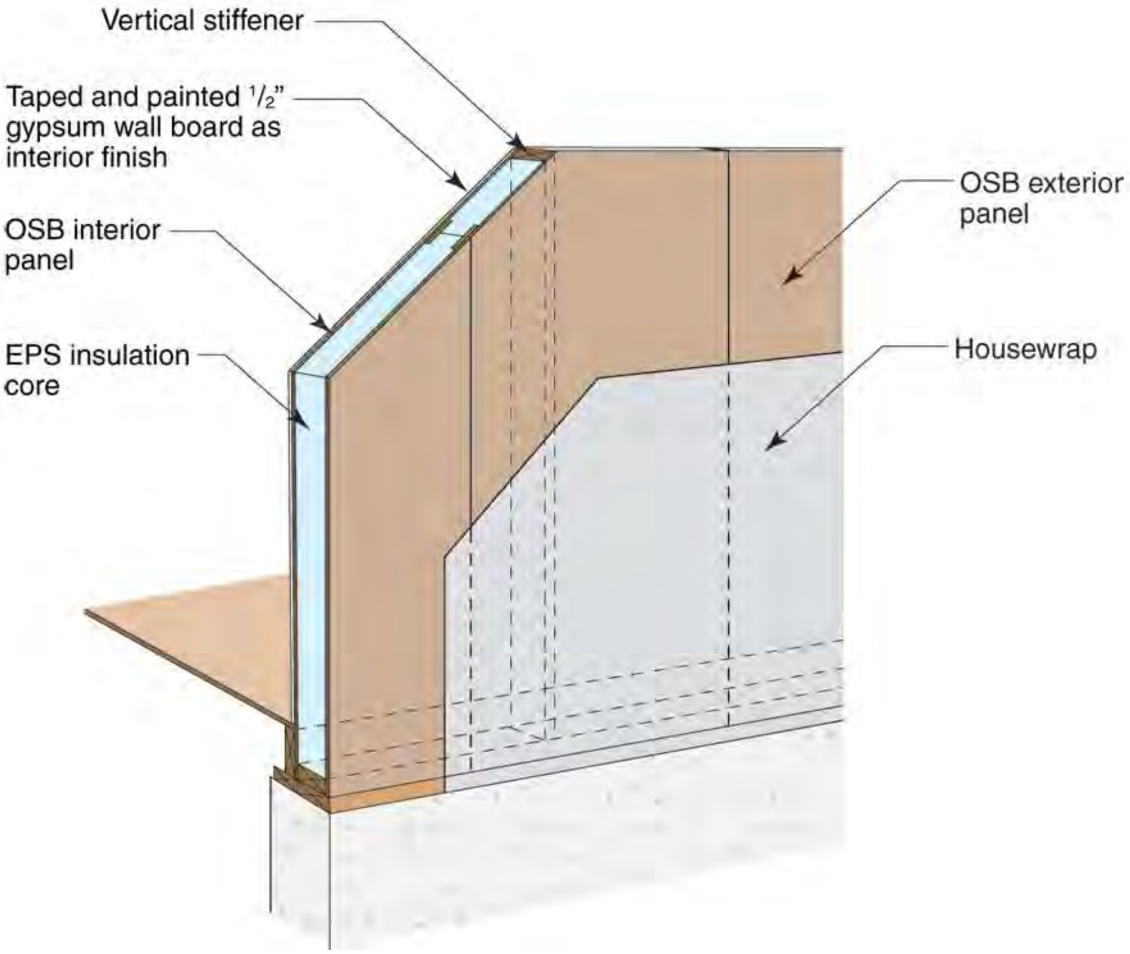


Figure 39 : SIPs wall construction

1.6.1. 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", 7.5"). 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.

The nominal value of this SIPs panel is R13, but because of a lack of thermal bridging through the wall (Figure 39), the calculated clear wall R-value of the wall is approximately R14.5 when the OSB and air films are taken into account. The whole wall R-value is approximately 13.6 when the top and bottom plate thermal bridges are accounted for (Table 10), which is actually higher than the installed insulation R-value.

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.

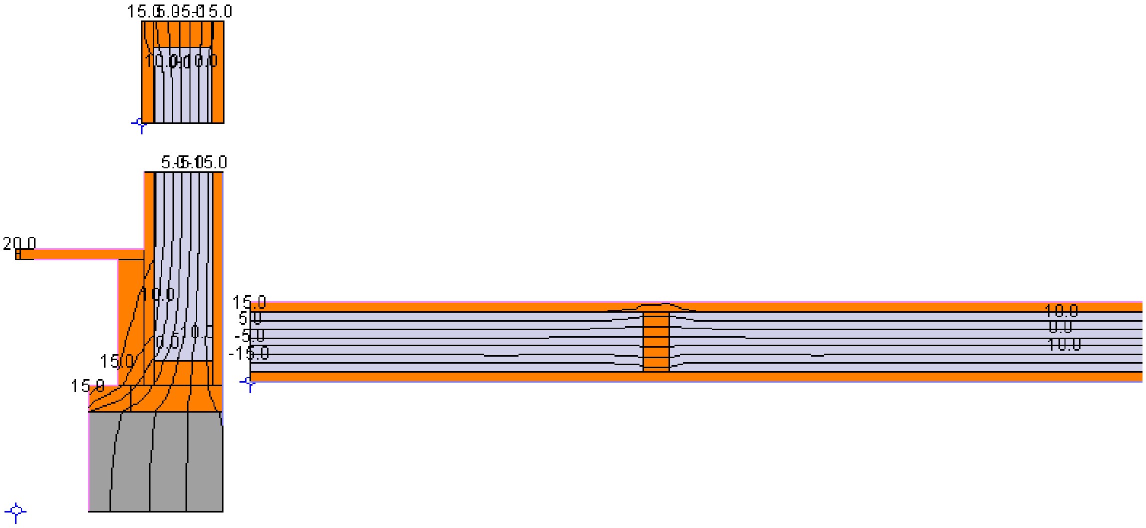


Figure 40 : Therm results of SIPs panel analysis

Table 10 : Calculated R-value for a Sips wall system

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
6a	SIPs (3.5" EPS)	**14.1**	12.3	14.5	10.6
6b	SIPs (11.25" EPS)	**36.2**	14	41.6	28.2

1.6.2. 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.

1.6.3. Constructability and Cost

Construction with SIPs panels requires training and education about construction techniques and design details. Generally, houses built from SIPs panels have very simple layouts and roof designs to help simplify the design of details at SIPs joints and roof-wall interfaces.

1.6.4. 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.

The 3.5" SIPs panel is not considered a High-R wall system, but as the thickness level, and insulation are increased, this system could be considered for more extreme cold climates.

1.7 Case 7: Insulated Concrete Forms (ICFs)

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.

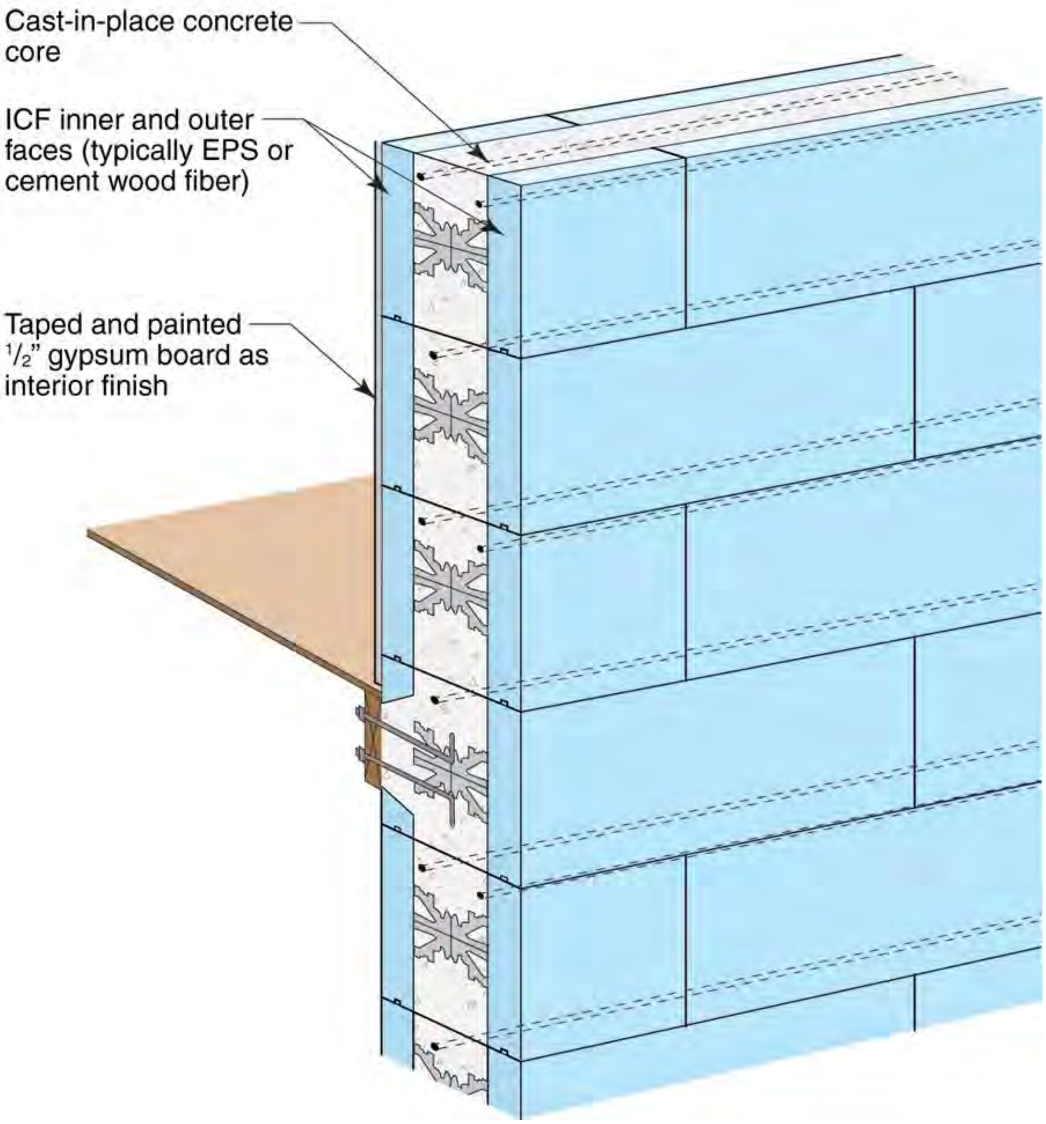


Figure 41 : ICF wall construction

1.7.1. 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 two different ICF systems. Figure 42 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. In comparison a 15" foam ICF with 5 total inches of EPS has an R-value of 20.6

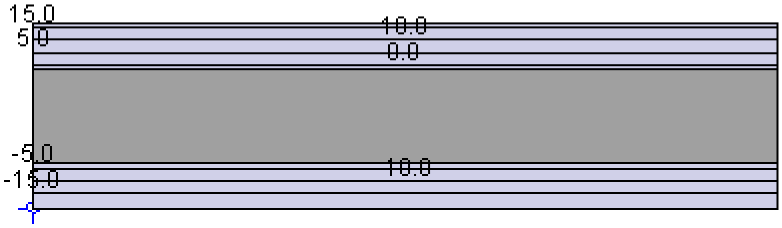


Figure 42 : Eight inch foam ICF with four inches of EPS

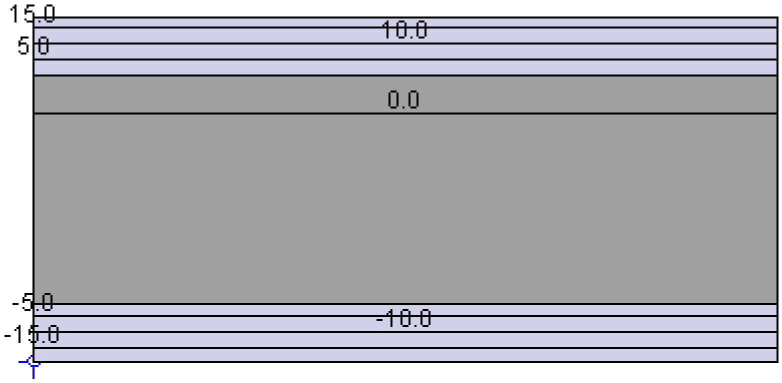


Figure 43 : Fifteen inch foam ICF with five inches of EPS

Neither of these ICF strategies would be considered a high-R enclosure in a cold climate, but these 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.

1.7.2. 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.

1.7.3. Constructability and Cost

ICFs are generally easy to use with some training on where and how to use steel reinforcement if necessary and installing services. Blocks are simply stacked on top of each other and concrete is poured into the centre. There have been reported issues with 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 perfectly flat substrate for drywall installation, but all of these problems can be dealt with by better training and quality control.

1.7.4. 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 alternative 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 mould if installed incorrectly.

1.8 Case 8: Advanced framing with spray foam

Polyurethane spray foam can be used in the stud cavity instead of fiberglass or cellulose insulation. Spray foam forms a very good air barrier when installed correctly and can be installed as low density (0.5 pcf) or high density (2.0 pcf) foam.

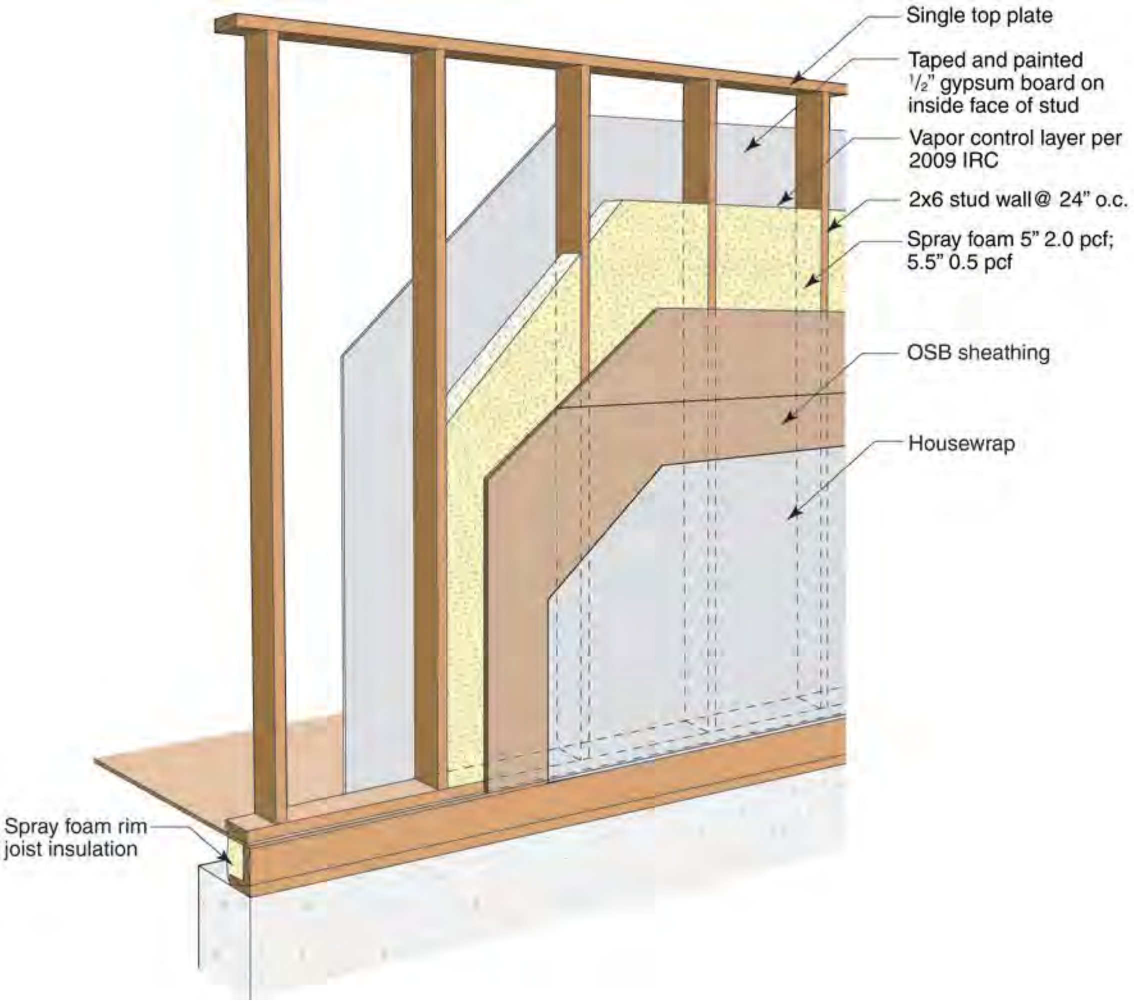


Figure 44 : 2x6 wall construction with spray foam insulation

1.8.1. Thermal Control

Using Therm to model different wall enclosure strategies does not accurate represent the benefits of spray foam insulation. Properly installed spray foam insulation completely stops air flow movement through and around the insulation so decreases in R-value associated with air leakage do not occur, either in the stud space or at the rim joist. There are different published R-values for both low and high density insulation but in this analysis for Case 8, 5.5" of R21 low density foam, and 5" of R28 high density foam were used. High density foam is installed short of the edge of the cavity to minimize trimming of the foam, while low density foam is softer, and installed to the edge of the cavity so that the excess can be trimmed flush with the stud wall framing.

Similar to standard construction practices, using spray foam does not address the concern of thermal bridging through the framing material as can be seen in Figure 45.

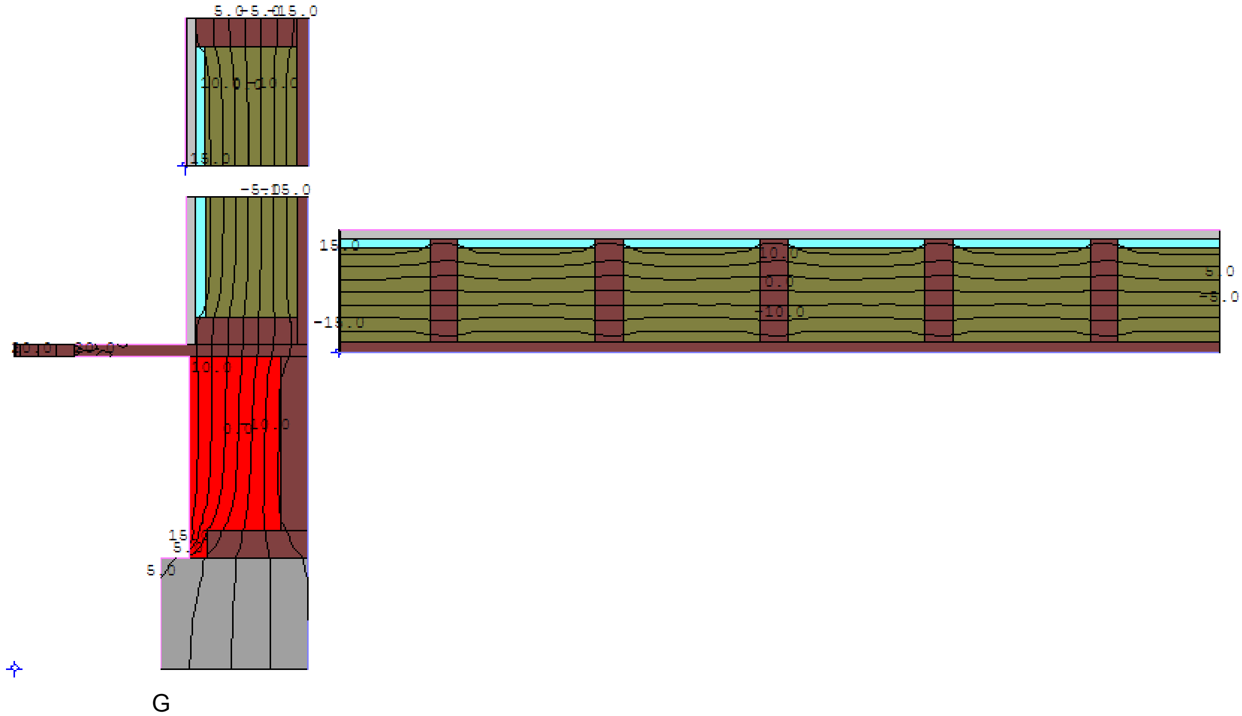


Figure 45 : Therm modeling of spray foam wall and rim joist

Calculating the whole wall R-values for the two spray foam assemblies results in R-values of R19.1 for high density spray foam, and R16.5 for the low density spray foam. The whole wall R-value of low density foam decreased by almost R4.5 versus the installed insulation R-value (from R20.9 to R16.5) because of thermal bridging. The whole wall R-value of the high density foam insulated wall decreased R9 from the installed insulation R-value due to the thermal bridging.

Table 11 : Therm results of spray foam insulation analysis

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
8a	2x6 AF, 24" o.c., 5" 2 pcf R29 SPF, OSB	**19.1**	13.6	20.3	19.5
8b	2x6 AF, 24" o.c., 5.5" R21 0.5 pcf SPF, OSB	**16.5**	13.1	17.2	16.6

1.8.2. Moisture Control

High density spray foam is both an air and vapor barrier. This limits the movement of moisture vapor and air leakage condensation. Low density foam is an air barrier, but it is permeable to water vapor and is susceptible to vapor diffusion condensation. Low density foam was modeled both with and without a class I vapor retarder to determine the performance differences of a class I vapor barrier with low density foam in climate Zone 6.

Both the high density foam and the low density foam with a vapor barrier had some of the lowest sheathing relative humidities in the winter months of all of the tested wall cases. The low density foam without a vapor barrier experienced high sheathing relative humidities sustained above 95% through the winter months (Figure 13).

Analysis of air leakage condensation shows that because the spray foam is an air barrier, there would be no condensation caused by air leakage, since the surface temperature of the interior face of the foam was always warmer than the dew point of the interior air (Figure 14).

Analysis of the summertime inward vapor drive shows that the low density sprayfoam with a poly vapor barrier experienced the highest relative humidity peaks of any of the test walls, approximately 5% higher than standard construction practice.

The high density foam and the low density foam without a vapor barrier experienced some of the lowest relative humidities of test walls because they were allowed to dry very easily to the interior.

Drying results (Figure 21) showed that the low density foam without poly dried to 100 kg/m3 in approximately 28 days similar to some of the other test walls, but the high density foam and low density foam with a vapor barrier took approximately 43 days to dry to 100 kg/m3.

1.8.3. Constructability and Cost

This wall is easier to build than a standard construction wall, since no care is required at installing fiberglass batts. The costs can be perceived as prohibitively expensive which is why sprayfoam is often only used where a perfect air barrier is required, and may be difficult to install, such as garage-house interface and rim joists.

1.8.4. Other Considerations

With the new era of environmentally friendly products, many spray foam companies are marketing green spray foams that are less or harmful to the environment. In most cases, spray foam may need to be protected with a fire rated material according to the code.

1.9 Case 9: Hybrid Wall Insulation – Flash and Fill

In this analysis, hybrid walls consist of two inches of 2.0 pcf closed cell foam sprayed against the interior surface of the exterior sheathing, and three and a half inches of fiberglass. Instead of fiberglass batt, cellulose or sprayed fiberglass could also be used. Flash and Fill or Flash and Batt is often used to describe the combination of spray foam and cellulose, or spray foam and fiberglass batt respectively. The framing strategy used is advanced framing with 2x6s 24” on centre with a single top plate. Spray foam insulation helps considerably with the air tightness of the wall assembly and will increase the temperature of the potential wintertime condensation plane. Two inches of high density spray foam in the cavity also decreases the need for an interior vapor control layer which simplifies construction.

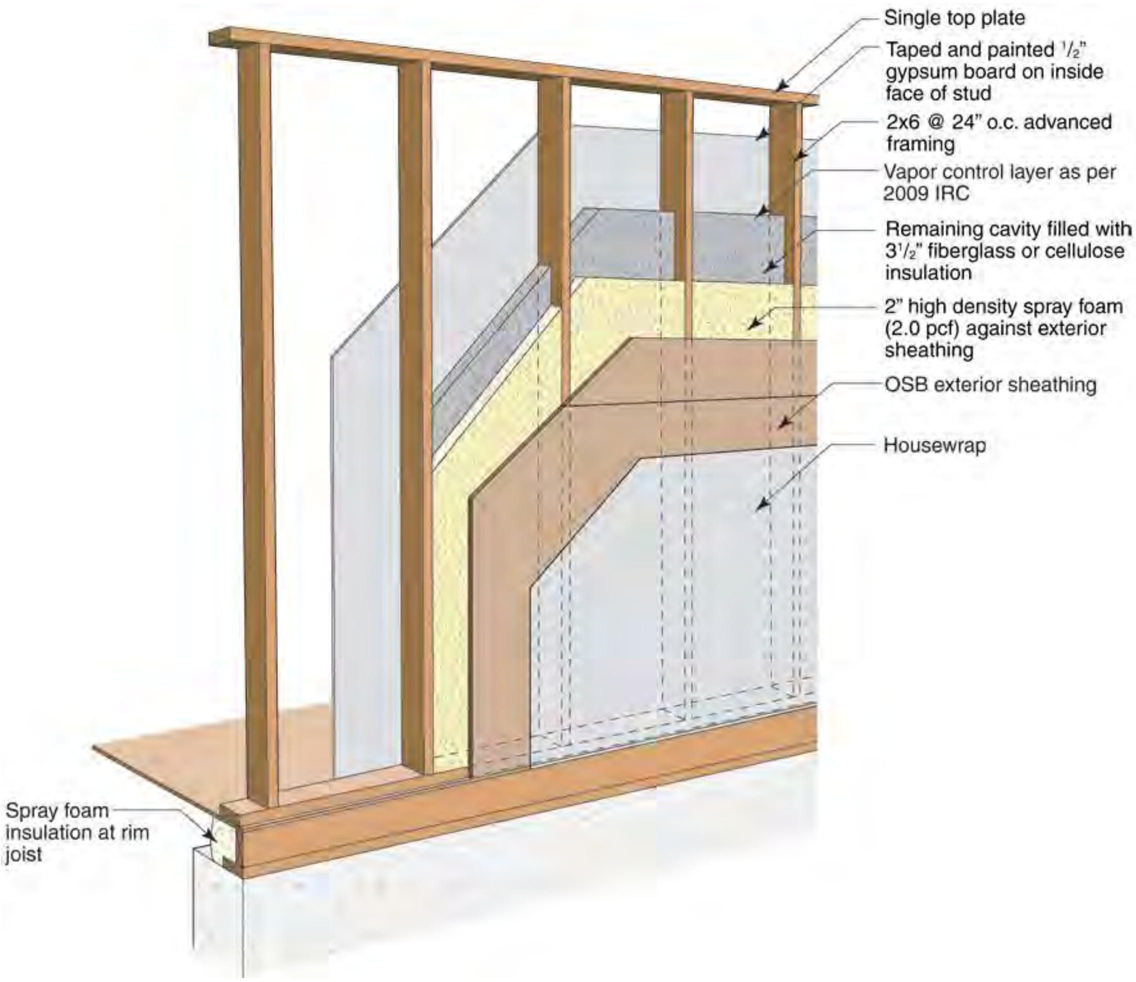


Figure 46 : Hybrid wall construction with 2" spray foam and fibrous fill

1.9.1. Thermal Control

The hybrid wall 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 true R-value. The whole wall R-value increases from R15.2 to R17.5 when comparing the same framing strategy with only fiberglass insulation (Case 1a) to Case 9. 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 and human comfort.

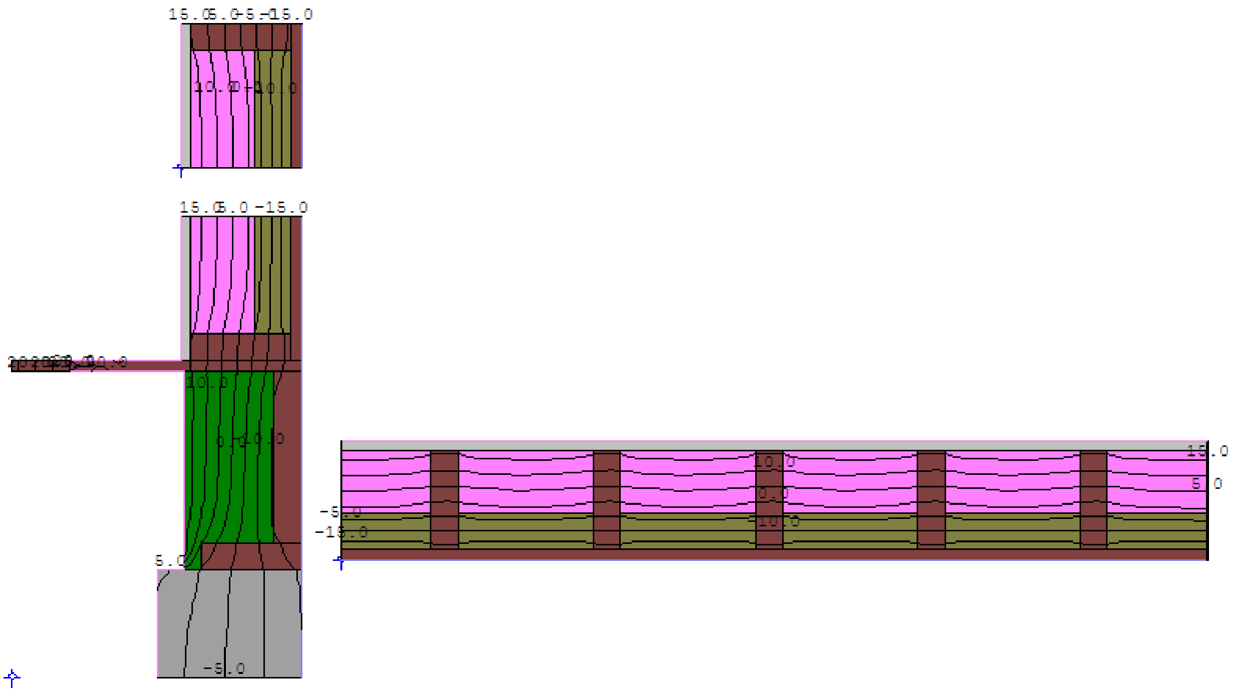


Figure 47 : Therm analysis of hybrid wall system

Table 12 : Calculated R-value for a hybrid wall system

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
9	2x6 AF, 24"oc, 2" SPF and 3.5" fibrous fill	**17.5**	13.2	18.4	17.7

1.9.2. Moisture Control

This wall performs very similarly to the Case 2 with 4" of exterior insulation with respect to summer inward vapor drives as shown in Figure 19.

During the winter months, there is a significant improvement in the potential air leakage condensation on the condensation plane in the hybrid wall, from the standard construction wall, as shown in Figure 11 because the condensation plane is kept warmer by the vapor impermeable spray foam insulation.

One disadvantage of this wall system over advanced framing with exterior insulation (Case 2) is that the sheathing is kept much colder in Case 9. Keeping enclosure materials warm and dry with exterior insulation has been known to increase enclosure durability since the 1960s (Hutcheon 1964).

1.9.3. Constructability and Cost

The constructability of this system is as easy as standard construction but the cost of construction is higher than using exclusively fiberglass insulation. This wall system is not as prone to air leakage moisture related damage as standard construction walls.

1.9.4. 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.

1.10 Case 10: Double Stud Wall with Spray Foam

Case 10 with spray foam insulation was chosen to try and improve the moisture related durability of the double stud wall in Case 4 which used cellulose insulation in the cavity space. The thermal performance of Case 4 was quite good, but the air leakage condensation potential could lead to premature enclosure failure. Case 10 analysis was conducted with two inches of spray foam since that is usually the maximum thickness that is sprayed in one pass during 2.0 pcf foam installation. This should increase the temperature of the condensation plane, thus increasing the moisture durability of the wall system. Depending on the climate zone for construction, more spray foam could be used to further decrease the risk of moisture related damage. Analyzing different thicknesses of spray foam for this single wall system are beyond the scope of this analysis report, but should be considered before this wall is constructed.

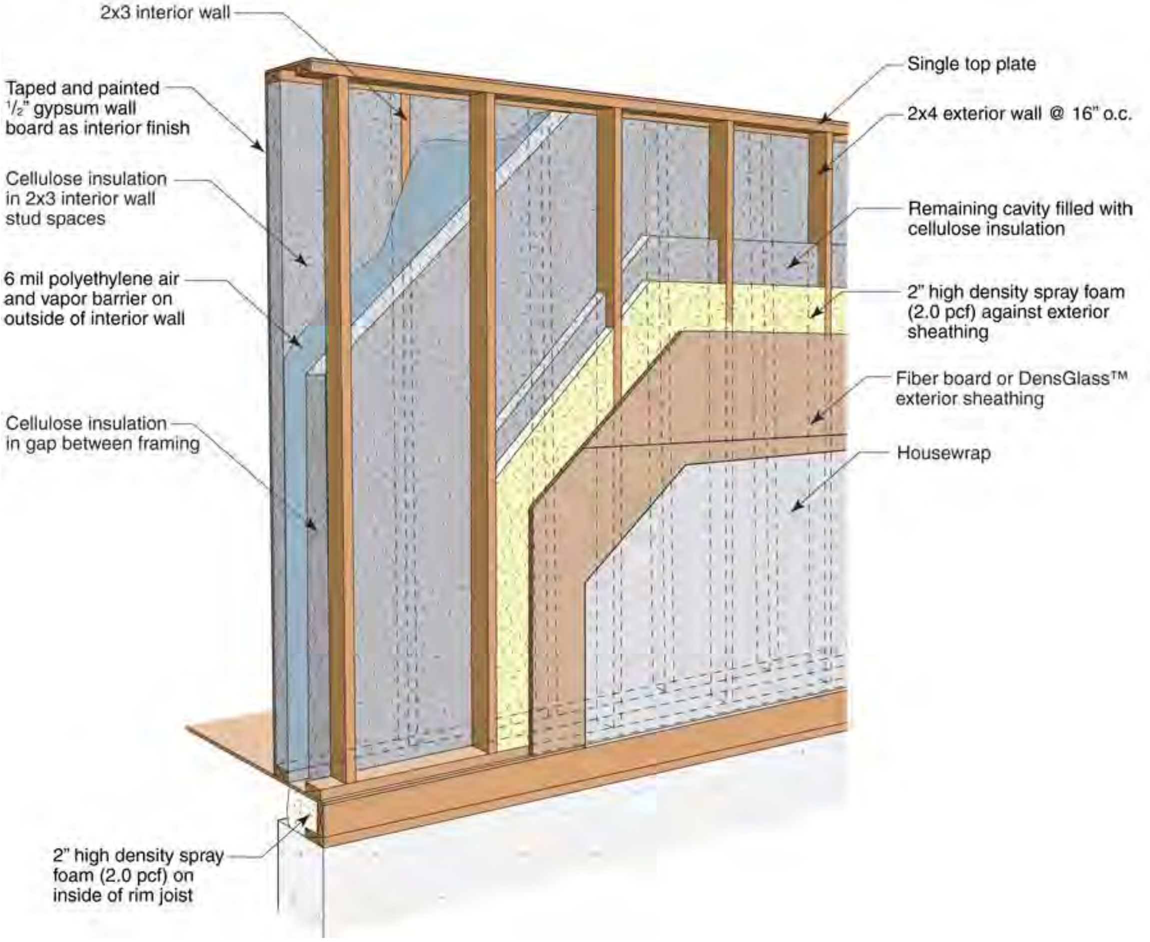


Figure 48 : Double stud wall with 2" of spray foam and cellulose fill

1.10.1. Thermal Control

This wall system has a slight improvement in whole wall R-value over Case 4, without spray foam insulation increasing from R30.1 to R32.4. This is only a minimal increase in the calculated whole wall R-value, but as in all cases with spray foam, there are improvements to the true R-value due to decreasing the air leakage through the wall and rim joist.

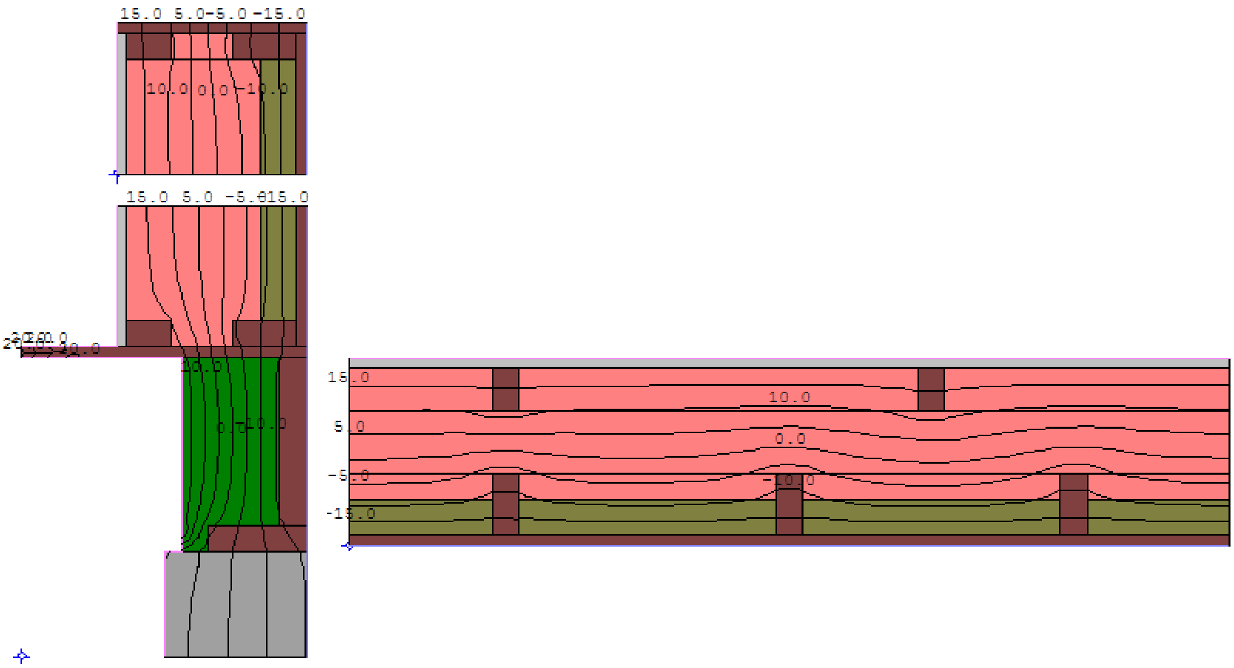


Figure 49 : Therm analysis of double stud wall construction with spray foam

Table 13 : Calculated whole wall R-value for a double stud wall system with 2” spray foam

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
10	Double stud with 2" 2.0 pcf foam, 7.5" cell.	**32.4**	15.9	36.2	28.5

1.10.2. Moisture Control

The most evident improvement to adding spray foam was shown in Figure 14 with less wintertime condensation potential. There are still periods of wintertime condensation risk in climate zone 6, the risks have been improved, and more spray foam would decrease the risk even further in climate zone 6 and should likely be required in colder areas. The hours of potential wintertime condensation decreased from approximately 4600 hours for Case 4 to approximately 2300 for Case 10 with spray foam insulation.

There is very little change to the drying results when comparing the double stud wall with and without spray foam insulation. The sheathing retains its moisture longer in Case 10 because the moisture can only dry to the exterior and is not buffered at all on the interior surface by the cellulose insulation (Figure 27). There are no significant changes to the summertime inward vapor drive by adding 2” of high density spray foam to the sheathing of the double stud wall (Figure 21). If a moisture storage cladding was used for simulations, adding the spray foam may reduce the inward vapor drive because of the vapor resistance of the spray foam.

1.10.3. Constructability and Cost

This wall system uses more framing material than most of the other test wall assemblies. The cost of this wall system is high relative to most of the other options, but does provide very high thermal resistance.

1.10.4. Other Considerations

The majority of the insulation is cellulose which is the lowest embodied energy insulation and readily available. The ratio of cellulose to spray foam insulation can be changed depending on the climate zone for construction to limit the potential winter time condensation.

Spray foam will burn, and therefore should always be protected by fire rated material, which in this case is the cellulose insulation.

1.11 Case 11: Offset Frame Wall with Exterior Spray Foam

Case 11 was included because of the increasing need for a retrofit solution that saves energy, increases durability and does not affect the interior space. This strategy also has several advantages as a new construction strategy as well, especially in extreme climates with a short construction season.

Standing lumber off of the sheathing using plywood trusses allows the cladding to be directly attached without requiring more exterior sheathing. High density foam acts as the drainage plane, air barrier, vapor barrier, and thermal control layer. Using plywood gusseted trusses can be a little work intensive since they all need to be made to identical dimensions.

An alternative solution to the traditional truss wall is shown in Figure 15. This method is less energy intensive in preparation. It uses large nails or spikes to support the framing lumber for the cladding installation. A spacer was used between the sheathing and the framing lumber to ensure even spacing and then was removed after the nails were installed. Even though this method does not appear to be strong enough to support cladding, it has supported approximately 200 lbs on a single truss prior to installing the foam, and is considerably stronger following the installation of the spray foam. An alternative method proposed for spacing the lumber off of the sheathing is to use plastic sleeves (possibly PVC pipe) which are cut to a constant length and used to set the depth of the nails that attach the lumber by driving the nails through the centre of them.

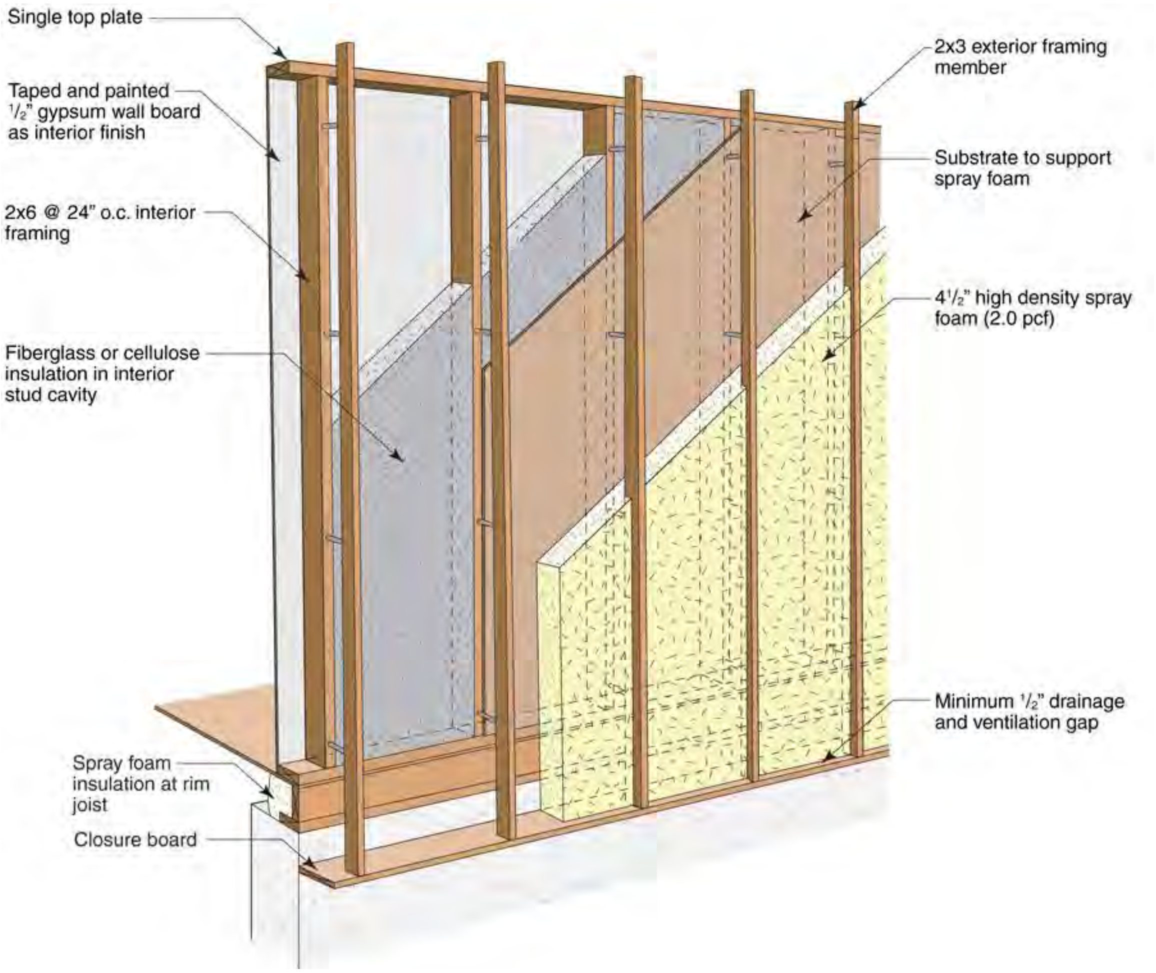


Figure 50 : Offset frame wall construction with exterior spray foam

1.11.1. Thermal Control

This wall with 4.5 inches of high density spray foam and 5.5 inches of fibrous insulation has a whole wall R-value of approximately R37, the highest total wall R-value of all walls analyzed which is, in part, because of the lack of thermal bridges through the entire system. Spray foam is installed over the rim joist, over the exterior of the wall, and up to the soffit, where ideally, it meets with the spray foam in the attic.

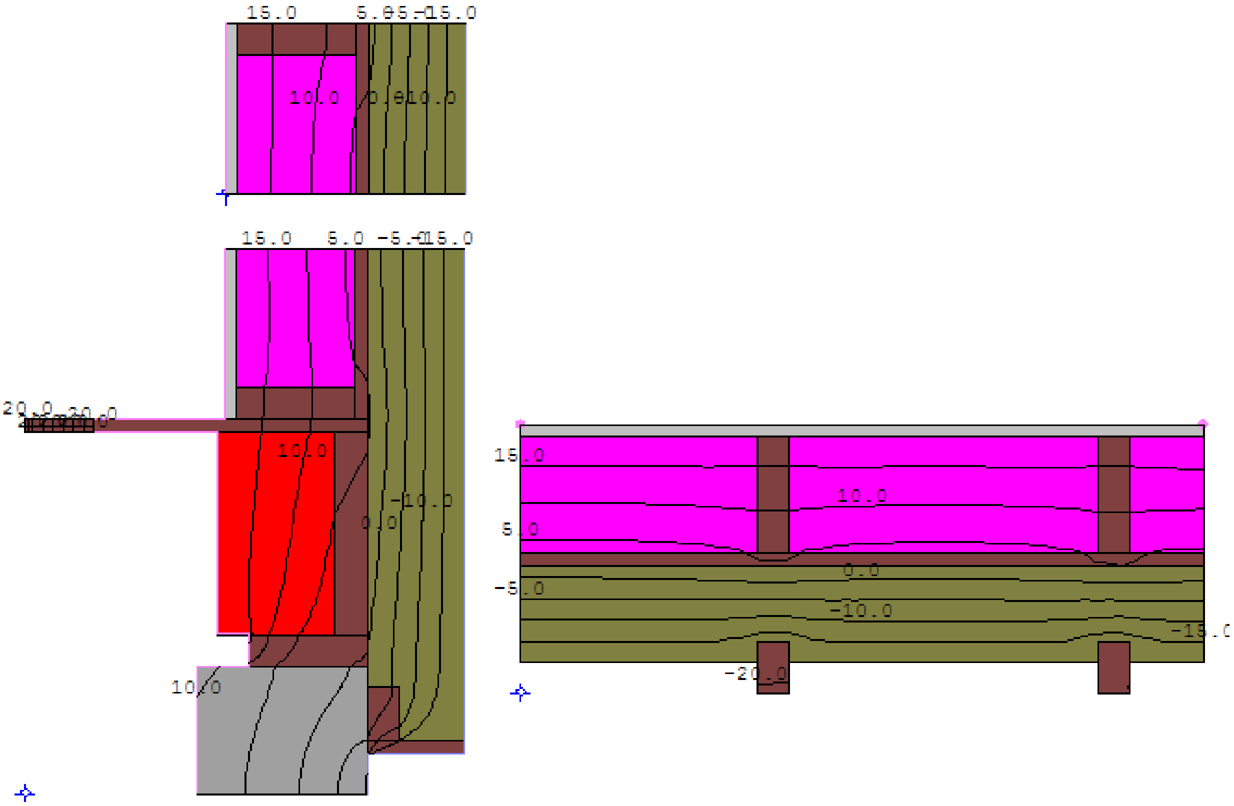


Figure 51 : Therm analysis of an offset truss wall with exterior spray foam

Table 14 : Calculated whole wall R-value for an offset framed wall with exterior spray foam

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
11	Offset frame wall with ext. spray foam	**37.1**	18.8	40.6	41.9

1.11.2. Moisture Control

Because of the high level of vapor control in the exterior spray foam insulation, a vapor barrier is not required on the interior of the wall assembly.   This allows any necessary drying to occur to the interior. In Minneapolis, (climate zone 6) there is no risk of winter time condensation on the interior of the exterior sheathing (Figure 16).

The summer time inward vapor drive sheathing relative humidity does not change significantly with the addition of the exterior foam (Figure 23). The relative humidity increases slightly in Case 11 because of the higher interior relative humidity, the low solar inward vapor drive load, and the inability for the exterior spray foam wall to dry to the outside.

The sheathing remains wet during the drying test significantly longer with exterior insulation than without since there is no moisture buffering capacity in the fiberglass batt in Case 11, and there is significant moisture buffering capacity of the cellulose insulation in Case 5 (Figure 28).

1.11.3. Constructability and Cost

High density spray foam is a relatively expensive choice for an insulation strategy.   In this case, it provides great thermal resistance, reduced thermal bridging, and minimal air leakage. Some of these benefits will result into operating energy costs savings, but other benefits can not be easily quantified such as greater occupant comfort, and quite possibly higher resale value in an uncertain energy future.

1.11.4. Other Considerations

This method could be used as a retrofit without greatly affecting the interior, or for new construction. It is a very quick, high quality method of sealing the exterior and drying in the interior during construction, so that care can be taken with the interior work including wiring, plumbing and HVAC. This is ideal for locations with short construction seasons. Since the foam is transported in liquid phase, more board feet of foam (and R-value) can be transported on a transport truck than any other type of insulation

1.12 Case 12: Exterior Insulation Finish System (EIFS)

Using an exterior insulation finish system (EIFS) is a valid option for cladding in almost every climate zone. The thickness of the exterior insulation can be varied to provide the thermal resistance required in combination with the stud space insulation. EIFs was one of the cladding strategies used on the CCHRC head office in Fairbanks AK (13980 HDD65 or 7767 HDD18) which is considered to be an extremely cold climate.

There is a stigma attached to EIFS because of the large number of failures in various climates in the past. Field and laboratory observations and testing have shown that this cladding technique is an effective and durable wall assembly, if drainage and water management details are constructed correctly. In most cases, during failures, water was trapped behind the EIFS due to poor water management details which eventually rotted the sheathing, causing corrosion and rot of the wall assembly. A properly detailed continuous drainage plane will ensure that this is a successful cladding technique in any climate zone.

Fiberglass-faced gypsum board exterior sheathing was used instead of OSB in the simulation because it is generally used underneath EIFS cladding systems due to its moisture tolerance.

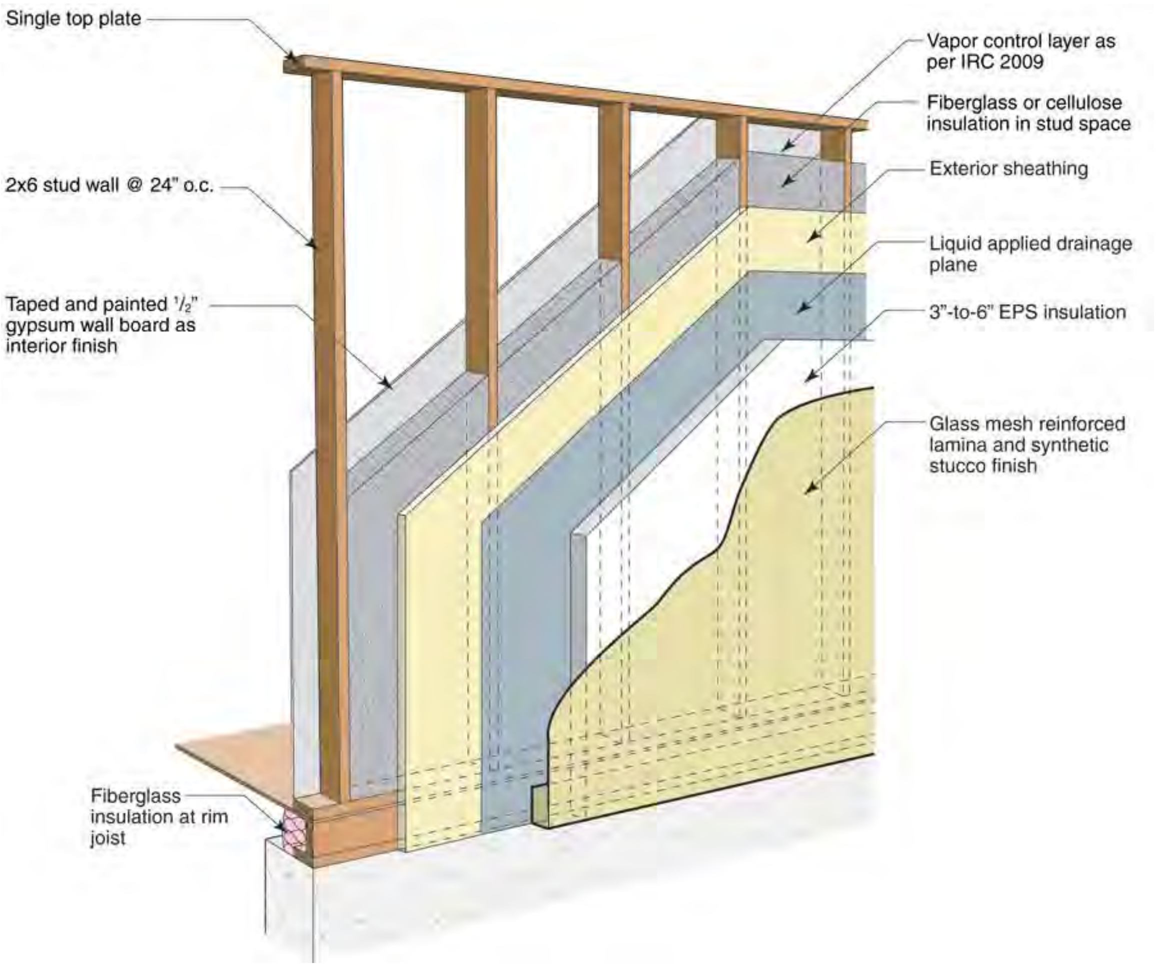


Figure 52 : Wall construction using the EIFS cladding system

1.12.1. Thermal Control

The amount of insulation installed on the exterior of the advanced framing will determine the thermal control of the assembly. In this analysis we used four inches of EPS board foam insulation, and achieved a whole wall R-value of R30. This strategy addresses the thermal bridging of both the framing and the rim joist and is very similar to advanced framing with four inches of XPS insulation in Case 2.

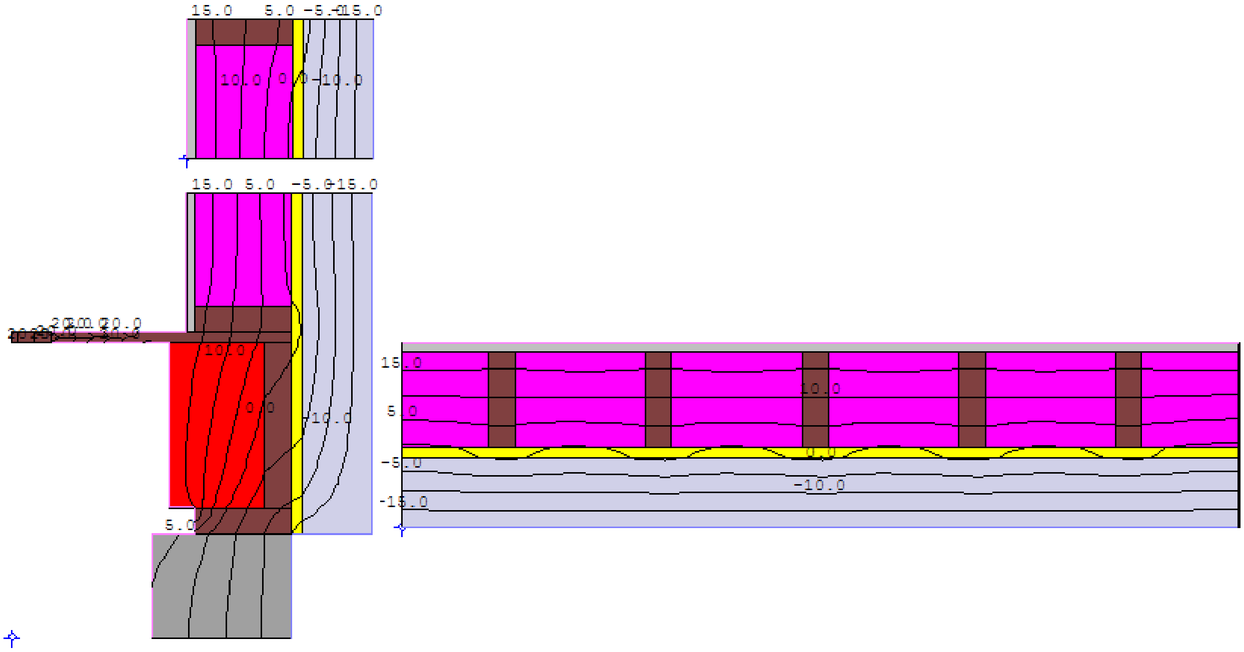


Figure 53 : Thermal analysis of an EIFS wall system

Table 15 : Calculated whole wall R-value for a EIFS wall system with 4" of EPS

Case	Description	Whole Wall R value	Rim Joist	Clear Wall R value	Top Plate
12	2x6 AF, 24"oc, EIFS - 4" EPS	**30.1**	23.8	31.4	31.1

1.12.2. Moisture Control

The moisture management details for this cladding type can be challenging but EIFS companies generally provide good documentation and design details with their product. For example, both Sto Corp and Dryvit Systems provide many details for all of their products on their websites to help builders and designers with moisture management details.

The performance of this wall system was nearly identical in winter time condensation, drying and summer time inward vapor drives to Case 2 with 4" of XPS insulation. EPS is more vapor permeable than XPS insulation, but laminate coating applied to the EPS insulation is usually less than 1 US perm.

1.12.3. Constructability and Cost

Because of the stucco appearance of this cladding system, it can be more expensive depending on the architectural detailing. EIFS is generally only done if the appearance of stucco is specifically desired. It is approximately the same performance and cost to use advanced framing with four inches of XPS insulation and cladding.

1.12.4. Other Considerations

EIFS are generally chosen when the owner or architect wants a stucco finish on a building. There are no significant performance differences between EIFS and the advanced framing with exterior insulation shown in Case 2. Both strategies minimize thermal bridging, and increase the temperature of the potential wintertime air leakage condensation plane. The main differences are the appearance of the finished cladding surface and water drainage details.

D. Conclusions

Whole wall R-values for all of the assemblies were calculated using Therm and the summary is shown in Table 16 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.

Table 16 : Summary of all calculated R-values

Case	Description	Whole Wall R-value	Rim Joist	Clear Wall R-value	Top Plate
1bii	2x4, 16"oc, R13FG + OSB (25%ff)	**10.0**	9.8	10.1	9.8
1b	2x4 AF, 24"oc, R13FG + OSB	**11.1**	9.8	11.5	9.8
1aii	2x6, 16"oc, R19FG + OSB (25%ff)	**13.7**	12.3	14.1	12.5
6a	SIPs (3.5" EPS)	**14.1**	12.3	14.5	10.6
1a	2x6 AF, 24"oc, R19FG + OSB	**15.2**	12.3	16.1	12.5
7a	ICF - 8" foam ICF (4" EPS)	**16.4**		16.4	
8b	2x6 AF, 24" o.c., 5.5" R21 0.5 pcf SPF, OSB	**16.5**	13.1	17.2	16.6
7c	ICF - 14" cement woodfiber ICF with Rockwool	**17.4**		17.4	
9	2x6 AF, 24"oc, 2" SPF and 3.5" cellulose	**17.5**	13.2	18.4	17.7
8a	2x6 AF, 24" o.c., 5" 2 pcf R29 SPF, OSB	**19.1**	13.6	20.3	19.5
2a	2x6 AF, 24"oc R19FG + 1" R5 XPS	**20.2**	18.5	20.6	20.3
7b	ICF - 15" foam ICF (5" EPS)	**20.6**		20.6	
3	2x6 AF, 24"oc, 2x3 R19+R8 FG	**21.5**	13.4	23.5	18.4
4	Double stud wall 9.5" R34 cellulose	**30.1**	14.4	33.5	28.8
12	2x6 AF, 24"oc, EIFS - 4" EPS	**30.1**	23.8	31.4	31.1
10	Double stud with 2" 2.0 pcf foam, 7.5" cell.	**32.4**	15.9	36.2	28.5
2b	2x6 AF, 24"oc R19FG + 4" R20 XPS	**34.5**	29.0	35.6	35.4
6b	SIPs (11.25" EPS)	**36.2**	14	41.6	28.2
5	Truss wall 12" R43 cellulose	**36.5**	18.6	40.5	34.4
11	Offset frame wall with ext. spray foam	**37.1**	18.8	40.6	41.9

*AF - Advanced Framing

The walls analyzed in this report can be grouped into three groups based on their calculated whole wall R-values. The first group have whole wall R-values less than approximately R20. These walls are not considered High-R wall systems for cold climates.

The second group of walls have whole wall R-values of approximately R-20. According to the IECC, the requirement for climate zones 7 and 8 is an installed R-value of R21. This report has shown that the whole R-value is less than the installed insulation R-value in almost every case, which means that often, the walls that the IECC allow in extremely cold climates are actually performing at a whole wall R-value of between R15 and R20. This is unacceptable in the future of uncertain oil reserves, increasing energy costs, and decreasing environmental health.

The third group of walls have whole wall R-values greater than R30. This is what the construction industry has been achieving in very small numbers, such as Building America prototype homes, and small custom home builders. The R-value of walls in the category can be modified easily by either decreasing or increasing the amount of insulation depending on the specific construction conditions. All of the walls in category three have minimized thermal bridging which increases the effectiveness of insulation.

The potential for wintertime air leakage was compared for all test walls, and the summary of the results are shown in Table 17. The walls were ranked from the least hours of potential condensation to the greatest. This potential condensation is only an issue if the airtightness details aren't constructed properly, but should still be used to assess the potential risk of a wall system, considering that field observations show the air barrier detailing is rarely perfect.

Table 17 : Hours of potential winter time air leakage condensation

Case	Description	Hours of Potential Condensation
8b	2x6 AF, 24" o.c., 5.5" R21 0.5 pcf SPF, OSB	0
8a	2x6 AF, 24" o.c., 5" 2 pcf R29 SPF, OSB	0
11	Offset frame wall with ext. spray foam	0
9	2x6 AF, 24"oc, 2" SPF and 3.5" cell or FG	934
2b	2x6 AF, 24"oc R19FG + 4" R20 XPS	1189
12	2x6 AF, 24"oc, EIFS - 4" EPS	1532
10	Double stud with 2" 2.0 pcf foam, 7.5" cell.	2284
2a	2x6 AF, 24"oc R19FG + 1" R5 XPS	3813
1a	2x6 AF, 24"oc, R19FG + OSB	4379
1b	2x4 AF, 24"oc, R13FG + OSB	4503
4	Double stud wall 9.5" R34 cellulose	4576
3	2x6 AF, 24"oc, 2x3 R19+R8 FG	4594
5	Truss wall 12" R43 cellulose	4622

*AF - Advanced Framing

The comparison matrix explained in the introduction was completed according to the analysis of each wall section in this report (Table 18), and it was found that three walls achieved the highest score of 20 out of a possible 25 points. The advanced framing wall (Case 2), sprayfoam insulation wall (Case 8) and EIFS wall (Case 12) achieved scores of 20 using an even weighting system of all selection criteria.

The main issue with most of the wood framed walls without exterior insulation is the probability of wintertime air leakage condensation depending on the quality of workmanship and the attention to detail. Inspections of production builder 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.

Table 18 : Wall Comparison Chart

	Thermal Control	Durability (wetting/drying)	Buildability	Cost	Material Use	Total
Criteria Weighting	1	1	1	1	1	
Case 1: Standard Construction	1	3	5	5	3	17
Case 2: Advanced Framing with Insulated Shtg	4	4	4	4	4	20
Case 3: Interior Strapping	3	3	3	4	4	17
Case 4: Double Stud	4	3	3	3	2	15
Case 5: Truss Wall	4	3	2	3	3	15
Case 6: SIPs	4	4	3	3	3	17
Case 7: ICF	4	5	4	2	3	18
Case 8: Sprayfoam	5	5	4	2	4	20
Case 9: Flash and Fill (2" spuf and cell.)	4	4	4	3	4	19
Case10: Double stud with 2" spray foam and cell.	5	4	3	3	3	18
Case 11: Offset Framing (ext. Spray foam insul.)	5	5	4	3	2	19
Case 12: EIFS with fibrous fill in space	5	5	4	3	3	20

Adding exterior insulation to most wall systems has many durability and energy benefits. Two dimensional heat flow modeling has shown that exterior insulation is very effective at minimizing the thermal bridging losses of wall framing, and hygrothermal modeling showed reduced condensation potential in the wall from vapor diffusion and air leakage, as well as increased drying potential to the interior with reasonable interior relative humidities. Adding exterior insulation was shown to increase the effectiveness of the fiberglass batt insulation in the stud space and increase the clear wall R-value greater than the amount of insulation added. This becomes even more important with higher thermal bridging such as a high framing factor or steel studs. Adding exterior insulation greater than approximately R5, the installed insulation R-value can be added directly to the clear wall R-value and is approximately equal to the increase in whole wall R-value since most of the thermal bridging is addressed.

Hygrothermal modeling showed that traditional double stud walls, truss walls and interior strapped walls, are at a greater risk of air leakage condensation because of the air permeable insulation, and cold exterior surface. Hybrid walls are a good strategy to help overcome this problem by using vapor impermeable spray foam insulation against the exterior, which increases the temperature of the condensation plane. The amount of spray foam required in a hybrid system is dependent on the climate zone for construction, but it may be difficult to get a high enough R value or thermal bridge control in cold climates for net zero housing.

ICF and SIPS walls both have insulation integral to the system, but require more insulation for a High R value wall assembly. Experience and modeling indicate that both of these techniques are susceptible to moisture issues if the details are not done correctly. SIPS are particularly susceptible to air leakage at the panel joints, and ICF walls need well designed penetrations, to avoid water ingress.

In extreme cold climates, and remote areas, high density spray foam appears to address most of the concerns that have been reported by NRC during visits and interviews with local residents. High density spray foam is easy to ship and install, not subject to damage during transit, and allows some variations in construction quality levels since it is both an air and vapor barrier. High density spray foam can be used in different wall construction strategies as demonstrated in this report, either on its own or as part of an insulation strategy with other insulations types. An offset frame wall with high density spray foam has the added advantage of drying in a house very quickly in the short construction season so that work can be done on the interior during inclement weather.

E. Works Cited

BSC. "BSP-035: Designs that Work: Very Cold Climate (Juneau, AK)." *buildingscience.com information.* 2008. http://www.buildingscience.com/documents/primers/bsp-035-designs-that-work-very-cold-climate-juneau-ak/section-2-the-basic-very-cold-climate-house/view?searchterm=haida%20house.

Carpenter, S C, and C J Schumacher. "Characterization of Framing Factors for Wood-Framed Low-Rise Residential Buildings." *ASHRAE Transactions v 109, Pt 1.*, 2003.

CCHRC. "Cold Climate Housing Research Center." *Research and Testing Faciility.* 2007. http://www.cchrc.org/research+_+testing+facility.aspx.

Christian, J E, and J Kosny. "Towards a National Opaque Wall Rating Label." *U.S. DOE VI Thermal Envelope Conference.* 1995.

Hutcheon, N B. "CBD-50. Principles Applied to an Insulated Masonry Wall." *Canadian Building Digest*, 1964.

Kosny, Jan, David Yarbrough, Phillip Childs, and Syed Azam Mohiuddin. "How the Same Wall Can Have Several Different R-Values: Relations Between Amount of Framing and Overall Thermal Performance in Wood and Steel-Framed Walls." *Buildings X.* ASHRAE, 2007.

Lstiburek, J. *YouTube.* May 3, 2007. http://www.youtube.com/watch?v=D_IrtDR3p0c&feature=channel_page (accessed March 6, 2009).

Niemz, Peter. "Untersuchungen zur Warmeleitfahigkeit ausgewahlter einheimischer und fremdlandischer Holzarten." *Verlag fur Architektur und technische Wissenschaften*, Bauphysik 29 (2007): 311-312.

Rousseau, M.Z., S.M. Cornick, M.N. Said, W Maref, and M.M. Manning. *PERD 079 Project - Report Task 4 - Review of Work Plan & Selection of Wall Assemblies.* Ottawa, Canada: National Research Council Canada, 2008.

Saïd, M.N.A. *Task 2: Literature Review: Building Envelope, Heathing, and Ventilating Practices and Technologies for Extreme Climates.* Ottawa, Canada: National Research Council Canada, 2006.

Simpson, William, and Anton TenWolde. "Physical Properties and Moisture Relations of Wood." In *Wood Handbook*, 3-1 - 3-24. Madison, WI: Forest Products Laboratory, 1999.

SIPA. "SIPA Report on the Juneau, Alaska Roof Issue." *Structural Insulated Panel Association.* February 2002. http://www.sips.org/content/technical/index.cfm?PageId=161 (accessed 03 10, 2009).

Smegal, Jonathan, and John Straube. *CCHRC Test Trailer at University of Alaska Southeast.* Waterloo, Canada: Balanced Solutions Inc., 2006.

Straube, John, and Eric Burnett. *Building Science for Building Enclosures.* Westford: Building Science Press, 2005.

About this Report

This report was prepared with the cooperation of the U.S. Department of Energy's, Building America Program.

Direct all correspondence to: Building Science Corporation, 30 Forest Street, Somerville, MA 02143.

Limits of Liability and Disclaimer of Warranty:

STANDARD WALL CONSTRUCTION

STANDARD WALL CONSTRUCTION DETAILS (*Walls 1A and 1B*)[1]

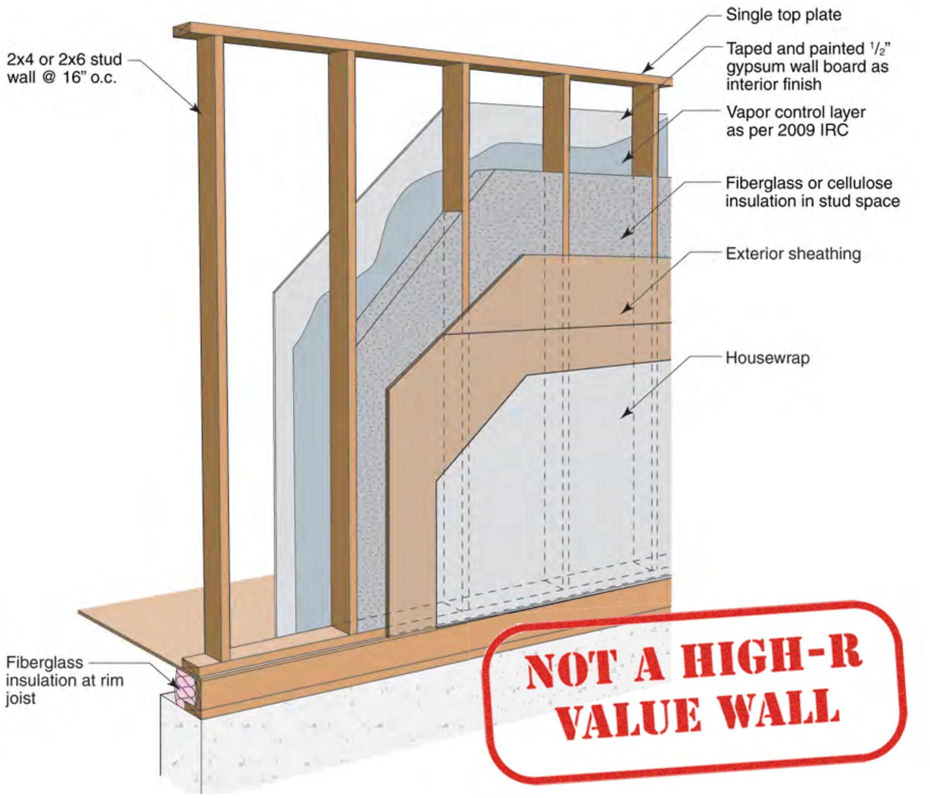
- 2x4 or 2x6 framing
- Fiberglass or cellulose cavity insulation in stud space
- Exterior sheathing
- Housewrap

SCORING: HOW IT RATES

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	1
Durability	3
Buildability	5
Cost	5
Material Use	4
Total	**18**

This wall has been the standard of construction for many years in many places but no longer meets the energy code requirements for insulation in some climates. Many higher performance designs exist.



INTRODUCTION

This two page summary briefly summarizes standard wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

THERMAL CONTROL

Installed Insulation R-value: There is a range of installed insulation R-values in commercially available fiberglass batts. The installed insulation R-value for 2x4 fiberglass batt ranges between R-11 and R-15 and for 2x6 the range is between R-19 and R-22. When blown or sprayed cellulose insulation is used, the R-values are typically R-13 for 2x4 and R-20 for 2x6 walls.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors, a 2x4 wall with R-14 studspace insulation has a whole-wall R-value of R-9. Similarly a 2x6 wall with R-19 stud space insulation has a whole wall R-value of R-11.[1] The framing factor used for standard construction framing 16 inches on center is 25%.[2] These whole wall R-values could decrease even further if there is significant air leakage or convective looping, or increased framing factor.

Air Leakage Control: Fiberglass batt, and both blown and sprayed cellulose are air permeable materials allowing possible air paths between the interior and exterior as well as convective looping in the insulation. Although densepack cellulose has less air permeance it does not control air leakage.

This summary has been prepared by Building Science Corporation for the Department of Energy's Building America Program, a private/public partnership that develops energy solutions for new and existing homes. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

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30 Forest Street
Somerville, MA 02143
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Typical Insulation Products: Fiberglass batt, blown fiberglass, blown cellulose, sprayed cellulose

DURABILITY

Rain Control: Rain leakage into the enclosure is the leading cause of premature building enclosure failure. Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). Intersections, windows, doors and other penetrations must be drained and/or detailed to prevent the penetration of rain water beyond the drainage plane.[3]

Air Leakage Control: Air leakage condensation is the second largest cause of premature building enclosure failure with this type of wall construction. It is very important to control air leakage to minimize air leakage condensation durability issues. An air barrier is required in this wall system to ensure that through-wall air leakage is eliminated (ideally) or at least minimized. An air barrier should be stiff and strong enough to resist wind forces, continuous, durable, and air impermeable.[4]

Air need not leak straight through an assembly to cause moisture problems; it can also leak from the inside, through the wall, and back to the inside; or it can leak from the outside, through the wall, and back to the outside. Condensation within the studspace is possible if this type of airflow occurs, depending on the weather conditions. Hence, wall designs should control airflow into the studspace.[5]

Vapor Control: Fiberglass and cellulose are highly vapor permeable materials, so a separate vapor control strategy must be employed to ensure that vapor diffusion does not result in condensation on, or damaging moisture accumulation in, moisture sensitive materials. The permeance and location of vapor control is dependent on the climate zone. Installing the vapor control layer in the incorrect location can lead to building enclosure failure.[6] The IRC building code should be consulted.

Drying: Cellulose and fiberglass insulation allow drying to occur relatively easily, so drying is controlled by other more vapor impermeable enclosure components such as the vapor barrier and OSB sheathing. Installing vapor control on both sides will seal any moisture into the stud space, resulting in low drying potential, and possibly resulting in moisture-related durability risks. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before close in. Cellulose is often sprayed in damp, and manufacturers recommend drying before close in and moisture content limits. Because of the polyethylene vapor barrier required in many climates, and relatively vapor impermeable OSB sheathing, drying could be slow if built-in moisture is present.

Durability Summary: The primary durability risks associated with these wall assemblies involve moisture damage related to rain water penetration or condensation (most likely the result of air leakage, but also potentially the result of vapor diffusion).

Cellulose insulated walls are slightly more durable because cellulose insulation is capable of storing and redistributing small amounts of moisture. Cellulose insulation is typically treated with borates that have been shown to protect itself and neighboring wood material from mold growth and decay. Cellulose insulation also has decreased flame spread potential relative to other insulation materials.

BUILDABILITY

Wood-framed walls with OSB exterior sheathing and fiberglass or cellulose insulation represent the most common wall assembly used in the construction of low-rise residential buildings in North America. Designers, trades and supply chains are well equipped to produce these walls and education is primarily needed to improve durability through better rainwater control and thermal performance through better air tightness and insulating practices.

COST

The cost to build this type of wall is well accepted, and is used as a baseline. Costs vary tremendously from region to region.

MATERIAL USE

This wall design contains redundant wood framing and wood sheathing. Framing lumber could be minimized further if advanced framing was used. In most of America, much of the sheathing could be removed. Cellulose has a significantly lower embodied energy than fiberglass or rockwool.

TOTAL SCORE

This wall has been the standard of construction for many years in many places. This wall no longer meets the energy code requirements for insulation in many climates, and thermal control requirements will only continue to increase. This wall system is difficult to air seal adequately and prone to air leakage related condensation and energy losses. Using advanced framing will reduce framing materials, and the cost of framing. Although this construction technique is usually allowed by code, many higher performance designs exist.

REFERENCES

1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis*. Retrieved from buildingscience.com.

2 Carpenter, S C, and C J Schumacher. "Characterization of Framing Factors for Wood Framed Low Rise Residential Buildings." *ASHRAE Transactions v 109, Pt 1.*, 2003

3 Lstiburek, J. W. (2006). *Water Management Guide.* Westford: Building Science Press Inc.

4 Lstiburek, J. (2008, 08 20). *BSD-104: Understanding Air Barriers*. Retrieved from buildingscience.com.

5 Straube, J. (2009, 04 22). *BSD-014 Air Flow Control in Buildings.* Retrieved from buildingscience.com.

6 Lstiburek, J. (2008, 10 17). *BSD-106 Understanding Vapor Barriers.* Retrieved from buildingscience.com.

2x6 ADVANCED FRAME WALL CONSTRUCTION

2x6 ADVANCED FRAME WALL CONSTRUCTION DETAILS

(Walls 2A and 2B)[1]

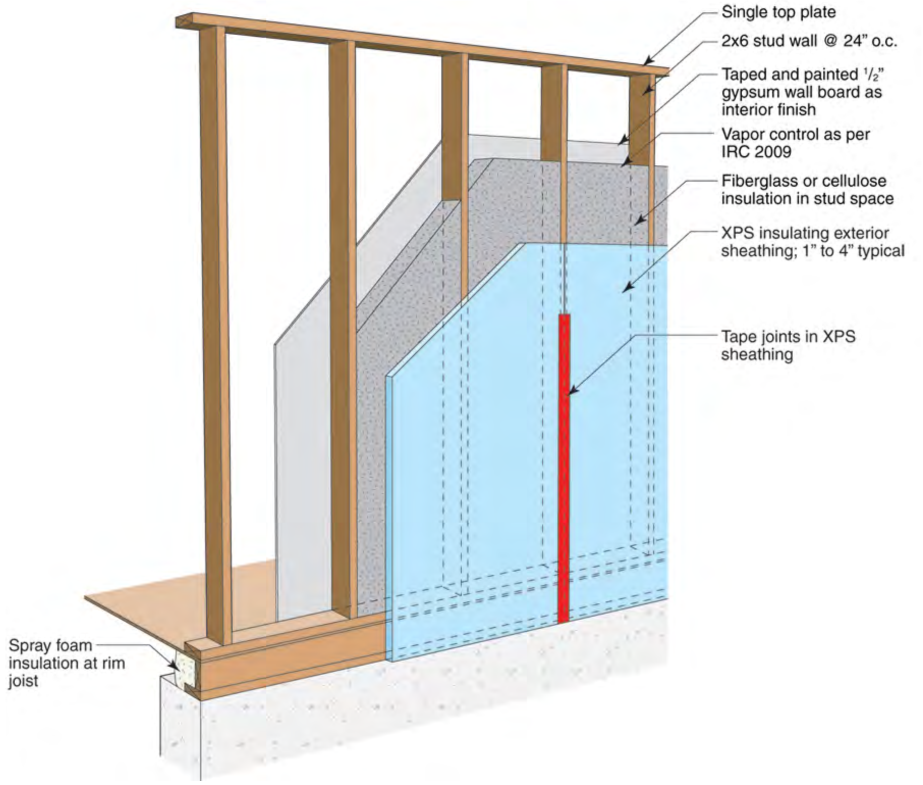
- 2x6 framing
- XPS insulating sheathing
- Fiberglass or cellulose cavity insulation in stud space

SCORING: HOW IT RATES

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	4
Durability	4
Buildability	4
Cost	4
Material Use	4
Total	**20**

Advanced framing with insulated sheathing significantly reduces the thermal bridging through the enclosure and improves the thermal efficiency of the fiberglass batt in the stud space. Using insulated sheathing decreases the potential for both wintertime condensation, and summer inward vapor drives, and helps mitigate issues caused by poor construction practices.



INTRODUCTION

This two page summary briefly summarizes 2x6 advanced frame wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

THERMAL CONTROL

Installed Insulation R-value: There is a range of installed insulation R-values in commercially available fiberglass batts for the stud space insulation in this wall system. The installed insulation R-value for 2x4 fiberglass batt ranges between R-11 and R-15 and for 2x6 the range is R-19 and R-22. When blown or sprayed cellulose insulation is used, the R-values are typically R-13 for 2x4 walls and R-20 for 2x6 walls.

Exterior insulating sheathing is typically added as expanded Ppolystyrene (EPS) at R-4/inch, extruded polystyrene (XPS) at R-5/inch or foil-faced polyisocyanurate at R-6.5/inch.

Whole-wall R-value: Two-dimensional heat flow analysis with thermal bridging effects and average framing factors (16%) shows increases the R-value of the assembly and improvements to the efficiency of the fiberglass batt in the stud space by decreasing the thermal bridging effects. Advanced framing walls with 1” and 4” of XPS insulated sheathing have whole wall R-values of R-20 and R-34 respectively.[1]

Air Leakage Control: Fiberglass, blown and sprayed cellulose are air permeable materials used in the stud space of the wall allowing possible air paths between the interior and exterior as well as convective looping in the insulation. Densepack cellulose has less air permeance but

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does not control air leakage. Insulating sheathing (EPS, XPS and foil-faced polyisocyanurate board foam) products are air impermeable. When joints between panels of insulation and the insulation and framing are properly sealed with tape, mastic, caulk, etc., an effective air barrier system can be created at the exterior sheathing.

Typical Insulation Products: Fiberglass batt, blown cellulose, sprayed cellulose, and sprayed fiberglass are typically used to insulate the stud space. Expanded polystyrene (EPS), extruded polystyrene (XPS) and foil-faced polyisocyanurate (PIC) board foam are used as the exterior insulating sheathing. Spray foam is used at the rim joist to control air leaks.

DURABILITY

Rain Control: Rain leakage into the enclosure is the leading cause of premature building enclosure failure. Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). It is possible to use insulated sheathing as the drainage plane if all the intersections, windows, doors and other penetrations are connected to the surface of the insulated sheathing in a watertight manner, and the seams of the insulation are taped or flashed to avoid water penetration.[2]

Air Leakage Control: Air leakage condensation is the second largest cause of premature building enclosure failure with this type of wall construction. It is very important to control air leakage to minimize air leakage condensation durability issues. Using insulating sheathing decreases the risk of air leakage condensation by increasing the temperature of the condensation plane, but condensation is still possible with insulated sheathing in cold climates. An air barrier is required in this wall system to ensure that through-wall air leakage is eliminated (ideally) or at least minimized.[3] An air barrier should be stiff and strong enough to resist wind forces, continuous, durable, and air impermeable.[4]

Vapor Control: Fiberglass or cellulose in the stud cavity are vapor permeable, while EPS, XPS and PIR are moderately permeable, moderately impermeable and completely impermeable respectively.

Insulated sheathing reduces the risk of wintertime condensation by increasing the temperature of the condensation plane, and reduces the risk of summer time inward vapor drives by slowing the vapor movement into the enclosure from storage claddings such as masonry or stucco. The level of vapor control in insulated sheathing walls is determined in the IRC and should be consulted as installing the incorrect vapor control layer or installing the vapor control layer in the incorrect location can lead to building enclosure failure.[5]

Drying: Insulating sheathing limits the drying to the exterior, and the wall must be able to dry to the interior. Poly vapor barriers are typically avoided so that this drying can occur. The minimum level of vapor control on the interior surface is determined by the IRC. Installing vapor control on both sides of the enclosure will seal any moisture into the stud space, resulting in low drying potential, and possibly resulting in moisture-related durability risks. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before close in. Cellulose is often sprayed in damp, and manufacturers recommend drying before close in and moisture content limits.

Durability Summary: The primary durability risks associated with these wall assemblies involve moisture damage related to rain water penetration. Condensation (most likely the result of air leakage, but also potentially the result of vapor diffusion) is decreased with insulated sheathing but may still occur, although the insulating sheathing is less susceptible to moisture related risks than structural OSB sheathing.

BUILDABILITY

Exterior insulation up to 1.5” requires minimal changes to standard enclosure construction practices. Exterior insulation in excess of 1.5” requires changes to window and wall construction and detailing which requires training and monitoring during the initial implementation.

Cladding can be easily attached to the studs directly through 1” of insulated sheathing. Thicker levels of insulation (>2”) require strapping or furring strips)anchored to the framing with long fasteners. Some cladding manufacturers allow their cladding to be fastened to the strapping directly.

COST

Advanced framing wall construction decreases the cost required for framing. There is a slight increase in cost for the insulating sheathing to replace most of the structural wood sheathing, but there are measureable cost benefits of saving energy, as well as improvements to comfort, which is difficult to quantify.

MATERIAL USE

If advanced framing is applied correctly (single top plates, correctly sized headers, two stud corners, etc.) the redundant wood framing from standard construction is removed, and the amount of framing will decrease. Using insulated sheathing instead of structural wood sheathing may require using structural panels or bracing in some locations.

TOTAL SCORE

Advanced framing with insulating sheathing is a logical choice as the minimum level of construction in most climates considering the more demanding insulation levels required for new construction in many climates. Using insulated sheathing can decrease the potential for both wintertime condensation, and summer inward vapor drives, and help mitigate issues caused by poor construction practices.

REFERENCES

1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis*. Retrieved from buildingscience.com.

2 Lstiburek, J. W. (2006). *Water Management Guide*. Westford: Building Science Press Inc.

3 Lstiburek, J. (2008, 08 20). *BSD-104: Understanding Air Barriers*. Retrieved from buildingscience.com.

4 Straube, J. (2009, 04 22). *BSD-014 Air Flow Control in Buildings*. Retrieved from buildingscience.com.

5 Lstiburek, J. (2008, 10 17). *BSD-106 Understanding Vapor Barriers*. Retrieved from buildingscience.com.

INTERIOR STRAPPING WALL CONSTRUCTION

INTERIOR STRAPPING WALL CONSTRUCTION DETAILS (*Wall 3*)[1]

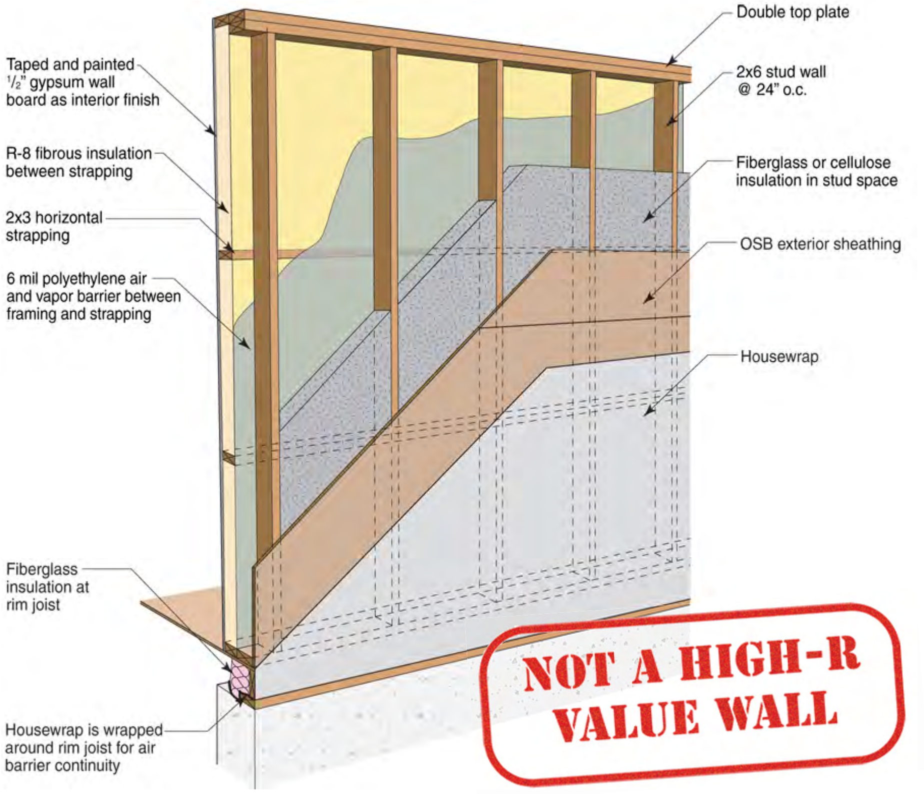
- 2x6 advanced framing
- 2x3 horizontal strapping
- Fibrous insulation between strapping
- 6 mil polyethylene air & vapor barrier
- Fiberglass or cellulose cavity insulation in stud space
- OSB exterior sheathing
- Housewrap

SCORING: HOW IT RATES

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	3
Durability	3
Buildability	3
Cost	4
Material Use	3
Total	**16**

Interior strapping in wall construction does increase the R-value over standard construction, but does not address thermal bridges at the rim joist, top plate or bottom plate. The minimal increases in whole wall R-value over standard construction may not be justified by the increased materials, cost and complexity of this wall system.



NOT A HIGH-R VALUE WALL

INTRODUCTION

This two page summary briefly summarizes interior strapping wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

THERMAL CONTROL

Installed Insulation R-value: There is a range of installed insulation R-values in commercially available fiberglass batts. The installed insulation R-value for 2x6 fiberglass batt ranges between R-19 and R-22 for the framed portion of this wall, the strapped interior section is typically R-8 fiberglass insulation, and for 2x6 the range is between R-19 and R-22. When blown or sprayed cellulose insulation is used, the R-value is typically R-20 for 2x6 walls.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors, this wall construction achieves a whole wall R-value of approximately R-21.5.[1] Adding horizontal strapping to the interior surface helps minimize the thermal bridges through the stud wall, but there are still thermal bridges at the top plate, bottom plate and rim joist that decrease the installed insulation R-value.

Air Leakage Control: Fiberglass batt, and both blown and sprayed cellulose are air permeable materials allowing possible air paths between the interior and exterior as well as convective looping in the insulation. Although densepack cellulose has less air permeance it does not control air leakage.[2]

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Typical Insulation Products: Fiberglass batt, blown fiberglass, blown cellulose, sprayed cellulose.

DURABILITY

Rain Control: Rain leakage into the enclosure is the leading cause of premature building enclosure failure. Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). Intersections, windows, doors and other penetrations must be drained and/or detailed to prevent the penetration of rain water beyond the drainage plane.[3]

Air Leakage Control: Air leakage condensation is the second largest cause of premature building enclosure failure with this type of wall construction. It is very important to control air leakage to minimize air leakage condensation durability issues. An air barrier is required in this wall system to ensure that through-wall air leakage is eliminated (ideally) or at least minimized. An air barrier should be stiff and strong enough to resist wind forces, continuous, durable, and air impermeable.[4]

Often the polyethylene vapor barrier will be constructed as the air barrier even though it is not stiff or strong enough to resist wind forces. If the polyethylene is installed between the stud wall and the interior strapping, there will be fewer holes made for electrical and plumbing services, and can be made more airtight than in standard construction.

Air need not leak straight through an assembly to cause moisture problems; it can also leak from the inside, through the wall, and back to the inside; or it can leak from the outside, through the wall, and back to the outside. Condensation within the studspace is possible if this type of airflow occurs, depending on the weather conditions. Hence, wall designs should control airflow into the studspace.[5]

Vapor Control: Fiberglass and cellulose are highly vapor permeable materials, so a separate vapor control strategy must be employed to ensure that vapor diffusion does not result in condensation on, or damaging moisture accumulation in, moisture sensitive materials. The permeance and location of vapor control is dependent on the climate zone. Installing the vapor control layer in the incorrect location can lead to building enclosure failure.[6] The IRC building code should be consulted.

Drying: Cellulose and fiberglass insulation allow drying to occur relatively easily, so drying is controlled by other more vapor impermeable enclosure components such as the vapor barrier and OSB sheathing. Installing vapor control on both sides will seal any moisture into the stud space, resulting in low drying potential, and possibly resulting in moisture-related durability risks. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before close in. Cellulose is often sprayed in damp, and manufacturers recommend drying before close in and moisture content limits. Because of the polyethylene vapor barrier required in many climates, and relatively vapor impermeable OSB sheathing, drying could be slow if built-in moisture is present.

Durability Summary: The primary durability risks associated with these wall assemblies involve moisture damage related to rain water penetration or condensation (most likely the result of air leakage, but also potentially the result of vapor diffusion).

Cellulose insulated walls are slightly more durable because cellulose insulation is capable of storing and redistributing small amounts of moisture. Cellulose insulation is typically treated with borates which have been shown to protect itself and neighbouring wood material from mold growth and decay. Cellulose insulation also has decreased flame spread potential relative to other insulation materials.

BUILDABILITY

This type of construction is a modification of standard construction, but is not common, and construction trades may have difficulty with some of the detailing. All window and door penetrations will require plywood box frames to pass through both the interior strapping and exterior framing. If the poly is installed properly between the stud wall and interior strapping, there is decreased risk of moisture related durability issues often caused by penetrations such as electrical and plumbing.

COST

There will be increased costs over standard construction due to an increase in framing material, and complexity for construction, since this is not a standard construction technique. Costs vary tremendously from region to region.

MATERIAL USE

Using sdvanced framing will reduce redundant wood framing in the wall, but overall framing still increases for the interior strapping. Cellulose has a significantly lower embodied energy than fiberglass or rockwool.

TOTAL SCORE

Interior strapping in wall construction does increase the R-value over standard construction, but does not address thermal bridges at the rim joist, top plate or bottom plate. The minimal increases in whole wall R-value over standard construction may not be justified by the increased materials, cost and complexity of this wall system. Many higher performance designs for wall construction exist.

REFERENCES

1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis*. Retrieved from buildingscience.com.

2 FINAS. *Determination of the air permeability, the short term water absorption by partial immersion, and the water vapour permeatbility of the blown losse-fill cellulose thermal insulation.* Test Report VTT-S-039880-08, VTT Technical Research Centre of Finland, 2008.

3 Lstiburek, J. W. (2006). *Water Management Guide.* Westford: Building Science Press Inc.

4 Lstiburek, J. (2008, 08 20). *BSD-104: Understanding Air Barriers*. Retrieved from buildingscience.com.

5 Straube, J. (2009, 04 22). *BSD-014 Air Flow Control in Buildings.* Retrieved from buildingscience.com.

6 Lstiburek, J. (2008, 10 17). *BSD-106 Understanding Vapor Barriers.* Retrieved from buildingscience.com.

DOUBLE STUD WALL CONSTRUCTION

DOUBLE STUD WALL CONSTRUCTION DETAILS (*Wall 4*)[1]

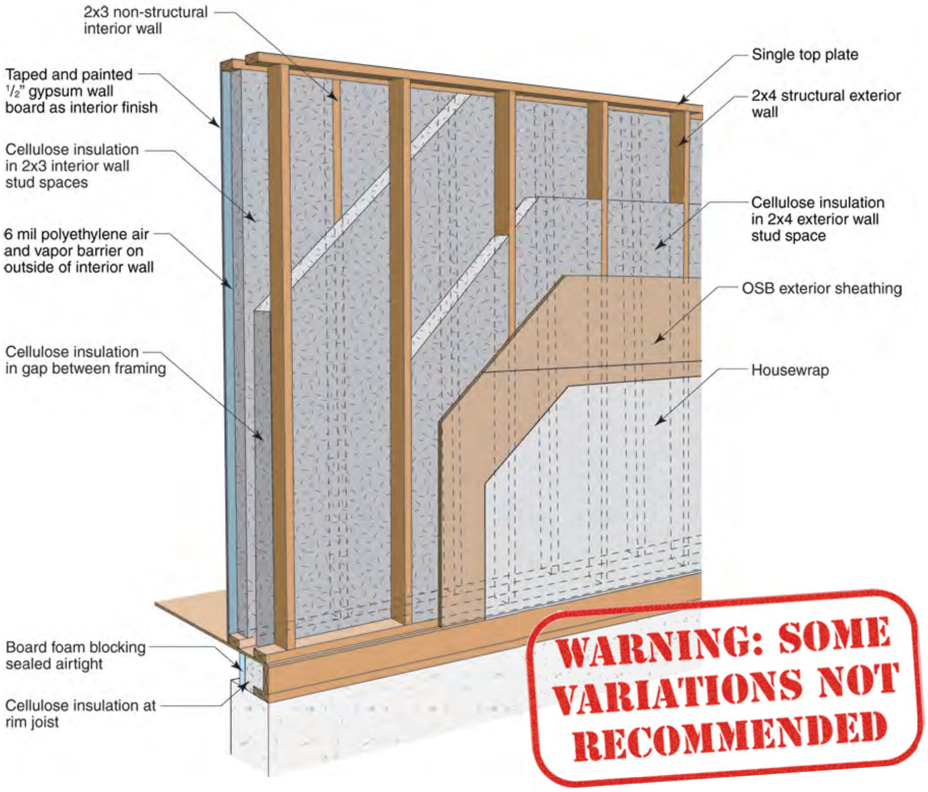
- 2x4 structural exterior wall with cellulose cavity insulation
- 2x3 non-structural interior wall with cellulose cavity insulation
- 6 mil polyethylene vapor barrier
- Cellulose insulation in gap
- OSB exterior sheathing
- Housewrap

SCORING: HOW IT RATES

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	4
Durability	3
Buildability	3
Cost	3
Material Use	2
Total	**15**

This is a highly insulated wall system that will work in extreme climates, but still has significant risks to moisture related durability issues and premature enclosure failure. This wall system decreases the interior floor area of a fixed floorplan and may experience thermal and moisture issues at the rim joist unless it's detailed correctly.



INTRODUCTION

This two page summary briefly summarizes double stud wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

THERMAL CONTROL

Installed Insulation R-value: The thickness of double stud walls varies, however, walls with overall insulation thickness of 9.5” appear to be most common. The insulation can be of either fiberglass batt (R-3.5/inch) or blown cellulose insulation (R-3.7/inch) resulting in overall installed insulation R-values of R-33 and 35 respectively.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors demonstrates that adding an interior framed wall with a insulation filled gap greatly reduces the thermal breaks through the stud wall and can increases the Clear wall R-value to R-34 depending on the thickness of insulation. However, because of the significant thermal losses at the rim joist, the whole-wall R-value is closer to R-30.[1]

Air Leakage Control: Fiberglass batt, and both blown and sprayed cellulose are air permeable materials allowing possible air paths between the interior and exterior as well as convective looping in the insulation. Although densepack cellulose has less air permeance it does not control air leakage.

Typical Insulation Products: Fiberglass batt, or blown cellulose; blown fiberglass is another option, but not too common.

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DURABILITY

Rain Control: Rain leakage into the enclosure is the leading cause of premature building enclosure failure. Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). Intersections, windows, doors and other penetrations must be drained and/or detailed to prevent the penetration of rain water beyond the drainage plane.[2]

Air Leakage Control: Air leakage condensation is the second largest cause of premature building enclosure failure with this type of wall construction. It is very important to control air leakage to minimize air leakage condensation durability issues. An air barrier is required in this wall system to ensure that through-wall air leakage is eliminated (ideally) or at least minimized. An air barrier should be stiff and strong enough to resist wind forces, continuous, durable, and air impermeable.[3]

Air need not leak straight through an assembly to cause moisture problems; it can also leak from the inside, through the wall, and back to the inside; or it can leak from the outside, through the wall, and back to the outside. Condensation within the stud space is possible if this type of airflow occurs, depending on the weather conditions. Hence, wall designs should control airflow into the studspace.[4]

Vapor Control: Fiberglass and cellulose are highly vapor permeable materials, so a separate vapor control strategy must be employed to ensure that vapor diffusion does not result in condensation on, or damaging moisture accumulation in, moisture sensitive materials. The permeance and location of vapor control is dependent on the climate zone. Installing the vapor control layer in the incorrect location can lead to building enclosure failure.[5] The IRC building code should be consulted.

Drying: Cellulose and fiberglass insulation allow drying to occur relatively easily, so drying is controlled by other more vapor impermeable enclosure components such as the vapor barrier and OSB sheathing. Installing vapor control on both sides will seal any moisture into the stud space, resulting in low drying potential, and possibly resulting in moisture-related durability risks. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before close in. Cellulose is often sprayed in damp, and manufacturers recommend drying before close in and moisture content limits. Because of the polyethylene vapor barrier required in many climates, and relatively vapor impermeable OSB sheathing, drying could be slow if built-in moisture is present.

Durability Summary: The primary durability risks associated with these wall assemblies involve moisture damage related to rain water penetration or condensation (most likely the result of air leakage, but also potentially the result of vapor diffusion).

Cellulose insulated walls are slightly more durable because cellulose insulation is capable of storing and redistributing small amounts of moisture. Cellulose insulation is typically treated with borates that have been shown to protect itself and neighboring wood material from mold growth and decay. Cellulose insulation also has decreased flame spread potential relative to other insulation materials.

BUILDABILITY

This type of wall construction is more typically found in party walls of multi unit residential because of its superior sound suppression and fire resistance. This wall construction is not very complicated, but does require custom frames around penetrations such as windows and doors. If polyethylene is used as the air barrier, it is critical to seal it perfectly to avoid wintertime air leakage condensation against the sheathing. This construction generally does not address the thermal losses or air leakage at the rim joist. Because the second framed wall is constructed on the interior of the structural wall, the interior floor space is decreased. This wall is quite susceptible to construction deficiencies in the air and vapor barrier.

COST

The cost of this wall is higher than standard construction, but with a significant increase in thermal performance. This wall construction requires more time and materials for construction.

MATERIAL USE

The wall framing material is increased significantly by building a secondary interior wall. This wall is often not structural, which means the stud spacing can be wider, and smaller framing lumber can be used provided an even surface is constructed to install the gypsum board. There is also an increase in insulation, but the embodied energy of cellulose is relatively small, and results in large increases in R-value.

TOTAL SCORE

This is a highly insulated wall system that will work in extreme climates as part of a high-R enclosure, if the air barrier details are perfect, and the thermal losses at the rim joist are minimized. This construction technique does cost the occupant interior floor space with the thick insulated wall. There is significant risk to moisture related durability issues from wintertime condensation, however, the large amount of cellulose in this wall system will be able to buffer some moisture in the enclosure as long as the safe moisture capacity of the cellulose is not exceeded.

REFERENCES

1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis.* Retrieved from buildingscience.com.

2 Lstiburek, J. W. (2006). *Water Management Guide.* Westford: Building Science Press Inc.

3 Lstiburek, J. (2008, 08 20). *BSD-104: Understanding Air Barriers*. Retrieved from buildingscience.com.

4 Straube, J. (2009, 04 22). *BSD-014 Air Flow Control in Buildings.* Retrieved from buildingscience.com.

5 Lstiburek, J. (2008, 10 17). *BSD-106 Understanding Vapor Barriers.* Retrieved from buildingscience.com.

TRUSS WALL CONSTRUCTION

TRUSS WALL CONSTRUCTION DETAILS *(Wall 5)*[1]

- 2x4 interior framing member
- 2x3 exterior framing member
- 6 mil polyethylene vapor barrier to interior
- Cellulose cavity insulation
- OSB exterior sheathing
- Housewrap

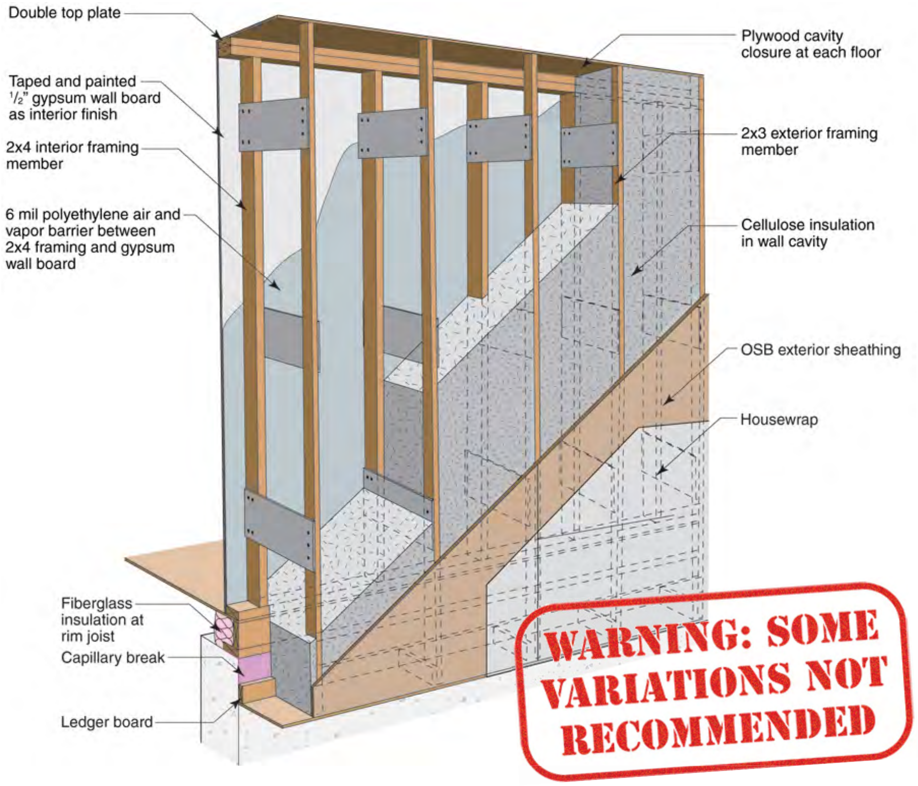

www.builditsolar.com/Projects/SolarHomes/LarsenTruss/LarsenTrussPics.htm

SCORING: HOW IT RATES

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	4
Durability	3
Buildability	2
Cost	3
Material Use	2
Total	**14**

The truss wall system can achieve a very high whole wall R-value with minimal thermal bridging and would be perform well in extreme climates provided the air barrier was detailed perfectly minimizing the high risk of air leakage condensation durability issues. It is time consuming to construct and susceptible to premature enclosure failures resulting from poor construction and detailing.



WARNING: SOME VARIATIONS NOT RECOMMENDED

INTRODUCTION

This two page summary briefly summarizes the truss wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

THERMAL CONTROL

Installed Insulation R-value: The thickness of truss walls varies greatly and because it is not a common wall construction, there does not appear to be a established standard construction insulation thickness. These walls are typically insulated with blown cellulose insulation (R-3.7/inch) or fiberglass batt insulation (R-3.5/inch), and overall installed insulation R-values in excess of 50 are possible.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors shows that adding the insulation to the exterior of the framing addresses the thermal bridge at the rim joist, studs and top plate. There is a large range of R-values possible with this type of construction, but 12" of cellulose provides a whole-wall R-value of approximately R-36.[1]

Air Leakage Control: Cellulose insulation is an air permeable material allowing possible air paths between the interior and exterior as well as convective looping in the insulation. Although densepack cellulose has less air permeance than some other air permeable insulations, it does not control air leakage.

Typical Insulation Products: Blown cellulose.

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DURABILITY

Rain Control: Rain leakage into the enclosure is the leading cause of premature building enclosure failure. Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). Intersections, windows, doors and other penetrations must be drained and/or detailed to prevent the penetration of rainwater beyond the drainage plane.[2]

Air Leakage Control: Air leakage condensation is the second largest cause of premature building enclosure failure with this type of wall construction. It is very important to control air leakage to minimize air leakage condensation durability issues. An air barrier is required in this wall system to ensure that through-wall air leakage is eliminated (ideally) or at least minimized. An air barrier should be stiff and strong enough to resist wind forces, continuous, durable, and air impermeable.[3]

Air need not leak straight through an assembly to cause moisture problems; it can also leak from the inside, through the wall, and back to the inside; or it can leak from the outside, through the wall, and back to the outside. Condensation within the stud space is possible if this type of airflow occurs, depending on the weather conditions. Hence, wall designs should control airflow into the stud space.[4]

The truss wall has a much higher R-value that standard construction, and the exterior sheathing is well insulated from the interior conditions. This wall system has greater risk for severe air leakage condensation since the sheathing is considerably colder than standard construction.

Vapor Control: Fiberglass and cellulose are highly vapor permeable materials, so a separate vapor control strategy must be employed to ensure that vapor diffusion does not result in condensation on, or damaging moisture accumulation in, moisture sensitive materials. The permeance and location of vapor control is dependent on the climate zone. Installing the vapor control layer in the incorrect location can lead to building enclosure failure.[5] The IRC building code should be consulted.

There is a higher risk of vapor diffusion condensation if the vapor barrier is not detailed correctly due to the lower wintertime temperature of the sheathing in the truss wall relative to standard construction.

Drying: Cellulose and fiberglass insulation allow drying to occur relatively easily, so drying is controlled by other more vapor impermeable enclosure components such as the vapor barrier and OSB sheathing. Installing vapor control on both sides will seal any moisture into the stud space, resulting in low drying potential, and possibly resulting in moisture-related durability risks. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before close in. Because of the polyethylene vapor barrier required in many climates, and relatively vapor impermeable OSB sheathing, drying could be slow if built-in moisture is present.

Durability Summary: The primary durability risks associated with these wall assemblies involve moisture damage related to rain water penetration or condensation (most likely the result of air leakage, but also potentially the result of vapor diffusion).

Cellulose insulated walls are slightly more durable than fiberglass insulated walls because cellulose insulation is capable of storing and redistributing small amounts of moisture. Cellulose insulation is typically treated with borates that have been shown to protect itself and neighboring wood material from mold growth and decay. Cellulose insulation also has decreased flame spread potential relative to other insulation materials.

BUILDABILITY

This wall construction is not a standard construction practice. The gussets used to space the exterior framed wall off the structure are time consuming to construct, and require tight tolerances to ensure smooth sheathing and cladding. This wall is highly susceptible to construction workmanship and requires a perfect air barrier in cold climates since the potential for wintertime condensation is high. Penetrations such as windows and doors require plywood boxes be installed through the wall.

COST

This construction requires increases in both time and materials for the enclosure. The wall framing material is essentially doubled, and constructing the exterior wall with gussets is time consuming. The increased thermal performance and decreased thermal bridges may be worth the extra time and money in specific cases.

MATERIAL USE

There is a significant increase to framing since every framing member in the structural wall has a corresponding exterior framing member attached with wood gussets.

TOTAL SCORE

The truss wall system can achieve a very high whole wall R-value with minimal thermal bridging and would be perform well in extreme climates provided the air barrier was detailed perfectly minimizing air leakage condensation durability risks. It is possible to reduce the risk of condensation by using a combination of the truss wall in combination with an air impermeable insulation. One advantage of the truss wall is that it is used in both new construction and retrofit situations to decrease energy consumption, and improve occupant comfort. The truss wall allows the extra insulation to be placed on the exterior of the structural wall that does not affect the interior space, unlike the double stud wall.

REFERENCES

1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis*. Retrieved from buildingscience.com.

2 Lstiburek, J. W. (2006). *Water Management Guide.* Westford: Building Science Press Inc.

3 Lstiburek, J. (2008, 08 20). *BSD-104: Understanding Air Barriers*. Retrieved from buildingscience.com.

4 Straube, J. (2009, 04 22). *BSD-014 Air Flow Control in Buildings.* Retrieved from buildingscience.com.

5 Lstiburek, J. (2008, 10 17). *BSD-106 Understanding Vapor Barriers.* Retrieved from buildingscience.com.

SIPs WALL CONSTRUCTION

SIPs WALL CONSTRUCTION DETAILS *(Wall 6)*[1]

- OSB interior and exterior panels
- EPS insulation core typical
- Housewrap

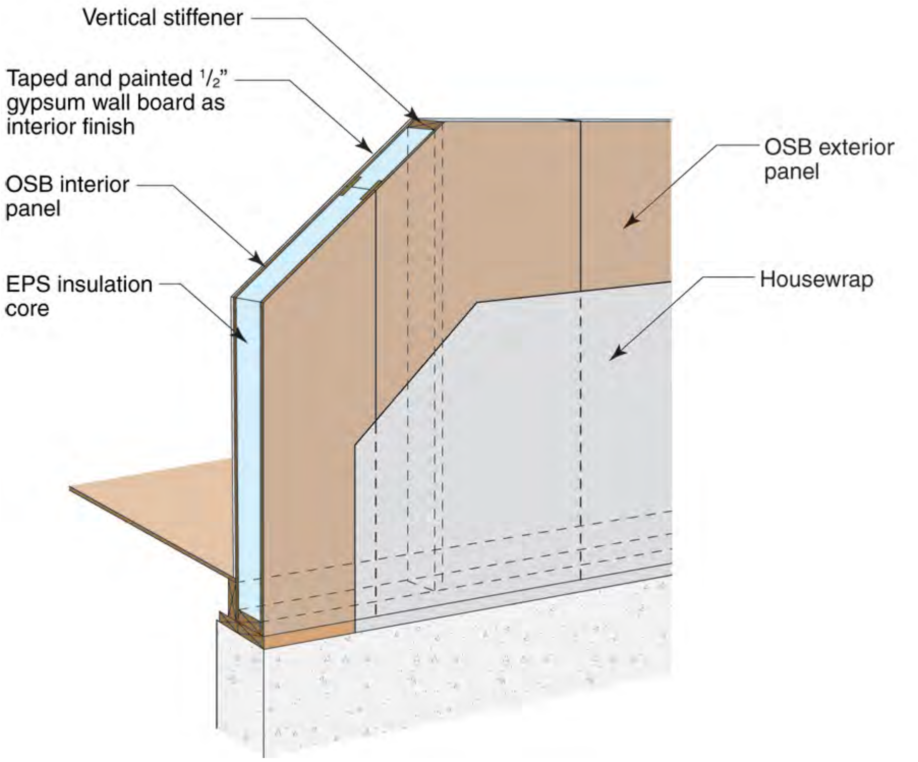

Photo: SIPA

SCORING: HOW IT RATES

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	4
Durability	4
Buildability	3
Cost	3
Material Use	3
Total	**17**

The typical SIPs panels are not constructed with enough insulation to be considered high-R assemblies in heating climates. SIPs installation requires specialized training but is quicker and easier than wood framed construction following training. Historical moisture related durability issues with SIPs have been solved with a better understanding of building science, and airtightness details.



INTRODUCTION

This two page summary briefly summarizes SIPs wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

THERMAL CONTROL

Installed Insulation R-value: Structural Insulated Panels (SIPs) are typically constructed using OSB panels adhered to both sides of an expanded polystyrene (EPS) foam insulation core. The most common SIP insulation thicknesses are 3.5" and 5.5" and are equivalent to R-14 and R-22. It is possible, although not as common, to use different insulation types, and thicker panels to achieve high R wall values.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors, the clear wall R-value with the OSB layers, drywall, cladding, and surface films often has an R-value higher than the installed insulation R-value because of fewer thermal bridges in the wall system. The whole-wall R-value depends on thermal bridging through vertical stiffeners, top and bottom plate, as well as the wood bucks for windows and doors.[1]

Air Leakage Control: Both OSB and EPS foam are air impermeable so there is no air leakage through the centre of the SIPS panels; however it is important to address the air tightness of joints between the panels as well as interfaces with other structural elements (i.e. foundation walls or roofs) and penetrations such as windows, doors and services.[2] It is relatively easy to achieve a high level of airtightness on a SIPs enclosure.

Typical Insulation Products: EPS foam is the most common, but SIPs have also been constructed with XPS and polyisocyanurate foam cores.

DURABILITY

Rain Control: Rain leakage into the enclosure is the leading cause of premature building enclosure failure. Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). Intersections, windows, doors and other penetrations must be drained and/or detailed to prevent the penetration of rainwater beyond the drainage plane.[3]

Air Leakage Control: There is no air leakage through the centre of the panel but there is risk of air leakage at the joints between panels if not detailed correctly. Historically, there were design detail issues with the air tightness of the joints between the panels allowing warm moist interior air to condense on the exterior cold OSB layer.[4] Standards of SIPs construction have improved and following the recommended construction guidelines mitigates nearly all of the risk of moisture related durability issues from air leakage.

Vapor Control: A SIPs panel controls vapor well. There is very minimal risk to vapor related moisture damage in SIPs construction.

Drying: Water on either the interior or exterior of the SIPs will dry easily to the interior or exterior in most climates. In very humid or wet climates with minimal drying potential, the OSB may remain wet for an extended period and could result in moisture related durability issues. If moisture accumulates between the interior and exterior OSB faces, it will be difficult to dry.

Built- in Moisture: Water on the surfaces of the panel during construction should dry easily following completion, any water trapped in the panel joints will dry much more slowly.

Durability Summary: If the SIPs are installed according to best practice, with proper air seals and flashed penetrations, the system is very durable in all climates.

BUILDABILITY

Using SIPs is relatively easy and quick once the training has been completed. Panels are ordered and shipped to site and assembled with a crane. More specific info can be found at www.sips.org. Generally, most of the services are run on interior partition walls, but there are methods of installing services on the interior of a SIPs panel. A SIPs house can be assembled and dried in more quickly than a wood framed house once the panels are on site.

COST

SIPs panels range considerably in price depending on the project details and the required thickness of wall panels. It is more expensive than standard construction and can generally only be used on simple geometries.

MATERIAL USE

SIPs panels require minimal framing lumber but an increase in structural sheathing panels.

TOTAL SCORE

SIPs wall panels are generally not constructed with enough insulation to be considered a high R enclosure system on its own in heating climates. It is possible to use thicker insulation panels or to combine SIPs with another insulation strategy in cold climates. It is relatively quick and easy to build with SIPs following training, and refined standard practice techniques have removed nearly all of the historical risks of air leakage condensation. The cost and simple geometries of SIPs houses are two of the main reasons why this technology is not used more often.

REFERENCES

1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis*. Retrieved from buildingscience.com.

2 Lstiburek, J. W. (2008). *Builder's Guide to Structural Insulated Panels (SIPs) for all Climates*. Westford: Building Science Press Inc.

3 Lstiburek, J. W. (2006). *Water Management Guide*. Westford: Building Science Press Inc.

4 SIPA (n.d.). *Report on the Juneau, Alaska Roof Issue*. Retrieved May 2009 from Structural Insulated panel Association: http://www.sips.org/content/technical/index.cfm?PageId=161.

ICF WALL CONSTRUCTION

ICF WALL CONSTRUCTION DETAILS (*Wall 7*)[1]

- ICF inner and outer faces; typically EPS or cement wood fiber
- Cast-in-place concrete core

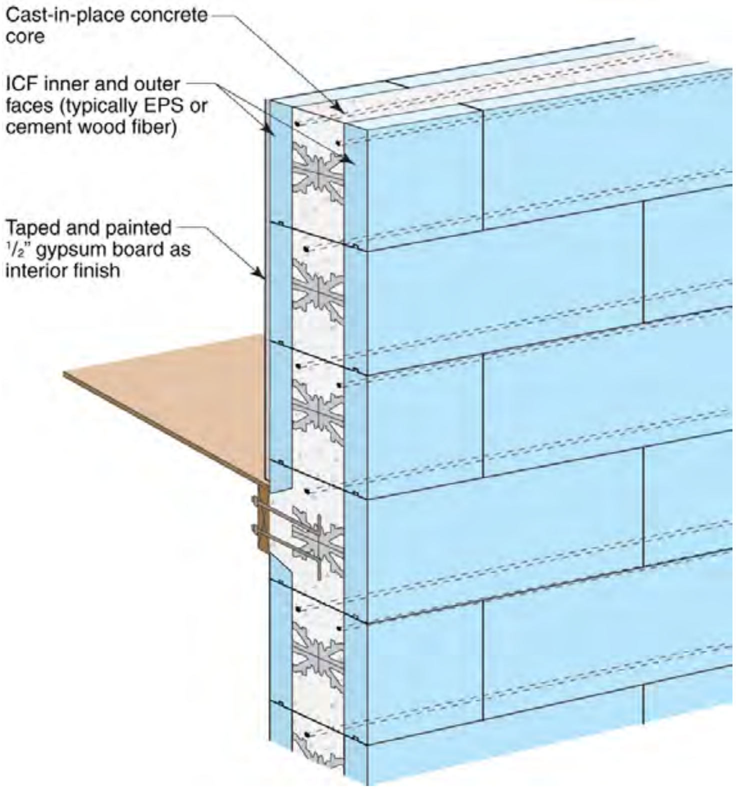
www.silverspurconstruction.com/icfphotogallery.htm

SCORING: HOW IT RATES

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	4
Durability	5
Buildability	4
Cost	2
Material Use	3
Total	**18**

ICF construction is a very durable construction strategy provided the rainwater management details are constructed correctly. Generally, ICF construction alone cannot achieve a high R-value and will require other insulation strategies in combination for cold climates, which is commonly done in practice.



INTRODUCTION

This two page summary briefly summarizes ICF wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

THERMAL CONTROL

Installed Insulation R-value: R-values of Insulated Concrete Form construction vary considerably with the type, and thickness of form. The most common ICF form is constructed of EPS insulation in the range of 2" thick on the interior and exterior. Other ICF materials include cementitious wood based forms, some of which are constructed with an extra layer of insulation (e.g. Rockwool) in the form.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors shows that there are few thermal breaks from the interior to the exterior on an ICF wall. An 8" foam ICF form with 4" of EPS has a whole-wall R-value of approximately R-16.[1]

Air Leakage Control: Many ICF construction strategies form air barriers in the field of the wall. Air leakage will occur at penetrations through the wall if they are not detailed correctly.[2]

Typical Insulation Products: EPS foam insulation forms, or cementitious wood based forms.

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DURABILITY

Rain Control: Rain leakage into the enclosure is the leading cause of premature building enclosure failure. Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). Intersections, windows, doors and other penetrations must be drained and/or detailed to prevent the penetration of rainwater beyond the drainage plane.[3] There is little to no moisture buffering capacity of and ICF wall so even a minimal amount of water, undetectable in standard construction, will have durability issues in ICF construction.

Air Leakage Control: ICF construction strategies form air barriers in the field of the wall. All through wall penetrations require air sealing details.[4]

Vapor Control: There are no significant risks to moisture durability from vapor drive in ICF construction.

Drying: ICFs will dry both to the interior and exterior depending on climate and time of year.

Built- in Moisture: Since ICFs are poured concrete walls in forms with relatively low vapor permeance surfaces, the concrete will dry very slowly, and should be allowed to dry to both sides following the completion of the wall system.

Durability Summary: There are very few risks associated with air leakage and vapor condensation of ICF construction. The most common durability issue is from rainwater leakage into the enclosure. ICF forms typically do not have any buffering capacity of leakage, so even a small leak, that may occur undetected with no durability risks in a wood framed wall, may affect the interior of and ICF building. The ICF wall itself is not susceptible to moisture related issues but interior finishes are generally sensitive to moisture.

BUILDABILITY

Generally, building with ICFs is quite easy and straightforward following initial training. Care should be taken to line the surfaces of the forms up to ensure even drywall if it is directly attached. Problems in the past have occurred with air pockets in the forms, as well as bulging and breaking of forms due to the hydrostatic pressure of concrete. These problems are well documented and there are strategies to address these issues.

COST

The cost of ICF construction varies considerably depending on the type of forms chosen, geometry of construction and location. ICF construction is more expensive that standard construction and is usually prohibitively expensive in residential housing.

MATERIAL USE

ICF walls use less concrete than an alternative wall built entirely with concrete, and concrete is very high in embodied energy. The wood framing can be minimized by attaching the drywall directly to the ICF block on the interior.

TOTAL SCORE

ICF construction is a very durable construction strategy provided the rainwater management details are constructed correctly. Generally, ICF construction alone cannot achieve a high R-value and will require other insulation strategies in combination for cold climates, which is commonly done in practice. ICF is generally only used in multifamily and mid rise buildings, and not in residential housing.

REFERENCES

1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis.* Retrieved from buildingscience.com.

2 Straube, J. (2009, 04 22). *BSD-014 Air Flow Control in Buildings.* Retrieved from buildingscience.com.

3 Lstiburek, J. W. (2006). *Water Management Guide.* Westford: Building Science Press Inc.

4 Lstiburek, J. (2008, 08 20). *BSD-104: Understanding Air Barriers.* Retrieved from buildingscience.com.

SPRAY FOAM WALL CONSTRUCTION

SPRAY FOAM WALL CONSTRUCTION DETAILS *(Wall 8a and 8b)*[1]

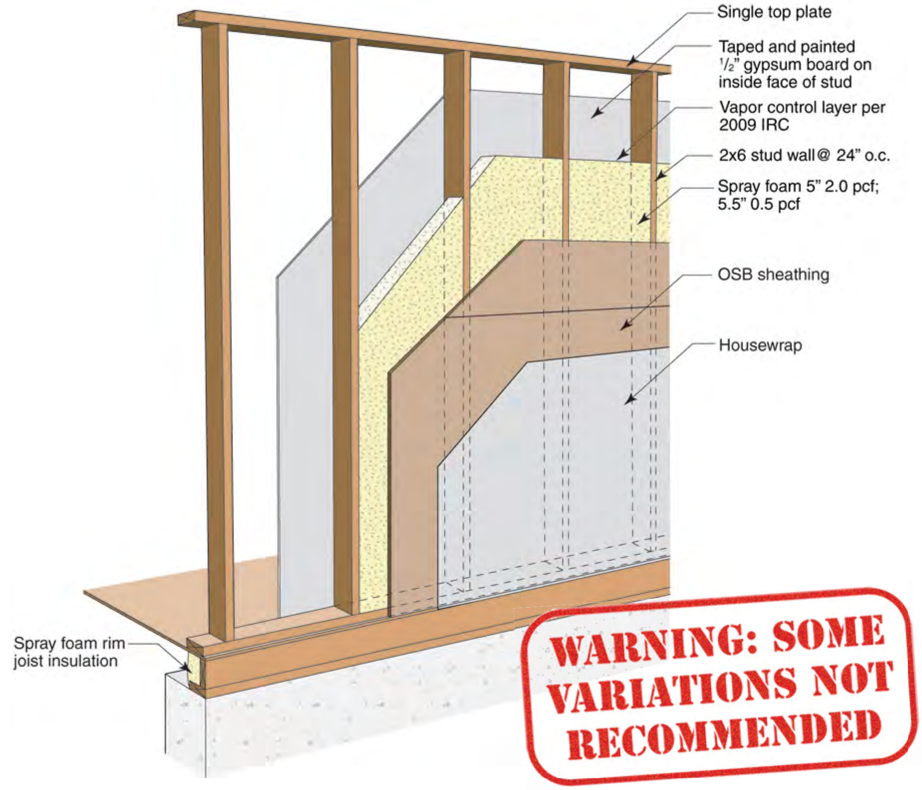
- 2x6 wood frame wall at 24" o.c.
- Spray foam cavity insulation
- OSB sheathing
- Housewrap

SCORING: HOW IT RATES

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	5
Durability	5
Buildability	4
Cost	2
Material Use	4
Total	**20**

Both low and high density foam increase the air tightness of the enclosure and reduce the risks to air leakage related durability risks. The R-values of both the low and high density spray foam are significantly reduced by thermal bridging of the wall framing and rim joist, demonstrating the value of insulated sheathing.



WARNING: SOME VARIATIONS NOT RECOMMENDED

INTRODUCTION

This two page summary briefly summarizes spray foam wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

THERMAL CONTROL

Installed Insulation R-value: The installed insulation R-value depends somewhat on the company and but generally speaking, high density foam (2.0 pcf) ranges between R-5.5 and R-6.5 per inch for the aged R-value, and low density foam (0.5pcf) has an R-value of approximately R-3.6/inch. Since high density foam is generally installed short of the cavity to avoid trimming, the installed insulation R-value is approximately R-30 (using R-6/inch). Low density is generally installed deliberately overflowing the cavity and trimmed off resulting in an R-value of approximately R-21.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors, it is clear that the thermal bridging through the framing, bottom plate, and top plate reduces the effectiveness of the spray foam insulation.[1] The R-value of the high density spray foam wall decreases from an installed R-value of R-30 to approximately R-20, a decrease of R-10 because of thermal bridging. The low density spray foam wall decreases from an installed insulation R-value of 21 to a whole wall R-value of approximately R-16.

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Air Leakage Control: Both low density and high density foam form an air barrier decreasing thermal losses through air leakage. Air leakage is still common under the bottom plate and at the rim joist if these areas are not detailed correctly.[2]

Typical Insulation Products: Low density 0.5 pcf foam, or high density 2.0 pcf foam.

DURABILITY

Rain Control: Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). Intersections, windows, doors and other penetrations must be detailed to prevent the penetration of rain water.[3]

Air Leakage Control: Air leakage is significantly minimized by installing spray foam insulation in the stud space since both low density and high density spray foam act as an air barrier. This increases the durability of the wall system considerably over standard construction.[4]

Vapor Control: High density (2.0 pcf) foam forms a vapor control layer reducing vapor movement through the enclosure, minimizing the potential for wintertime vapor condensation and summertime inward vapor drive. Low density foam allows moisture vapor movement through the foam so other methods of vapor control such as poly, kraft paper, or vapor barrier paint may be required based on the geographic location.[5] The IRC building code should be consulted.

Drying: Both of the spray foam walls dry relatively slowly if water enters the enclosure, since they do not experience convective looping and air movement similar to air permeable insulations. Spray foam does not provide any buffering capacity or redistribution. Foam is relatively moisture tolerant and will be able to dry given enough time. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before close in. High density foam will inhibit the drying of wet building materials more than low density vapor permeable foam.

Durability Summary: The primary durability risks associated with these wall assemblies involve moisture damage related to rain water penetration. Both air leakage and vapor diffusion durability is significantly increased with spray foam but some vapor control may be necessary with low density spray foam in cold climates.

BUILDABILITY

Using spray foam as the stud space insulation is a very simple modification to the construction technique. Generally, the wall construction is the same as standard or advanced framing construction, and spray foam is sprayed into the cavity. Spray foam significantly reduces risks of poor air tightness detailing of the exterior sheathing or interior drywall.

COST

Using spray foam will increase construction costs considerably but these increased costs may be outweighed by the benefits to energy efficiency, and occupancy comfort from reduced drafts.

MATERIAL USE

Wood framing required for spray foam insulation is the same required for the standard construction, or advanced framed wall depending on the framing strategy used.

TOTAL SCORE

Both low and high density foam increase the air tightness of the enclosure and reduce the risks to air leakage related durability risks. A vapor control (ie. polyethylene, kraft paper, SVR) with high density foam is generally not required and vapor control with low density spray foam will be climate specific. The R-values of both the low and high density spray foam are significantly reduced by thermal bridging of the wall framing and rim joist, demonstrating the value of insulated sheathing. It may be possible to use spray foam insulation in combination with another insulation strategy to maximize the R-value gained with the spray foam insulation.

REFERENCES

1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis*. Retrieved from buildingscience.com.

2 Straube, J. (2009, 04 22). *BSD-014 Air Flow Control in Buildings.* Retrieved from buildingscience.com.

3 Lstiburek, J. W. (2006). *Water Management Guide.* Westford: Building Science Press Inc.

4 Lstiburek, J. (2008, 08 20). *BSD-104: Understanding Air Barriers*. Retrieved from buildingscience.com.

5 Lstiburek, J. (2008, 10 17). *BSD-106 Understanding Vapor Barriers.* Retrieved from buildingscience.com.

FLASH-AND-FILL HYBRID WALL CONSTRUCTION

FLASH-AND-FILL HYBRID WALL CONSTRUCTION DETAILS *(Wall 9)*[1]

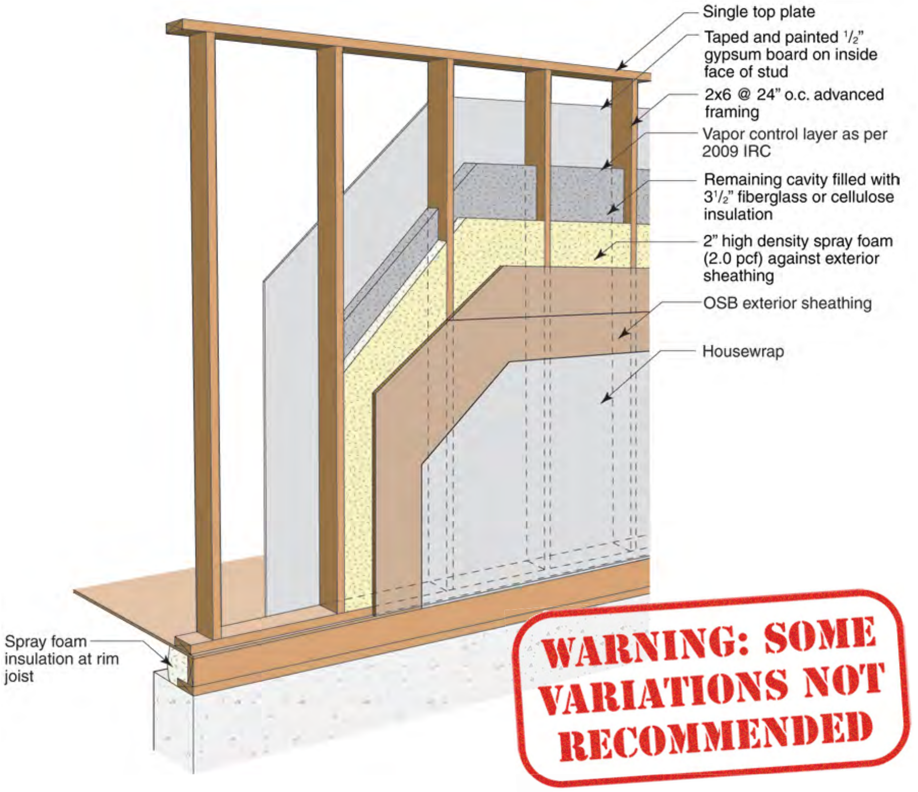
- 2x6 wood frame wall at 24” o.c.
- 2” high density spray foam
- Fiberglass or cellulose cavity insulation
- OSB sheathing
- Housewrap

SCORING: HOW IT RATES

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	4
Durability	4
Buildability	4
Cost	3
Material Use	4
Total	**19**

The hybrid wall system significantly reduces air leakage over standard construction or advanced framing, which conserves energy, and reduces the potential for both air leakage and vapor condensation durability issues. Unfortunately, the added cost of the spray foam insulation only adds a minimal amount to the R-value since the thermal bridging of the wall is not addressed. Addressing the thermal bridges would improve this wall construction.



WARNING: SOME VARIATIONS NOT RECOMMENDED

INTRODUCTION

This two page summary briefly summarizes flash-and-fill hybrid wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

THERMAL CONTROL

Installed Insulation R-value: The installed R-value is approximately R-12 for two inches of high density spray foam (2.0 pcf) and R-13 for three and a half inches of fiberglass batt, totaling R-25.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors, the R-value decreases from an installed insulation R-value of R-25 to whole wall R-value of approximately R-17 for a the hybrid wall construction in this case.[1] The decrease in R-value is due to the thermal bridging of the wall framing, top and bottom plates.

Air Leakage Control: Fiberglass batt, and both blown and sprayed cellulose are air permeable materials allowing possible air paths between the interior and exterior as well as convective looping in the insulation. Although densepack cellulose has less air permeance it does not control air leakage. In the case of the hybrid wall system, the spray foam is used as an air barrier in the stud space to limit the air movement between the interior and exterior so there are fewer energy losses due to air leakage. It is still possible and common to get air leakage below the bottom plate if is not sealed.[2] When spray foam is used in the wall system, it is beneficial to also use it in the rim joist which has a high potential for air leakage.

Typical Insulation Products: Spray foam insulation and fiberglass batt, blown fiberglass, blown cellulose, or sprayed cellulose.

DURABILITY

Rain Control: Rain leakage into the enclosure is the leading cause of premature building enclosure failure. Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). Intersections, windows, doors and other penetrations must be drained and/or detailed to prevent the penetration of rainwater beyond the drainage plane.[3]

Air Leakage Control: Air leakage condensation is the second largest cause of premature building enclosure failure with wood framed wall construction. It is very important to control air leakage to minimize air leakage condensation durability issues. An air barrier is required in this wall system to ensure that through-wall air leakage is eliminated (ideally) or at least minimized. An air barrier should be stiff and strong enough to resist wind forces, continuous, durable, and air impermeable.[4]

In the hybrid wall system, two inches of spray foam is used as an air barrier to reduce the air leakage. This also reduces the air leakage condensation against the sheathing in the winter as it significantly warms the condensation plane. Since air leakage from the interior, into the studspace and back into the interior can also cause condensation in some climates, it is still important to detail the interior surface as an air barrier as well.

Vapor Control: Fiberglass and cellulose are vapor permeable materials, but including two inches of high density spray foam acts as a vapor barrier limiting vapor movement to the cold exterior sheathing, and significantly reduces the risk of vapor condensation durability issues. High density spray foam also decreases the summer inward vapor drives. If low density spray foam is used, it is not a vapor barrier, and other vapor control may be required depending on the climate. Calculations should be done to ensure a minimum risk to vapor condensation durability issues.[5] The IRC building code should be consulted.

Drying: Using high density spray foam will slow the movement of moisture across the enclosure. and there is no moisture buffering capacity or redistribution within the spray foam. Some vapor control may still be required at the interior surface in cold climates which slows drying. Proper flashing of all penetrations should help minimize moisture in the enclosure. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before close in. High density spray foam may slow drying across the enclosure since it is a vapor barrier. In geographic regions with reduced drying potential, the moisture content of the sheathing may stay elevated for an extended period due to the inability to dry or redistribute moisture into the wall.

Durability Summary: Hybrid wall construction has a greater resistance to both air leakage condensation and vapor diffusion condensation because of the high density spray foam increasing the dew point of the condensation surface. The primary durability risks associated with these wall assemblies involve moisture damage related to rain water penetration.

BUILDABILITY

Hybrid wall construction is not very different from standard wall construction or advanced framing. By filling the stud space with two inches of spray foam, an R-13 batt can still easily be installed against the foam, or cellulose could be sprayed in the remaining stud space. All other aspects of the construction are the same as standard construction or advanced framing. Using high density spray foam reduces the risks from poor workmanship during construction.

COST

Using spray foam insulation can be costly, and while it reduces the risks of moisture related durability issues, the minimal increase in R-value due to the thermal bridging may not be worth the increased cost of the spray foam insulation.

MATERIAL USE

There is no increase in framing materials from standard construction, but the embodied energy of the system increases with the addition of high density spray foam insulation.

TOTAL SCORE

The hybrid wall system significantly reduces air leakage over standard construction, which conserves energy, and reduces the potential for both air leakage and vapor condensation durability issues. Reducing the air leakage may also increase occupancy comfort by reducing drafts. Unfortunately, the added cost of the spray foam insulation only adds a minimal amount to the R-value since the thermal bridging of the wall is not addressed. This wall is very similar to build as standard construction and less susceptible to poor workmanship during construction. Addressing the thermal bridges would improve this wall construction.

REFERENCES

1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis*. Retrieved from buildingscience.com.

2 Straube, J. (2009, 04 22). *BSD-014 Air Flow Control in Buildings.* Retrieved from buildingscience.com.

3 Lstiburek, J. W. (2006). *Water Management Guide.* Westford: Building Science Press Inc.

4 Lstiburek, J. (2008, 08 20). *BSD-104: Understanding Air Barriers*. Retrieved from buildingscience.com.

5 Lstiburek, J. (2008, 10 17). *BSD-106 Understanding Vapor Barriers.* Retrieved from buildingscience.com.

DOUBLE STUD WITH SPRAY FOAM WALL CONSTRUCTION

DOUBLE STUD WITH SPRAY FOAM WALL CONSTRUCTION DETAILS *(Wall 10)*[1]

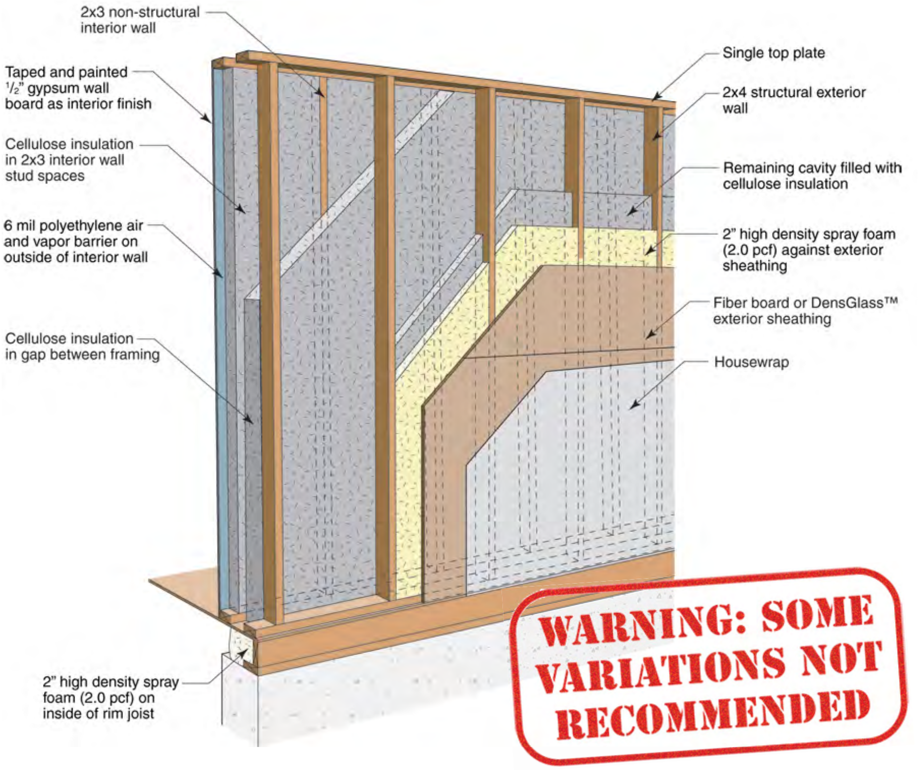
- 2x4 exterior wall framing
- 2" high density spray foam
- Fiberglass or cellulose cavity insulation
- 2x3 interior wall framing
- Fiber board or DensGlass™ sheathing
- Housewrap

SCORING: HOW IT RATES

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	5
Durability	4
Buildability	3
Cost	3
Material Use	3
Total	**18**

This is truly a high-R wall assembly, and with the addition of spray foam, there is a reduction in moisture related durability issues. In some extreme climates, two inches of spray foam may not be enough to sufficiently reduce the risk, which means that more spray foam is required, or an interior air barrier and some form of vapor control, likely a Class II or Class II would be sufficient.



WARNING: SOME VARIATIONS NOT RECOMMENDED

INTRODUCTION

This two page summary briefly summarizes double stud with spray foam wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

THERMAL CONTROL

Installed Insulation R-value: The thickness of double stud walls varies, however walls with overall insulation thickness of 9.5" appear to be most common. The insulation is most commonly cellulose insulation but could also be sprayed fiberglass. In this system with two inches of high density spray foam (R-6/inch) the installed insulation R-value is approximately R-40. This is an increase of R-5 over the same double stud construction insulated only with cellulose.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors shows that adding an interior framed wall with a insulation filled gap greatly reduces the thermal breaks through the stud wall and can increases the Clear wall R-value to R-36 depending on the thickness of insulation. However, because of the thermal losses at the rim joist, the Whole-wall R-value is closer to R-33.[1]

Air Leakage Control: Fiberglass batt, blown and sprayed cellulose are all air permeable materials allowing possible air paths between the interior and exterior as well as convective looping through the material. In this case, the spray foam is used as an air barrier in the stud space to limit the air movement between the interior and exterior so there are fewer energy losses due to air leakage. It is still possible and common to get air leakage below the bottom plate if is

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Building Science Corporation
30 Forest Street
Somerville, MA 02143
www.buildingscience.com

not sealed.[2] When spray foam is used in the wall system, it is beneficial to also use it in the rim joist that has a high potential for air leakage. Reducing the air leakage with spray foam may also increase occupancy comfort by reducing drafts.

Typical Insulation Products: High density spray foam, blown cellulose, sprayed fiberglass.

DURABILITY

Rain Control: Rain Control – Rain leakage into the enclosure is the leading cause of premature building enclosure failure. Rain control is typically addressed using a shingle lapped and/or taped drainage plane such as building paper or a synthetic WRB (i.e. homewrap). Intersections, windows, doors and other penetrations must be drained and/or detailed to prevent the penetration of rainwater beyond the drainage plane.[3]

Air Leakage Control: Since fibrous insulations are air permeable, air leakage condensation may occur if air moves into the stud space from the interior, or the exterior, depending on the climate. An air barrier is required in this wall system to ensure that air leakage is ideally eliminated, but at least minimized. Air leakage condensation is one of the greatest causes of premature building enclosure failure. An air barrier should be stiff, continuous, durable, strong, and impermeable.[4]

Air need not leak straight through an assembly to cause moisture problems; it can also leak from the inside, through the wall, and back to the inside. Condensation within the stud space is possible if this type of airflow occurs, depending on the weather conditions. Hence, wall designs should control airflow into the stud space.

Vapor Control: Fiberglass and cellulose are vapor permeable materials, so a separate vapor control strategy must be employed to ensure that vapor diffusion from does not result in condensation on or damaging moisture accumulation in moisture sensitive materials. In this case, the high density foam acts as a vapor control layer in the assembly. The permeance and location of vapor control is dependent on the climate zone and in cold climates, further vapor control may be required due to the ratio of insulation interior of the vapor control layer. Some level of vapor control may be needed on the interior surface or the amount of spray foam insulation could be increased. Installing the vapor control layer in the incorrect location can lead to building enclosure failure.[5] The IRC building code should be consulted.

Drying: Cellulose and fiberglass insulation allow drying easily, so drying is controlled by other enclosure components such as the high density spray foam and OSB sheathing. Installing vapor control on both sides will seal any moisture into the stud space, resulting in low drying potential, and possibly resulting in moisture-related durability risks. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before close in. Cellulose is often sprayed in damp, and manufacturers recommend drying before close in and moisture content limits. Interior vapor control may be required depending on the climate zone, and with the combination of vapor semi-impermeable foam and OSB, will increase the time required for adequate drying.

Durability Summary: The primary durability risks associated with these wall assemblies involve moisture damage related to rain water penetration or condensation (most likely the result of air leakage, but also potentially the result of vapor diffusion). In some extreme cold climates, two inches of spray foam may not be enough insulation to minimize the risk of air leakage and vapor condensation durability issues because of the ratio of insulation to the interior and exterior of the surface of the spray foam. Increasing the amount of spray foam (the amount of insulation exterior of the condensation plane) will further decrease the risk.

An airtight drywall construction approach will also reduce risks associated with air leakage condensation, and some form of vapor control may be needed (poly, kraft paper or vapor barrier paint depending on climate).

Cellulose insulated walls are slightly more durable because cellulose insulation is capable of storing and redistributing small amounts of moisture. Cellulose insulation is typically treated with borates that have been shown to protect itself and neighboring wood material from mold growth and decay. Cellulose insulation also has decreased flame spread potential relative to other insulation materials.

BUILDABILITY

A double stud wall requires more effort and time to construct properly compared to standard construction practices. The thickness of the wall requires plywood boxes to install all windows and doors in the enclosure. Installing spray foam reduces the risks from poor workmanship but in some climates more than two inches of high density spray foam may be required to completely avoid the risk of air leakage and vapor condensation. Double stud wall construction reduces the interior living space of the building by adding insulation to the interior of the structural framed wall.

COST

There are increased costs in the addition of a secondary interior wall, and spray foam insulation. The benefits of reduced condensation potential may not be worth the cost of adding spray foam since there are only minimal benefits to the R-value of the wall assembly.

MATERIAL USE

A secondary interior framed wall increases the amount of framing material required for wall construction. Spray foam insulation significantly increases the embodied energy over using cellulose insulation with minimal returns in R-value.

TOTAL SCORE

This is truly a high-R wall assembly, and with the addition of spray foam, there is a reduction in moisture related durability issues. In some extreme climates, two inches of spray foam may not be enough to sufficiently reduce the risk, which means that more spray foam is required, or an interior air barrier and some form of vapor control, likely a Class II or Class II would be sufficient. The other disadvantage to this wall system is that it reduces the living space of the building.

REFERENCES

1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis*. Retrieved from buildingscience.com.

2 Straube, J. (2009, 04 22). *BSD-014 Air Flow Control in Buildings.* Retrieved from buildingscience.com.

3 Lstiburek, J. W. (2006). *Water Management Guide.* Westford: Building Science Press Inc.

4 Lstiburek, J. (2008, 08 20). *BSD-104: Understanding Air Barriers*. Retrieved from buildingscience.com.

5 Lstiburek, J. (2008, 10 17). *BSD-106 Understanding Vapor Barriers.* Retrieved from buildingscience.com.

OFFSET FRAME WALL CONSTRUCTION

OFFSET FRAME WALL CONSTRUCTION DETAILS *(Wall 11)*[1]

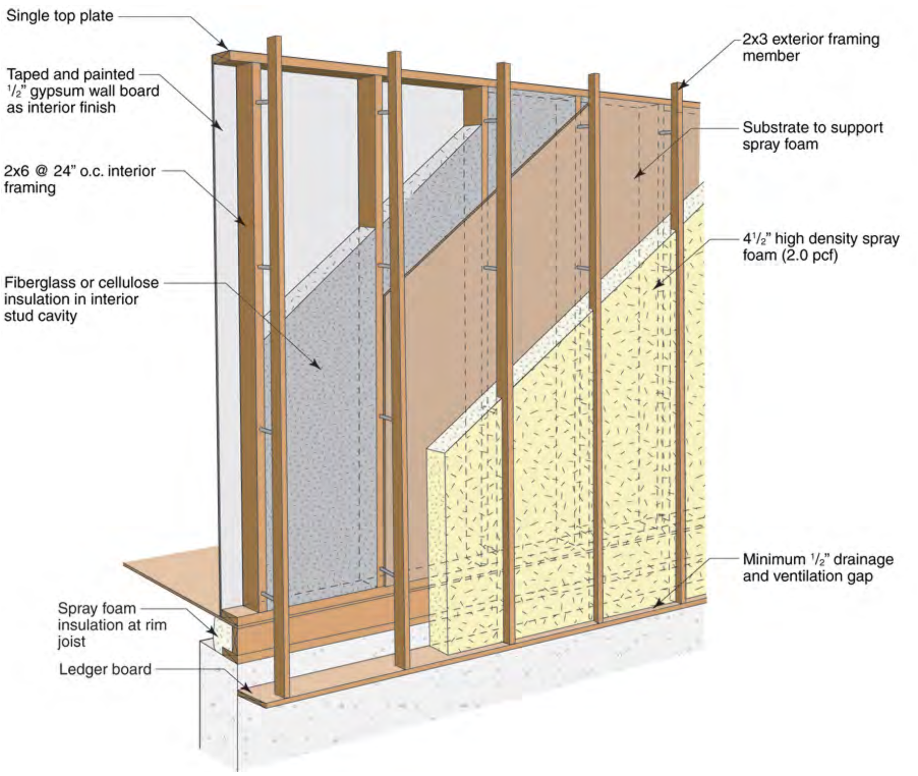
- 2x6 structural framing wall
- 2x3 cantilevered wall
- 4.5" high density spray foam
- Fiberglass or cellulose cavity insulation
- OSB sheathing

SCORING: HOW IT RATES

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	5
Durability	5
Buildability	4
Cost	3
Material Use	2
Total	**19**

The offset frame wall system is ideal in many situations where the cost of high density spray foam is justified. There is very minimal risk to moisture related durability issues from rain penetration or condensation because off the continuous exterior spray foam insulation if the penetrations are detailed correctly. This is a very durable wall system for all climates, and can be built as new construction or a deep retrofit.



INTRODUCTION

This two page summary briefly summarizes the offset frame wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

THERMAL CONTROL

Installed Insulation R-value: The amount of insulation installed in this wall system can be modified quite easily but in this case, 4.5" of high density spray foam (R-6/inch) was used on the exterior, and 5.5" of cellulose (R-3.7/inch) was installed in the stud space for a total installed insulation R-value of R-47. It is possible to install as much or as little spray foam insulation on the exterior as practical in specific cases.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors, the thermal bridging in this wall system is significantly reduced by the uniform layer of spray foam over the exterior covering the rim joist and wall framing. The whole wall R-value for this assembly is approximately R-37.[1]

Air Leakage Control: The exterior spray foam insulation is a perfect air barrier for this enclosure eliminating heat losses by air leakage through the wall. Air still could leak around penetrations such as windows, doors, and services if not detailed correctly.[2]

Typical Insulation Products: High density spray foam and fiberglass batt, blown cellulose, sprayed cellulose, or sprayed fiberglass.

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Durability

Rain Control: For this wall system, the continuous drainage plane will be the exterior surface of the high density foam. Rain screen cladding will be installed directly on the exterior framing, and any moisture that passes through the cladding will drain against the high density spray foam. Intersections, windows, doors and other penetrations must be detailed to prevent the penetration of rainwater.[3]

Air Leakage Control: The continuous layer of high density spray foam prevents all air leakage through the enclosure system. Care should be taken to make sure that penetrations through the enclosure (windows, doors, services) are airtight. There should be no risk of air leakage condensation against the sheathing in most climates with 4.5" of exterior spray foam. In climate zone 8, more spray foam may be required, or the stud space insulation can be removed to ensure that there is no condensation.[4]

Vapor Control: The continuous layer of high density spray foam prevents vapor movement through the enclosure system. There should be no risk of vapor condensation against the sheathing in most climates with 4.5" of exterior spray foam. In climate zone 8, more spray foam may be required, or the stud space insulation can be removed to ensure that there is no condensation.[5]

Drying: This enclosure system will dry both to the interior, if the moisture is in the stud space, and to the exterior, if the moisture is in the cladding. Proper flashing of all penetrations should help minimize moisture in the enclosure. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before closing in. Cellulose is often sprayed in wet, and manufacturer's recommendation is to allow drying before closing in. Because no polyethylene vapor barrier is required, moisture in the stud space will be able to dry quite easily to the interior.

Durability Summary: Provided the minimum amount of spray foam insulation is exceeded for a given climate to keep the condensation plane above the dew point, there is virtually no risk to moisture condensation in the enclosure, and any small amounts of moisture in the enclosure will dry easily.

Cellulose insulation is typically treated with borates that have been shown to protect itself and neighboring wood material from mould and decay. Cellulose insulation also has decreased flame-spread potential.

Buildability

This wall system does require some attention to detailing, and likely some initial training to install the exterior framing material1, but the risks from poor construction are very minimal. Spray foam insulation is shipped as a liquid in two components and only mixed as it is installed, so shipping is much more efficient and reliable than board foam, which has been reported to arrive on the job site damaged, especially in remote areas. It is very quick and easy to dry in a structure with spray foam insulation to weatherproof it, which is critical in environments with short construction seasons. Interior finishing can be done even in inclement weather. This enclosure system has been used both in new construction and in retrofit situations in cold climates.

Cost

In most regions high density spray foam is a relatively expensive method of insulating the enclosure, however the benefits, of a complete air and vapor barrier, occupancy comfort, reduced energy consumption, and reduced risks to contractor errors may be worth the increased cost in some locations and situations.

Material Use

More framing materials are required for this enclosure assembly, as well as the higher embodied energy high density spray foam. Cellulose in the stud space has very low embodied energy.

Total Score

This wall system is ideal in many situations where the cost of high density spray foam is justified. One of the locations where the cost is justified is the extremely cold climates and short construction seasons of the north. Most of the durability related issues are caused by air leakage and vapor condensation on the sheathing causing rot and mold in the enclosure. The common complaints in the remote locations is that the board foam arrives on trucks badly damaged, but with spray foam, the foam is shipped in two liquid components, and more board feet of foam could be shipped on the same truck. The construction season is very short but houses can be dried in during the best weather, and the interior finished later if necessary.

References

1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis*. Retrieved from buildingscience.com.

2 Straube, J. (2009, 04 22). *BSD-014 Air Flow Control in Buildings.* Retrieved from buildingscience.com.

3 Lstiburek, J. W. (2006). *Water Management Guide.* Westford: Building Science Press Inc.

4 Lstiburek, J. (2008, 08 20). *BSD-104: Understanding Air Barriers.* Retrieved from buildingscience.com.

5 Lstiburek, J. (2008, 10 17). *BSD-106 Understanding Vapor Barriers.* Retrieved from buildingscience.com.

EXTERIOR INSULATION FINISH SYSTEMS (EIFS) WALL CONSTRUCTION

EXTERIOR INSULATION FINISH SYSTEMS (EIFS) WALL CONSTRUCTION DETAILS

(Wall 12)[1]

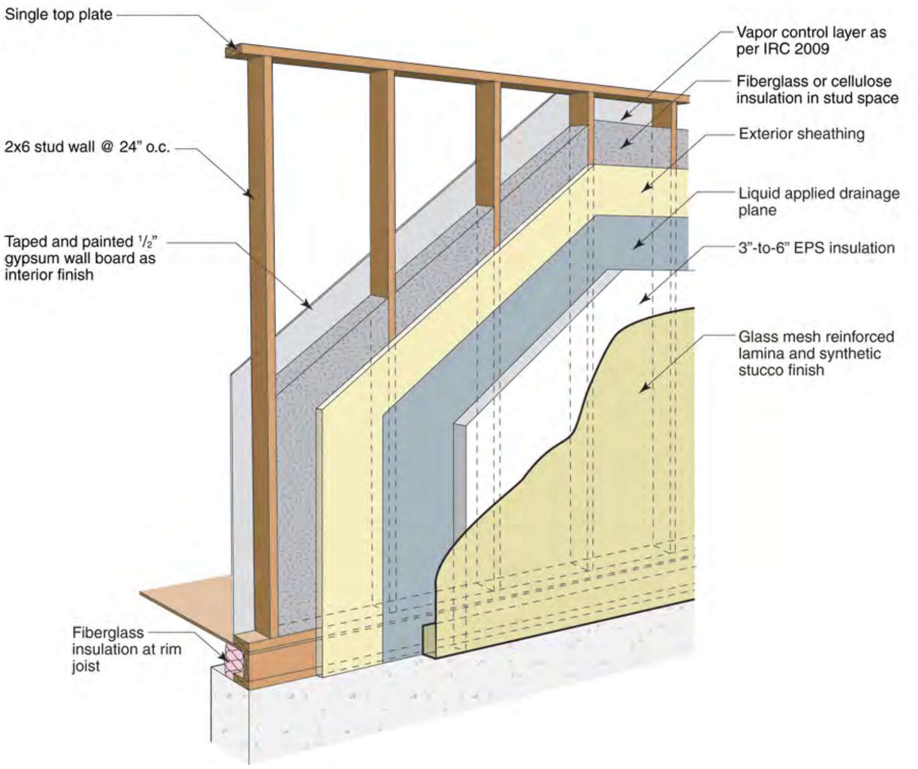
- 2x6 structural framing wall
- Fiberglass or cellulose cavity insulation
- Glass-faced gypsum sheathing
- Exterior EPS insulation
- Stucco finish

SCORING: HOW IT RATES

The scoring of each wall system is based on the following five categories. A score of 1 is the lowest score in each category and represents the worst possible technology for each category or highest possible relative cost. A score of 5 is the highest score available in each category, and is representative of the best available technology available on the market or lowest relative cost.

Thermal Control	5
Durability	5
Buildability	4
Cost	3
Material Use	3
Total	**20**

This wall system is a durable and reliable choice regardless of the historical failures of this construction strategy. A better understanding of enclosure design and building science with drained and ventilated claddings and better design details have nearly eliminated the historical moisture related issues. This wall system has the appearance of a stucco finish, but with significant energy improvements, which is often the reason for using this construction strategy.



INTRODUCTION

This two page summary briefly summarizes EIFS wall construction including the advantages and disadvantages of this construction strategy. A more detailed analysis and direct comparison to several other walls can be found online.[1] The scoring system is somewhat subjective based on the relative performance and specifications between different wall systems. Complex two dimensional heat flow analysis and one dimensional hygrothermal modeling were used to determine moisture related durability risks for analysis.

For a more complete analysis of this and other wall constructions, go to www.buildingscience.com.

THERMAL CONTROL

Installed Insulation R-value: The framed portion of this wall assembly typically has an R-value of R-19-20 when insulated with fiberglass batt or cellulose. Exterior insulation for EIFS is typically EPS at R-4/inch.

Whole-wall R-value: Using two dimensional heat flow analysis with thermal bridging effects and average framing factors demonstrates improvements in the efficiency of the fiberglass batt or cellulose in the stud space by decreasing the thermal bridging effects of the framing and the rim joist. Adding 4" of EPS insulation for a total an increase of R-16 increases the Clear-wall R-value of standard construction by slightly more than R-16 because of thermal bridging of the framing and rim joist. The whole-wall R-value for this system is approximately R-30.[1]

Air Leakage Control: Fiberglass batt, blown and sprayed cellulose are all air permeable materials allowing possible air paths between the interior and exterior as well as convective looping through the material. The air tightness of an EIFS system is typically at the surface of the exterior sheathing (usually glass-faced exterior gypsum) because it is the drainage plane.

Typical Insulation Products: EPS exterior insulation, fiberglass batt, blown cellulose, sprayed cellulose.

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DURABILITY

Rain Control: In the EIFS system, it is critical to correctly detail the drainage plane to adequately handle rain. Historically EIFS were constructed using a face-sealed approach, but this lead to many moisture related durability issues. EIFS can be used as part of a very durable and reliable enclosure system, provided it is drained and ventilated. Intersections, windows, doors and other penetrations must be detailed to prevent the penetration of rain water.[2]

Air Leakage Control: By adding exterior insulation as part of the EIFS construction, the temperature of the sheathing (condensation plane) increases, and the risk of air leakage condensation is reduced. It is always good practice to build airtight enclosure systems, often with both an interior and exterior air barrier to avoid air leakage condensation and windwashing. Air leakage condensation is one of the greatest causes of premature building enclosure failure. An air barrier should be stiff, continuous, durable, strong, and impermeable.[3]

Air need not leak straight through an assembly to cause moisture problems; it can also leak from the inside, through the wall, and back to the inside. Condensation within the stud space is possible if this type of airflow occurs, depending on the weather conditions. Hence, wall designs should control airflow into the studspace.[4]

Vapor Control: By adding exterior insulation as part of the EIFS construction, the temperature of the sheathing (condensation plane) increases, and the risk of moisture vapor condensation is reduced. It may be possible to avoid the use of an interior vapor control layer, or use a higher permeance vapor control layer (Class II or III) depending on the amount of insulation on the exterior and regional building codes. Installing the incorrect vapor control layer or installation in the incorrect location can lead to building enclosure failure.[5] The IRC building code should be consulted.

Drying: Insulating sheathing limits the drying to the exterior, and the wall must be able to dry to the interior. Poly vapor barriers are typically avoided so that this drying can occur. The minimum level of vapor control on the interior surface is determined by the IRC. Installing vapor control on both sides of the enclosure will seal any moisture into the stud space, resulting in low drying potential, and possibly resulting in moisture-related durability risks. Ventilation behind vapor impermeable claddings and interior components (e.g. kitchen cabinets) can encourage drying.

Built- in Moisture: Care should always be taken to build with dry materials where possible, and allow drying of wet materials before close in. Cellulose is often sprayed in damp, and manufacturers recommend drying before close in and moisture content limits.

Durability Summary: The primary durability risks associated with these wall assemblies involve moisture damage related to rain water penetration. Insulating sheathings keep the condensation plane temperature elevated so there is less risk of condensation due to air leakage or vapor diffusion. Framing members are also kept warmer so they are exposed to lower relative humidity levels and generally have lower equilibrium moisture contents. Board foam products are typically less moisture sensitive than wood-based structural sheathing products.

Cellulose insulated walls are somewhat more durable because cellulose insulation is capable of storing and redistributing small amounts of moisture. Cellulose insulation is typically treated with borates that have been argued to protect adjacent wood members from mold and decay.

BUILDABILITY

Exterior insulation up to 1.5” requires minimal changes to standard construction practices. Exterior insulation in excess of 1.5” requires minor changes to window and wall construction and detailing which requires training and monitoring during the initial implementation. The EIFS finish system is directly applied to the exterior foam, and requires skilled trades to install. Some EIFS companies produce detail drawings for their products to reduce the risk of construction issues resulting in premature enclosure failure. www.stocorp.com and www.dryvit .ca are two examples that provide detailed drawings on their websites.

COST

There is an increased cost to EIFS wall construction because of the specialized stucco like finish. It is possible to add exterior insulation with a rain screen cladding as an alternative to the stucco appearance finish that may be more cost effective.

MATERIAL USE

Typically, in EIFS construction, structural wood sheathing is exchanged for a more moisture tolerant sheathing such as glass mesh reinforced exterior gypsum board. The addition of EPS foam can usually be sourced locally, and has relatively low embodied energy relative to other board foam insulations.

TOTAL SCORE

This wall system is a durable and reliable choice regardless of the historical failures of this construction strategy. A better understanding of enclosure design and building science with drained and ventilated claddings and better design details have nearly eliminated the historical moisture related issues. This wall system has the appearance of a stucco finish, but with significant energy improvements, which is often the reason for using this construction strategy. It is possible to use exterior insulation with many different cladding options if a stucco appearance is not the desired architectural result.

REFERENCES

1 Straube, J., & Smegal, J. (2009). *Building America Special Research Project - High-R Walls Case Study Analysis*. Retrieved from buildingscience.com.

2 Lstiburek, J. W. (2006). *Water Management Guide.* Westford: Building Science Press Inc.

3 Lstiburek, J. (2008, 08 20). *BSD-104: Understanding Air Barriers*. Retrieved from buildingscience.com.

4 Straube, J. (2009, 04 22). *BSD-014 Air Flow Control in Buildings.* Retrieved from buildingscience.com.

5 Lstiburek, J. (2008, 10 17). *BSD-106 Understanding Vapor Barriers.* Retrieved from buildingscience.com.

1.5.4. High-R Foundations Case Study Analysis

by Jonathan Smegal, October 2009 – DRAFT

Building America Special Research Project
High-R Foundations Case Study Analysis

2009 10 30

DRAFT

Jonathan Smegal MASc
John Straube, PhD, P.Eng

Building Science Corporation
30 Forest Street
Somerville, MA 02143

www.buildingscience.com

Table of Contents

A. 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 improving to require higher levels of thermal control than ever before for new construction. This report considers a number of promising foundation and basement insulation strategies that can meet the requirement for better thermal and moisture control in colder climates. By code, basements in DOE climate zones require a continuous layer of R10 insulation or R13 in a framed wall. High R basements, for cold climates, in this report are walls that exceed R20. In a warmer climate, that does not require basement insulation, high-R may be considered less.

Basements are stereotypically cool, damp, musty smelling areas of the building that were historically unfinished, unoccupied and used mostly as storage. More and more often, people are finishing their basements to increase the living environment and frequently the basement is transformed into a media room, bedroom, or extra living room. These new environments require greater control of both heat and moisture to provide a healthy living environment with minimal risk to equipment and finishes.

A successful foundation will perform the following tasks
- Hold the building up
- Keep the groundwater out
- Keep the soil gas out
- Keep the water vapor out
- Let the water vapor out that gets in the wall
- Keeps the heat in during the winter
- Keeps the heat out during the summer

Basement failures occur often due to flooding, or vapor diffusion condensation, both of which may result in mould or dust mite problems. By designing the basement or foundation enclosure system properly, the majority of all basement moisture and comfort issues can be avoided.

This study compares over a dozen basement and foundation enclosure designs including historical construction strategies, code minimum construction and highly insulated construction. This demonstrates through computer based simulations and field experience, differences in energy consumption, thermal control, and moisture related issues.

This study is an extension of the previous Building America study of High R wall assemblies (Straube and Smegal 2009), to continue to improve the overall building enclosure and achieve greater energy savings.

1. OBJECTIVE

The goal of this research is to find a optimally designed, cost effective basement insulation system that can be included with other enclosure details to help reduce whole house energy use by 70%.This report will compare a variety of basement and foundation insulating strategies and present their advantages and disadvantages according to several comparison criteria.

2. SCOPE

This study is limited to basement and foundation systems for cold climates. A previous study was conducted for wall systems and further studies should be conducted to address roofs and attics. In general, only cold climates are considered in this report since enclosures in cold climates benefit the greatest from a highly insulated building enclosure, but important conclusions can also be drawn for other climate zones.

3. APPROACH

The quantitative analysis for each wall system is based on a three-dimensional energy modeling program and a one-dimensional dynamic heat and moisture (hygrothermal) model. Minneapolis, MN in IECC climate Zone 6 was used as the representative cold climate for most of the modeling, because of the cold winter weather and fairly warm and humid summer months.

B.Analysis

1. WALL ASSEMBLIES REVIEWED

Because there are a number of variables for each possible wall system depending on the local practices, climate, and architect or general contractor preferences, an attempt was made to choose the most common wall systems and make notes about other alternatives during analysis. This list of chosen systems is explained in more detail in the analysis section for each wall system.

- Case 1 : Un-insulated Basement
- Case 2 : Code minimum R10 continuous insulation
- Case 3 : 3.5 inches fibreglass batt in 2"x4" SPF wood framed wall
- Case 4 : 1 inch XPS + 3.5 inches fibreglass batt in 2"x4" SPF wood framed wall
- Case 5 : 2 inches XPS + 2 inches polyisocyanurate with R10 under slab
- Case 6 : 3.5 inches 2.0 pcf spray foam with R10 under slab
- Case 7 : 6 inches 0.5 pcf spray foam with R10 under slab
- Case 8 : 2 inches XPS + 3.5 inches fibreglass batt in 2"x4" SPF wood framed wall with R10 under slab
- Case 9 : 2 inches polyisocyanurate +3.5 inches cellulose in 2"x4" SPF wood framed wall with R10 under slab
- Case 10 : 6 inches 0.5 pcf spray foam in offset 2"x4" SPF wood framed cavity with R10 under slab
- Case 11 : 4 inches XPS on exterior of basement with R10 under slab
- Case 12 : 4 inches XPS in centre of foundation wall with R10 under slab
- Case 13 : ICF wall with 4" XPS and R10 under slab
- Case 14 : 2 inches XPS + 5.5 inches fibreglass batt in 2"x6" SPF wood framed wall with R10 under slab

2. ANALYSIS CRITERIA

A comparison matrix will be used to quantitatively compare all of the different basement insulation 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/dr	Buildability	Cost	Material Use	Total
Criteria Weighting	1	1	1	1	1	
Case 1: uninsulated						
Case 2: R10 continuous with poly (roll batt)						
Case 3: R13 batt, 2x4 wall with poly						
Case 4: 1" XPS, 2x4 framed wall with fgb						
Case 5: 2" XPS, 2" PIC						
Case 6: 3.5" 2.0pcf cc spuf						
Case 7: 6" 0.5pcf oc spuf						
Case 8: 2" XPS, 2x4 framing with fgb						
Case 9: 2" PIC, 2x4 framing with cellulose						
Case10: 2.5" 0.5 oc spuf, 2x4 framing with same foam						
Case 11: 4" XPS on the exterior						
Case 12: 4" XPS in the centre of foundation wall						
Case 13: ICF – 2" XPS interior and exterior						
Case 14: 2" XPS, 2x6 framing with fgb						

The criteria scores will be summed for each insulation strategy, 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 wall design. 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 of this report.

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 costs of different insulations may be uncertain, fibreglass batt insulation is always less expensive than low density (0.5 pcf) spray foam which is less expensive than high density (2.0 pcf) spray foam, so these systems can be ranked accordingly regardless of the actual costs.

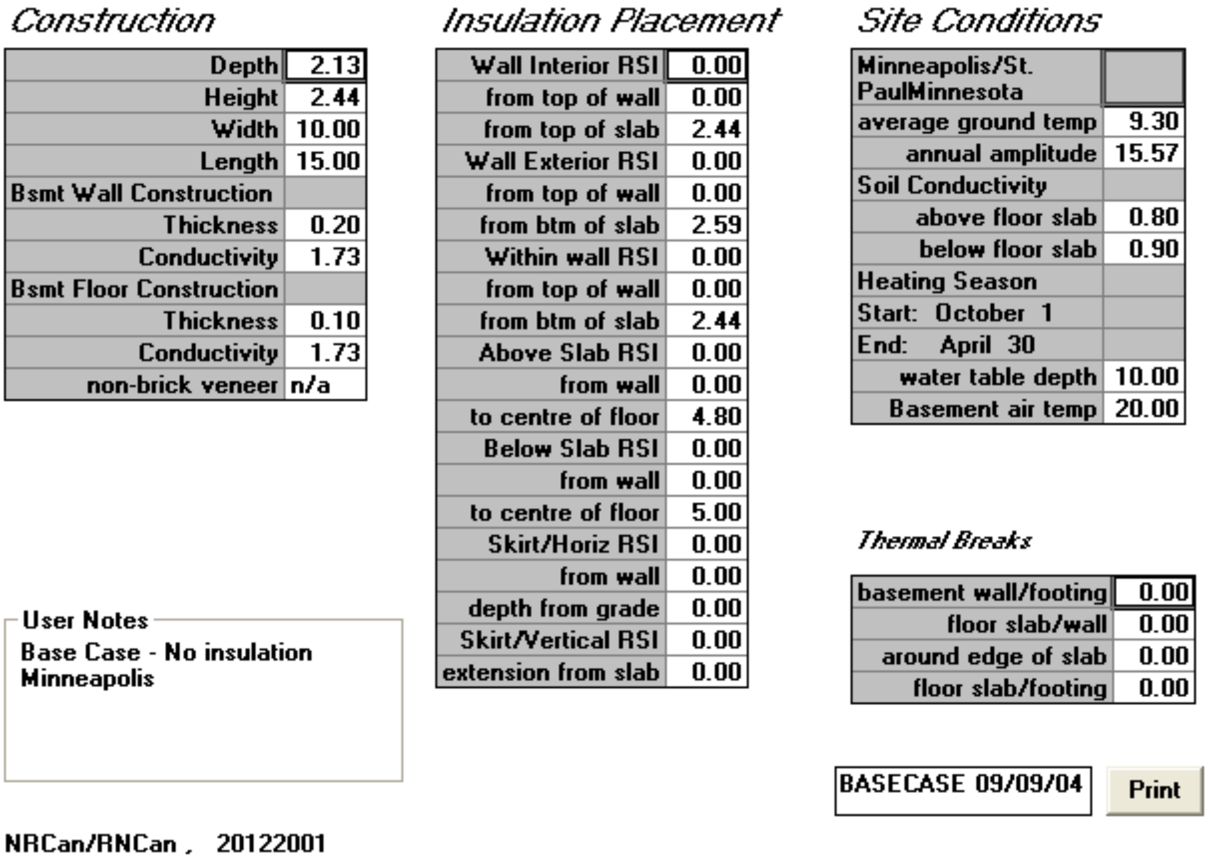
Each of the criteria are described in detail below.

2.1 Thermal Control and Heat Flow Analysis

The Heat flow and energy analysis of each basement system was conducted with Basecalc, developed by Canmet ENERGY and is based on the National Research Council of Canada's Mitalas method. Mitalas used mainframe computers to perform finite-element analyses of a large number of basements and analyzed the results to produce a series of basement heat-loss factors, which were then published as a reference (Mitalas 1983).

A user can apply the Mitalas method by using the correct heat-loss factors from the published tables and perform a series of calculations to predict heat and energy losses. Basecalc incorporates the finite-element approach Mitalas used to generate the heat-loss factors. During this study an analysis spreadsheet model was constructed using the Mitalas method and comparisons of the results between the analysis spreadsheet and Basecalc have been conducted.

The Basecalc software is a relatively simple menu driven program that has many options for construction strategies, insulation placement and site conditions (Figure 1).



Construction

Depth	2.13
Height	2.44
Width	10.00
Length	15.00
Bsmt Wall Construction	
Thickness	0.20
Conductivity	1.73
Bsmt Floor Construction	
Thickness	0.10
Conductivity	1.73
non-brick veneer	n/a

Insulation Placement

Wall Interior RSI	0.00
from top of wall	0.00
from top of slab	2.44
Wall Exterior RSI	0.00
from top of wall	0.00
from btm of slab	2.59
Within wall RSI	0.00
from top of wall	0.00
from btm of slab	2.44
Above Slab RSI	0.00
from wall	0.00
to centre of floor	4.80
Below Slab RSI	0.00
from wall	0.00
to centre of floor	5.00
Skirt/Horiz RSI	0.00
from wall	0.00
depth from grade	0.00
Skirt/Vertical RSI	0.00
extension from slab	0.00

Site Conditions

Minneapolis/St. PaulMinnesota	
average ground temp	9.30
annual amplitude	15.57
Soil Conductivity	
above floor slab	0.80
below floor slab	0.90
Heating Season	
Start: October 1	
End: April 30	
water table depth	10.00
Basement air temp	20.00

Thermal Breaks

basement wall/footing	0.00
floor slab/wall	0.00
around edge of slab	0.00
floor slab/footing	0.00

User Notes

Base Case - No insulation
Minneapolis

BASECASE 09/09/04

Figure 1 : Screen Capture showing inputs for Basecalc

Some assumptions were made for all of the Basecalc analysis to ensure comparison was possible between resulting simulations. The energy calculated is only for these specific cases, and modifying any of the variables may change the resulting energy requirements. These assumptions are listed below:

- All simulations were run for Minneapolis/St. Paul MN, data included in Basecalc
- Basement interior height - distance from top of slab to top of foundation wall 2.44 m (8 ft)
- Depth (below grade foundation) – distance from top of slab to surface of ground, 2.13 m (7 ft)
- Width - exterior of structural wall to exterior of structural wall, 10 m (32.8 ft)

- Length – exterior of structural wall to exterior of structural wall, 15 m (49.2 ft)

In Basecalc, the rim joist is not considered, but this was analyzed in past research(Straube and Smegal 2009), but thermal bridging across the top of the foundation wall is considered depending on above grade wall construction. For example, one of the most common thermal bridges in construction is the exterior above grade brick cladding sitting on the outside edge of the foundation wall. **(Find image maybe?)** This thermal bridging can be taken into account in Basecalc. For all simulations in this study, the above grade cladding was assumed to be non-brick veneer, to alleviate the issue of a significant thermal break at the top edge of the foundation wall.

All of the Basecalc results are presented in units of MBtus. For clarification 1 MBtu and it's equivalent energy in other common units of measure are show in Table 2.

Table 2 : Conversion of 1 MBtu to Other Common Energy Units

Million Btu's (MBtu's)	**1**
Btu's	**1,000,000**
Therms	**10**
Kilojoules	**1,057,000**
Kilowatt hours	**293.6**

The best way to explain energy savings to homeowners is often in dollars saved since the value of a dollar is commonly known and can be compared to other design decisions. Unfortunately, prices vary considerably across the continent for heating energy, and also vary depending on the technology used for heating, whether it be electricity, natural gas, oil, etc. For analysis purposes, if cost comparisons are used it will always be for electric heating at 15 cents per kilowatt hour ($44/MBtu). This value should be kept in perspective since heating methods and costs will vary. The cost of energy is sure to rise, and even though the rate of increase is unknown, but dollar savings today will be higher in the future.

2.1.1. Building Code Requirements

According to the IECC in climate zones 4 or higher, the building code requires a minimum of R10 continuous insulation (fiberglass roll batt) or R13 discontinuous (framed wall with R13 fiberglass batt). Adding this required amount of insulation makes a significant difference from an energy perspective as shown in Figure 2, but does not adequately address the comfort, moisture and health concerns that can occur in basements. Case 1 in this study is an un-insulated basement as many such cases can be found in new and existing buildings, and Cases 2 and 3 are typical of code minimum basements built in many cold climates.

An initial analysis was conducted to determine the effects of different amounts of insulation and strategies on the total heat loss prior to analyzing the various wall systems. Figure 2 shows the improvements in annual energy loss by insulating the full height of the basement wall with different insulation values over an un-insulated basement. The most significant improvement is achieved by adding R5, which shows that adding any insulation could help with energy losses. Increasing the insulation to R10 which is the code minimum as a continuous insulation results in a predicted energy savings of 31.2 MBtus (savings of $1372/year based on $0.15/kWhr or $44/MBtu). The energy savings should be considered when determining the cost of adding insulation, and whether or not it is cost effective.

Figure 2 also shows the predicted energy savings if the slab is insulated with R10 below the slab. In the un-insulated case there is an improvement of Heating Season Energy Loss of 1.3 MBTUs, and in the R20 insulated wall comparison the improvement is slightly improved with underslab insulation at 1.5 MBtus. However, the most important aspects of the underslab insulation are not shown on this graph. Comfort levels and moisture related issues including dampness and musty smells will decrease if underslab insulation is used. In some cases when radiant floor heating is used, R20 or greater underslab insulation is necessary to reduce the heat loss to the ground.

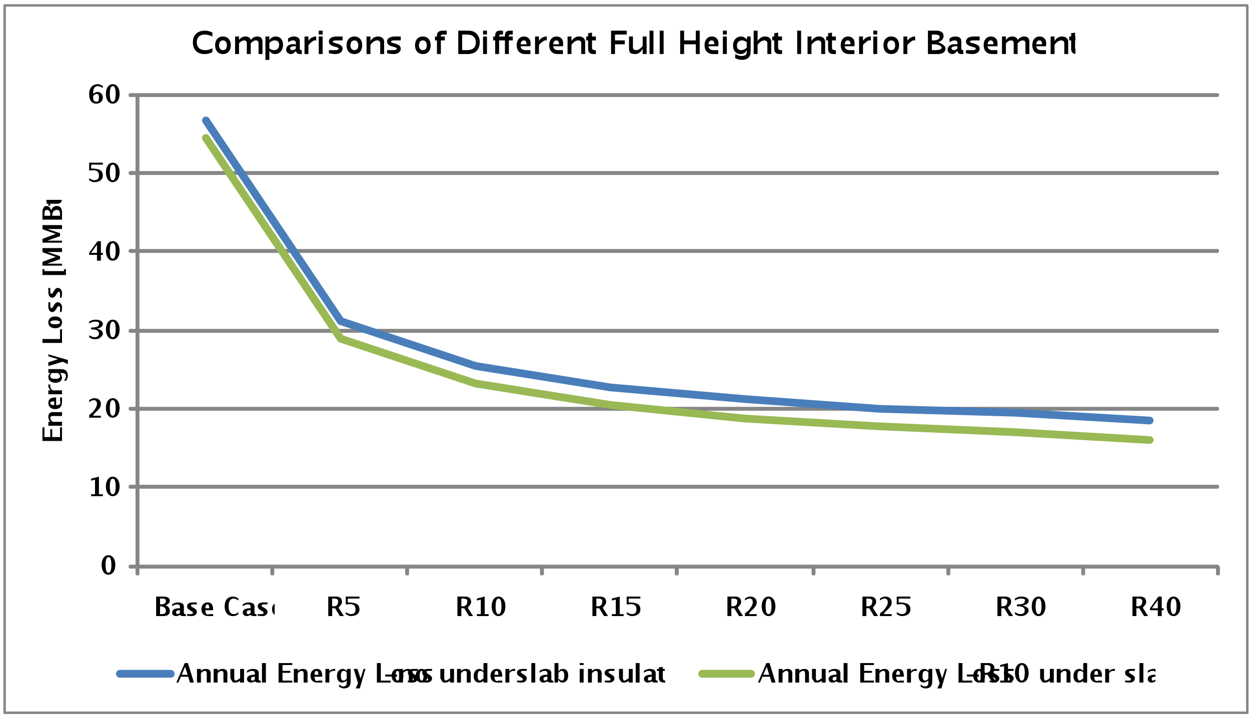


Figure 2 : Reduction in Energy Loss with the Addition of Full Height Foundation Wall Insulation

Two different underslab insulation strategies are compared in Figure 3, while keeping the foundation wall insulation constant at the code minimum continuous R10. Insulating only the perimeter 1.0 m (3.28 ft) saves approximately 1 MBtu when the underslab insulation is increased from 0 to R20, and insulating the entire slab saves approximately 4 MBtus of annual energy loss.

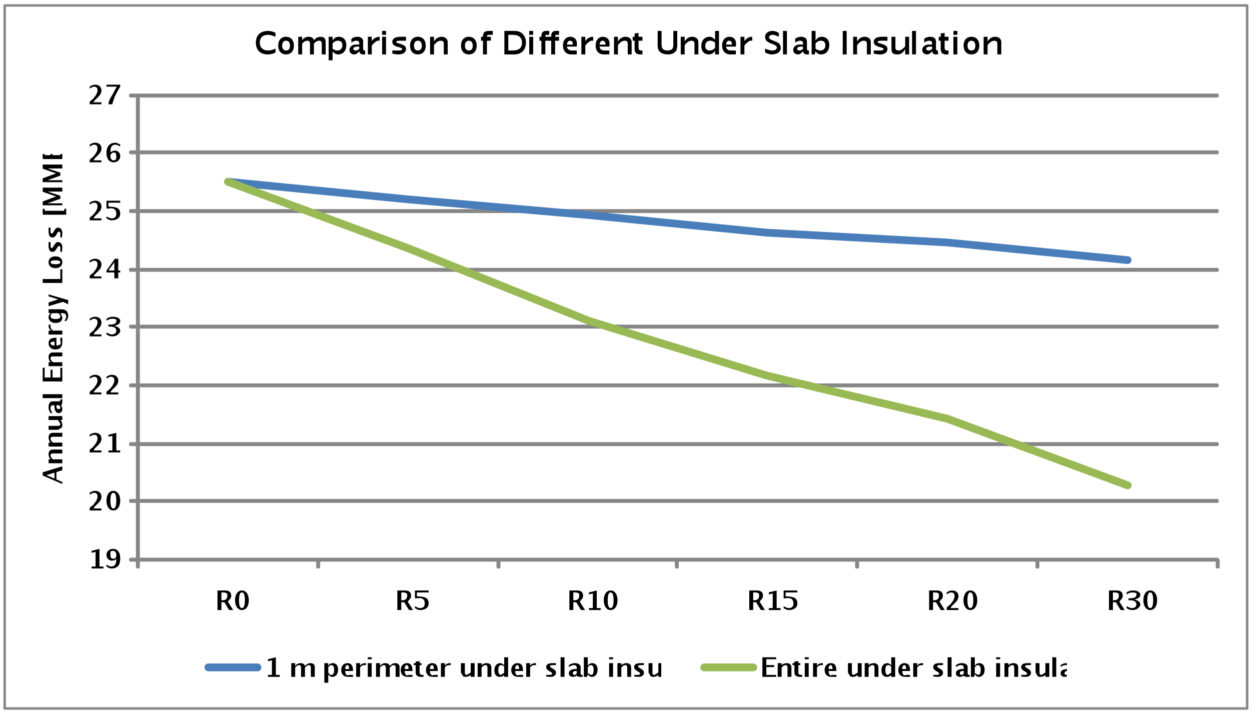


Figure 3 : Comparison of Different Underslab Insulation Techniques

In typical construction, there is a significant thermal break at the connection of the basement slab to the foundation footing and it allows capillary movement of water as discussed previously. If the wall is insulated correctly, and there is underslab insulation, there can still be heat lost and moisture gained through the concrete connection where the edge of the concrete slab meets the foundation wall. There are several methods to limit the capillary wicking of the foundation wall, but to improve both the heat loss and capillary at one time, a non hygroscopic thermal break is recommended between the slab and foundation wall as shown in the analysis wall drawings later in the report. Basecalc is able to predict the energy savings by adding a thermal break. Some common software packages such as Energy Gauge are incapable of assessing the impact of underslab insulation and thermal break. Since the thermal break around the perimeter is installed at the same time as the underslab insulation, this study assumes that the same foam board insulation is used for both applications (typically R10 is recommended as a minimum).

Figure 4 shows the energy improvements realized by installing a thermal break between the edge of the slab and the foundation wall, assuming that there is code minimum R10 continuous insulation on the wall and R10 installed under the slab. The largest improvement occurs when increasing from no insulation to R5 or 1" of XPS, but typically R10 is used since that is also used under the slab. A savings of 1.8 MBtus are predicted with the mentioned assumptions, but there are also improvements to moisture control that cannot be easily quantified in dollars.

[but how do you quantify these improvements? Should more insulation be used? Would be work saying what our recommendation is based on what you have already said about moisture. In the moisture section, this makes me think that you need a strong statement of what the consequences of too much moisture damage in the basement are. Maybe get something out of Joe's BSD on basements?]

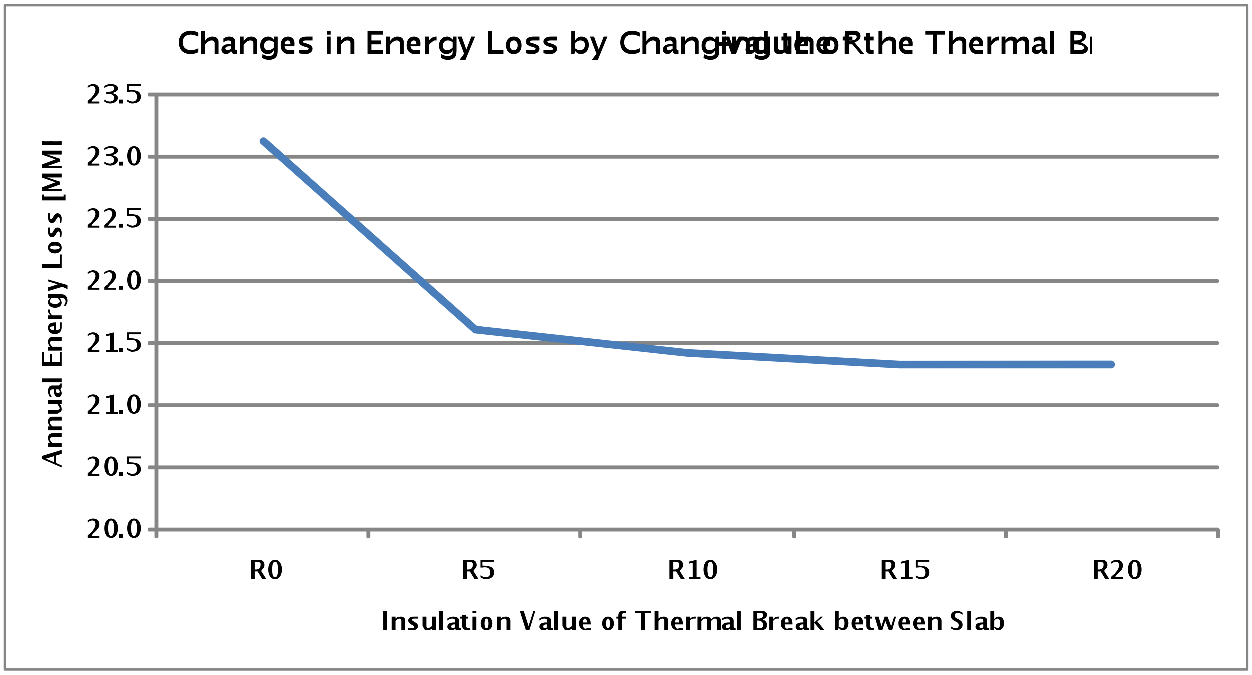


Figure 4 : Energy Savings From Thermal Break Insulation Between Concrete Footing and Slab

2.1.2. Practical Applications – Westford Prototype House

Recently, Building Science Corporation designed and monitored construction of a Building America prototype home in Westford Mass.[1] Simulations were conducted with both Energy Gauge and HOT2000 (H2K) to predict the heating energy losses of the enclosure. The Westford prototype house was constructed with R26 insulation (2 layers of 2" (50 mm) foil faced polyisocyanurate) on the interior of the foundation, R10 under the slab and an R10 thermal break around the perimeter of the slab.

Energy Gauge predicted a whole house heating loss of 277 Therms or 27.7 MBtus. Energy Gauge is not capable of dividing up the energy losses for specific areas of the house nor is it capable of simulating underslab insulation and thermal breaks around the perimeter of the slab.

H2K was also used to simulate the heating energy losses of the Westford prototype house and it was predicted that 6.96 MBtus are lost below grade, and 2.36 MBtus are lost above grade in the basement for a total basement heat loss of 9.32 MBtus in a year. H2K also predicted the total house heating energy losses of 27.16 MBtus, very similar to the Energy Gauge value.

Basecalc was used to determine the total annual energy loss through the basement is 7.1 MBtus which is similar to the H2K value. By modifying some of the insulation values in the basement, the effect on the total house energy can be seen to determine if increases in insulation values are cost effective.

Table 3 shows the effect on the predicted whole house heating energy losses by changing the amount of insulation under the slab.

Table 3 : Effects of Whole House energy by changing Underslab Insulation

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[1] Information on this project can be found at http://www.buildingscience.com/documents/case-studies/cs-ba13_MA_Westford_HFH/

	Change in Basement Energy Losses [MBtu]	Change in Whole House Energy Losses [%]
Removing Underslab insulation	-1.3	4.8%
R20 under slab	0.9	3.4%
R30 under slab	1.4	5.0%

Table 3 shows that 1.3 MBtus were saved by adding underslab insulation, a savings of almost 5% of the entire house's heating energy losses. As the underslab insulation is increased, the changes to the entire house's heating energy loses is less significant.

Table 4 shows the effect on the predicted whole house heating energy losses by changing the amount of insulation on the foundation walls.

Table 4 : Effects of Whole House Energy by Changing Foundation Wall Insulation

	Change in Basement Energy Losses [MBtu]	Change in Whole House Energy Losses [%]
R10 code minimum foundation wall insulation	-3.3	11.9%
R40 foundation wall insulation	0.9	3.4%

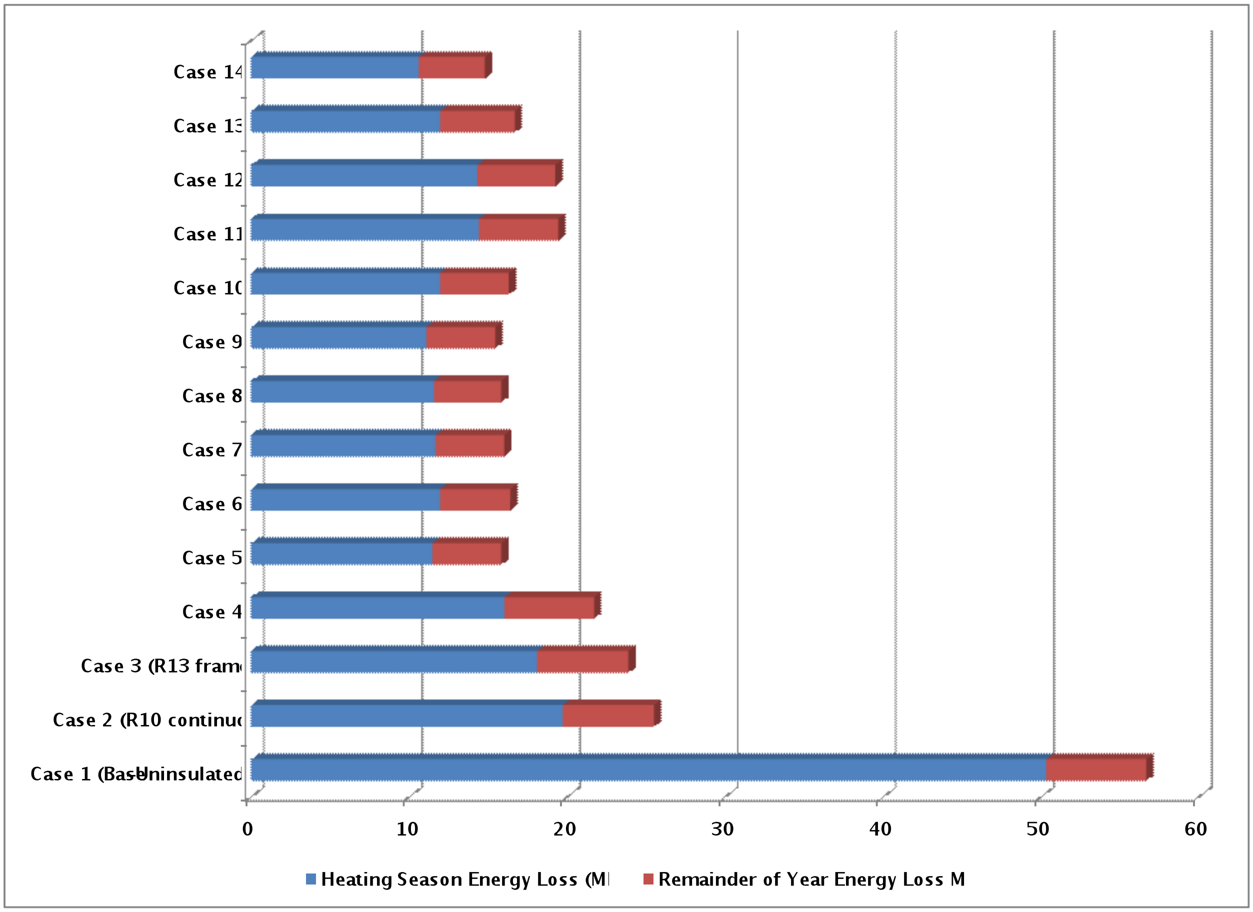
Table 4 shows that 12% of the heating losses of the house are saved from increasing the foundation wall insulation from the code minimum R10 to R26, which is a significant portion of the heating energy losses. This shows that it can be cost effective to insulate the basement in cold climates based on heating energy alone, without considering all of the moisture related benefits.

By increasing the insulation another R13 to R40, results in only a 3.4% decrease in the heating energy losses for the entire house, which is relatively insignificant.

2.1.3. Basement Wall Analysis

Fourteen cases listed previously were simulated in Basecalc, and the heating energy losses were simulated. Some of the proposed wall systems had continuous insulation and the R-values were assumed to be constant. Other proposed wall systems were framed or furred out to the interior and insulated with cavity insulation. The framing materials in these assemblies act as a thermal bridge bypassing the insulation. For the framed walls, the parallel path method was used to calculate the R-value, which is a ratio of the R value through the framing to the R-value through the center of the stud space, assuming a framing spacing of 24" on center. Also taking into account the gypsum wall board and surface film, the thermal bridging of the framing did not significantly affect the R-value, in fact, in some cases the calculated parallel path R-value was slightly higher than the installed insulation R-value.

Underslab insulation and a slab-edge thermal break were only included in simulations for Cases 5 to 14, since it is unlikely in the field to install underslab insulation with minimal foundation wall insulation.



As stated previously, even R10 foundation wall insulation showed a significant amount of energy savings compared to un-insulated basements. However, in some cases, increasing the insulation increases the risk for moisture related problems that will be analyzed in the Hygrothermal Analysis section.

The range of energy loss for the recommended foundation insulation strategies (Cases 5 – 14) is 14.8 to 19.43 MBtus per year. The value of this savings depends on the characteristics of the house, the climate zone, the type of energy used and its associated cost .

The best performing foundation insulation strategies from a heat loss perspective are Case 14 (2” XPS, 5.5” fibreglass batt) and Case 9 (2” PIC, 3.5” cellulose), but there are several others that perform very well. The advantages and disadvantages of the various insulation strategies will be compared further in the Analysis section.

2.2 Hygrothermal Analysis

Moisture Balance

Assessing moisture related durability risks involves three different moisture processes; wetting, drying and moisture redistribution. These three processes in combination with the safe storage capacity of each component will determine the risk of moisture damage to a basement assembly. This report only includes a brief overview of the wetting mechanisms, and was covered in more detail by Joseph Lstiburek 2006.

There are four main wetting mechanisms generally occurring in the foundation and basement. They are:

- Bulk water penetration from the exterior
- Capillary wicking or "rising damp"
- Vapor diffusion (from exterior or interior)
- Plumbing issues on the interior (not considered in this analysis)

The first source of wetting is bulk water from the exterior or from plumbing related issue on the interior. These will cause the greatest amount of damage in the quickest time. The best strategy to avoid water ingress into the basement from the exterior is to drain all of the components away from the building including the site and the exterior of the foundation (**Error! Reference source not found.**). Sometimes it is unavoidable to have liquid water in contact with the foundation and other strategies must be used including exterior drainage mats and sump pumps. In older buildings, foundation walls may have been constructed of rubble or stone and often allow water directly through the foundation wall in the rainy season. Ensuring basement drains are properly located and that they are clear of obstructions will minimize flooding caused by interior plumbing issues. This study does not deal specifically with retrofit strategies, but the possibility of use in retrofit applications will be mentioned for any relevant insulation strategies. Some information regarding the retrofit of basements was written by Betsy Pettit 2005.

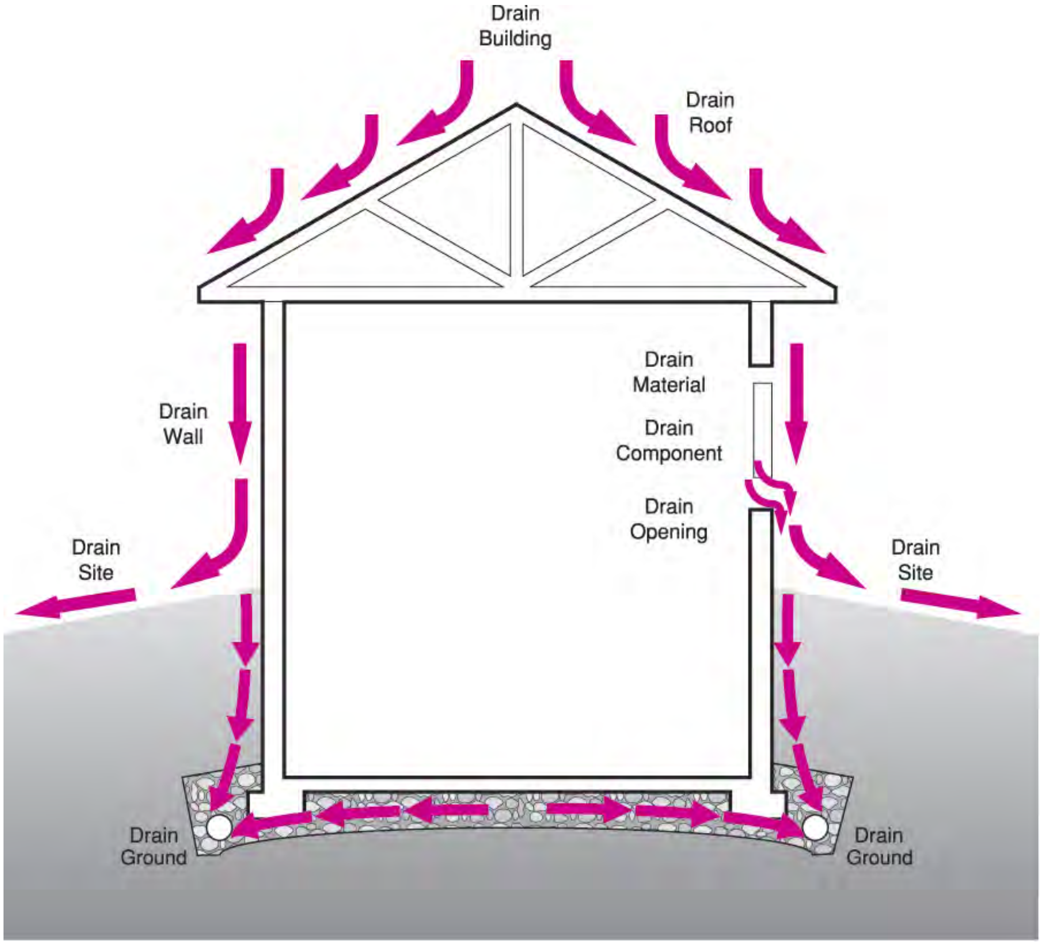


Figure 5 : Drainage details to minimize foundation moisture issues

The second source of moisture in the basement enclosure is caused by capillarity wicking. The physical characteristics and pore size of concrete (10 – 1000 nm) allow it to wick moisture quite effectively against the force of gravity, often with suction pressures of 100 kPa to 10MPa (Straube and Burnett 2005). The most common source of water for capillarity wicking is the footing. In many cases a moisture barrier such as damp-proofing, or a drainage membrane, or both are applied to the exterior of the wall minimizing the risk of absorption through the foundation wall. The floor slab is often poured over gravel which generally acts as a capillary break and should be drained to the exterior drainage tile. In many house foundations, there is no capillary break installed on the footing, and therefore water drawn into the footing is also wicked further up the foundation wall. In a typical basement, the liquid water is drawn to the surfaces of the concrete foundation wall, it will evaporate and dry to the interior or to the exterior as environmental conditions permit. If drying is hindered by a polyethylene vapor barrier, elevated relative humidities may occur near the wall surface or within the wall cavity eventually resulting in mould and other moisture related issues.

As homeowners finish and insulate their basement spaces, a polyethylene vapor barrier is often installed to meet the building code. Some builders who have learned from past experience will remove the bottom couple feet of the polyethylene vapor barrier to avoid mold problems that have been discovered in many basements. Removing the bottom section of the vapor barrier allows liquid water wicked up the footing and into the foundation wall to dry to the interior space. The preferred solution, of course, would be to install a capillary break between the footing and foundation wall during the original construction process to stop moisture from being wicked into the foundation wall.

(Figure if can find one)

The third source of moisture in the basement enclosure is caused by vapor diffusion. As discussed with capillarity above, vapor diffusion occurs from the interior surface of the concrete after water is wicked up the foundation wall. Vapor diffusion can also occur through floor slab if no vapor barrier is installed below the slab. The rate of vapor diffusion is slow, but still may cause durability issues with vapor impermeable floorings installed with water based adhesives, as well as increasing the moisture load in the basement, which can contribute to the common damp, musty odour. Vapor diffusion through the slab can be virtually eliminated by installing a vapor control layer (6 mil polyethylene, board foam insulation or spray foam) under the slab. Interior moisture vapor could also be an issue, especially in late spring and early summer as the environmental relative humidity increases but the concrete foundation temperatures are still cooler because of the seasonal temperature lag of the earth and thermal mass.

Vapor diffusion drying of the concrete can last for several years until the concrete fully hydrates, even if other sources of moisture are eliminated. If there is no moisture barrier on the exterior of the concrete, then the concrete will never dry completely and water vapor will always be passing into and through the concrete.

Drying is important since nearly all building enclosures will experience wetting at some point. In above-grade foundation walls, there is drying potential to both the interior and exterior if the enclosure design allows. Below grade, however, drying can only occur to the interior since the exterior surface of a below grade wall is at essentially at 100% humidity all year round.

The safe storage capacity (balance of wetting and drying) of an individual material or enclosure system is fundamental to good building design (**Error! Reference source not found.**). 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.

[So, was there any analysis done for moisture? Or maybe you should say that all walls are assessed based on their ability to handle the three moisture sources that you mention by a combination of "safely" draining, deflecting or drying.]

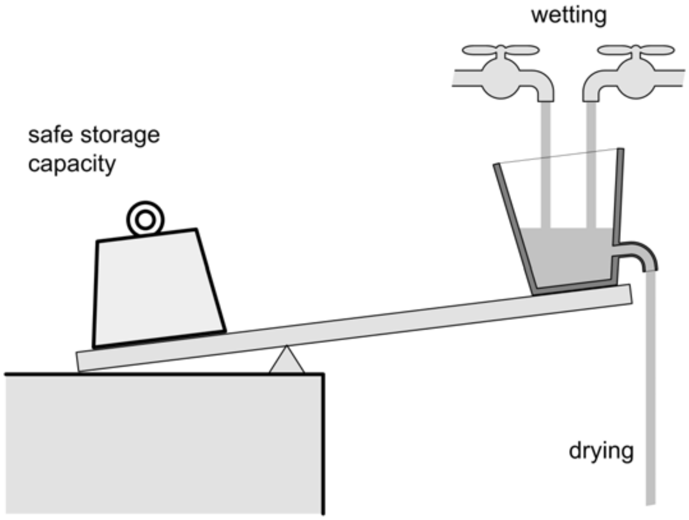


Figure 6 : Moisture balance

Many houses have damp, musty smelling basements that are uncomfortable, and can be unhealthy. Historically, people did not finish their basements into living spaces so it was not as much of a concern, but now basements are being converted to living areas, entertainment centres and bedrooms, so health and comfort are as much a concern as for above-grade space.

A foundation should control the amount of liquid water and water vapor entering the interior space from the exterior environment. This study assumes drainage details have been constructed correctly to limit the exposure of the exterior of the foundation to liquid water. There are many different strategies to ensure water is drained away from the foundation, but all systems require properly detailed drainage along the foundation footing to remove standing water. The foundation wall needs to have a drainage plane that directs bulk water to this footing drain. Often, a drainage membrane is installed against the exterior of the foundation wall to perform as both liquid water and water vapor barrier. The drainage membrane is rippled or corrugated and forms a space between the membrane and dampproofed concrete foundation wall, allowing any water against the foundation to drain to the drainage tile. This ensures that the foundation does not experience any liquid pressure head.

Even in arid climates, the ground is very close to 100% relative humidity. This means that moisture experienced by the foundation wall varies both over the height and over the year. At the bottom of the basement wall, the vapor drive is to the interior for the entire year, and the temperature is relatively stable. The above grade portion of the foundation wall is very different from below grade: the vapor drive is cycled daily through environmental variations of precipitation, wind and sun.

The hygrothermal simulations in this study do not consider liquid water uptake by capillarity into the footing and foundation wall, only vapor diffusion. It is important to recognize that water is often wicked up through the footing into the concrete wall. Once the liquid water reaches the interior or exterior of the basement wall, it must be evaporated to water vapor and travels by vapor diffusion. Since the exterior of the foundation is already close to 100% relative humidity, the moisture cannot dry to the exterior and it can only evaporate to the inside, which adds to the moisture load at the insulation layer. Water that is wicked through the footing can be stopped by applying a capillary break between the footing and the foundation wall. There are both liquid and sheet applied capillary breaks that will decrease the moisture load into the foundation wall and into the interior environment.

Since the foundation wall below grade is unable to dry to the exterior and there can be a significant amount of moisture present in the concrete, intuitively, the vapor drives should be allowed to dry to the interior and a polyethylene vapor barrier should not be built into the interior of the wood framed wall. Unfortunately, building codes have often specified polyethylene vapor barriers on the interior of framed walls in finished basements and these walls will be analyzed to understand why they often have serious moisture related problems.

The hygrothermal simulations conducted for this study are a one dimensional approximation of the hygrothermal behaviour of each wall system. In reality there are two and three dimensional interactions such as heat transfer up and down the concrete foundation wall as well as convective looping and moisture transport through air and vapor permeable insulations.

Boundary Conditions

The WUFI simulations were conducted in three parts because of the different hygrothermal regimes at the top above grade portion, middle and bottom below grade portions of the wall. The exterior below grade temperatures used for hygrothermal simulations were based on monitoring of ground temperatures in St. Paul MN as shown in Figure 7. The above grade temperatures for Minneapolis are included in the weather data for WUFI.

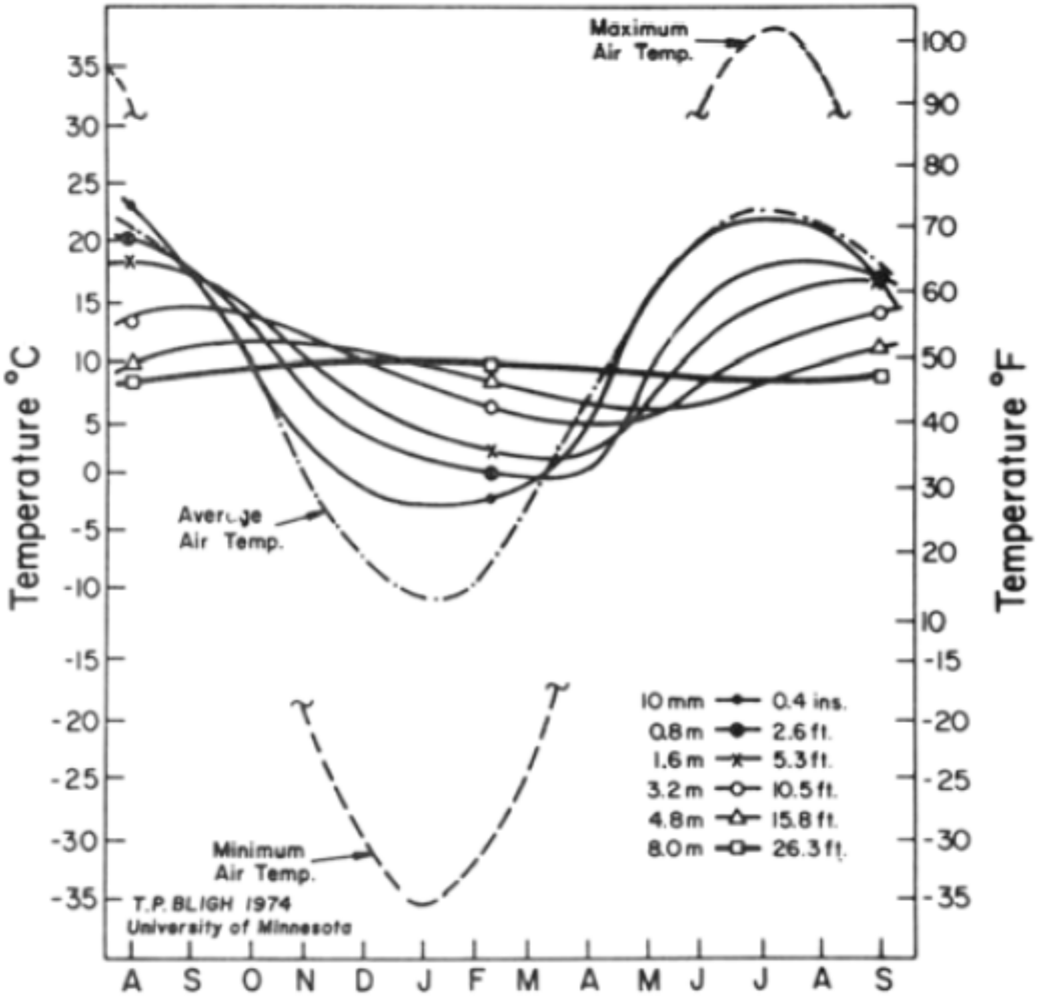


Figure 7 : Monthly temperature variation with soil depth, St.Paul, MN (Bligh 1975)

The relative humidity of the exterior for both the mid height and bottom of the foundation wall were set at 99.9%. In these simulations, only vapor diffusion from both the interior and exterior were simulated. If the concrete is in contact with liquid water, which is not uncommon, especially at the footing, capillary wicking will occur and significantly increase the moisture load to the surface of the concrete not only at the base of the wall but further up as well.

Interior temperature and relative humidities were chosen to represent a slightly higher than average moisture load for a cold climate house (Figure 8). These boundary conditions were simulated for 10 years to ensure that the foundation system was at equilibrium with both the exterior and interior environments.

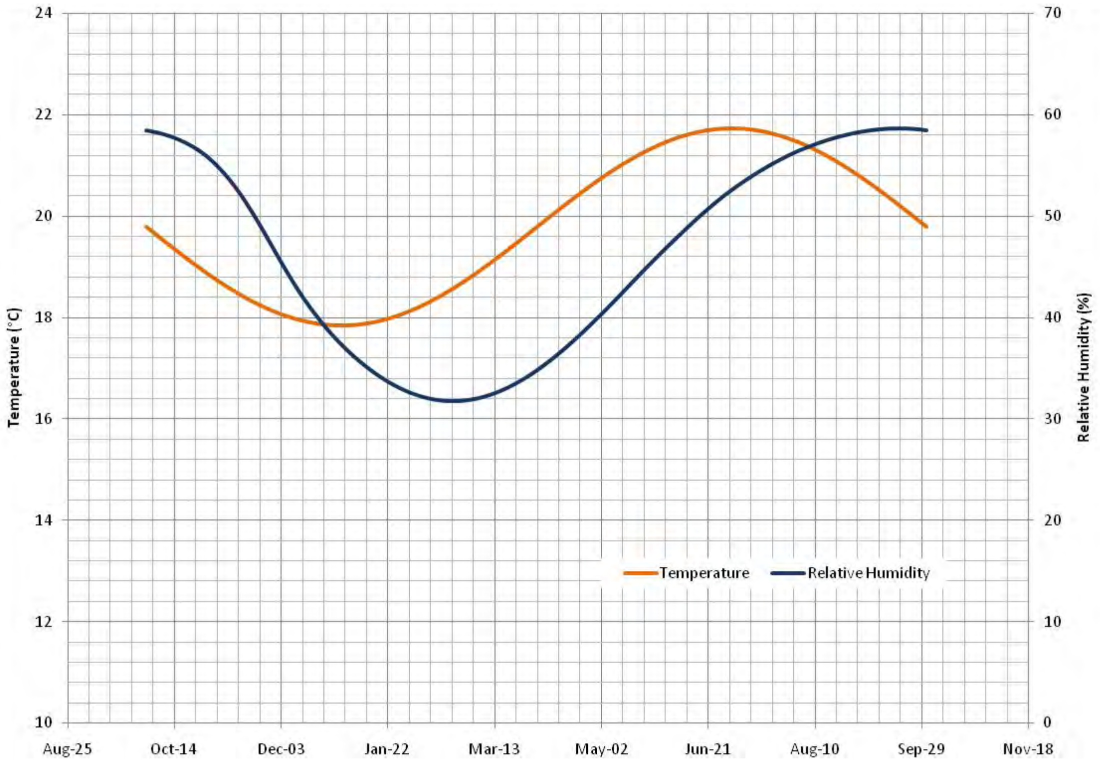


Figure 8 : Interior Temperature and Relative Humidity for Hygrothermal Simulations

2.2.1. Wintertime Condensation

In above grade walls, winter time air leakage and vapor condensation are concerns in cold climates. In the basement, the below grade foundation wall is often warmer than the exterior environment in the winter due to the heat sink of the ground, and the thermally massive storage. This means that winter time condensation is less of a concern on the foundation wall itself. In the above grade portion of the basement wall, there can be condensation as shown in the following hygrothermal analysis.

Of greater concern is the early summer when the foundation wall is cooler than the exterior environment and often the relative humidity in the environment can be quite high. If the relative humidity increases in the basement, this could result in condensation and elevated humidities at enclosure surfaces such as on the walls and floor. In basements with a carpet, the concrete slab is slightly insulated from the interior warmth and higher relative humidities are possible since the carpet is vapor permeable.

2.2.2. Summer Inward Vapor Drives

At the top of the foundation above grade wall there is potential for inward vapor drives because it is subjected to the warm summertime temperatures and solar drives. This will only occur where the wall is heated sufficiently to drive the vapor into the enclosure, and is evident in some wall assemblies in the hygrothermal analysis.

Polyethylene sheet bonded to batt insulation has typically been the construction strategy used for insulating basements in the past, but now, with increased understanding about the moisture physics of basements and below grade walls, the IRC states that Class I and II vapor retarders should not be used on any below grade wall or basements.

Some insulations installed directly against the foundation are effective vapor control layers and insulation layers as shown in the hygrothermal analysis.

2.2.3. ***Wall Drying***

Below grade walls experience elevated relative humidites on the exterior and thus must dry to the interior at all times. The above grade portion of the foundation wall can dry to either the interior or exterior depending on wall construction, but it is recommended that the entire basement wall be able to dry to the interior. In some cases, lower permeance coatings may be required but a Class I or II vapor control layer should be avoided.

2.2.4. Case 1 Un-insulated

Figure 9 shows the moisture behaviour of an un-insulated basement wall. Predicted relative humidities at the surface of the concrete wall show there is very little potential for condensation, only at the coldest time of year on the north orientation with no solar energy does the interior of the concrete get cold enough to condense water vapor from the interior environment with the simulated interior relative humidity levels.

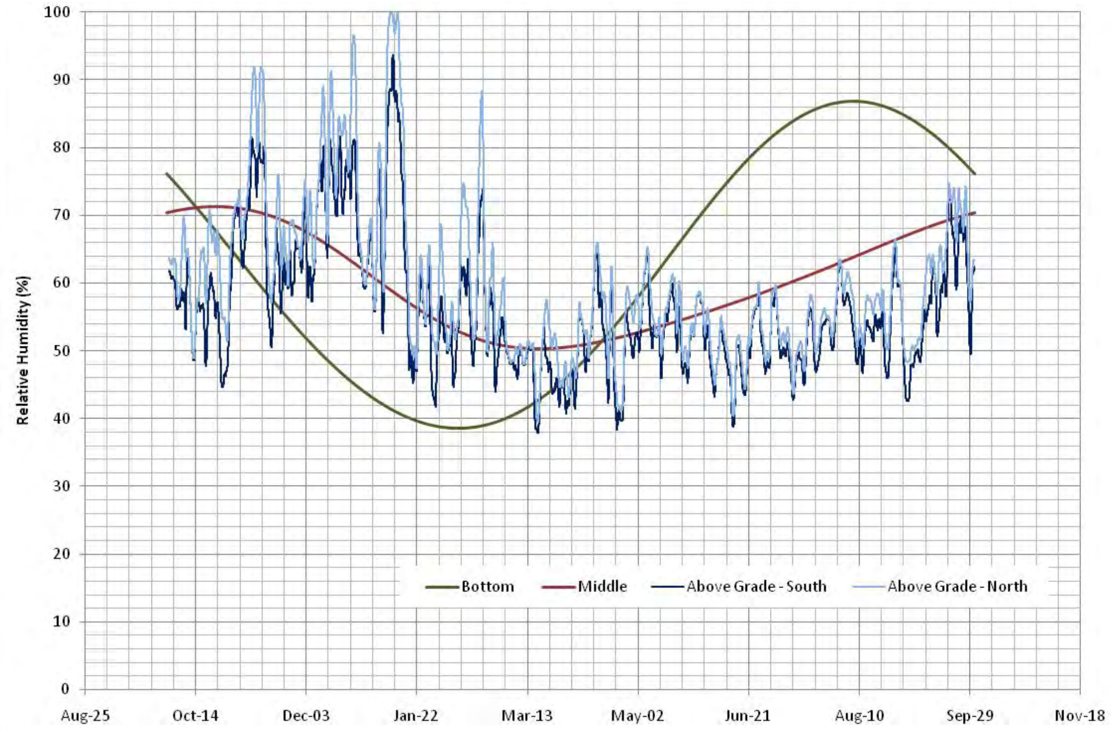


Figure 9 : Predicted Relative Humidity at the Surface of the Concrete Foundation Wall for Case 1

The predicted surface temperatures of the foundation wall and the dewpoint of the interior air are shown in Figure 10. This shows only a couple short instances of predicted condensation in early January, and only on the above grade portion of the north wall.

This analysis for the un-insulated basement assumes that the interior relative humidity is controlled to XX. This would likely require a dehumidifier since there are no vapor control layers on the foundation wall or basement slab and the moisture load from these surfaces would keep the RH in the basement space high. If the relative humidity is controlled to the these relative humidities as a minimum control, then this basement will perform reasonably from a moisture perspective, with little risk of mould. From a thermal control perspective, however, this wall is a very poor performer.

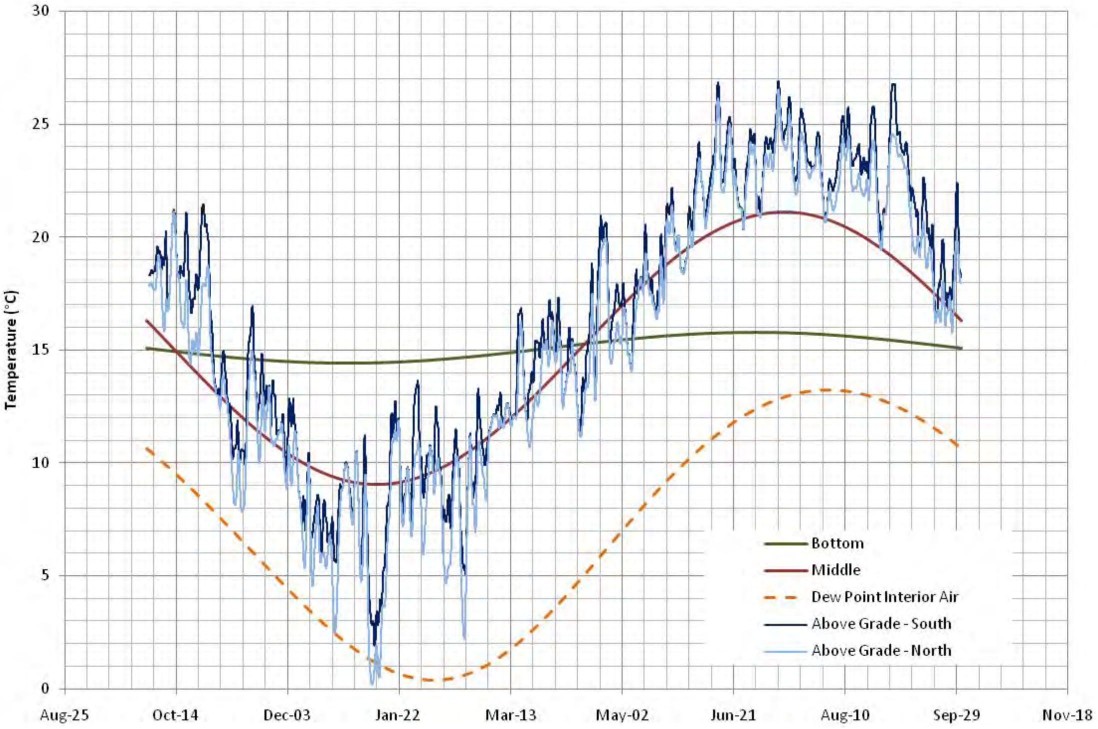


Figure 10 : Condensation Potential for Interior air on the Surface of the Concrete Foundation Wall

2.2.5. Case 3 code basement

Cases 2 and 3 were similar enough that separate simulations for both conditions were not required. These simulations were conducted with a polyethylene vapor barrier because there are many basements in existence built with a polyethylene vapor barrier on the interior surface of the wall. The IRC says in R601.3 that a Class I or II vapor retarder is not required on basement walls or the below grade portion of any wall. In other geographic areas such as parts of Canada, the building code with respect to basements has not been modified to reflect the large number of building failures, and the moisture physics of basements.

Many companies have an insulation product similar to a traditional roll batt with poly, but with a perforated facer that allows vapor to pass both ways through the interior surface, depending on the time of year and interior conditions. Simulations were not conducted yet to address a perforated facer, but intuitively, vapor diffusion will be higher both ways, and air leakage condensation will be significantly greater across a perforated facer than a non perforated facer. This is not a recommended insulation strategy.

Figure 11 shows the relative humidity at the surface of the foundation wall for wall Case 3. Not surprisingly it is quite high. The concrete is generally wet, both from capillary wicking and by vapor diffusion from the exterior. The relative humidity does decrease at the top of the foundation wall in the summer months, when the concrete is warmed by exterior temperatures. A perforated facer may decrease the relative humidity slightly, depending on the vapor permeance.

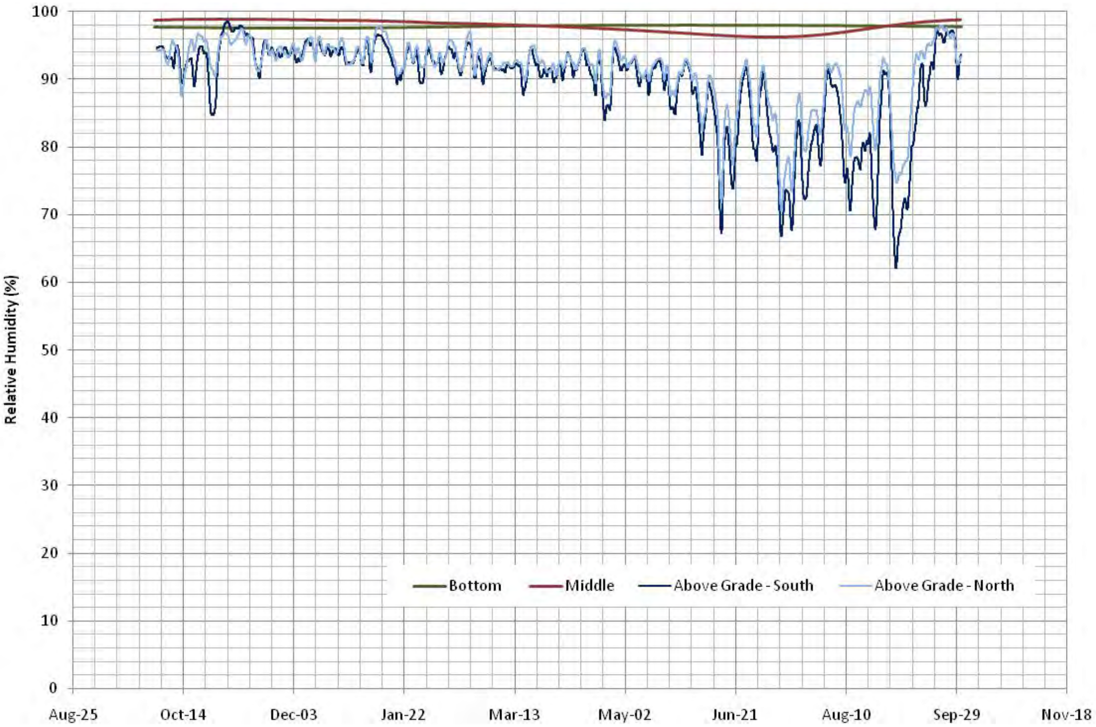


Figure 11 : Predicted Relative Humidity at the Surface of the Concrete Foundation Wall for Case 3

In the case of a well detailed polyethylene vapor barrier, it traps significant moisture in the wall as the wet concrete dries to the interior, but does not allow air leakage condensation. Figure 12 shows the potential air leakage condensation when the temperature of the foundation wall falls below the dewpoint of the interior air. There is significant condensation potential between October and January for the top half of the foundation wall, and from June to October at the bottom of the foundation wall. There is condensation potential for most of the year on the concrete foundation wall with the assumed conditions. A perforated facer would allow air leakage condensation to occur resulting in significant condensation.

This means that the wood framing near the concrete is sustained at or above 90% relative humidity all year, which will eventually cause mould since it is likely that there will be liquid water condensation in the wall system under these sustained conditions.

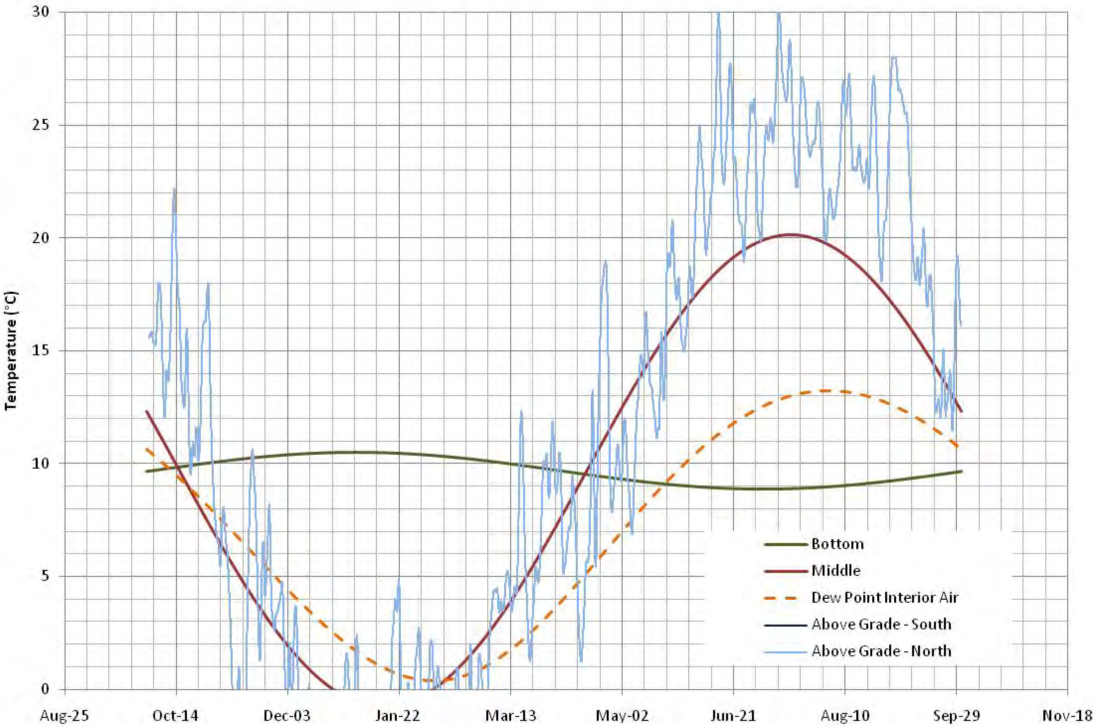


Figure 12 : Interior Air Leakage Condensation Potential for Case 3 Code Minimum Wall

Predictions were also made for the relative humidity at the exterior surface of the polyethylene vapor barrier since it is common in a basement to see condensation on the exterior surface of the poly. Figure 13 shows that between June and August, the relative humidity near the top of the wall is approximately 100% (higher on the south than north) resulting from inward vapor drives. A perforated facer could decrease this potential for increased relative humidity at the poly.

As mentioned previously, these simulations do not include capillary wicking for this analysis. In the future, this may be included, since the capillary wicking is a significant source of moisture in the concrete and basement wall system.

Figure 13 : Predicted Relative Humidity at the Surface of the Polyethylene Vapor Barrier for Case 3

2.2.6. Case 4 - 1" XPS and 3.5" Fibreglass Batt

Case 3 has serious moisture related risks caused by both vapor diffusion and air leakage condensation. One method of minimizing the potential risks is to install a vapor retarding layer that also provides insulation against the concrete foundation. 1" of XPS is only slightly vapor permeable, and has an R-value of R5. Assuming the XPS is well sealed to the concrete foundation, the condensation plane is now the interior XPS surface and will be warmer than the concrete, which should result in less potential condensation, and less vapor diffusion from the concrete. Expanded polystyrene (EPS) would also work as an air barrier but has a higher vapor permeance, so there would be more vapor diffusion from the exterior. Simulations would need to be conducted to assess the durability of substituting EPS for XPS.

Figure 14 shows the predicted relative humidity at the surface of the concrete foundation wall at the bottom and at the top of the foundation wall on the north orientation with three different vapor control strategies. Using only latex paint, the relative humidity reaches approximately 100% at the top in the winter and at the bottom in the summer. By using a vapor barrier paint (approximately 1 perm) on the drywall, the relative humidity in both the winter and summer improved.

Intuitively, by adding a polyethylene vapor barrier, the relative humidities were expected to increase. At the top of the wall, the relative humidity increased and was sustained for approximately three months, but the bottom of the wall showed no increase in relative humidity.

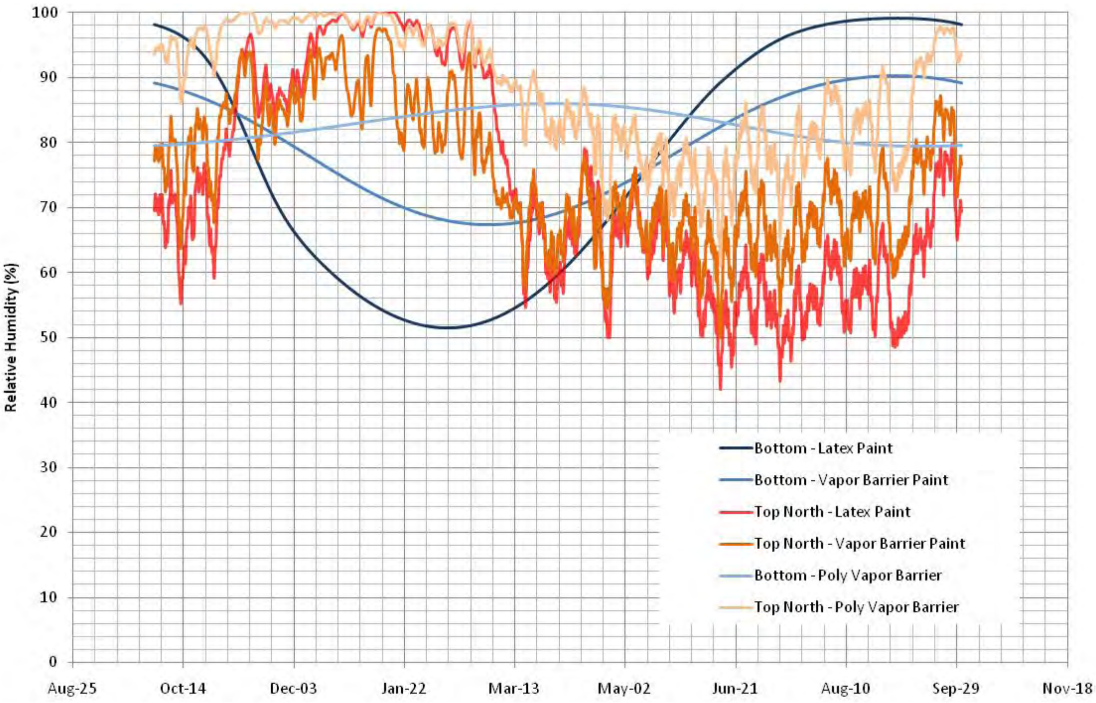


Figure 14 : Predicted Relative Humidity at the Interior Surface of XPS for Case 4

The air leakage condensation potential of Case 4 was much improved over Cases 2 and 3 as shown in Figure 15. There is still air leakage potential so the drywall must be made as air tight as possible.

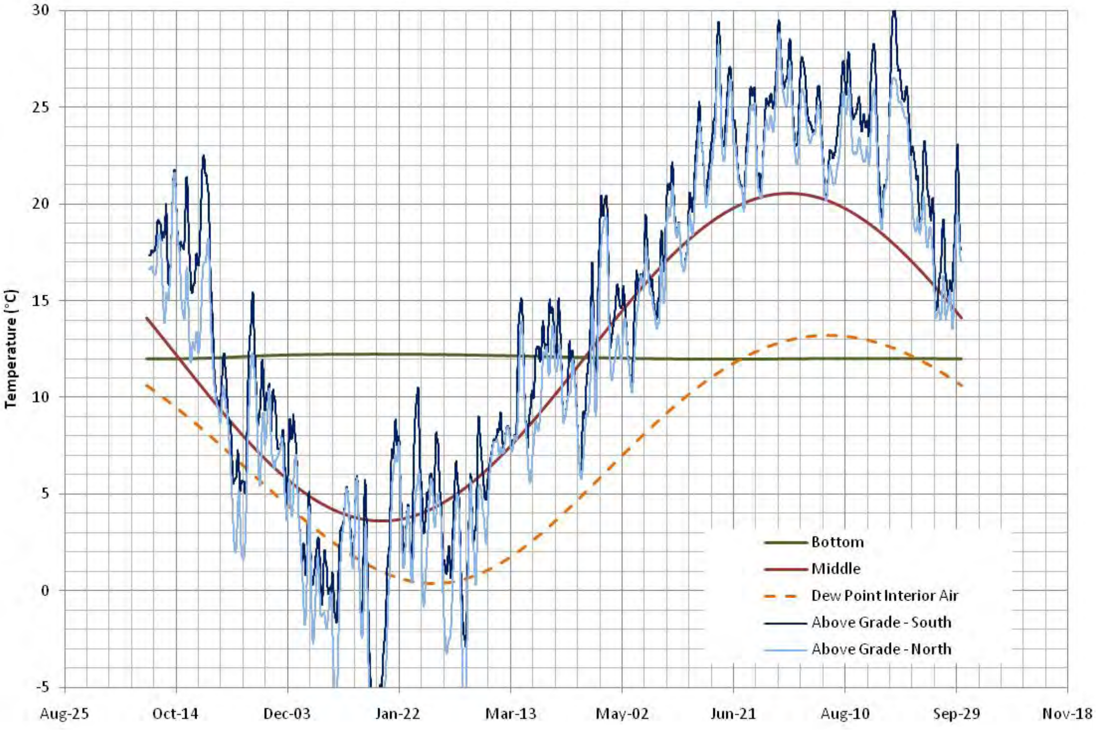


Figure 15 : Interior Air Leakage Condensation Potential for Case 4 Wall

Figure 16 shows the predicted surface relative humidites at the exterior of the drywall/poly vapor barrier depending on construction for Case 4. The top of the wall experiences inward vapor drives, so the wall with poly has the highest relative humidity. The vapor barrier paint allows more drying, and the latex painted wall has the lowest relative humidity.

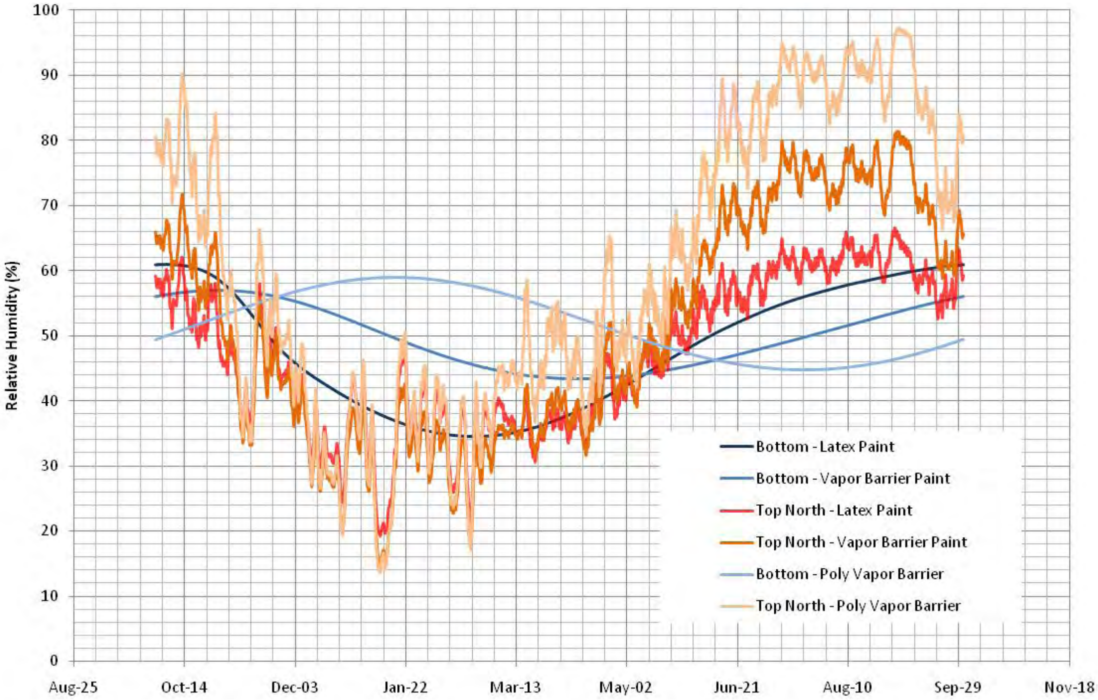


Figure 16 : Predicted Relative Humidity at the Exterior Surface of the Gypsum Board for Case 4

Case 5 - 2” XPS, 2” foil faced polyisocyanurate (PIC)

There was no reason to conduct hygrothermal simulations on Case 5. Provided there is no way for air to bypass the board foam insulation installed against the concrete foundation, there are no moisture related risks. The Insulation is an air barrier and vapor retarding, and is not moisture sensitive.

2.2.7. Case 6 - 3.5” 2.0 pcf spray foam

There were no expected moisture related issues with 3.5” of closed cell spray foam since the insulation is completely air impermeable and highly vapor retarding. The relative humidity between the concrete and spray foam is maintained at approximately 100% but neither material is moisture sensitive. One simulation was conducted to show the relative humidity at the midpoint of the spray foam once the system reaches equilibrium (Figure 17). There are no moisture related concerns with this wall construction strategy.

Closed cell spray foam is a useful method for retrofitting basements that have moisture and/or energy related issues, since it can act as a vapor barrier, air barrier, and capillary break.

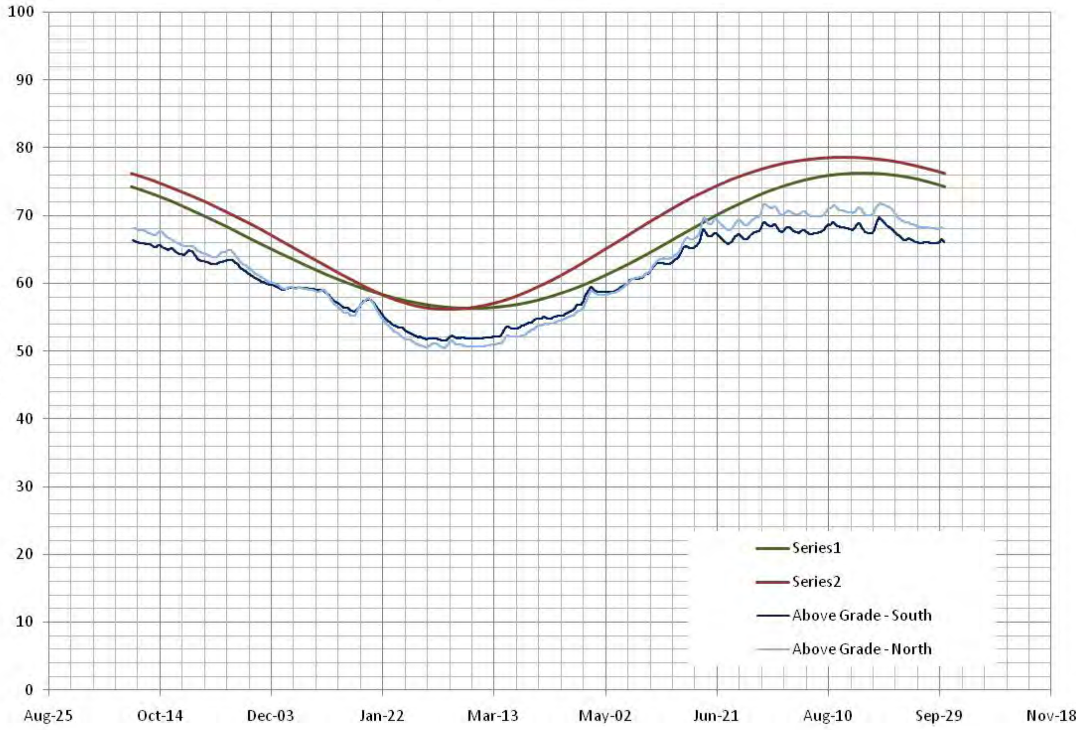


Figure 17 : Predicted Relative Humidity in the Center of Closed Cell Spray Foam Case 6

2.2.8. Case 7 - 6" 0.5 pcf spray foam

Similar to Case 6, open cell spray foam can be sprayed directly against the concrete foundation wall as an insulation strategy to form an excellent air barrier system. However, 0.5 pcf open cell foam is vapor permeable, so moisture related issues could occur under specific conditions. Using six inches of foam will help retard the vapor, and a simulation were conducted in the midpoint of the foam after the system reaches equilibrium to ensure that the relative humidities have decreased significantly from the foundation wall interface, which will be at approximately 100% relative humidity. Figure 18 shows that the relative humidities in the foam have dropped significantly and there are no moisture related risks for this system, provided no polyethylene vapor barrier is used on the interior surface to trap moisture into the system.

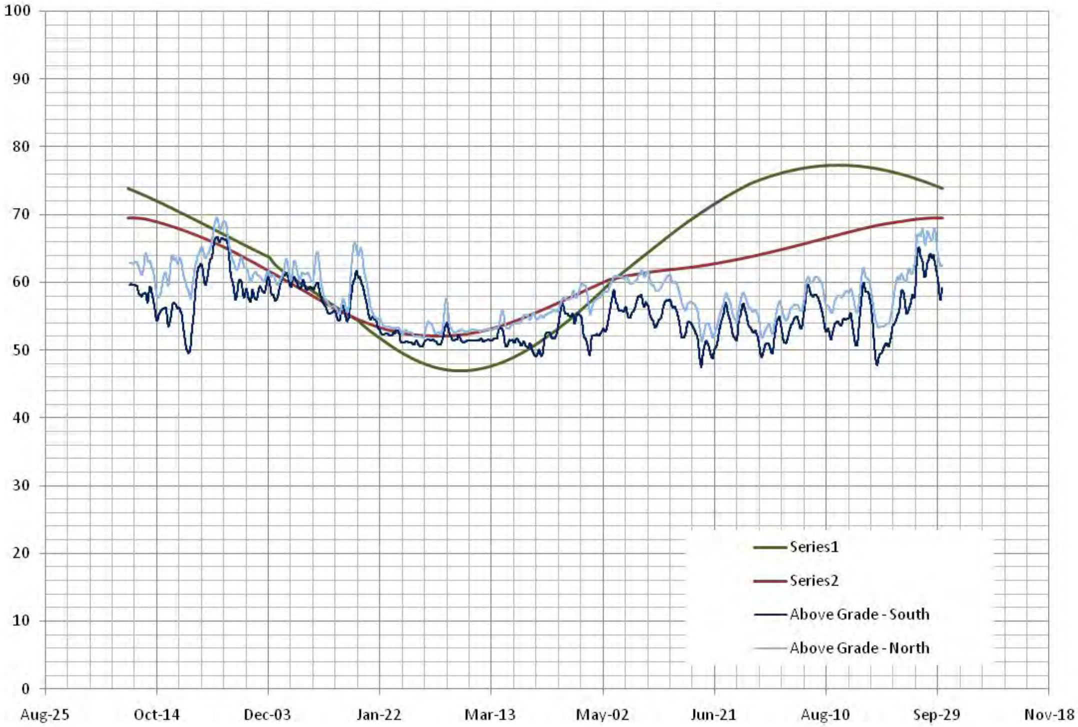


Figure 18 : Predicted Relative Humidity in the Center of Open Cell Spray Foam Case 7

2.2.9. Case 8 - 2” XPS and 3.5” fibreglass batt

Case 8 was not simulated because it will perform even better than Case 14, due to decreased insulation on the exterior of the condensation plane.

2.2.10. Case 9 - 2” PIC and 3.5” cellulose

Simulations were not conducted on Case 9 because of the similarity to Case 8 and Case 14. The PIC in Case 9 has a greater insulation value and decreased vapor transmission, so less moisture will enter the framed wall from the concrete foundation than in both Case 8 and Case 14.

2.2.11. Case 10 – 6” 0.5 pcf open cell foam with 2x4 framing offset 2” from foundation

No simulations were conducted on Case 10 because it will perform the same from a moisture perspective as case 7 as it also has 6” of 0.5 pcf open cell foam.

2.2.12. Case 11 - 4” XPS on the exterior

There are no moisture related issues with Case 11 if a capillary break is used at the bottom of the foundation wall. The XPS on the exterior acts as a vapor control layer, and capillary break, so the foundation sill stay warm, and drier (following drying of construction moisture). The largest source of moisture will be capillary wicking through the footing and bottom of foundation wall if it is not addressed.

2.2.13. Case 12 - 4” XPS in the center of foundation wall

Adding 4” of XPS to the center of the foundation wall acts as both a capillary break and vapor control layer resulting in less moisture on the interior and warmer surface temperatures. There is no need to simulate this assembly and little chance of moisture related issues. The largest source of moisture will be capillary wicking through the footing and bottom of foundation wall if that is not addressed.

2.2.14. Case 13 – ICF, 2” XPS on interior and exterior

Insulated Concrete Form foundations are a very durable and reliable construction strategy. The total of 4” of XPS will perform as both a capillary break and vapor control layer resulting in less moisture on the interior and warmer surface temperatures. The concrete in this wall system will take a very long time to dry completely since it is poured between two vapor control layers. This will not affect moisture related durability issues provided there is no Class I or II vapor retarder on the interior.

2.2.15. Case 14 - 2” XPS 5.5” Fibreglass Batt

Case 14 is the highest R-value assembly in this study at an installed insulation R-value of R29 with 2” of XPS at R10 and an R19 fibreglass batt. This wall was simulated with both latex paint and vapor barrier paint, since simulations with Case 4 a similar wall construction showed that a polyethylene vapor barrier increased moisture related durability risks.

Figure 19 shows that there are elevated relative humidities at the surface of the XPS caused by vapor diffusion for a short period during the winter months at the above grade portion of the wall. This risk is decreased slightly with a vapor barrier paint on the gypsum board.

In the summer months, the relative humidity is elevated at the bottom of the wall if latex paint is used as vapor control but decreased if a vapor barrier paint is used.

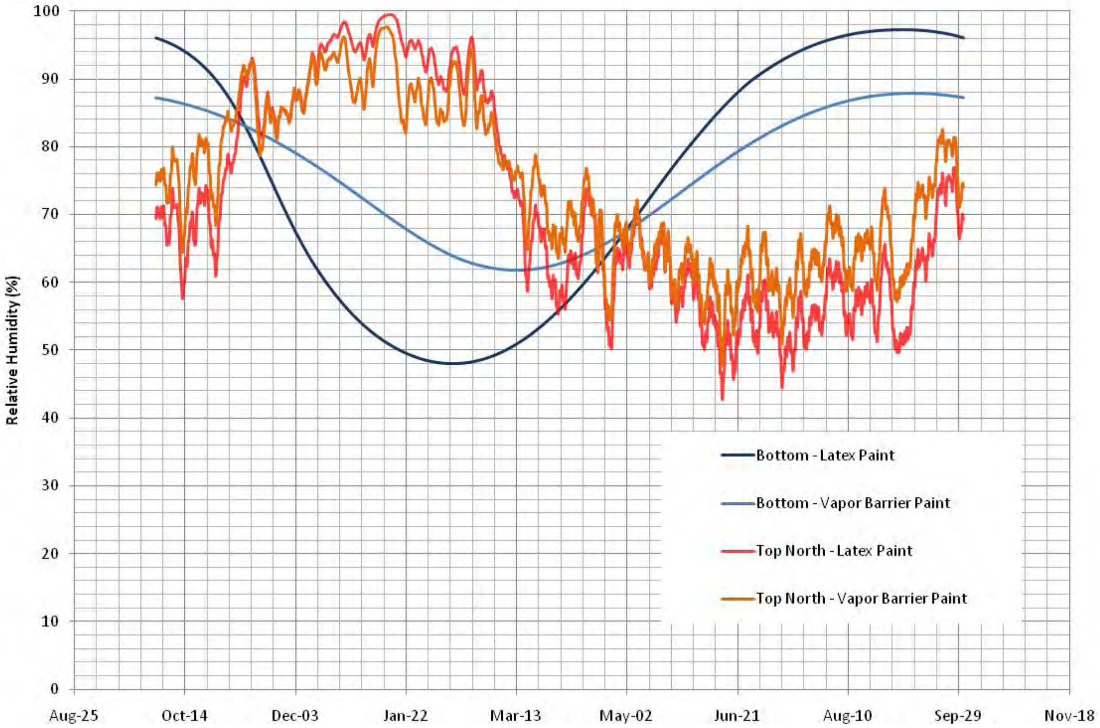


Figure 19 : Predicted Relative Humidity at the interior Surface of the XPS for Case 14

There is potential for some air leakage condensation in the above grade portion of this wall system although significantly less than Case 4. Cases 8 and 9 with less air permeable insulation to the interior of the XPS will have even less potential since the condensation plane will be warmer. Airtight drywall details can be used to minimize the potential for air leakage condensation.

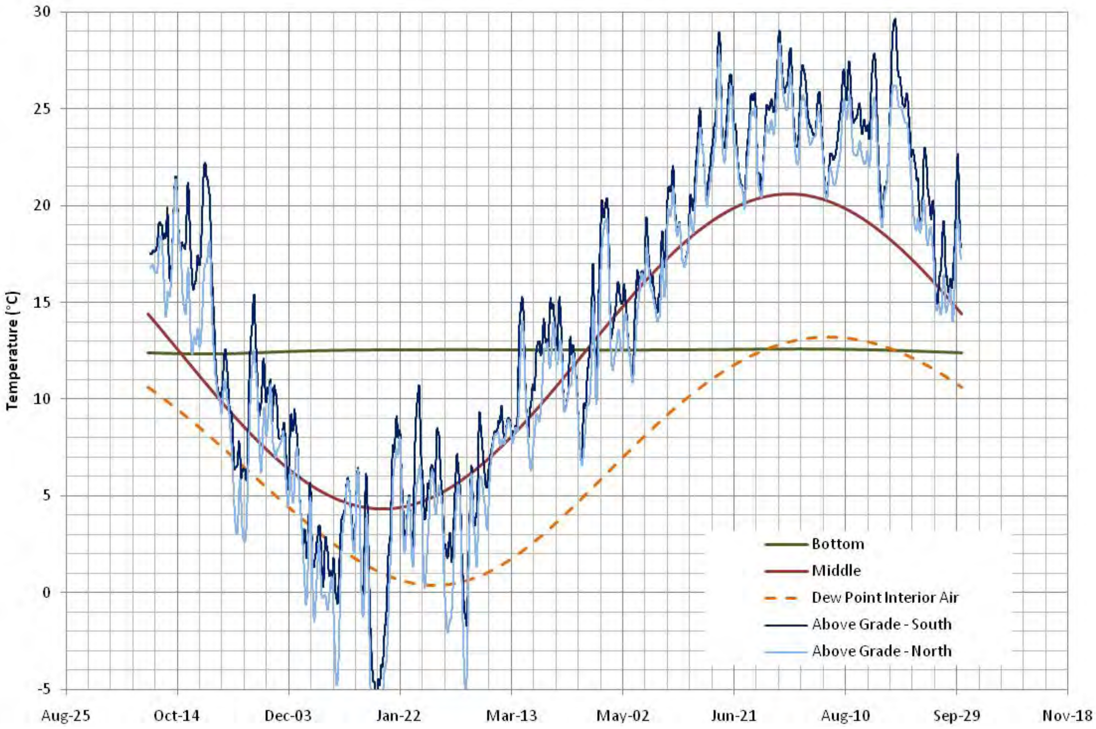


Figure 20 : Interior Air Leakage Condensation Potential for Case 14 Wall

The relative humidity was predicted at the exterior surface of the gypsum wall board in Figure 21, which shows there is no moisture related issues at the interior of the wall system. As shown previously, a polyethylene vapor barrier would increase the relative humidity in the system, and significantly decrease drying of the wall system.

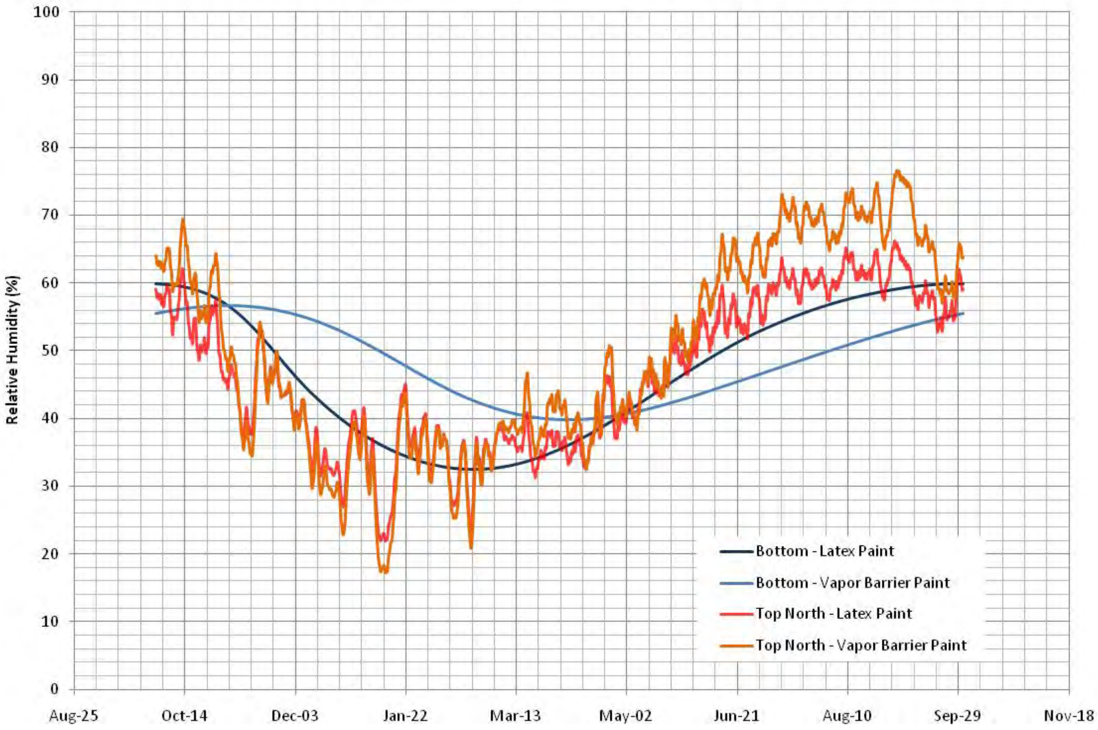


Figure 21 : Predicted Relative Humidity at the Exterior Surface of Gypsum Board for Case 14

2.3 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 drying of water leakage events, air leakage 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, hygric buffering capacity, and susceptibility to moisture related damage.

2.4 Buildability

Buildability is a key comparison criterion 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 buildability. The simpler a system is to install correctly, the more preferable it is to use.

2.5 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, and the advantages of increased thermal control should be balanced against the disadvantages of increasing the building materials and embodied energy.

In the case of some insulations such as XPS and high density spray foams, the global warming potential is quite high, meaning the effect on global warming can be two orders of magnitude greater than other insulation strategies. These significant global warming potentials are caused by the use of chemicals used in the production of the insulation such as HFC-142b, HFC-134a, and HFC-245fa. These chemical have between 1000 and 2000 times more global warming potential than Carbon dioxide meaning that one kg of HCFC-142b is 2000 times worse for blobal warming than 1 kg of CO_2.

Embodied energy is the total energy required to get a specific product to the construction site including all energy to obtain the raw materials, processing energy and transportation 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 insulations. Materials that are produced locally require less shipping and decrease the embodied energy required.

2.6 Cost

The factor which generally has the greatest influence on implementation of a building enclosure strategy, particularly for production builders, 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. When deciding which recommended system to use, some cost estimates should be determined for your locale.

2.7 Other Considerations

There are often factors, such as occupancy comfort and health that do not quite fit in the other categories, but are rather a combination of the other comparison criteria. One health related criteria, generally associated with basements is radon gas. Radon protection is not dealt with in this report, but during construction, it is very easy to install components that will make radon protection simple in the future should radon be an issue. In fact, some recommended measures taken to increase the thermal resistance of a basement assembly can be detailed to be part of a passive radon system. For example, the subslab gravel bed, which has been identified as a capillary break in this report, also serves the purpose of collecting soil gas if a vent stack is also installed during construction. Also, detailing air barrier system in a continuous manner through the foundation assemblies increases the thermal performance and blocks soil gas infiltration.

In some geographic areas, some levels of radon protection will be required in new construction under the building code in the near future. More information about radon and soil gas resistant construction can be found on the US EPA’s website (http://www.epa.gov/radon/).

C.Results

1. CASE 1 : UNINSULATED FOUNDATION WALLS AND SLAB

The uninsulated basement case was included in this analysis because there are uninsulated basements in existence even though the code requirements in DOE climate zones 4 and higher do not allow an uninsulated basement in new construction. The uninsulated basement was included as a baseline for comparison purposes.

1.1 Thermal Control

There is no thermal control in the foundation walls or slab. This results in high energy losses for most of the year. Significant whole house energy savings can be experienced if the basement is insulated but care should be taken to design the thermal control appropriately to the construction type to decrease the risk of moisture related issues following an energy retrofit. Predicted annual heating energy loss based on the selected simulation criteria is 57 MBtus.

1.2 Moisture Control

Since there is no insulation, there is likely no moisture control in the basement. Water vapor from the exterior is a constant moisture source, and capillary wicking through the footing and/or foundation wall may also be a significant moisture source increasing the risk of moisture related issues.

WUFI analysis of the uninsulated basement in the Hygrothermal analysis section showed no significant moisture related issues (Figure 9 and Figure 10), if the relative humidity is controlled with a dehumidifier, although the basement will likely still smell damp and musty.

1.3 Constructability and Cost

There is no construction cost to leaving the basement uninsulated, but there are significantly higher energy costs.

1.4 Other Considerations

It is not recommended to leave the basement uninsulated from an energy, comfort, and health perspective. There are many different retrofit strategies that could be used, some of which are included in this analysis.

2. CASE 2 : CODE MINIMUM R10 CONTINUOUS INSULATION

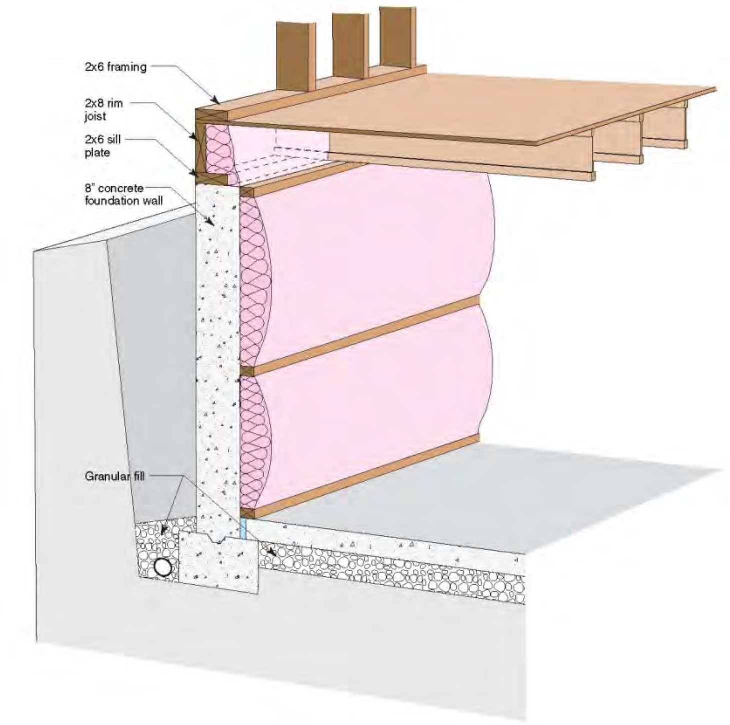


Figure 22 : Typical Code Compliant Basement Insulation Strategy

According to the IECC, new residential construction in DOE climate zones 4 and greater must be constructed with continuous R10 insulation or R13 in a framed wall. Continuous R-10 is typically installed by applying a roll batt directly to the foundation wall which consist of fiberglass batt. In some areas, the roll batt is covered with a polyethylene vapor barrier, as was simulated in the hygrothermal analysis. In the IRC, there have been improvements to the building code which do not allow Class I or II vapor control layers in the basement or on the below grade portion of any wall. Commonly a perforated facer is used which is vapor and air permeable.

2.1 Thermal Control

The installation of R10 continuous insulation, even as a roll batt, has significant energy improvements over uninuslated foundations, with savings of approximately 31 MBtus (more than half of an uninsulated basement) according to simulations. Roll batt is used because it is very inexpensive and meets code, although there are other alternatives that peform better, as shown in some of the following cases. These alternatives are more expensive for the contractor, and homeowners are unaware of the benefits.

2.2 Moisture Control

There are moisture issues with this insulation strategy that are evident both in field investigations and simulations. Fiberglass batt is air and vapor permeable, so moisture and air can move through the insulation. As can be seen in Figure 11, the relative humidity against the concrete foundation wall is elevated through the entire year. If there is air leakage (or the facer is air permeable) there is condensation potential on the concrete foundation through most of the year as shown in Figure 12. Because these simulations are one dimensional, they are good approximations, but heat flow in the foundation wall is three dimensional. Also, in the air permeable insulation, convective looping is likely, which may increase the condensation above predicted results. Field investigations show that it is quite common to get high quantities of mould in this wall system

2.3 Constructability and Cost

This is the most inexpensive alternative in terms of initial capital cost, which is the reason it is chosen. Continuous roll batt makes finishing the basement with gypsum board difficult, unless the roll batt is removed.

2.4 Other Considerations

This wall is not recommended based on this analysis, other reports, and field investigations of mouldy basements.

3. CASE 3 : R13 FIBERGLASS BATT IN A 2X4 FRAMED WALL

Case 3 is a second alternative to the minimum code required basement insulation in DOE climate zones 4 and higher. This construction uses a 2x4 framed wall against the concrete foundation with R13 batts in the stud space. The hygrothermal simulation and a polyethylene vapor barrier on the interior.

3.1 Thermal Control

This construction technique performs very similarly to Case 2. The parallel path method, taking into account the higher conductivity of the framing members at 24" on center results in a R-value inside the concrete wall of R12.6**.** This results in a total annual predicted heating energy loss 23.9 MBtus.

3.2 Moisture Control

This insulation strategy has a very similar poor moisture control level to Case 2. Moisture is constantly moving from the below grade exterior portion of the foundation wall to the interior, and becoming trapped in the framed wall cavity. The relative humidity is elevated and condensation is almost guaranteed both on the concrete wall and on the polyethylene vapor barrier throughout the year (Figure 11**)**. If there is air leakage (or the facer is air permeable) there is condensation potential on the concrete foundation through most of the year as shown in Figure 12. Because these simulations are one dimensional, they are good approximations, but heat flow in the foundation wall is three dimensional. Also, in the air permeable insulation, convective looping is likely, which may increase the condensation above predicted results. Field investigations show that it is quite common to get high quantities of mould in this wall system

3.3 Constructability and Cost

This wall is slightly more expensive than Case 2 because of the framing lumber required but does have the added benefit of being able to finish it easier by adding services and ddrywall easier.

3.4 Other Considerations

This wall construction technique is not recommended, because of the obvious moisture related durability issues observed continuously in the field, and shown by simulations. The wood framing in this wall is at risk for mould and rot after prolonged exposure to the conditions predicted in the wall system.

4. CASE 4 : 1" XPS, 2X4 WOOD FRAMED WALL WITH FIBREGLASS BATT

This insulation strategy is similar to case 3 but with the added insulation value, and moisture control, of 1" of XPS between the framed wall and concrete foundation wall.

4.1 Thermal Control

This wall has a parallel path calculation method of R18 because the thermal bridging of the framed wall is minimized, the overall improvement in Rvalue is R5.4 for one inch of R5 insulation. Adding 1" of XPS results in an energy savings of 2.2 MBtu over Case 3 without an inch of XPS, but will also reduce convective looping because the temperature gradient in the framed wall is less.

4.2 Moisture Control

The greatest benefit to adding 1" of XPS is arguably for moisture control and not thermal control. XPS controls the flow of water vapor from the concrete to the framed wall, from both vapor diffusion through the concrete and capillary wicking up the wall, reducing the relative humidity in the wall cavity. Small amounts of moisture (too small to drain) between the XPS and concrete is irrelevant because neither concrete or XPS is susceptible to moisture issues. The XPS must be well attached to the concrete foundation, and sealed, so air is not able to bypass the XPS insulation.

Ths XPS insulation also increases the temperature of the condensation plane, minimizing condensation of elevated interior relative humidity. Figure 15 shows that there is still potential for moisture condensation but it is significantly less than Case 3.

Figure 14 shows the relative humidity levels at the interior surface of the XPS which are significantly lower than the surface of the concrete in Case 3. The relative humidity is shown to be a function of the vapor control on the interior surface, with vapor barrier paint (approx 1 perm) performing better than latex paint or a poly vapor barrier. Even with just latex paint, the risk of moisture issues is minimal, if the relative humidity in the basement is controlled.

4.3 Constructability and Cost

The constructability of this wall system is not difficult, but care should be taken that air is unable to get behind the XPS. This could be accomplished with tape, caulking, cans of spray foam or a combination of the three. It is not likely that tape will maintain a good air seal for the desired lifetime of the wall system. This wall performs significantly better than Case 3, at only a small increased cost.

4.4 Other Considerations

This wall construction is recommended over Cases 2 and 3, but there are better options for thermal and moisture control that are more recommended and discussed in the following Cases. This is an affordable option that many people could do themselves, with significantly less moisture related risks than Cases 2 and 3, resulting in a more comfortable and healthy space.

5. CASE 5 : 2" XPS, 2" FOIL FACED POLYISOCYANURATE

When constructing with plastic board foams, the building codes require that the foam not be left exposed as a fire hazard. Thermal barriers are required over both board foams and spray foams in many cases. Thermax™ from Dow is a thermally rated foam board insulation that can be left exposed and could be used in this system. Gypsum board could also be used to cover the insulation, but in some geographic areas, gypsum board can only be installed if the basement is wired to code.

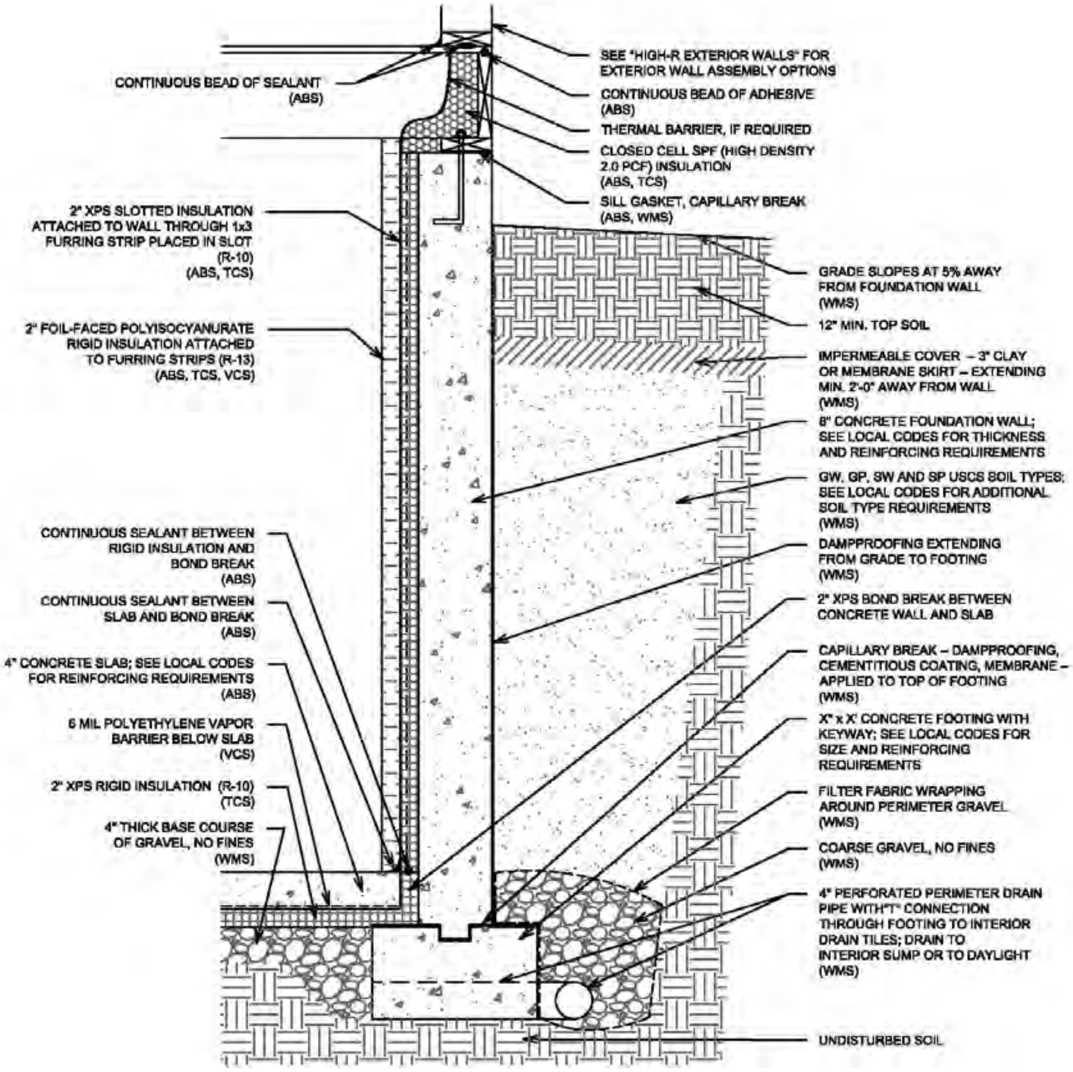


Figure 23 : Case 5 Detailed Drawing – Recommended Foundation Wall System

5.1 Thermal Control

This proposed wall system performs very well thermally at approximately R23, and in combination with underslab insulation and thermal break at the slab edge as shown in Figure 23, the predicted annual heating energy loss is 15.8 MBtus. This is an improvement of 40.8 MBtus over an uninsulated wall.

5.2 Moisture Control

Provided that air can not bypass the insulation layers, this strategy will not experience any moisture related issues from vapor diffusion, or capillary wicking. Capillary wicking is limited by the thermal/capillary break at the edge of the slab, and specified on top of the footing.

5.3 Constructability and Cost

The seams in the two layers of foam insulation should be offset and well sealed. A thermal barrier is required by code in most jurisdictions. Thermax ™ by Dow is a foil faced polyisocyanurate insulation that is code compliant.

5.4 Other Considerations

A stud wall will still need to be constructed to finish this basement with services and drywall, so if the long term plan is to finish basement, this proposed wall system may not be the most economical choice.

This basement insulation strategy is recommended as a durable, comfortable, and healthy basement system.

6. CASE 6 : 3.5" 2PCF CLOSED CELL SPRAY POLYURETHANE FOAM

As shown in Figure 24, the spray foam can be applied directly to the concrete, but as previously mentioned (and specified in the design details), if the foam is left exposed it will require a thermal barrier, typically a spray-on thermal barrier. The other option is to build a stud wall in front of the spray foam and use gypsum wall board is the thermal barrier.

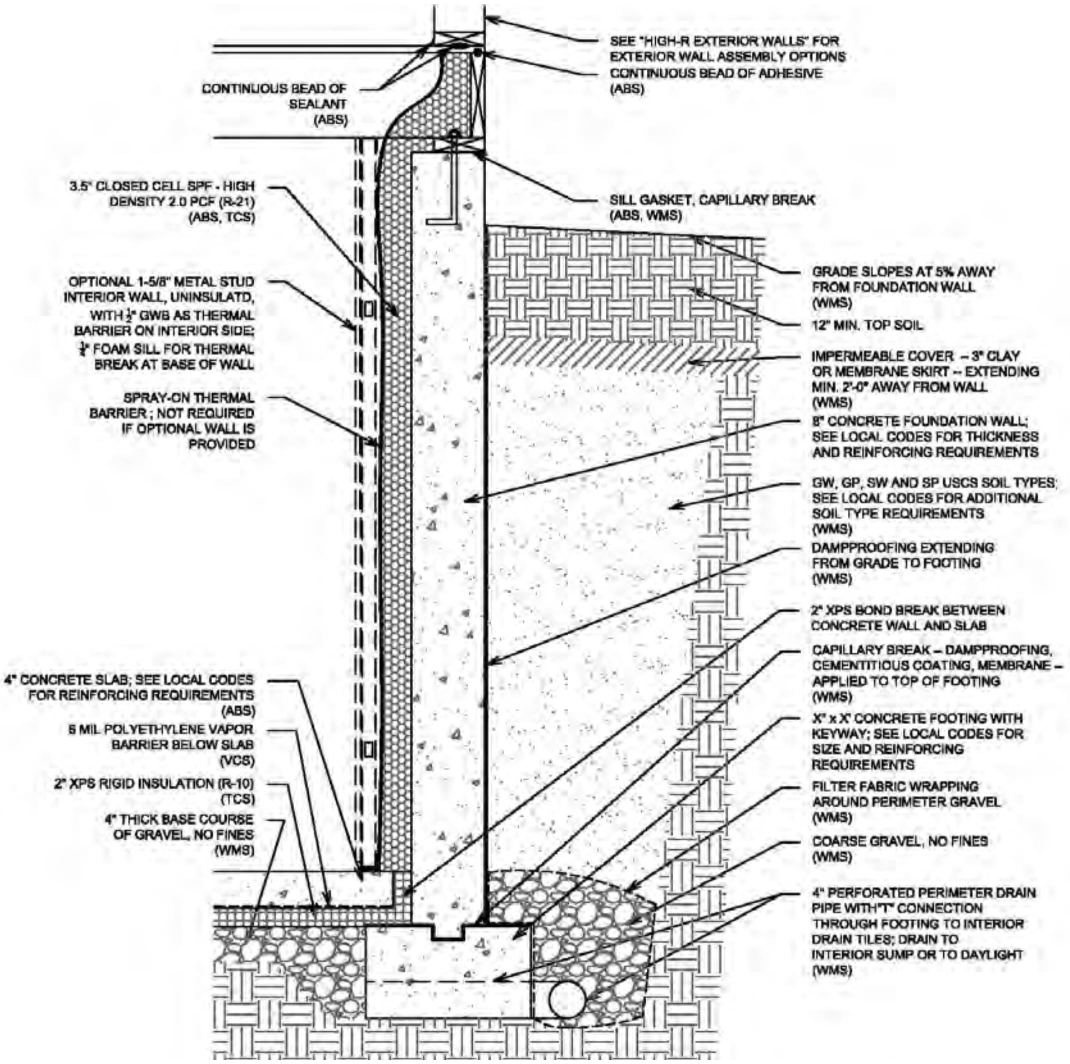


Figure 24 : Case 6 Detailed Drawing – Recommended Foundation Wall System

6.1 Thermal Control

Closed cell spray foam provides very good continuous thermal control. Spray foam is an air barrier, so convective looping and air leakage thermal losses do not occur. This wall system has an R-value of R21 and a predicted annual heating energy loss of 16.4 MBtus. More thermal control could easily be added by spraying more foam against the wall.

6.2 Moisture Control

Because closed cell spray foam is an air and vapor barrier, there are no risks to air leakage or vapor diffusion condensation. The concrete is unable to dry to the interior through closed cell spray foam, but concrete is generally not affected by a high moisture content. Figure 17 shows the relative humidity in the middle of the foam does not exceed 80%, which means there are no moisture related risks from vapor diffusion.

6.3 Constructability and Cost

In this proposed wall system, it is possible to embed the framing members in the foam (similar to Case 10, to increase the interior space. The framing should not be in contact with the foundation wall to limit thermal bridghing, and potential moisture related issues with the framing members. Closed cell spray foam can be more expensive than other options, but reduces labour time over some of the other walls, and is applied by a skilled labourer so the system is very durable as a long term solution.

Spray on thermal barriers can add significant cost to the spray foam installation, but are region specific.

Closed cell spray foam installed on the interior of the concrete foundation wall is the easiest and safest way to retrofit an existing basement. Spray foam can be installed in combination with a drainage matt and interior drainage tile in basements that are very leaky.

6.4 Other Considerations

Spray foams have been improved considerably for human health and the environment. Ozone depleting substances in the process have been removed, but some spray foams use greenhouse gases that are much worse than carbon dioxide. There are options available of more environmentally friendly spray foams that do not release green house gases, such as water blown foams, on the market and should be considered.

7. CASE 7 : 6” 0.5PCF OPEN CELL SPRAY FOAM

As shown in Figure 25, open cell spray foam can be applied directly to the concrete, but as previously mentioned (and specified in the design details), if the foam is left exposed it will require a thermal barrier, typically a spray-on thermal barrier.

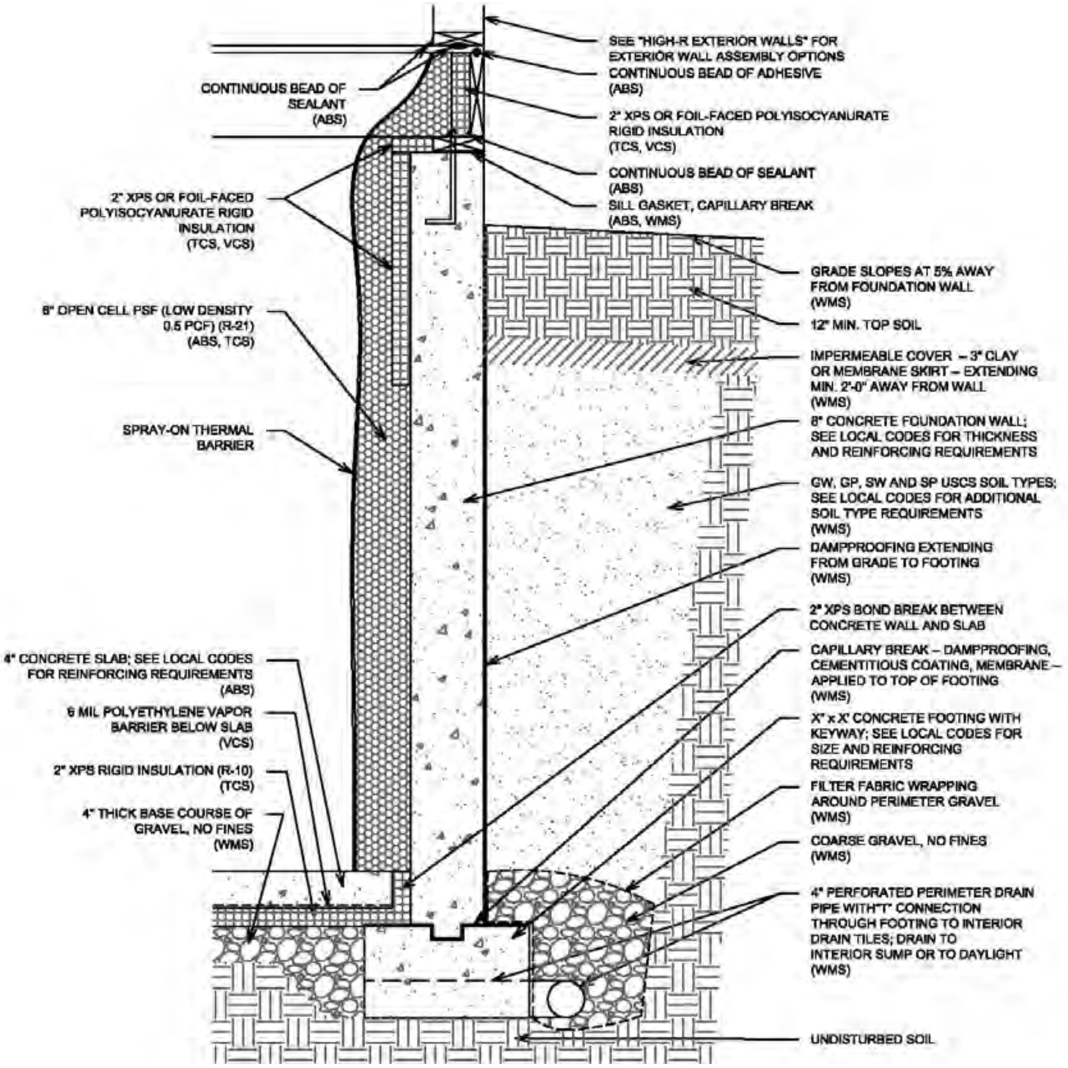


Figure 25 : Case 7 Detailed Drawing – Recommended Foundation Wall System

7.1 Thermal Control

Open cell spray foam provides very good continuous thermal control. Spray foam is an air barrier, so convective looping and air leakage thermal losses do not occur. This wall system has an R-value of R21 and a predicted annual heating energy loss of 15.8 MBtus.

7.2 Moisture Control

Open cell spray foam is an air barrier, but is vapor permeable. Figure 25 shows the XPS insulation detail required at the above grade portion of the foundation wall for cold climate construction to minimize moisture condensation at the cold concrete in the winter months, and minimize inward driven vapor in the summer months.

The relative humidity was predicted in the center of the open cell spray foam insulation and was found to be at safe levels (Figure 18).

Low permeance interior wall finishes should be avoided with this construction strategy.

7.3 Constructability and Cost

Open cell spray foam is less expensive than closed cell spray foam but vapor control should be considered, and does decrease the interior useful space.

This proposed wall system does not allow for finishing of the basement without installing an interior framed wall. If the longterm goal is to finish the interior of the basement, Case 10 should be considered instead.

Spray on thermal barriers can add significant cost to the spray foam installation, but are region specific.

7.4 Other Considerations

This is a recommended wall construction provided that the details for cold climates are followed, including an extra layer of vapor condensation protection for the above ground portion of the wall.

Spray foams have been improved considerably for human health and the environment. Ozone depleting substances in the process have been removed, but some spray foams use greenhouse gases that are much worse than carbon dioxide. There are options available of more environmentally friendly spray foams that release green house gases, such as water blown foams, on the market and should be considered.

8. CASE 8 : 2” XPS, 2X4 FRAMING WITH FIBREGLASS BATT

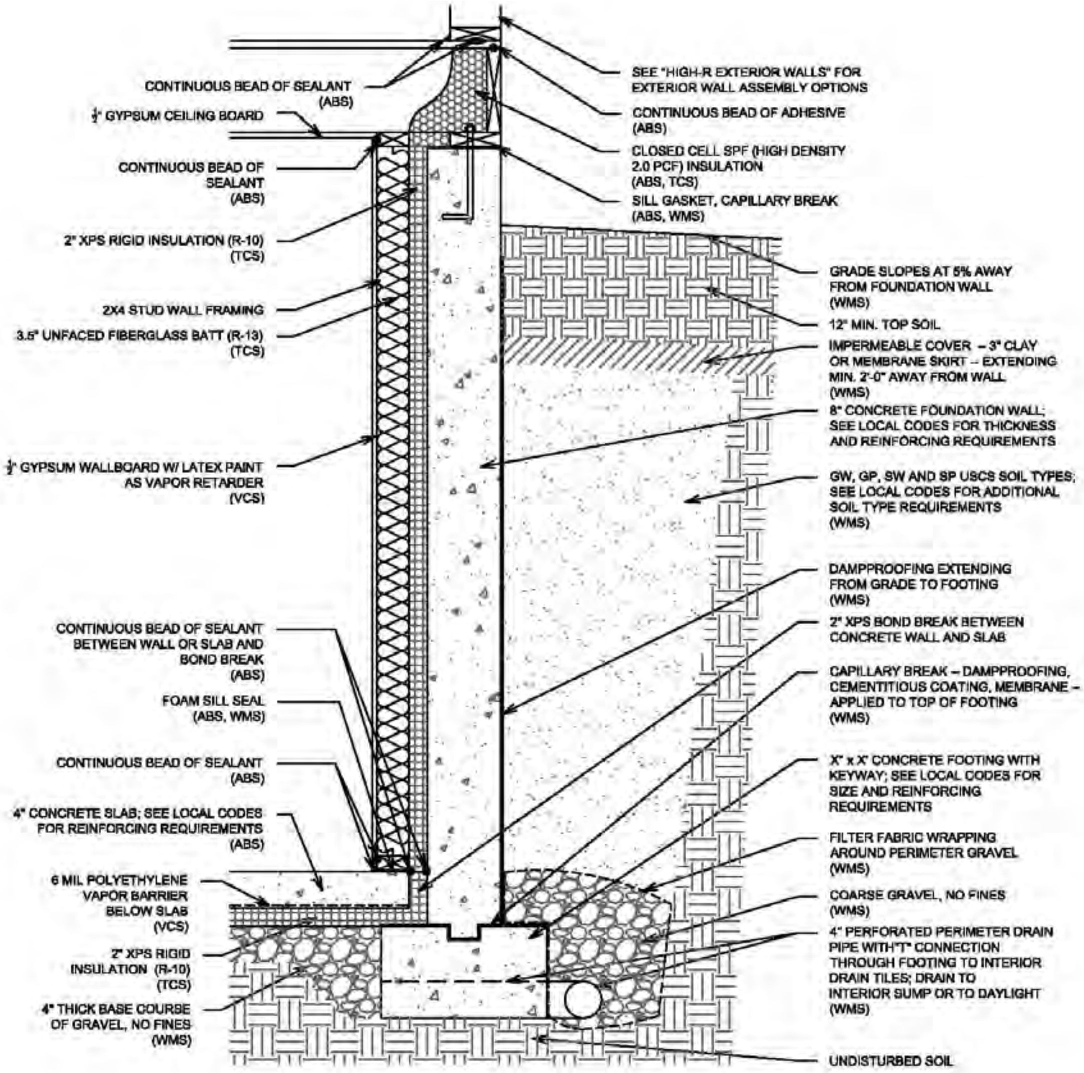


Figure 26 : Case 8 Detailed Drawing – Recommended Foundation Wall System

8.1 Thermal Control

This wall system has an installed insulation R-value of R23 which is only slightly lower based on the parallel path calculation method which accounts for the wall framing assuming 24” on center. This basement combined with R10 under the slab and R10 thermal break results in an annual predicted heating energy loss of 15.83 MBtus.

8.2 Moisture Control

The water vapor diffusion and capillary wicking are controlled by 2” of XPS insulation assuming that the XPS is well sealed to the concrete. This wall system was not hygrothermally simulated since it will perform better than Case 14 from a moisture point of view, and Case 14 performed well. Case 14 has 5.5” of fibreglass batt insulation which will result in colder condensation plane. Case 14 had some condensation potential but improved performance with a vapor retarding paint. There was some potential for air leakage condensation at the above grade section of the wall in the winter alternating with drying periods.

8.3 Constructability and Cost

It may be difficult to get 2” boards of XPS attached well to the nonuniform surface of the concrete foundation because the insulation is so stiff. It is easier in some cases to use 2 1” thick boards, that will flex over imperfections. The joints in the insulation should be offset if two layers of 1” XPS are used.

8.4 Other Considerations

Case 8 is one of the simplest and least expensive methods of minimizing the moisture risk and saving energy. It is possible to use other air permeable insulations instead of fibreglass batt including damp spray cellulose, or spray fibreglass.

9. CASE 9 : 2” POLYISOCYANURATE INSULATION, 2X4 FRAMING WITH CELLULOSE

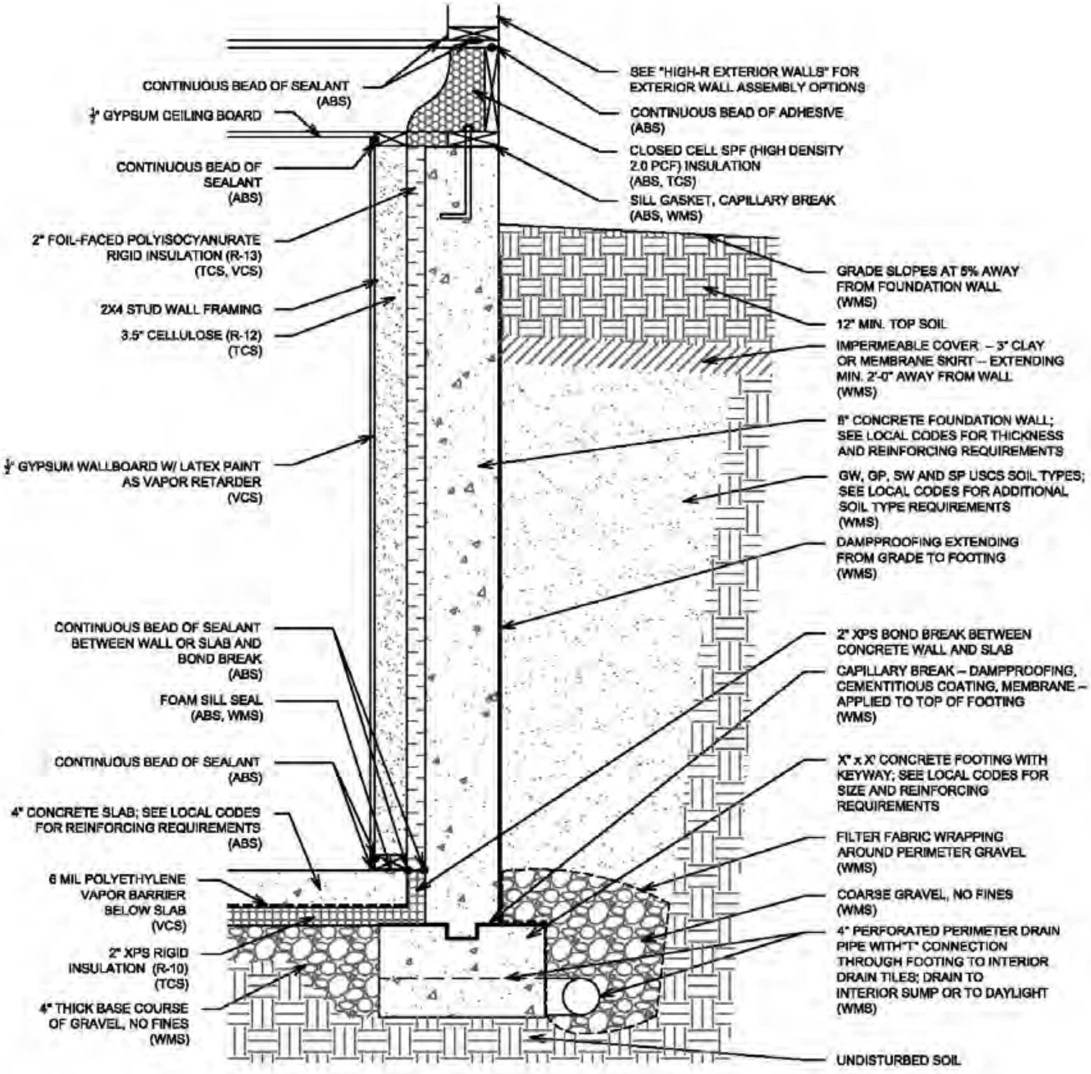


Figure 27 : Case 9 Detailed Drawing – Recommended Foundation Wall System

9.1 Thermal Control

This wall system has an installed insulation R-value of R25 which is only slightly lower based on the parallel path calculation method which accounts for the wall framing assuming 24” on center. This basement combined with R10 under the slab and R10 thermal break results in an annual predicted heating energy loss of 15.45 MBtus.

9.2 Moisture Control

The water vapor diffusion and capillary wicking are controlled by 2” of PIC insulation assuming that the PIC is well sealed to the concrete. This wall system was not hygrothermally simulated since it will not experience any moisture related issues. The foil face on the polyisocyanurate will not allow vapor diffusion from the concrete foundation, and the increased R-value of PIC compared to XPS will increase the condensation surface temperature compared to Case 8 and Case 14, resulting in decreased condensation potential.

9.3 Constructability and Cost

Fiberglass batt insulation could be used in the place of cellulose to decrease the cost of the assembly.

9.4 Other Considerations

Case 8 is one of the simplest methods of minimizing the moisture risk and saving energy which also allows the basement to be finished. It is possible to use other air permeable insulations instead of cellulose including fibreglass batt or spray fibreglass.

10. CASE 10 : 6” 0.5 PCF SPRAY FOAM WITH 2X4 FRAMING OFFSET 2.5” FROM CONCRETE

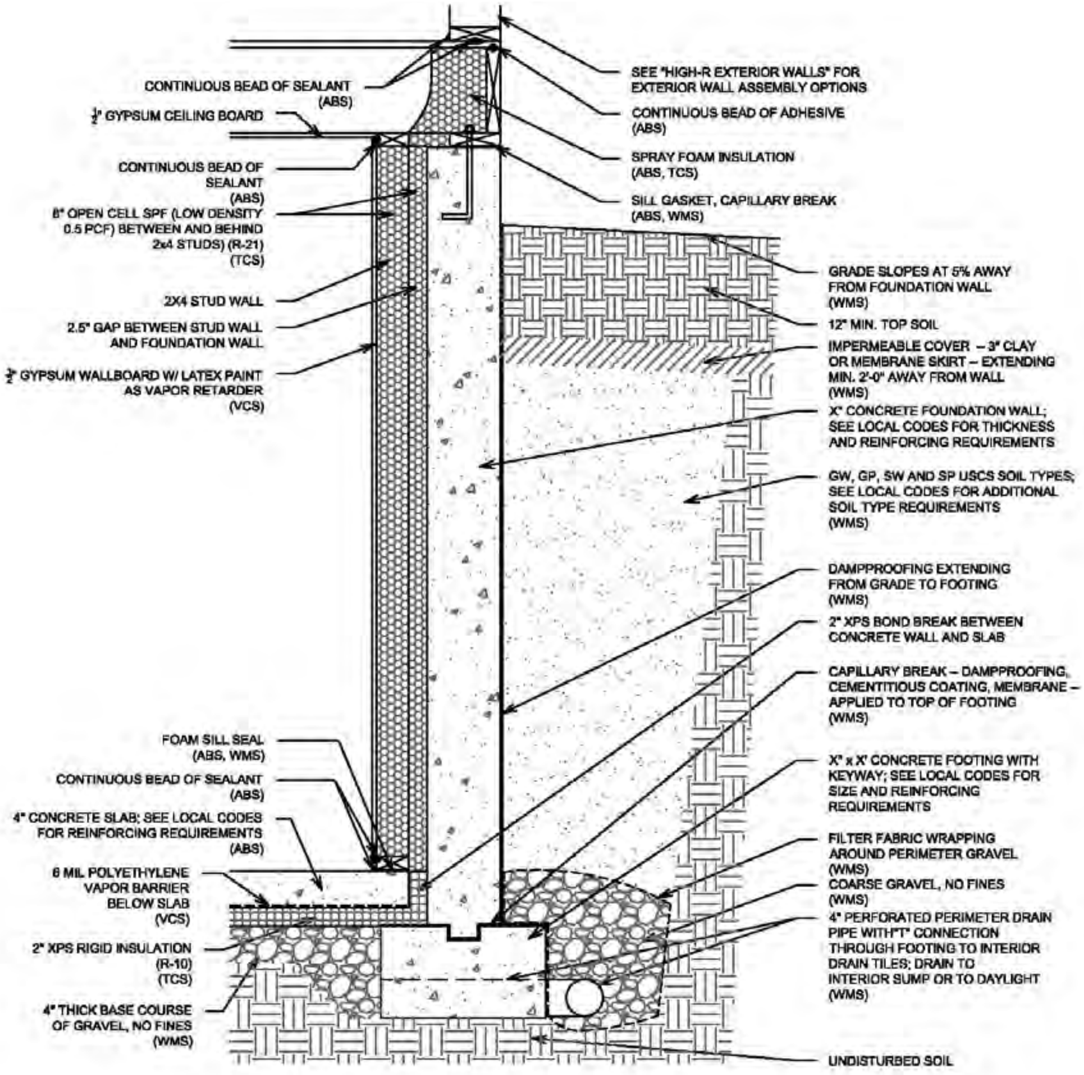


Figure 28 : Case 10 Detailed Drawing – Recommended Foundation Wall System

10.1 Thermal Control

Open cell spray foam provides very good continuous thermal control. Spray foam is an air barrier, so convective looping and air leakage thermal losses do not occur. This wall system has an R-value of R21 and a predicted annual heating energy loss of 16.3 MBtus.

10.2 Moisture Control

Open cell spray foam is an air barrier, but is vapor permeable. The relative humidity was predicted in the center of the open cell spray foam insulation and was found to be at safe levels (Figure 18).

Low permeance interior wall finishes should be avoided with this construction strategy.

10.3 Constructability and Cost

This solution is more practically than Case 7 if the plan is to finish the interior of the basement.

10.4 Other Considerations

Spray foams have been improved considerably for human health and the environment. Ozone depleting substances in the process have been removed, but some spray foams use greenhouse gases that are much worse than carbon dioxide. There are options available of more environmentally friendly spray foams that release green house gases, such as water blown foams, on the market and should be considered.

11. CASE 11 : 4” XPS INSULATION ON THE EXTERIOR OF FOUNDATION WALL

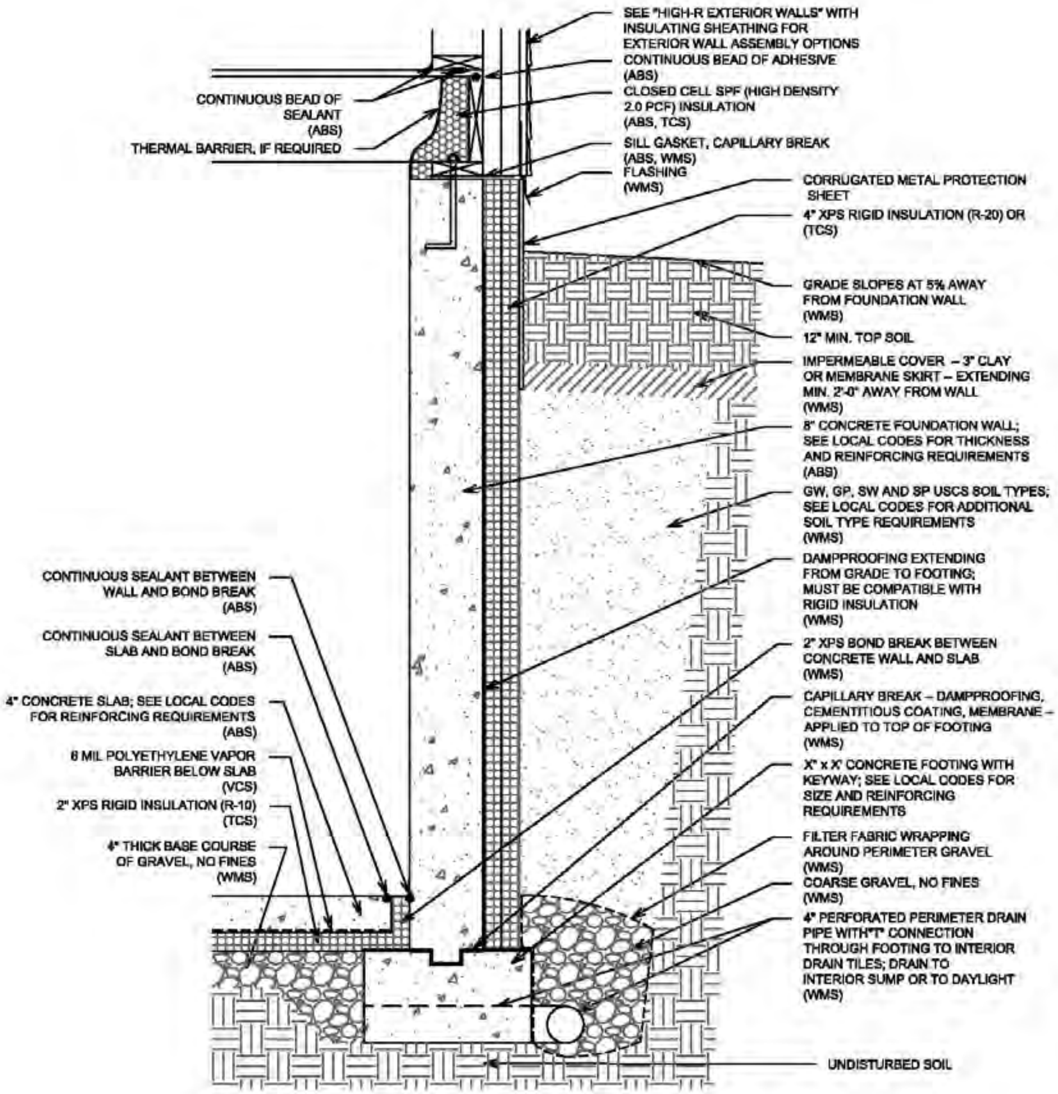


Figure 29 : Case 11 Detailed Drawing – Recommended Foundation Wall System

11.1 Thermal Control

This proposed wall system has an installed insulation R-value of R20 and results in heating energy use of 19.43 MBtus for the specific chosen parameters. The advantage of insulating on the exterior is that the insulation on the exterior of the foundation can be joined with the exterior insulation on the first floor, which forms a continuous layer of insulation and vapor control. The disadvantages of this system are that there is a thermal bridge through the concrete wall, and footing into the ground, and the above grade portion of the foundation insulation is perceived to be difficult to detail.

11.2 Moisture Control

Four inches of XPS is a great vapor diffusion resister and capillary break for inward moisture movement. There is still capillary wicking potential through the footing into the interior surface of concrete resulting in moisture at the interior surface evaporating into the interior space if it is not detailed correctly. This potential moisture issue can be solved by using a capillary break (either liquid applied or plastic based) on the top of the footing as noted in the design details. Unlike some of the other proposed foundation wall systems, the exposed concrete in this system will provide moisture buffering capacity, once it has dried.

11.3 Constructability and Cost

This proposed wall system with exterior insulation is perceived as difficult to the construction trades, and the finishing of the above grad portion may not be architecturally desirable. In some cases the timing of the insulation installation trades can be tricky since the entire house is not insulated at once in this case.

11.4 Other Considerations

In some cases, exterior foundation is not allowed by the building code due to complications with termites and other insects. Where insects may be an issue, Case 12 proposed wall system could be used.

12. CASE 12 : 4” XPS INSULATION IN THE CENTER OF FOUNDATION WALL

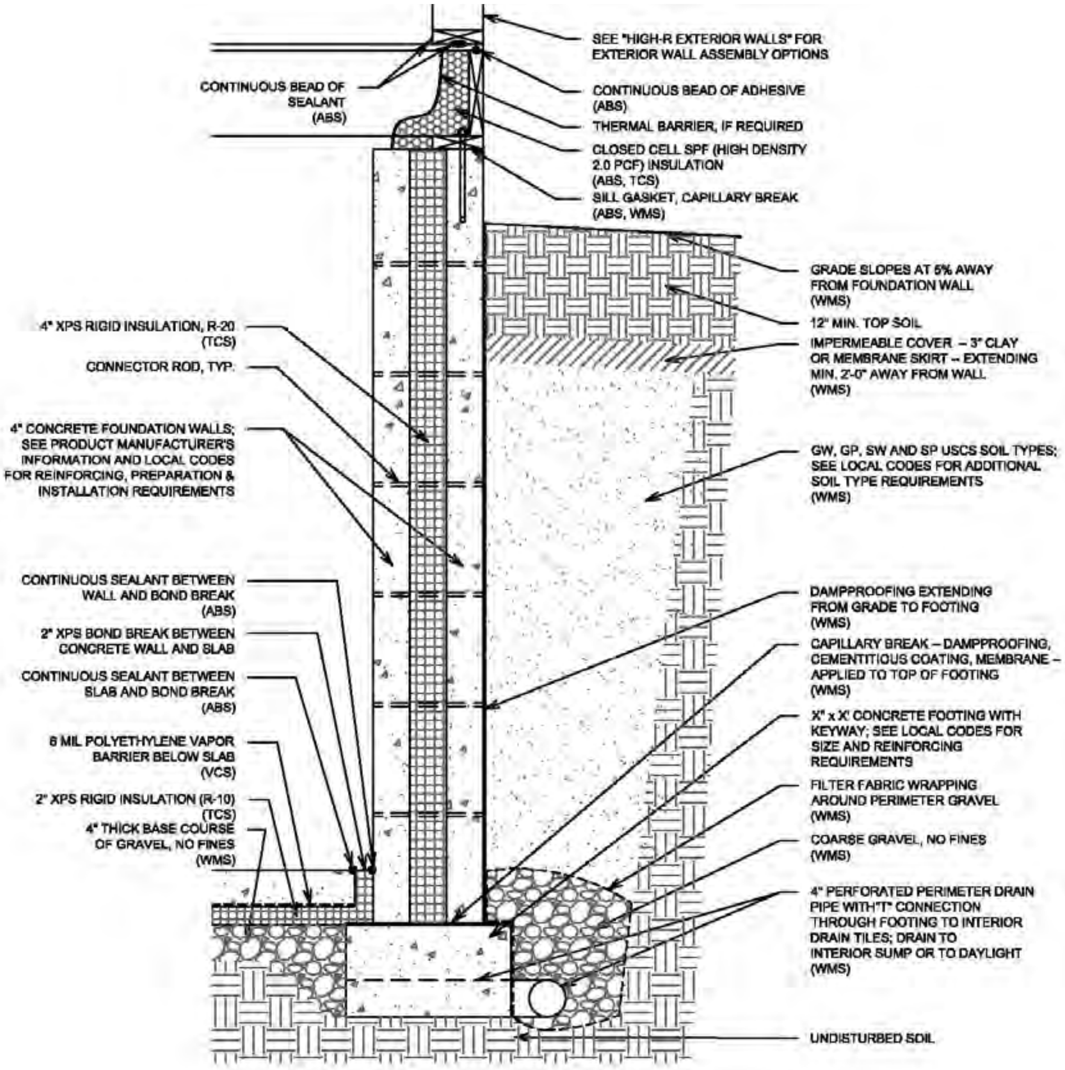


Figure 30 : Case 12 Detailed Drawing – Recommended Foundation Wall System

12.1 Thermal Control

This construction strategy has an installed insulation R-value of R20, and has a predicted annual heating energy loss of 19.24 MBtus. Unlike some of the other wall systems there are thermal mass benefits of the interior exposed surface of concrete. There is a small thermal bridge through the footing and interior surface of concrete that does increase the energy required over a wall that is insulated completely on the interior

12.2 Moisture Control

Four inches of XPS is a great vapor diffusion resister and capillary break for inward moisture movement. There is still capillary wicking potential through the footing into the interior surface of concrete resulting in moisture at the interior surface evaporating into the interior space if it is not detailed correctly. This potential moisture issue can be solved by using a capillary break (either liquid applied or plastic based) on the top of the footing as noted in the design details (Figure 30). Unlike some of the other proposed foundation wall systems, the exposed concrete in this system will provide moisture buffering capacity, once it has dried.

12.3 Constructability and Cost

This construction strategy is not very common, but is very durable because the XPS is sealed into the concrete and protected from interior and exterior damage. This wall design is more expensive than installing 4” on the interior or the exterior.

12.4 Other Considerations

This proposed wall type may not be locally available.

13. CASE 13 : INSULATED CONCRETE FORMS, 2” XPS ON INTERIOR AND EXTERIOR

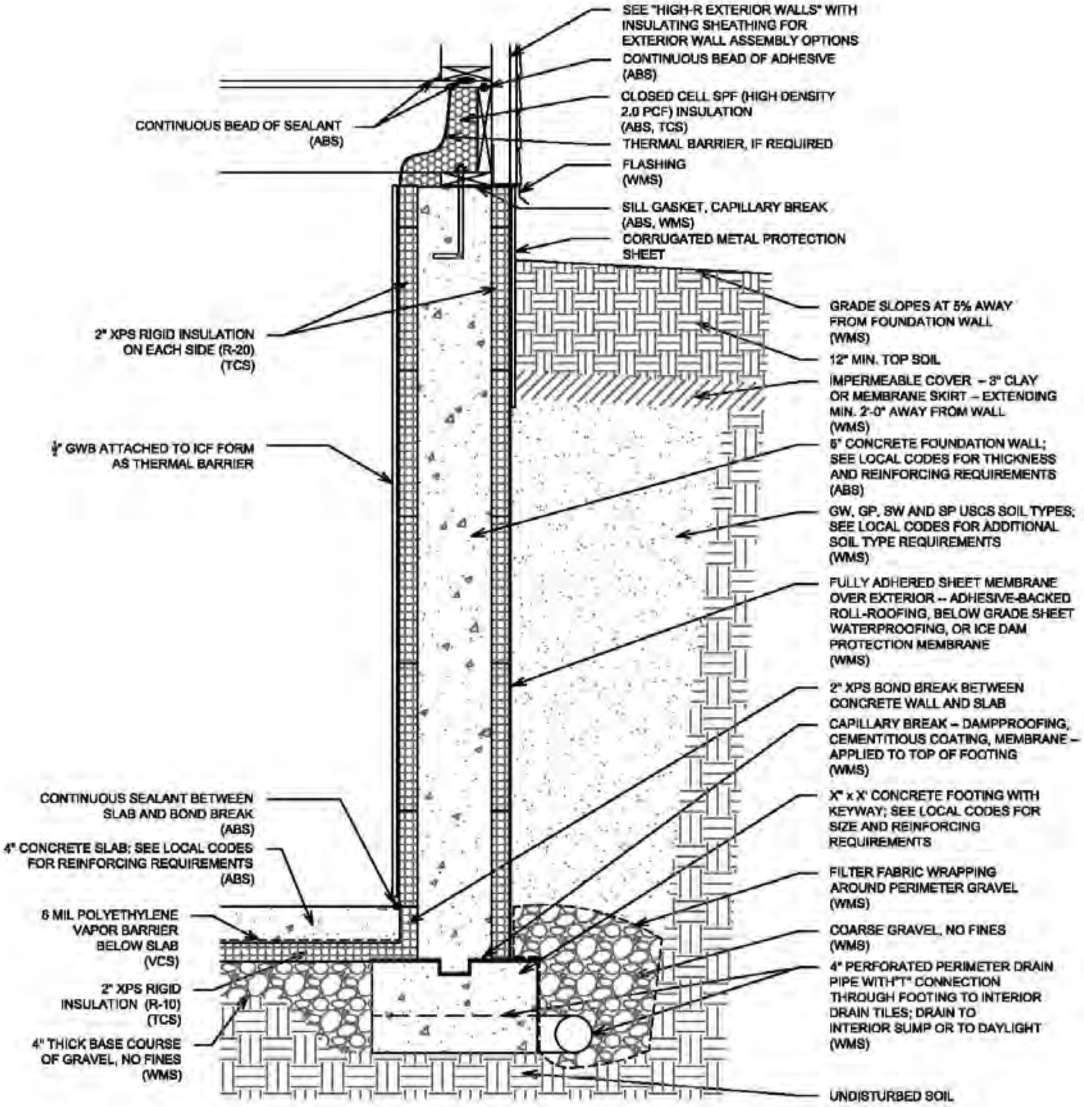


Figure 31 : Case 13 Detailed Drawing – Recommended Foundation Wall System

13.1 Thermal Control

This construction strategy has an installed insulation R-value of R20, and has a predicted annual heating energy loss of 16.7 MBtus.

13.2 Moisture Control

Two inches of XPS on the interior, connected to the thermal break at the slab edge, controls the interior vapor drive and capillary wicking to the interior so there are no moisture related issues from inward vapor diffusion or capillary wicking.

13.3 Constructability and Cost

The interior of the insulated concrete form will require drywall or other thermal barrier to achieve the fire rating required by code. The gypsum board is very easy to attach to the plastic clips designed into the ICF. The drywall should not be painted, if it is not necessary, to allow maximum drying of the concrete. It may be easier and more practical to install a thin framed wall (eg. 2x3 wood or steel framing) on the interior of the ICF to allow any necessary services to be run in the wall, and potentially more insulation.

13.4 Other Considerations

Because the concrete is installed between two vapor retarding layers, it will take several years for the concrete to dry to equilibrium. The interior vapor control should be no more than latex paint on the interior surface of the drywall.

14. CASE 14 : 2" XPS, 2X6 FRAMING WITH FIBREGLASS BATT

14.1 Thermal Control

This foundation wall system has a calculated parallel path R-value of R28.7, and a yearly heating energy consumption of 14.79 MBTus assuming R10 under the slab and in the thermal break.. This is the highest Rvalue foundation system in this study, and likely the maximum insulation that could cost effectively be used in the basement based on Figure 2 in the Heat Flow Analysis section. Only if the rest of the enclosure is super insulated, and airtight, in a very cold climate will it make sense to increase the R-value of the foundation wall. It may make sense with an R30 foundation wall to increase the underslab insulation to R15 or R20. This should be examined in more detail.

14.2 Moisture Control

This wall was analyzed in WUFI to predict the moisture related risk in the wall system, and it was shown that the RH at the surface of the XPS in the above grade portion of the wall is elevated in the winter months (Figure 19), and that there is some condensation potential alternating with periods of drying potential at the top of the foundation wall. (**Error! Reference source not found.**). There is little risk of moisture related issues in this all system if the interior RH is controlled with a dehumidifier, and the interior drywall is well air sealed.

14.3 Constructability and Cost

This wall system is slightly more expensive than Cases 8 and 9 by increasing the depth of the framed cavity with 2x6 framing instead of 2x4 framing. It is possible to use 2x4 framing stood out from the XPS by 2 inches, and use R19 fiberglass batts, or blown cellulose or fibreglass. R19 fiberglass batts should be less expensive than R13 fiberglass batts because the manufacturing process for both R19 and R13 batts uses the same amount of fibreglass, but the R13 batts require more time and effort to compact to 3.5" making them more expensive to produce.

14.4 Other Considerations

D.Conclusions

Heating energy loss calculations for all of the assemblies were calculated using Basecalc and the summary is shown in Table 5 below. The heating energy losses were conducted for a basement in Minneapolis (DOE climate zone 6), with an area of 1614 ft^2.

Table 5 : Summary of Basecalc Results

Case	Descrption	location	Installed Insualation R-value	Parallel Path Method	underslab and thermal break R10	MMBtus Annual Enery Lo
1	no insulation	NA	0	na	N	56.7
2	R10 continuous, code min. (roll batt)	interior	10	na	N	25.5
3	2x4 wood framed, R13 fiberglass batt (code min.)	interior	13	12.6	N	23.9
4	1" XPS, 2x4 wood framed, R13 fiberglass batt	interior	18	18	N	21.7
5	2" Polyisocyanurate, 2" XPS	interior	23	23.4	Y	15.8
6	3.5" 2.0 pcf closed cell spray foam	interior	21	na	Y	16.4
7	6" 0.5 pcf open cell spray foam	interior	21	22.3	Y	16.0
8	2" XPS, 2x4 wood framed, R13 fiberglass batt	interior	23	23.2	Y	15.8
9	2" Polyisocyanurate, 2x4 wood framed, R	interior	25	25.4	Y	15.4
10	6" 0.5 pcf spuf, 2x4 wood framed offset 2" from concrete	interior	21	21.3	Y	16.3
11	4" XPS on the exterior of foundation wall	exterior	20	na	Y	19.4
12	4" XPS in the middle of foundation wall	interstital	20	na	Y	19.2
13	Insulated Concrete Form - 2" XPS int. and ext.	int/ext (ICF)	20	na	Y	16.7
14	2" XPS, 2x6 wood framed, R19 fiberglass batt	interior	29	28.7	Y	14.8

Analysis showed that even a small amount of insulation on the foundation wall decreased the heating energy losses significantly compared to an uninsulated basement, and the benefits of increasing insulation decrease as more insulation is added. In Cases 5 through 13, none of the walls perform significantly better than the others from a heating energy losses perspective, so any decisions will be made on cost, durability and desired finish.

Insulating below the basement slab and at the interface of the foundation wall and basement slab will result in energy savings, but the greatest benefit is moisture related since they form a vapor diffusion and capillary break between the moisture and the interior environment, resulting in a drier, healthier interior environment.

Besides bulk water movement, which is not specifically addressed in this report, there are two modes of wetting in the foundation; vapor diffusion and capillary wetting. The exterior surface of the below grade portion of any foundation wall is maintained at approximately 100% relative humidity so moisture movement below grade is always to the interior and drying is not possible to the exterior. The IRC has been modified to reflect this, not recommending a Class I or II vapor control layer on the interior of any below grade wall.

Capillary wicking through the footing into the foundation wall is generally not addressed by production builders, and can result in significant amounts of moisture evaporating from the interior surface of the basement wall.

Cases 2 and 3 represent code minimum basement insulation amounts, although these were hygrothermally simulated with an interior poly layer instead of a perforated layer, which should be simulated in future work. With a polyethylene vapor barrier, these walls perform very poorly, with high relative humidities in the insulation, and air leakage condensation potential for nearly the entire year. Intrusive investigations of buildings in the field have shown that moisture related issues (including mould, rot, and odours) can be expected with this type of wall construction.

Cases 4, 8, 9, and 14 with a rigid foam against the concrete foundation and air permeable insulation in a wood framed wall (fiberglass batt or cellulose) showed significant improvements in moisture performance over Case 2 and

3. There is still some predicted air leakage condensation potential, but generally isolated to the above grade portion of the wall, due to the very cold exterior temperatures.

Case 5 with 2” of XPS and 2” of polyisocyanurate has no moisture related issues and performs very well, but does not easily allow for interior finishes compared to some other proposed foundation insualation systems.

Case 6, 7, and 10 use spray foam applied directly against the foundation wall, which forms an air barrier system resulting in no air leakage condensation. Closed cell spray foam is a vapor barrier limiting diffusion to the interior and open cell foam is more vapor permeable, but simulations predicted no moisture related issues from vapor diffusion due to the thickness of foam, and the ability of small amount of vapor to dry to the interior through the foam and interior finish. At the above grade portion of the wall in cold climates, a lower permeance board foam is recommended to control the inward vapor drive in the summer months, and limit the vapor diffusion condensation in the winter months. There are no moisture related issues predicted for the spray foam walls.

Cases 11, 12, and 13 are all constructed with 4” of XPS in different locations on the foundation wall, and all result in good moisture performance. A capillary break is always recommended between the footing and the foundation wall, and in Case 11, and 12, it is required since the vapor control layer, that decreases the evaporation and vapor diffusion from the interior surface, is discontinuous on the interior surface. Cases 11, and 12 also have slightly higher heating energy losses because of the thermal bridge along the interior surface of the foundation wall through the footing, but they do have the advantage of both thermal and moisture buffering if the interior of the concrete wall is left exposed.

Following the analysis of all proposed foundation wall systems, values were assigned for the five comparison criteria;

- Thermal control
- Durability
- Buildability
- Cost
- Material use

These walls were scored on a scale of 1 to 5 for each criterion, one being the lowest, and five being the best performing, and the results are shown in Table 6. Based on the selected criteria, the two highest scoring walls were the 6” of open cell spray foam with and without framing. Because some of the criteria such as Material Use and Cost could be different in other regions, the final results could be different in different parts of the continent.

All of the criteria are currently weighted evenly, but they could be changed depending on the concerns of the contractor or homeowner. Using multipliers between 1 and 5 before summing the scores could result in different results based on the importance of different criteria.

Table 6 : Comparison Criteria Matrix with Scoring Results

	Thermal Control	Durability (wetting/dry	Buildability	Cost	Material Use	Total
Criteria Weighting	1	1	1	1	1	
Case 1: uninsulated	-	-	-	-	-	
Case 2: R10 continuous with poly (roll batt)	1	1	5	5	5	17
Case 3: R13 batt, 2x4 wall with poly	1	1	4	4	5	15
Case 4: 1" XPS, 2x4 framed wall with fgb	2	3	3	3	4	15
Case 5: 2" XPS, 2" PIC	4	4	3	3	3	17
Case 6: 3.5" 2.0pcf cc spuf	4	5	5	3	3	20
Case 7: 6" 0.5pcf oc spuf	4	4	5	4	4	21
Case 8: 2" XPS, 2x4 framing with fgb	3	3	3	3	4	16
Case 9: 2" PIC, 2x4 framing with cellulose	3	3	3	3	4	16
Case10: 2.0" 0.5 oc spuf, 2x4 framing with sam	4	4	4	3	3	18
Case 11: 4" XPS on the exterior	4	4	2	2	3	15
Case 12: 4" XPS in the centre of foundation	4	4	3	1	3	15
Case 13: ICF 2" XPS interior and exterior	4	5	4	1	3	17
Case 14: 2" XPS, 2x6 framing with fgb	5	4	3	2	3	17

E. Future Work

While conducting this analysis, some questions were encountered that require further research, analysis and simulations to more completely understand the moisture and thermal performance of basement insulation systems. These areas include;

- Determining the effect of perforated facers on code compliant R10 roll batts
- Researching field testing data on basement monitoring data that has been conducted and correlate to the proposed wall systems.
- Further analysis of the Mitalas finite element analysis method of heating energy loss for basements.
- Attempt to quantify the role of capillary wicking through the basement wall relative to the vapor diffusion load.

Following the completion of the High-R basement and foundation report, an analysis report will be completed for roofs and attics regarding historical, code compliant and super insulated roof strategies. Similarly to the previous High R Wall Report and this Basements/Foundations report, the Roof and Attic report will be a combination of both field testing/monitoring, thermal and hygrothermal analysis, years of experience.

F. Works Cited

Lstiburek, J. *Understanding Basements,* Building Science Digest 103, Westford, Building Science Press, 2006

Mitalas, G.P., *Calculation of Basement Heat Loss,* National Research Council Canada

Pettit, B., *Renovating Existing Basements,* Research Report – 0509c, Westford, Building Science Press, 2008

Straube, J., and Burnett, E., *Building Science for Building Enclosures.* Westford, Building Science Press, 2005

Straube,J., Smegal, J., *Building America Special Research Project: High-R Walls Case Study Analysis,* Building Science Press, MA, 2009

1.5.5. Construction, Commissioning & Calibration of a Novel Hot Box Apparatus for High-R Enclosure Performance Measurement

by Christopher Schumacher, December 2009

Building America High-R Enclosures Research Project: Construction, Commissioning & Calibration of a Novel Hot Box Apparatus for High-R Enclosure Performance Measurement

2009 December
Chris Schumacher

Abstract:

*This report documents the construction, commissioning and calibration of a novel hot box apparatus designed and constructed to measure the heat transfer through high-*R *building enclosures under real temperature conditions, with and without airflow in and through the enclosure.*

Introduction

The R-value has long been the industry standard for assessing the thermal performance of insulation materials. Building designers directly apply R-value to the thermal performance of building enclosures. This practice has recently come into question as energy-cost and security issues have generated demand for building enclosures that exhibit higher levels of thermal performance. The market has responded with new insulation products and novel building enclosure systems such as: various types of spray foam and spray-applied fibrous insulations, exterior insulated sheathing, Structural Insulated Panel Systems (SIPS), Insulated Concrete Forms (ICF), and Radiant Barrier Systems (RBS), etc.

Because contemporary insulation materials and systems control heat flow in different, new and non-traditional ways, they are more or less sensitive to thermal bridging, workmanship (i.e. quality of installation), internal convection and through convection (i.e. infiltration, exfiltration, windwashing & re-entrant looping). The impact of such ‘anomalies’ and ‘defects’ is not captured in the R-value metric. Furthermore, the discrepancy between the real heat flow and that predicted by combining R-values increases the absolute temperature, the temperature difference and the net resistance to heat flow increase. These realizations have generated an increasing amount of interest in the development of a new metric for the thermal performance of building enclosures.

The goal of this work is the development of a new metric for the thermal performance of building enclosures that better accounts for the known physical heat flow mechanisms (particularly natural and forced convection) and operating conditions. The metric employs equipment and techniques based on existing ASTM procedures as much as practical.

Previous BSC Work

In FY07 BSC completed a report entitled “Review of the R-value as a Metric for High Thermal Performance Building Enclosures” that summarized the extensive existing research of heat flow through walls and highlighted physical mechanisms that are not usually included in codes and designer specifications. The impact of thermal bridging, and convective loops, although well understood, has not been sufficiently well quantified to allow for prediction. Air infiltration and exfiltration through the wall assembly were identified as a major unquantified heat flow mechanisms in current approach to building enclosure thermal testing. From this review, a need was identified for measuring and rating heat flow across a wall under realistic temperature ranges (both cold & hot exterior conditions) and under the influence of air movement (both in and through the building enclosure).

This was followed by a FY08 report entitled “Development of a Test Procedure and Apparatus for Measuring High Thermal Performance Walls” that outlined a new metric for the thermal performance of building enclosures. New equipment and techniques, based on existing ASTM standards, were proposed to better account for the known physical heat flow mechanisms (particularly natural and forced convection) and operating conditions.

BSC assembled a consortium of 6 building product manufacturers to participate in the privately-funded development of the new thermal performance metric and the associated test method. These partners include:

- NAIMA (North America Insulation Manufacturer's Association) with technical representatives from Certainteed and Johns Manville
- Huntsman Polyurethanes
- Honeywell
- Icynene
- Dow Chemical
- US Greenfiber

The partners designed and built (with private funding) a novel hot box apparatus to permit the highly accurate measurement of heat flow under realistic operating conditions. This report documents the apparatus construction and summarizes the commissioning and calibration activities that were undertaken in 2009.

Test Apparatus

This section of the report provides a summary of the construction and operation of the apparatus as context for later discussion on commissioning and calibration.

In general the test apparatus has been designed & constructed in accordance with ASTM C1363, "Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus." A number of modifications were made to meet the specific objectives of the research.

The key improvements over other (i.e. conventional) hot box testing is the ability to test higher R-value enclosure assemblies (which have lower heat fluxes), a procedure and apparatus that exposes enclosure wall samples to realistic temperature differences while maintaining the interior temperature at normal room temperatures, and the ability to measure the impact of imposed air flow.

Conventional Hot Boxes

ASTM C1363 recognizes two configurations for hot box test apparatuses: *guarded* and *calibrated*. Figure 1 provides a schematic of a conventional guarded hot box apparatus which comprises three boxes: the climate box, the meter box and the guard box. The wall test specimen is installed between a climate box and a meter box so that the drywall side (i.e. inside) of the wall faces the meter box and the cladding side (i.e. outside) of the wall faces the meter box.

The climate box is typically cooled to maintain a temperature of 50 or 55°F (10 or 12.8°C) and a measured amount of heat is added to the meter box to maintain a temperature of 95 or 100°F (35 or 37.8°C) so that the average temperature across the test wall specimen is 75°F (23.9°C). Air is typically heated and circulated through the space between the guard box and the meter box to minimize the temperature difference (deltaT), and therefore the heat flux across the meter box wall so that any heat added to the meter box must flow through the test wall specimen.

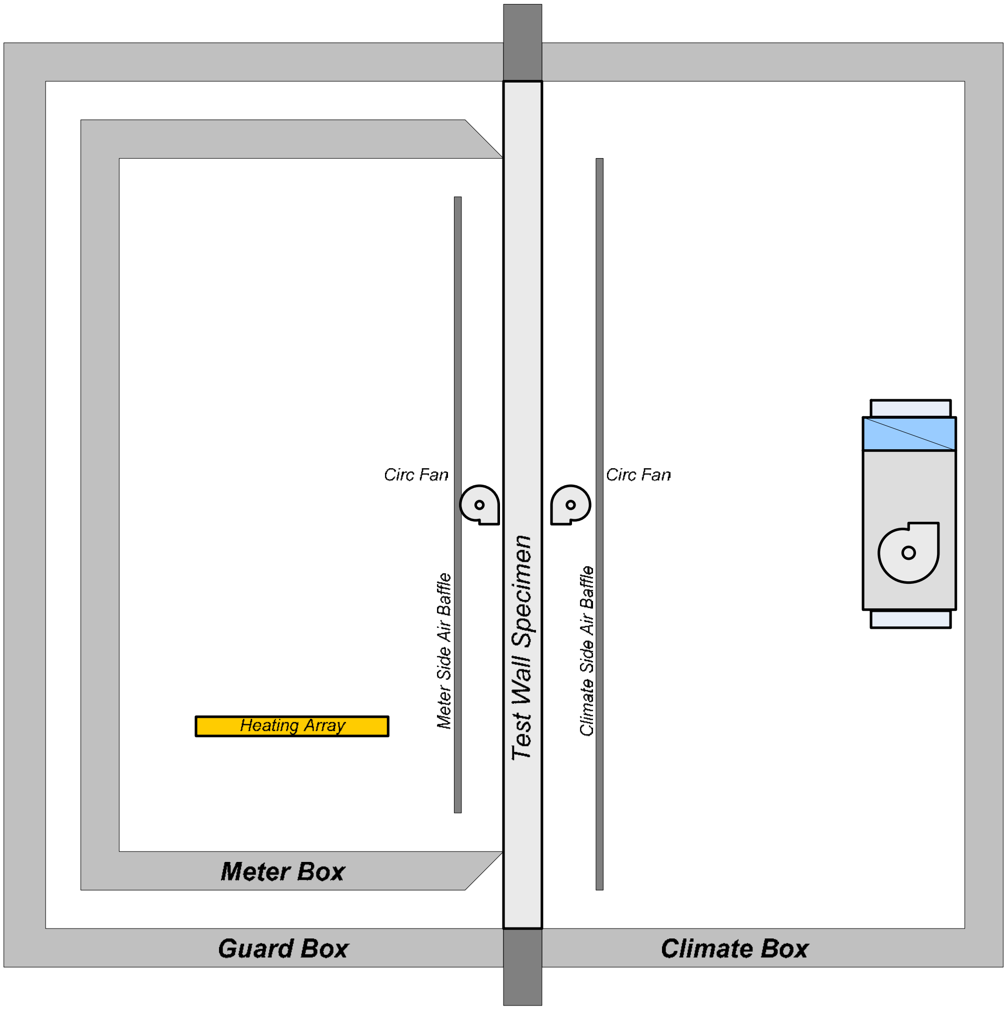


Figure 1 – Schematic of Conventional Guarded Hot Box Apparatus

Guarded Hot Boxes

In a conventional guarded hot box apparatus, the test wall specimen is larger than the opening of the meter box. The meter box walls taper to a thin edge that interfaces (i.e. seals against) the test wall specimen. When the temperatures in the guard box and the meter box are equal, all of the heat flow at this interface is perpendicular to the plane of the wall so there is no “flanking loss.”

Calibrated Hot Boxes

In a conventional calibrated hot box apparatus, there is no guard box; the meter box opening is the same size as the climate box opening; and the test wall specimen is typically the same size as the meter box opening. Conditions in the lab space are controlled sufficiently to permit calculation of the heat flux across the calibrated meter box walls so the measured heat input can be corrected.

Limitations of Conventional Hot Boxes

Most conventional hot boxes apparatuses are designed to operate within a limited temperature range. Temperatures in the climate box and the meter box are often not representative of real climate and room temperature conditions.

Few meter boxes are equipped with the ability to provide any measured cooling. This means that hot weather (i.e. cooling climate) tests must be run well above the temperature of the laboratory (calibrated boxes only) or the specimen must be removed from apparatus and turned around so that the cladding side (i.e. outside) of the wall faces into the meter box while the drywall side (i.e. inside) faces the climate box.

Finally, it is common to install axial fans at mid-height between the test wall specimen and the air baffle. These fans drive airflow parallel to the surface of the wall specimen and can easily be setup to switch direction, however the fan location can create non-uniform pressure gradients in the plane of the wall specimen.

Thermal Metric Research Hot Box

With the aid of industrial partners, a novel hot box apparatus was designed and constructed for the purposes of the Thermal Metric (TM) research project. In as much as possible, the apparatus, depicted by the schematic in Figure 2, has been based on ASTM C1363, however a number of improvements have been made to facilitate the research. These include:

- A deeper meter box to permit the testing of wall-wall and wall-floor intersections at close to full scale.
- Metered equipment to both heat & cool the meter box
- Draw-through fans to create more realistic airflow over the inside surface of the wall specimen
- A double guard (insulated guard box + liquid guard loop) to improve control over the temperature differential across the meter box walls and minimize uncertainties.
- A modified specimen frame or ‘cartridge’ to control flow of heat & mass at the perimeter of the metered area of the test wall specimen
- An air transfer system to induce infiltration / exfiltration

General Construction Details

The walls of the TM hot box are custom assembled structural insulated panels comprising 11 mm (7/16 in) good one side plywood adhered to either side of a solid layer of 100 mm (4 in) XPS insulation to create a stiff, strong, airtight wall with an unbridged, continuous thermal resistance of more than RSI 3.7 (R21). These SIPs are attached to the inside of a steel exo-skeleton using fasteners that only penetrate the outer layer of plywood.

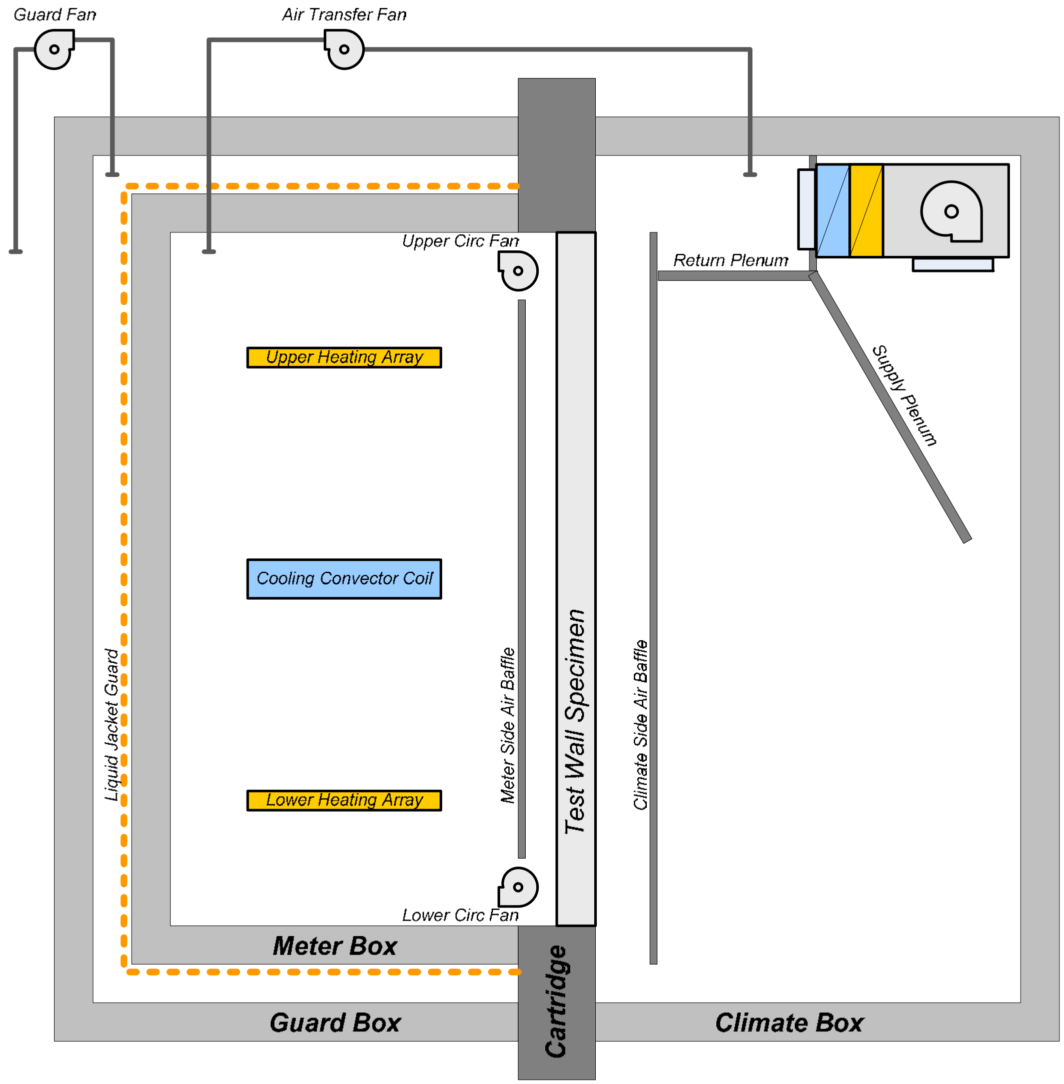


Figure 2 – Schematic of Thermal Metric Research Hot Box Apparatus

Meter Box

The meter box walls are insulated with an additional RSI 1.76 (R10) of foil-faced insulation. The foil acts as an isothermal surface to which to fasten temperature sensors, and as a low emissivity surface that ensures a uniform radiant exposure behind the insulated air baffles.

The insulated baffles are used to form consistent vertical airflow patterns over the interior faces of the test wall specimen. The baffles consist of RSI 0.88 (R5) insulation boards with a low emissivity foil skin facing the inside of the meter box and a painted plastic skin facing the wall specimen. The low emissivity foil skin and the insulation ensure that the baffle is at a constant temperature close to that of the air that is travelling across the face of the test wall specimen. The painted plastic skin ensures that the surface of the test wall specimen radiates to the baffle as a real wall would to its surrounding environment. Calibrated precision thermistors (+/-0.1°C) are used to measure temperatures at 24 points on the baffle surface, 24 corresponding points in the air stream and at 24-36 points on the interior surface of the wall test specimen.

Airflow in the baffle space is induced by a set of DC axial circulation fans at the top or the bottom of the baffle. The fan speed can be adjusted to draw the air through the baffle space at velocities representative of natural convection in real world conditions, typically 0.3 m/s (1 fps). The lower fans are used to draw air in and down the wall during cold climate tests while the upper fans are used to draw air in and up the wall during hot climate tests. The use of draw through fans ensures that velocities over the test wall specimen are uniform and the flow is not turbulent. The voltage and current to the circulation fans are measured across precision (+/-0.01%) resistors so that the power may be calculated.

The temperature in the meter box is controlled by electric heat and hydronic cooling. Two heating arrays, each consisting of 16 heaters and 8 mixing fans, are installed in the upper and lower portions of the mixing part of the meter box as seen in Figure 3. The size, number and distribution of the heaters and fans ensure that the temperature is relatively uniform throughout the meter box. Again, voltage and current supplied to the heaters and mixing fans are measured across precision (+/- 0.01%) resistors so that the power may be calculated.

Figure 3 – Upper & Lower Heating Arrays & Cooling Coil in Meter Box

Cooling is achieved by a large, finned convection coil mounted at mid-height in the mixing part of the meter box. The large heat transfer area permits the removal of significant amounts of heat with only modest (e.g. 1°C or 1.8°F) temperature increases across the coil. Distilled water is pumped from a chilled, constant temperature (+/- 0.05°C) buffer tank, into the meter box, through the convection coil, and back out of the meter box. The flow rate is measured using a NIST traceable +/-0.2% of reading flow meter and the supply and return temperatures are measured using a pair of precision thermistors (+/-0.1°C) and a pair of ultra precision RTDs (+/-0.012ohm). These measurements can then be used to calculate the power extracted by the cooling.

The cooling coil and the two heating arrays are mounted on a rack that can be moved forward or deeper into the meter box as necessitated by the geometry of the test specimen.

The meter box has a depth of 1.5 m (5 ft) to permit testing of wall-wall and wall-floor intersections at full scale. This is significantly deeper than conventional hot boxes which are usually designed to minimize depth and, as a result, wall area in an effort to minimize heat loss across the meter box walls. The TM hot box design uses a double guard and significant meter box wall insulation to offset the additional wall area associated with the increased depth of the box.

The Double Guard

The TM hot box employs a double guard: an insulated guard box surrounds the meter box and a hydronic (liquid) guard loop is installed over the outside surface of the meter box as seen in the photograph of Figure 4. The guard box minimizes the influence of temperature changes in the lab and reduces spatial temperature gradients over the surface of the meter box. The liquid guard loop further reduces any spatial temperature gradients and all but eliminates any temperature difference between the inside and the outside of the meter box walls.

The temperature difference is measured by paired precision thermistor arrays that are applied to the inside & outside of each of the five faces of the meter chamber at a density of more than 5 sensors per square meter. In all, the temperature difference is measured at 176 locations. The hot box control system uses the aggregated differential temperature measurements to control the guard loop supply temperature to reduce the average temperature difference across the meter box walls to less than 0.05°C (0.09°F).

Each of the guard loops can be individually controlled with metering valves to allow the flows to be calibrated from time to time to ensure spatial uniformity of the temperature. The water flow of each loop has been designed to absorb or release the expected heat flow through the R20 walls of the guard chamber walls (in the range of 2 to 4 W per loop) with a temperature rise of less than 0.005°C (0.009°F).

Figure 4 – Double Guard: Guard Box (Left) and Liquid Guard Loop on Meter Box (Right)

The Wall Cartridge

Section 6.7.1 of ASTM C1363 requires the provision of a specimen frame to support the wall test specimen in position between the meter box and climate box and to insulate the perimeter of the specimen to reduce flanking losses. In a conventional guarded hot box, the wall test specimen area extends beyond the perimeter of the meter box so that the portion of the wall that is between the meter box and the climate box see the same heat flow as the portion of the wall that is between the guard box and the climate box. This is an extremely effective method of minimizing flanking losses; however, when hollow (e.g. framed) walls are tested, it provides paths for to flow not just between the climate box and the meter box, but also between these two boxes and the guard box.

The interaction between heat and airflow is of particular interest in the Thermal Metric research program, hence the team felt it necessary to design a specimen frame that would not only minimize flanking losses, but also eliminate airflow outside of the area of the wall test specimen. The TM hot box specimen frame or ‘cartridge’ comprises alternating layers of 11 mm (7/16 in) plywood and 100 mm (4 in) XPS foam board glued up to create an exceptionally stiff sandwich panel as seen in Figure 5. Two 38 x 38 mm (nominal 2 x 2 in.) nailers are embedded in the cartridge to provide fastening support. A 100 mm (4 in) thick XPS thermal break lines the entire rough opening of the cartridge so that the finished opening and the size of the wall test specimen match the meter box opening: 3.66 m (12 ft) wide by 2.44 (8 ft) high.

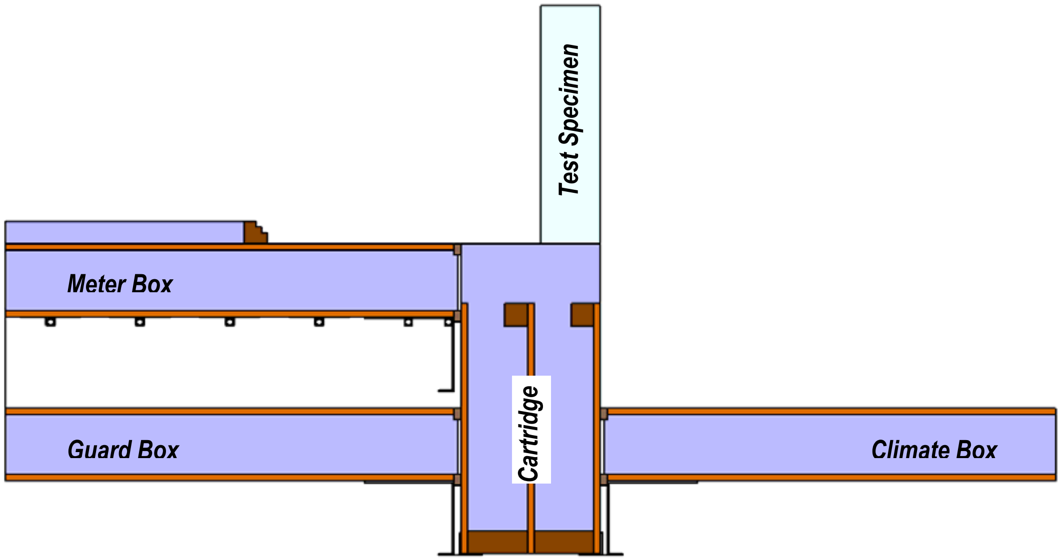


Figure 5 – Section through Wall Cartridge with Meter, Guard and Climate Boxes in Position

The wall test specimen is positioned so that its cladding is in plane with the climate side of the wall cartridge. The geometry allows space for air in the climate box to turn the corner and regain some uniformity before it passes over the surface of the wall test specimen. This is important when considering the interaction between heat flow and airflow. The arrangement does however complicate the flanking loss because there is a portion of the cartridge that is exposed to the meter box yet is not guarded (i.e. that portion of the thermal break that lies between the inside face of the drywall and outside of the meter box gasket. Steady state 2-dimensional heat flow analysis was conducted using HEAT2 to optimize the wall cartridge design and to reduce flanking losses so that they were comparable to those in heat boxes operated by the industry partners that were participating on the Thermal Metric research team. Figure 6 shows the temperature distribution and heat flux vectors acting across the wall cartridge for meter box temperature of 22°C (71.6°F) and a climate box temperature of -18°C (0.4°F).

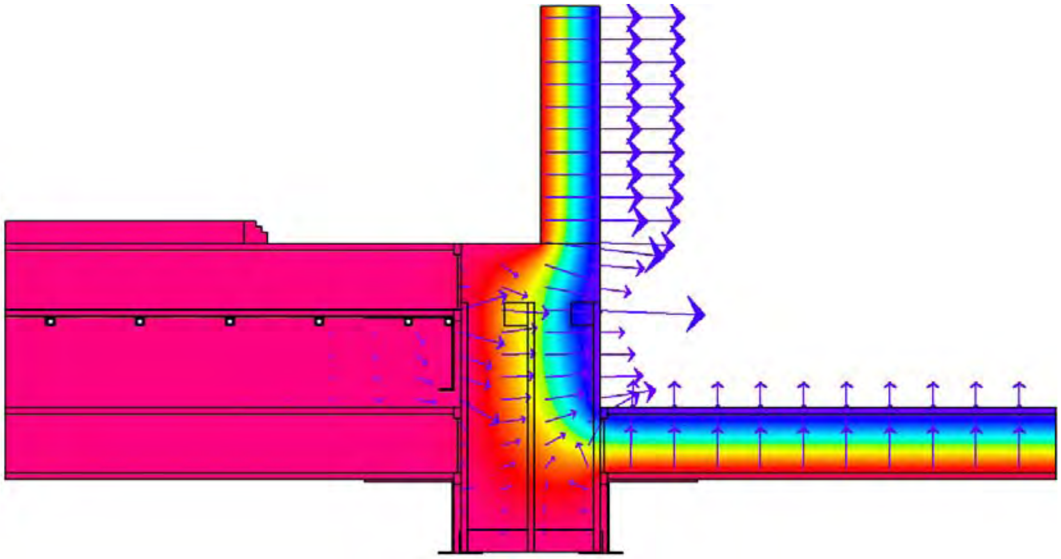


Figure 6 – Temperatures & Heat Flux @ 22°C (71.6°F) Meter Side & -18°C (0.4°F) Climate Side

The wall cartridge is completed by a heat shrink air barrier is applied over the thermal break to prevent air from moving from one box to another through the wall cartridge. The heat shrink cover over the thermal break is evident as the black border in the photo of Figure 7.

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Figure 7 – Wall Cartridge with Test Wall Specimen Installed & Instrumented for Testing

Climate Box

The climate box has the same dimensions and construction as the guard box. The climate side air baffles are constructed using the same materials and methods as the air baffles in the meter box. Foil-faced insulation is also used to form the return plenum at the ceiling and the supply plenum that runs half way down the back wall of the climate box.

The temperature in the climate box is controlled by a series of four fan coils connected to a 8 kW @-20 °C (and 4.5 kW@-30C), capacity air-cooled liquid chiller and a 6 kW hydronic heater. The airflow in the climate side can be adjusted between approximately 150-1000 lps (300-2000 cfm) to control mixing and air velocity over the test wall specimen. The oversized coils allow for a very small temperature drop across the coil during most test conditions. Reheat coils and individually-controlled tight-fitting dampers allow for individual defrost. This feature allows three fan coils to continue conditioning and circulating air while the fourth is defrosted. The reheat coils can be used for humidity control, and the low temperature drop cooling coils allow RH levels of 90 to 95RH to be maintained over most of the temperature range.

Air Transfer System

One of the most novel aspects of the TM hot box is the air transfer system (ATS). The system, pictured in Figure 8, generates a pressure difference between the meter box and the climate box to drive airflow through available paths in the test wall specimen. The system comprises an inline fan, an inline heater, a high accuracy (+/-2% of reading) mass flow sensor and piping and valves to allow negatively pressurize (i.e. induce infiltration) or positively pressurize (i.e. induce exfiltration) the meter box. A guard fan is used to minimize the pressure difference between meter and guard boxes so that airflow only occurs between the meter and the climate boxes.

Typical flow rates are expected to be in the range of 0.1 and 20 liters per minute (2 to 50 cfm) at pressures of 2 to 25 Pa. This will impose leakage rates of 0.01 to 2.25 lps/m2 (0.02 to 0.50 cfm/ft2).

Heat transfer associated with the airflow is calculated using the measured flow rate, the heat capacity of air at the measured pressure, temperature & humidity and the temperature difference between the delivered air temperature (measured using an ultra precision RTD @ +/-0.012 ohm) and the air temperature in the meter box (measured using an array of precision thermistors @ +/-0.1°C).

Figure 8 – Guard Fan (Left) & Air Transfer System (Center)

TM Hot Box Operating Modes & Energy Balances

The TM hot box has been designed to operate in a number of different modes to facilitate testing over a realistic range of temperatures and representative air leakage scenarios. This section of the report describes the typical operating modes and summarizes the equipment, measurements and energy balance for each.

General Energy Balance without Induced Airflow

All measurements of heat flow are made in the meter box, regardless of the operating mode. When no airflow is induced, the TM hot box operates in a manner similar to other hot boxes. Heat is added to the box by the heating arrays and the circulation fans. These are indicated in the diagram of Figure 9 as Q_h and Q_f respectively. Heat is removed from the box by the cooling coil (Q_c). A small amount of heat flows into or out of the meter box walls (Q_{mw}) depending on how well the guard loop eliminates the temperature difference across the walls of the box. When the climate box is maintaining heating climate (i.e. cold) temperatures heat will flow out of the perimeter, flanking the guard. In hot box terminology this is usually referred to as a flanking loss (Q_{fl}). When the climate box is maintaining cooling climate (i.e. hot) temperatures, heat will flow into the perimeter so that the flanking loss appears as a gain.

Q_h, Q_f and Q_c can be measured directly; Q_{mw} and Q_{fl} can be predicted using temperature measurements and calibration factors. The only missing heat flow in the meter box system is then the heat that flows into or out of the test wall specimen. This is typically idealized as conductive heat flow ($U \cdot A \cdot \Delta T$) and can be calculated using the other five heat flow terms and the heat balance equation shown in Figure 9.

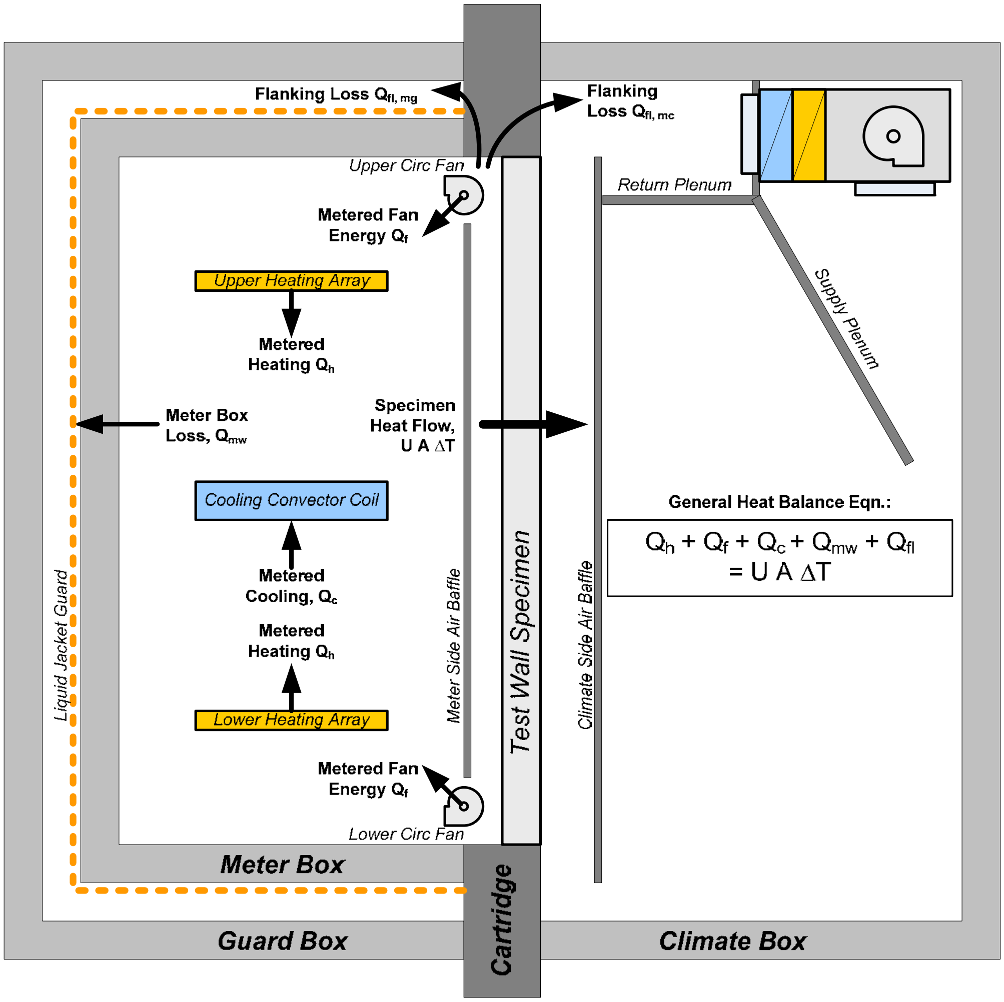


Figure 9 – General Energy Balance Diagram for Modes with No Induced Airflow

General Energy Balance with Induced Airflow

When airflow is induced, two additional heat flows must be considered: heat moved with the air through the transfer fan and heat moved with the air infiltrating or exfiltrating through the test wall specimen. The transfer air heat flow, denoted by Q_t in Figure 10, is measured directly. It is much more difficult to isolate the heat moved by infiltration or exfiltration.

If the meter and climate boxes are connected with airtight seals against the cartridge, then the system is closed and the airflow through the test wall specimen must be equal to the airflow measured by the mass flow sensor in the air transfer system (ATS). In theory, the heat moved by this airflow can be calculated using $m \cdot c \cdot \Delta T$ and the general heat balance equation would be as shown in Figure 10, however airflow through the test wall specimen changes the temperature field in the test wall specimen so that the apparent conductance of the test wall specimen is changed. This is referred to as the 'interaction' between airflow and heat flow. The TM research team plans to account for this interaction in the new thermal metric.

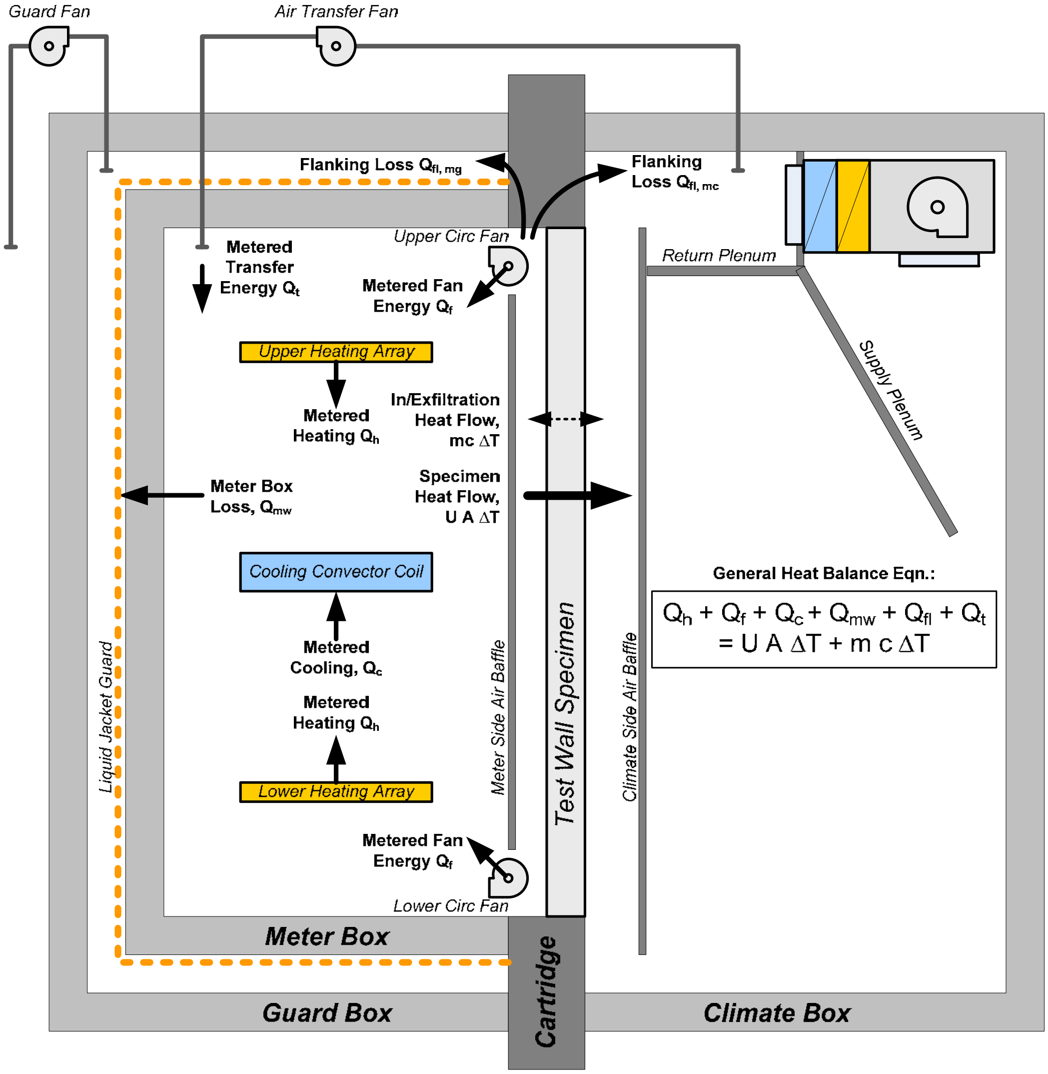


Figure 10 – General Energy Balance Diagram for Modes with Induced Airflow

Cold Climate, No Induced Airflow

Figure 11 shows the equipment state, air circulation patterns and heat flows associated with the cold climate mode when there is no induced airflow. The temperature in the meter box is maintained by adding heat using the upper and lower heating arrays. The lower circulation fans are used to generate a cold climate convection pattern on the inside of the wall test specimen; air enters the top of the baffle space, cools as it passes down the wall and is pushed back into the mixing portion of the meter box at the bottom of the baffle space. Q_h & Q_f are measured directly while Q_{mw} & Q_{fl} calculated from measurements and calibration factors. The test wall specimen heat flow is then calculated using the heat balance equation of Figure 11.

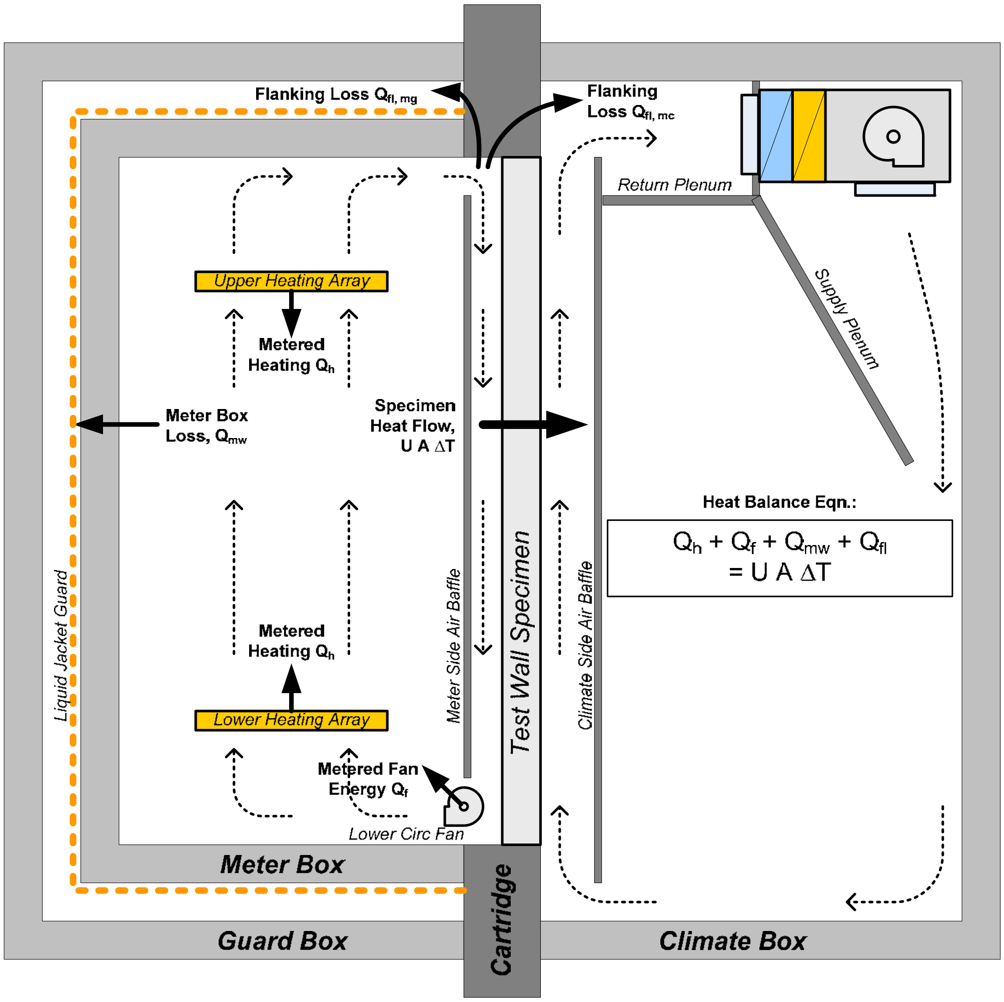


Figure 11 – Cold Climate Mode with No Induced Airflow

Cold Climate, Induced Infiltration

In the cold climate mode with induced air infiltration, the air transfer fan is used to negatively pressurize the meter box relative to the climate box as illustrated in Figure 12. The pressure difference causes air to move through the wall specimen from outside to in, opposite the direction of heat flow. For cold climates, infiltration represents contraflux heat flow.

Under the cold climate infiltration mode the mass flow sensor is used to measure the air transfer flow rate which is assumed to be equal to the infiltration flow rate. If there were no interaction between the air infiltration and heat flow through the wall, then air transfer heat flow, Q_t, would be equal to the infiltration heat flow, m·c·ΔT.

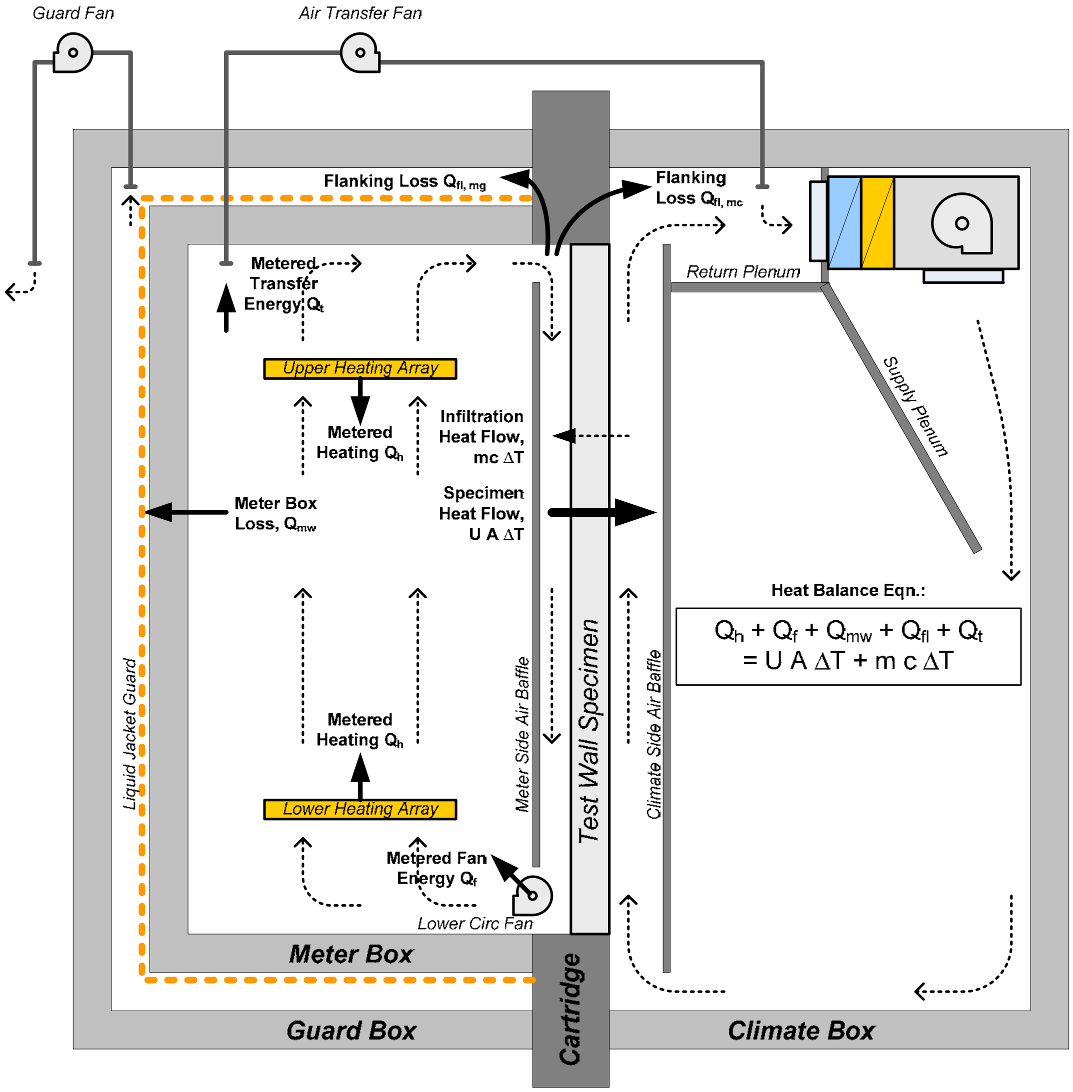


Figure 12 – Cold Climate Mode with Induced Air Infiltration

Cold Climate, Induced Exfiltration

In the cold climate mode with induced air exfiltration, the air transfer fan is used to positively pressurize the meter box relative to the climate box as illustrated in Figure 13. The pressure difference causes air to move through the wall specimen from inside to out, in the same direction as the heat flow. For cold climates, exfiltration represents proflux heat flow.

Under the cold climate exfiltration mode the mass flow sensor is used to measure the air transfer flow rate which is assumed to be equal to the exfiltration flow rate. If there were no interaction between the air exfiltration and heat flow through the wall, then air transfer heat flow, Q_t, would be equal to the exfiltration heat flow, $m \cdot c \cdot \Delta T$.

The design of the ATS permits the transfer air to be heated so it can be delivered at the temperature of the air in the meter box.

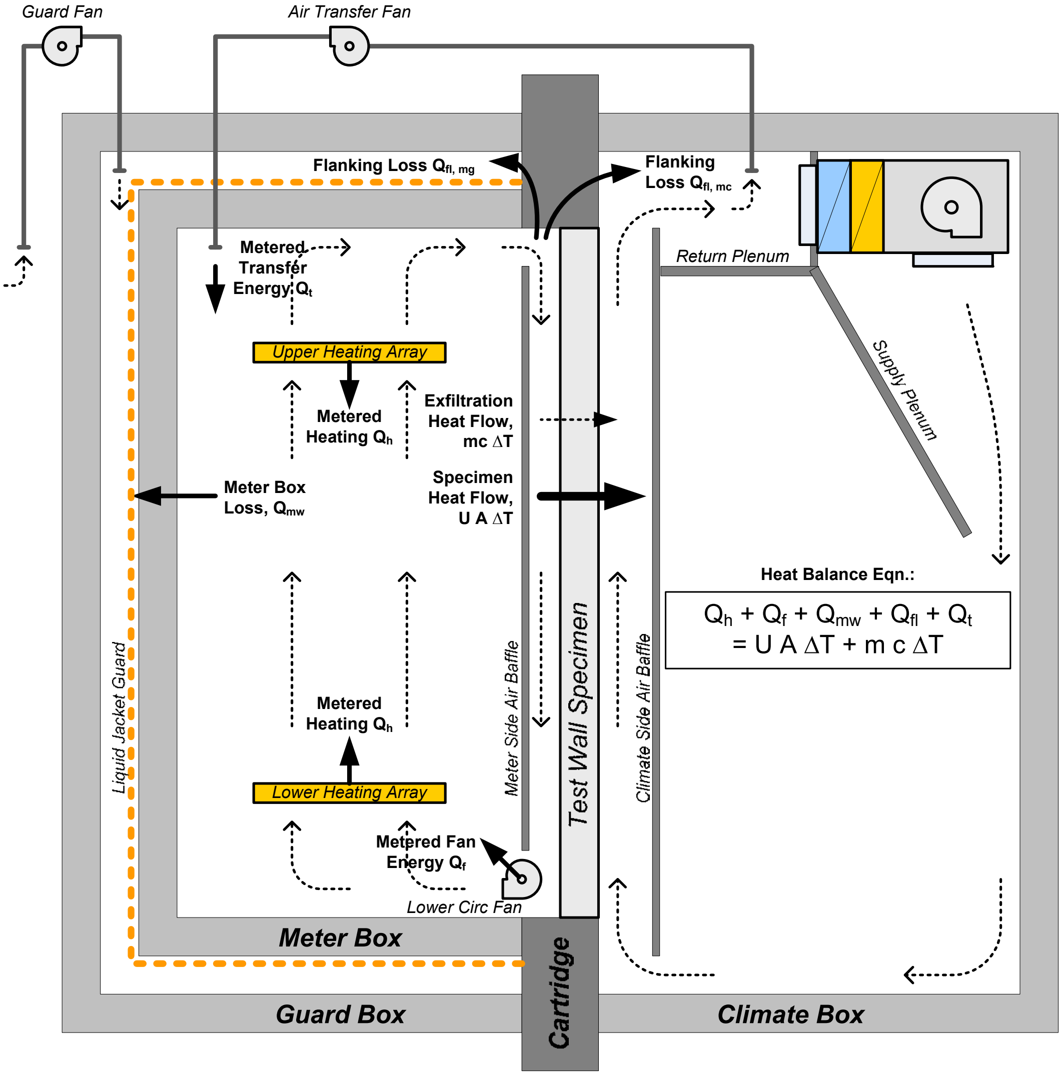


Figure 13 – Cold Climate Mode with Induced Air Exfiltration

Hot Climate, No Induced Airflow

Figure 14 shows the equipment state, air circulation patterns and heat flows associated with the hot climate mode when there is no induced airflow. The temperature in the meter box is maintained by removing heat using the cooling coil. Where extremely fine temperature control is necessary, some heat can be added using the upper and lower heating arrays. The upper circulation fans are used to generate a hot climate convection pattern on the inside of the wall test specimen; air enters the bottom of the baffle space, warms as it passes up the wall and is pushed back into the mixing portion of the meter box at the top of the baffle space. Q_h & Q_f are measured directly while Q_{mw} & Q_{fl} calculated from measurements and calibration factors. The test wall specimen heat flow is then calculated using the heat balance equation of Figure 14Figure 11.

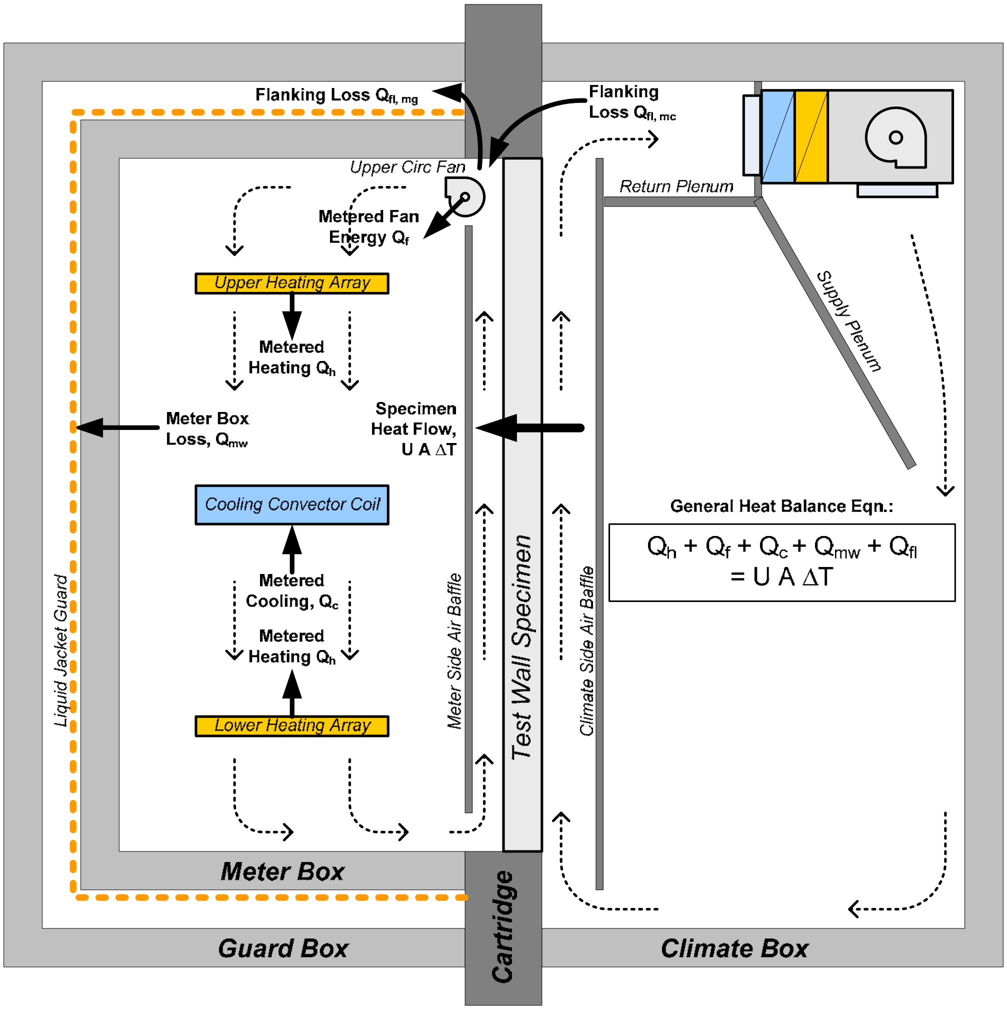


Figure 14 – Cold Climate Mode with No Induced Airflow

Hot Climate, Induced Infiltration

In the hot climate mode with induced air infiltration, the air transfer fan is used to negatively pressurize the meter box relative to the climate box as illustrated in Figure 15. The pressure difference causes air to move through the wall specimen from outside to in, in the same direction as the heat flow. For hot climates, infiltration represents proflux heat flow.

Under the hot climate infiltration mode the mass flow sensor is used to measure the air transfer flow rate which is assumed to be equal to the infiltration flow rate. If there were no interaction between the air infiltration and heat flow through the wall, then air transfer heat flow, Q_t, would be equal to the infiltration heat flow, $m \cdot c \cdot \Delta T$.

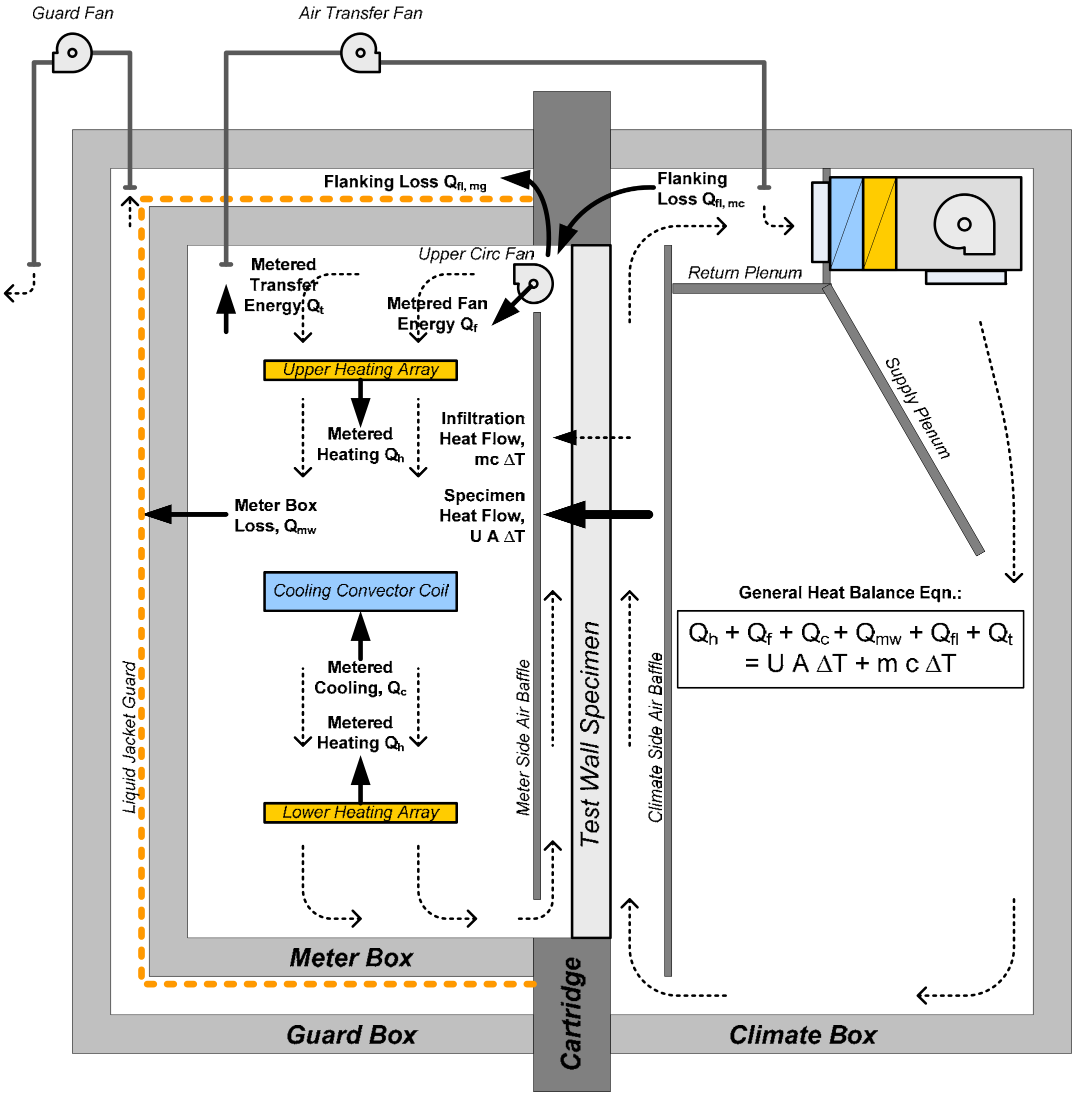


Figure 15 – Hot Climate Mode with Induced Air Infiltration

Hot Climate, Induced Exfiltration

In the hot climate mode with induced air exfiltration, the air transfer fan is used to positively pressurize the meter box relative to the climate box as illustrated in Figure 16. The pressure difference causes air to move through the wall specimen from inside to out, in the opposite the direction of heat flow. For hot climates, exfiltration represents contraflux heat flow.

Under the hot climate exfiltration mode the mass flow sensor is used to measure the air transfer flow rate which is assumed to be equal to the exfiltration flow rate. If there were no interaction between the air exfiltration and heat flow through the wall, then air transfer heat flow, Q_t, would be equal to the exfiltration heat flow, $m \cdot c \cdot \Delta T$.

At this point in time the design of the ATS does not permit cooling of the transfer air so, in hot climate modes it is not possible to deliver transfer air at the temperature of the air in the meter box.

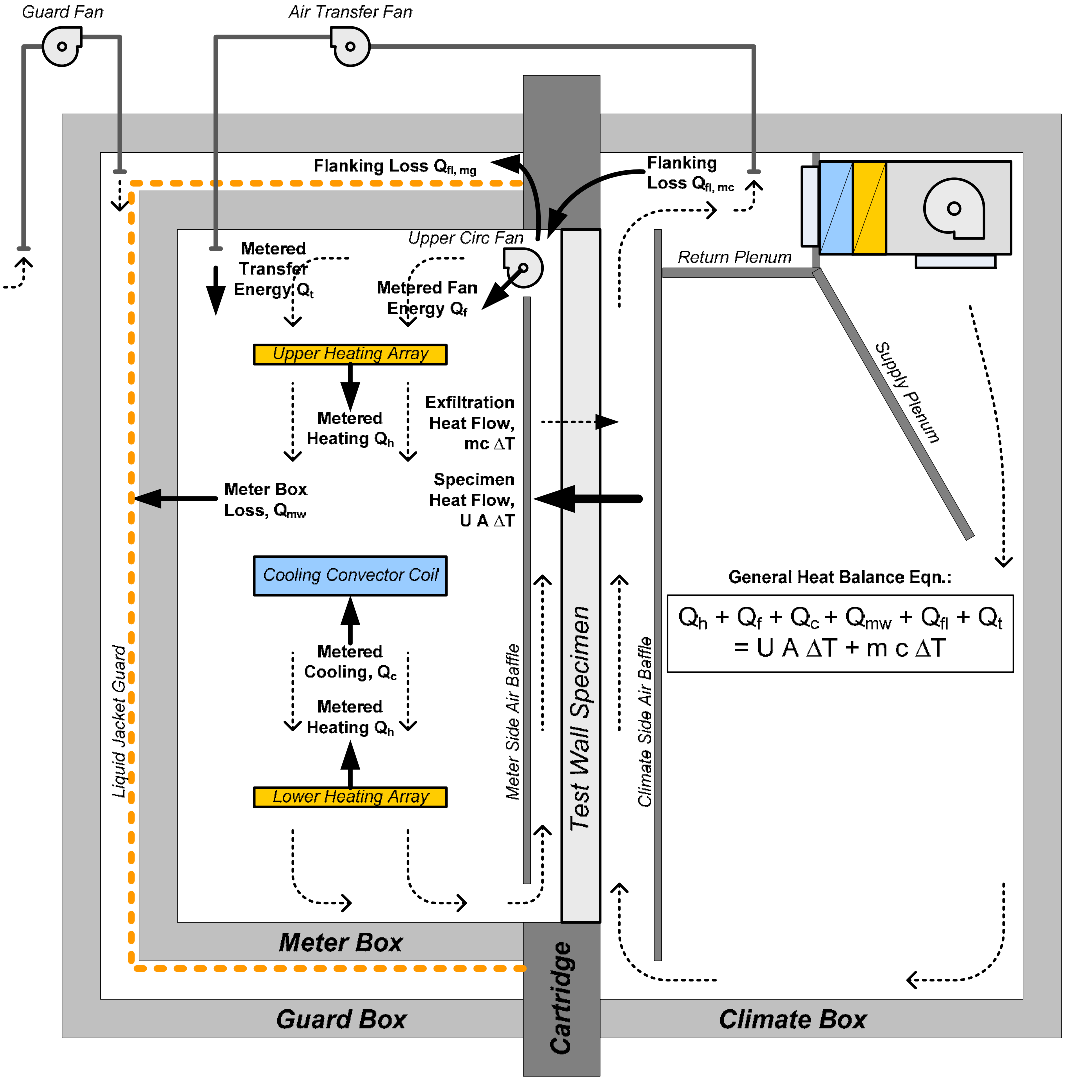


Figure 16 – Hot Climate Mode with Induced Air Exfiltration

Commissioning & Calibration of Subsystems

The TM hot box uses several subsystems to control the different operating modes and make measurements necessary for calculating the energy balances. This section of the report addresses the commissioning & calibration of these subsystems.

Meter Box Temperature Differences

The liquid guard loop controls the temperature on the outside of the meter box to minimize the temperature difference (delta-T) across the meter box walls. Temperature differences are measured using custom fabricated & calibrated temperature sensors.

The sensors were fabricated using 10 kOhm NTC precision thermistor components (Honeywell/Fenwall 192-103LET-A01) soldered to 28 AWG leads. The resulting temperature sensors, pictured in Figure 17, are approximately the same size as the thermocouples that are typically used in hot box research.

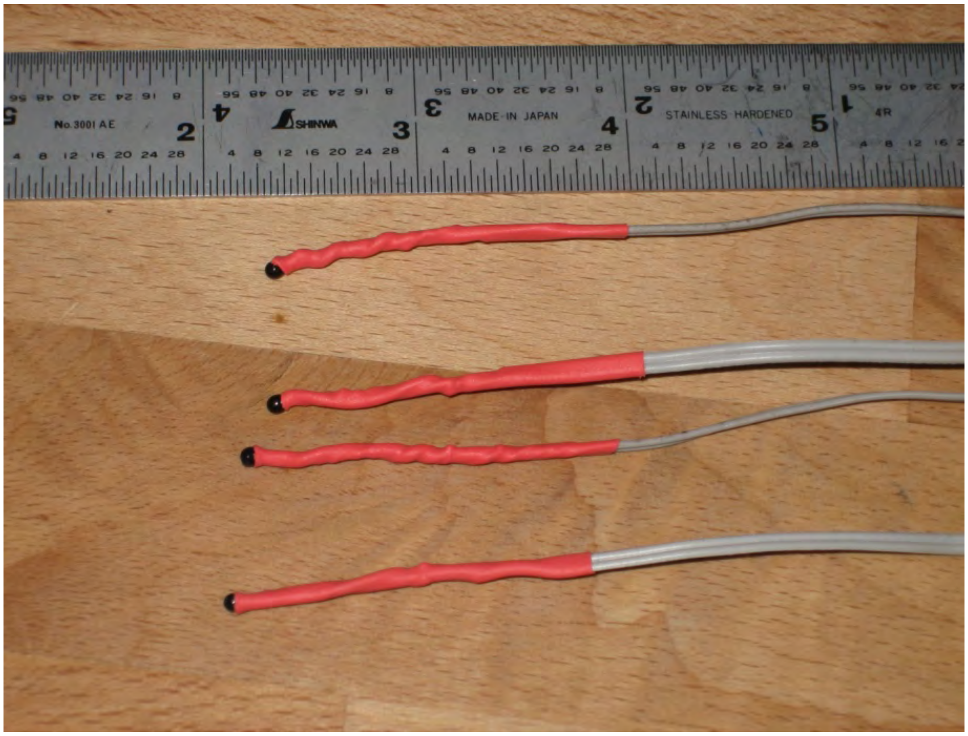


Figure 17 – Small Package Thermistor-based Temperature Sensors

From the manufacturer these sensors have a tolerance of +/- 0.2°C. The research team sought to reduce as many uncertainties as possible; hence sensors were individually calibrated over the range of temperatures in which they were to be used. The meter box guard sensors were calibrated at 16, 18, 20, 22, and 24°C while the baffle surface, air space and wall specimen sensors were calibrated at -30, -20, -10, 0, 10, 20 and 30°C.

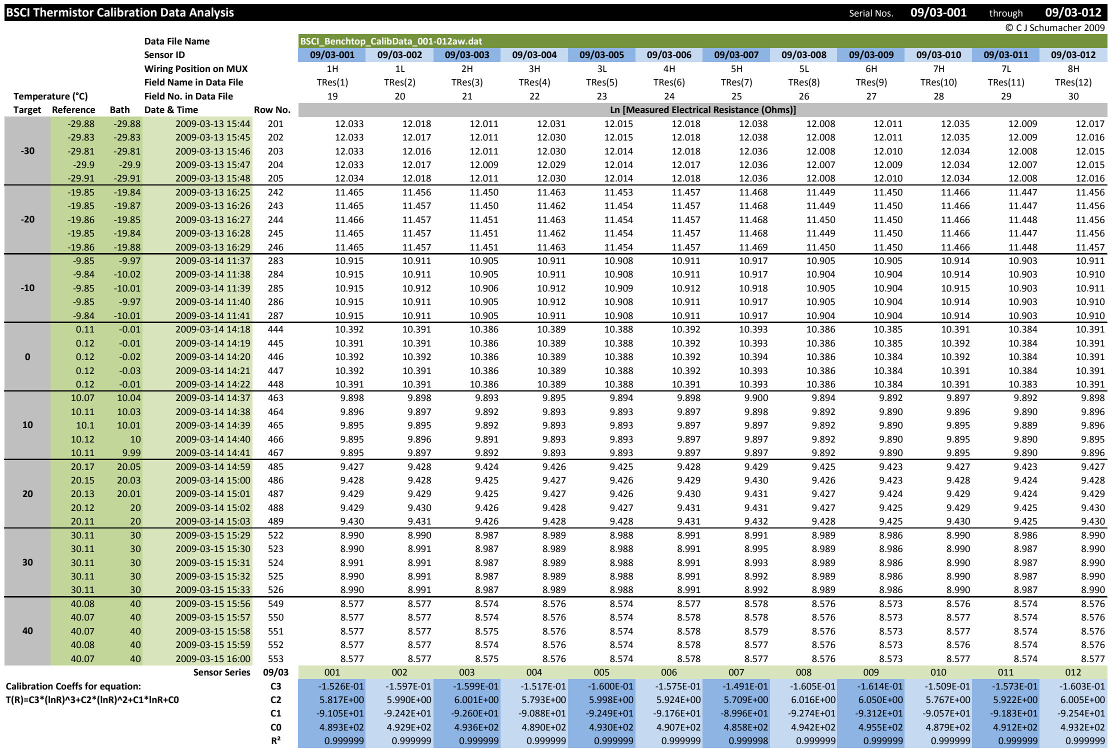
Roughly 600 of the temperature sensors were fabricated to instrument the TM hot box and use on the test wall specimens for the first phase of research. Each sensor was assigned a unique serial number and calibrated in an aluminum calibration block set in a controlled temperature bath as pictured in Figure 18.

Figure 18 – Temperature Sensor Calibration Setup

The controlled temperature bath, a VWR 1157P, is capable of maintaining the bath temperature within +/- 0.01°C of the setpoint. The aluminum calibration block further ensures the spatial and temporal stability of the temperature during calibration. A NIST traceable HH41 reference thermometer (+/- 0.023°C or over the range of -20 to 60°C) was inserted in a 100 mm (~4 in.) deep hole in the middle of the block. Sensors were calibrated in sets by inserting them in the 12 holes that circle the reference thermometer.

For each setpoint, the bath was brought to equilibrium and allowed to run for 15-20 minutes after which 5 readings were taken at 1 minute intervals. For each reading, the time, the bath temperature and the reference thermometer temperature were manually recorded. Meanwhile, the resistances of the thermistor-based temperature sensors were automatically measured and recorded using a Campbell Scientific CR1000 measurement & control system and a half-wheatstone bridge circuit with a precision (+/- 0.01%) sense resistor.

The data was then summarized in a spreadsheet, an example of which is presented in Figure 19, and regression was performed to determine sensor specific calibration coefficients for a 3rd order polynomial equation. Figure 20 shows a typical regression graph for one of the TM hot box temperature sensors. As a result of the custom calibration, temperature sensor uncertainty is better than +/- 0.05°C.



BSCI Thermistor Calibration Data Analysis Serial Nos. **09/03-001** through **09/03-012**

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			Wiring Position on MUX		1H	1L	2H	3H	3L	4H	5H	5L	6H	7H	7L	8H
			Field Name in Data File		TRes(1)	TRes(2)	TRes(3)	TRes(4)	TRes(5)	TRes(6)	TRes(7)	TRes(8)	TRes(9)	TRes(10)	TRes(11)	TRes(12)
Temperature (°C)			**Field No. in Data File**		19	20	21	22	23	24	25	26	27	28	29	30
Target	**Reference**	**Bath**	**Date & Time**	**Row No.**	**Ln [Measured Electrical Resistance (Ohms)]**											
-30	-29.88	-29.88	2009-03-13 15:44	201	12.033	12.018	12.011	12.031	12.015	12.018	12.038	12.008	12.011	12.035	12.009	12.017
	-29.83	-29.83	2009-03-13 15:45	202	12.033	12.017	12.011	12.030	12.015	12.018	12.038	12.008	12.011	12.035	12.009	12.016
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	-19.85	-19.87	2009-03-13 16:26	243	11.465	11.457	11.450	11.462	11.454	11.457	11.468	11.449	11.450	11.466	11.447	11.456
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	10.12	10	2009-03-14 14:40	466	9.895	9.896	9.891	9.893	9.893	9.897	9.897	9.892	9.890	9.895	9.890	9.895
	10.11	9.99	2009-03-14 14:41	467	9.895	9.897	9.892	9.893	9.893	9.897	9.897	9.892	9.890	9.895	9.890	9.896
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	20.15	20.03	2009-03-14 15:00	486	9.428	9.428	9.425	9.427	9.426	9.429	9.430	9.426	9.423	9.428	9.424	9.428
	20.13	20.01	2009-03-14 15:01	487	9.429	9.429	9.425	9.427	9.426	9.430	9.431	9.427	9.424	9.429	9.424	9.429
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	30.11	30	2009-03-15 15:30	523	8.990	8.991	8.987	8.989	8.988	8.991	8.995	8.989	8.986	8.990	8.987	8.990
	30.11	30	2009-03-15 15:31	524	8.991	8.991	8.987	8.989	8.988	8.991	8.993	8.989	8.986	8.990	8.987	8.990
	30.11	30	2009-03-15 15:32	525	8.990	8.991	8.987	8.989	8.988	8.991	8.992	8.989	8.986	8.990	8.987	8.990
	30.11	30	2009-03-15 15:33	526	8.990	8.991	8.987	8.989	8.988	8.991	8.992	8.989	8.986	8.990	8.987	8.990
40	40.08	40	2009-03-15 15:56	549	8.577	8.577	8.574	8.576	8.574	8.577	8.578	8.576	8.573	8.576	8.574	8.576
	40.07	40	2009-03-15 15:57	550	8.577	8.577	8.574	8.576	8.574	8.578	8.578	8.576	8.573	8.577	8.574	8.576
	40.07	40	2009-03-15 15:58	551	8.577	8.577	8.575	8.576	8.574	8.578	8.579	8.576	8.573	8.577	8.574	8.576
	40.08	40	2009-03-15 15:59	552	8.577	8.577	8.574	8.576	8.574	8.578	8.577	8.576	8.573	8.576	8.574	8.576
	40.07	40	2009-03-15 16:00	553	8.577	8.577	8.575	8.576	8.574	8.578	8.577	8.576	8.573	8.577	8.574	8.577
			Sensor Series	**09/03**	001	002	003	004	005	006	007	008	009	010	011	012
Calibration Coeffs for equation:				**C3**	-1.526E-01	-1.597E-01	-1.599E-01	-1.517E-01	-1.600E-01	-1.575E-01	-1.491E-01	-1.605E-01	-1.614E-01	-1.509E-01	-1.573E-01	-1.603E-01
T(R)=C3*(lnR)^3+C2*(lnR)^2+C1*lnR+C0				**C2**	5.817E+00	5.990E+00	6.001E+00	5.793E+00	5.998E+00	5.924E+00	5.709E+00	6.016E+00	6.050E+00	5.767E+00	5.922E+00	6.005E+00
				C1	-9.105E+01	-9.242E+01	-9.260E+01	-9.088E+01	-9.249E+01	-9.176E+01	-8.996E+01	-9.274E+01	-9.312E+01	-9.057E+01	-9.183E+01	-9.254E+01
				C0	4.893E+02	4.929E+02	4.936E+02	4.890E+02	4.930E+02	4.907E+02	4.858E+02	4.942E+02	4.955E+02	4.879E+02	4.912E+02	4.932E+02
				R²	0.999999	0.999999	0.999999	0.999999	0.999999	0.999999	0.999998	0.999999	0.999999	0.999999	0.999999	0.999999

Figure 19 – Screen Capture of Temperature Sensor Calibration Spreadsheet

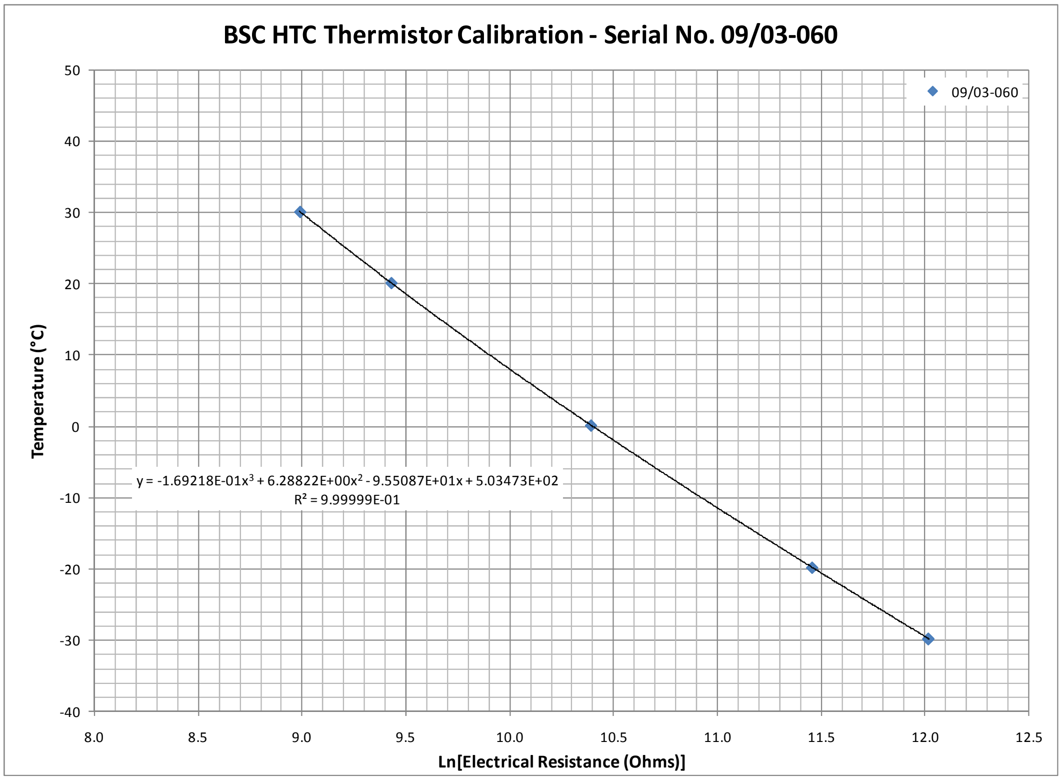


Figure 20 – Typical Data Regression for Temperature Sensor Calibration

In total, 176 pairs of the calibrated temperature sensors were installed on the inside and outside of the meter box as guard sensors. Individual sensors are measured using the hot box measurement and control system (MCS), a CR1000 and the temperature difference of each pair of sensors is determined, then area weighted temperature differences calculated for each surface of the meter box. Finally, the average temperature difference over all five sides of the meter box is calculated and this is relayed to the liquid guard loop controller, an Omega CN3251.

Heat is removed from the distilled water in the guard loop by running it through a heat exchanger that is temperature modulated by a 3-way valve controlled by the hot box MCS. This provides coarsely controlled temperature of the guard loop. Fine tuning of the guard loop temperature is achieved using in-line heaters that are controlled by the Omega CN3251. Once tuned, the liquid guard is capable of limiting meter box temperature differences to less than 0.05°C (0.09°F) and often on the order of +/-0.02°C (0.036°F). Figure 21 shows the temperature difference recorded over a typical 6 hr period. The potential error associated with this tight control is less than 0.03 W.

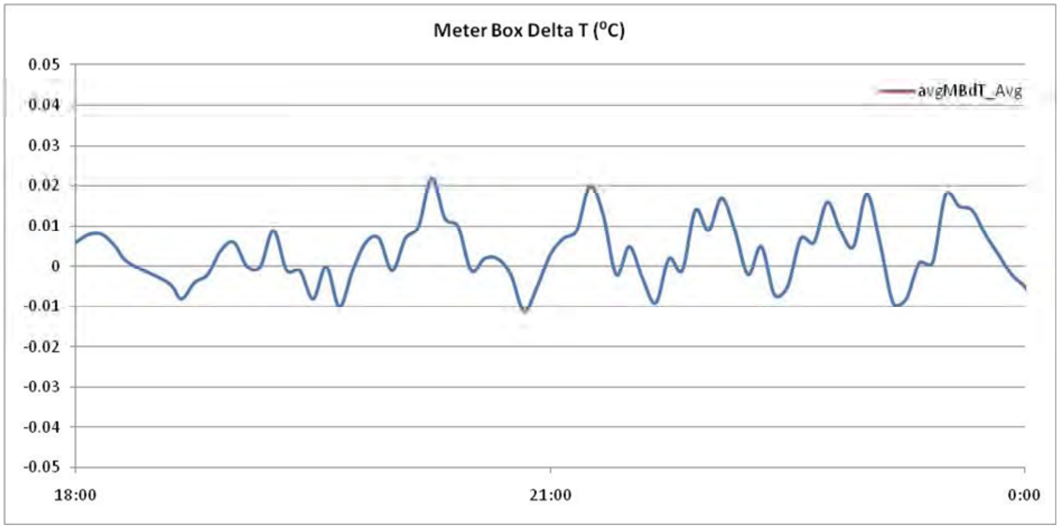


Figure 21 – Typical Meter Box Temperature Difference

Meter Box Resistance Heater & Fan Arrays

Heat is added to the meter box by a system of 96 resistors and 16 DC mixing fans. The resistors, each 4 ohm +/-1% 50 W with built in heat sink, are divided into 4 banks of 4 branches of 6 resistors each (i.e. 4 parallel banks of 4 parallel circuits of 6 resistors in series). The mixing fans are then wired in parallel with the 4 branches in 2 of the resistor banks. Figure 22 shows an arrangement of 6 resistors for one branch in the foreground with another 6 resistors for a second branch in the background. One can also make out the white label on the impeller of one the mixing fans on the right side of the photo.

Each bank of resistors has two branches on the lower heater array, located roughly 600 mm (24 in.) above the finished floor, and two branches on the upper heater array, located the same distance below the finished ceiling.

By distributing a large quantity of oversized resistors with built in heat sinks and forced convection (i.e. by the mixing fans), the team was able to maximize uniformity of temperature in the mixing portion of the meter box.

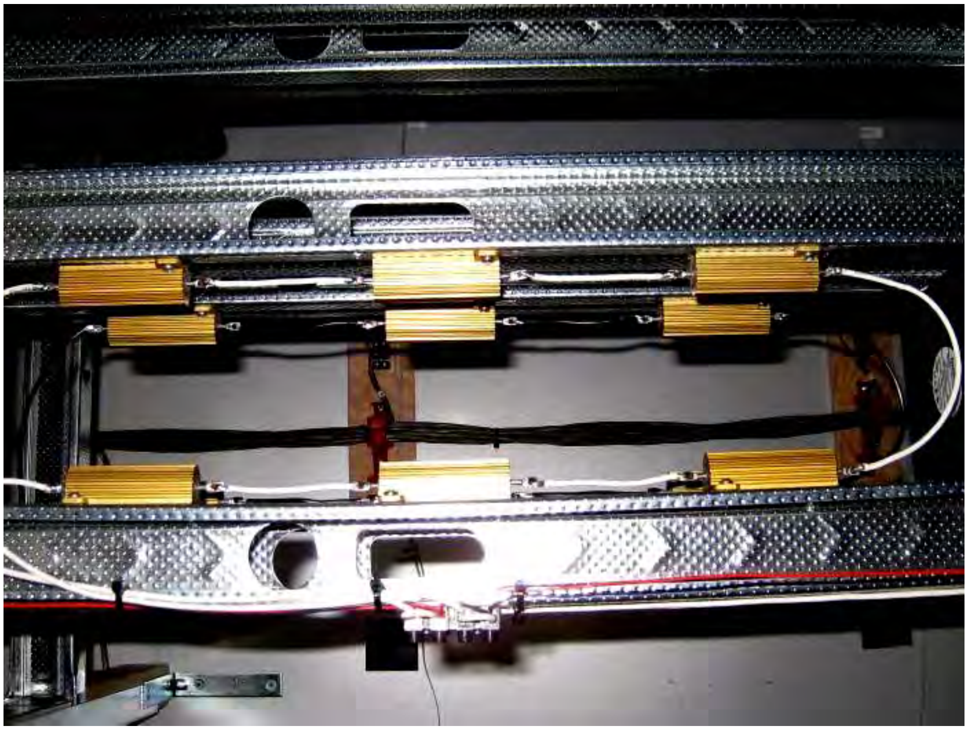


Figure 22 – Meter Box Resistance Heaters

Power for the resistors and fans is provided by a BK Precision VSP4030 remotely programmable power supply controlled by an Omega CN3251 controller that receives its process signal from an ultra precision RTD located in the middle of the mixing portion of the box. At 40 VDC, with all 4 resistor banks engaged, the system is capable of adding over 1 kW of heat to the meter box.

The power added by the heater resistors is calculated as the sum of the products of the measured voltage and the current for each of the 4 resistor banks:

$$Q = \sum V \cdot I$$

The voltage drop across each bank is measured, using the hot box MCS, across a voltage divider comprising eight 1 Mohm +/- 0.1% installed in parallel with the resistors. The MCS also measures the current in each branch of each bank (i.e. 16 measurements) as the voltage drop across 1 ohm +/- 0.01% 7 W resistors with Kelvin connections. The measurement circuits for the ‘blue’ and ‘red’ resistor banks can be seen in Figure 23.

The total uncertainty associated with the heating power measurement depends on the voltage supplied to the circuit and the number of resistor banks that are engaged. The purple line in Figure 24 shows the heating power uncertainty when all 4 banks are engaged and 0-40 VDC power is provided.

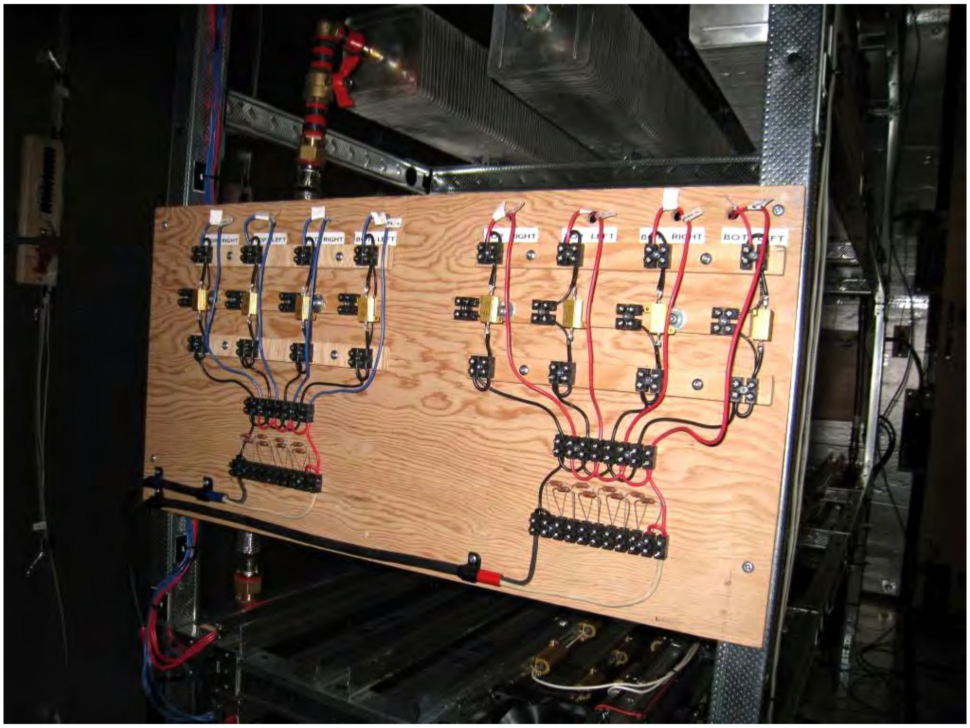


Figure 23 – Resistance Heater Measurement Circuit

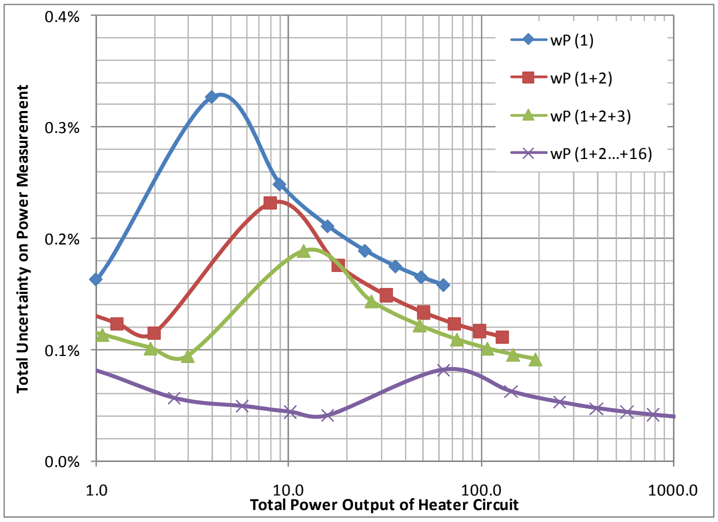


Figure 24 – Heating Power Measurement Uncertainty

Very tight temperature control results from the combination of the distributed resistance heaters, mixing fans, variable voltage power supply and PID controller. Figure 25 shows the baffle inlet temperature (i.e. the temperature of the air coming out of the mixing portion of the meter box) over a 24 hr period of testing.

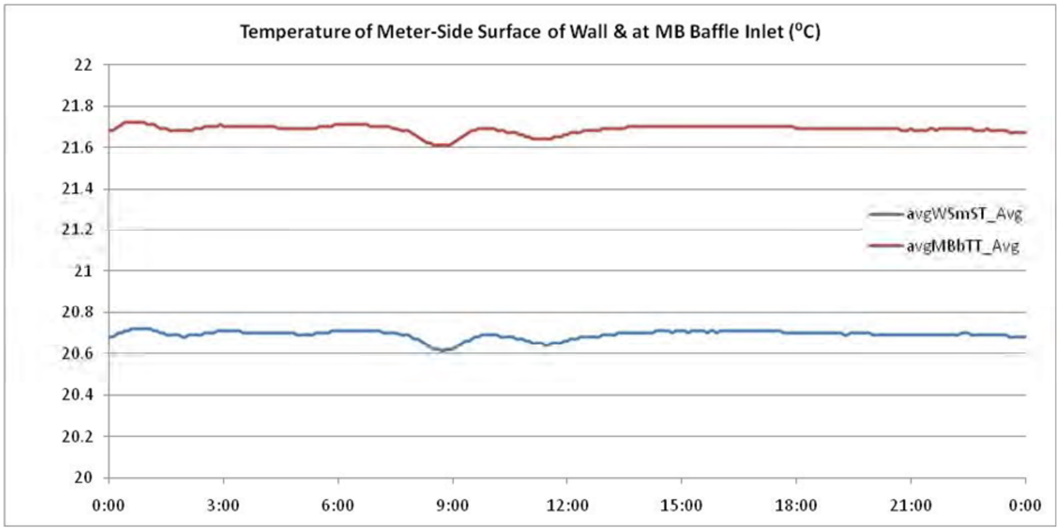


Figure 25 – Typical Meter Box Baffle Inlet (red) and Wall Specimen Surface (blue) Temperatures

Meter Box Convective Cooling Coil

Heat is removed from the meter box by chilled, distilled water circulated through the large finned cooling coil that can be seen in the upper portion of the photo of Figure 23. The coil is located at mid height on the equipment rack, half way between the upper and lower heating arrays.

By using a large format coil, adequate heat can be removed with low temperature differences and low convection velocities, both of which serve to maximize temperature uniformity in the mixing portion of the meter box.

The power removed by the cooling coil can be calculated using the product of the mass flow rate of the liquid, its heat capacity and the temperature difference:

$$Q = \dot{m} \cdot c \cdot \Delta T$$

The cooling water temperature difference (deltaT) is measured by ultra precision RTDs that are positioned within 50 mm (2 in.) of the location where the cooling water supply and return pipes penetrate the meter box. The sensor is installed in a tee fitting so that its tip is held in position in the middle of the flow. To minimize gains from the meter box and ensure measurement accuracy, the entire assembly is well insulated as seen in the photograph of Figure 26.

The accuracy of the heat removal calculation is highly dependent on the uncertainty of the cooling water temperature measurement. Water has a relatively high heat capacity, so large amounts of heat can be moved even when temperature differences are small. At a flow rate of 0.095 lps (1.5 gpm), an error in deltaT of 0.01°C (0.018°F) results in an error of approximately 4 W.

To minimize the uncertainties associated with the temperature measurements, the system was modified during commissioning so that 4-20 mA transmitters are used to read the RTDs and relay a high level signal to the hot box MCS so that the influence of electrical noise is minimized. The 4-20 mA transmitter were scaled over the range of 12-44°C (53.6-111.2°F) using a precision decade box (0.01 ohm resolution, +/-0.1 ohm) and calibrated with the controlled temperature bath.

Figure 26 – Insulation around Meter Box Cooling Water Return Temperature Measurement

Several of the custom calibrated thermistor sensors were installed in parallel with the RTDs as a second, verification measurement of deltaT.

The cooling water flow rate is measured using a NIST traceable Omega FTB-901T flow meter (+/- 0.5% of reading) and a FLSC-61 signal conditioner as seen in the picture of Figure 27.

The cooling water flow measurement system was calibrated by pumping water out of a constant head reservoir and into a tank on a electronic scale to allow for a gravimetric comparison. Results for a flow rate of approximately 0.095 LPS (1.51 GPM) are presented in Figure 28. The 0.0004 LPS discrepancy between the flow meter measurement and the gravimetric measurement represents an error of approximately 0.8 W when the deltaT is accurately measured.

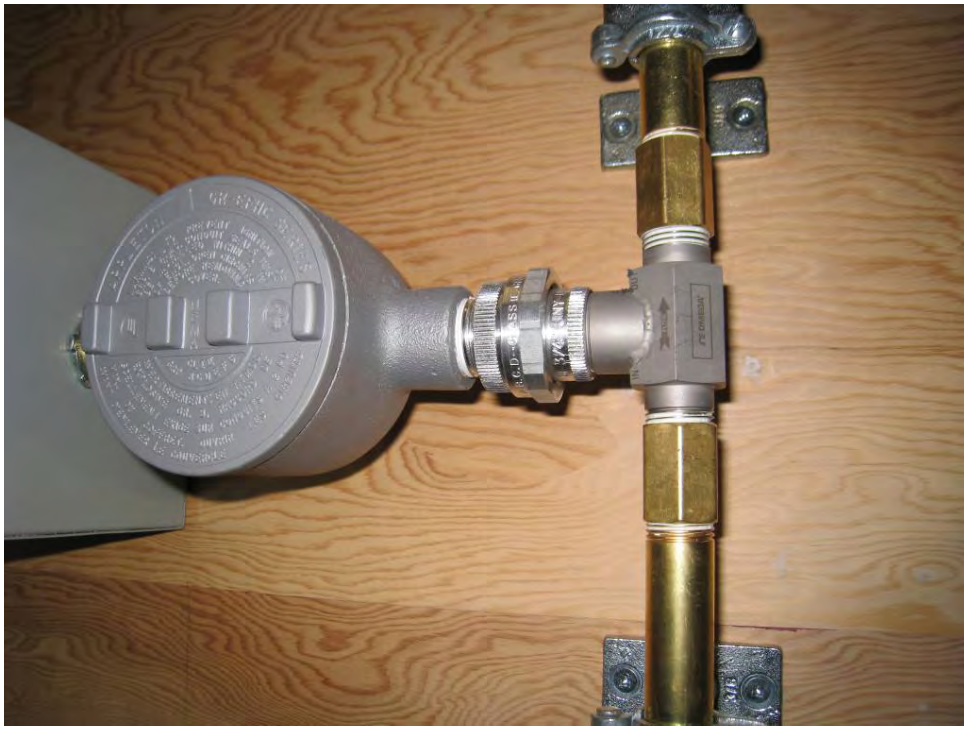


Figure 27 – Cooling Water Flow Meter (right) and Signal Conditioner (left)

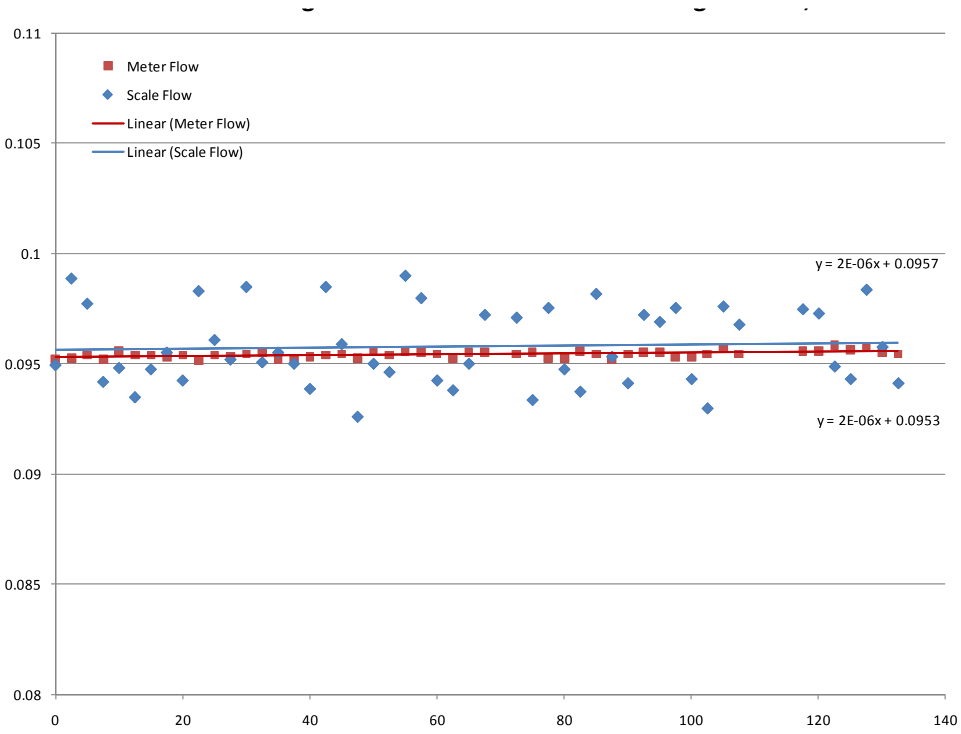


Figure 28 – Cooling Water Flow Meter Commissioning – Approx 380 Hz, 0.095LPS

Air Transfer System

The Air Transfer System (ATS) moves air between the meter box and the climate box to generate a pressure difference between the two and induce either infiltration or exfiltration. Heat is moved through the ATS along with the air and it is therefore necessary to calculate the additional load applied to or heat provided to the meter box.

The additional load or heat provided by the ATS can be calculated using the product of the mass flow rate of the air, its heat capacity and the temperature difference:

$$Q = \dot{m} \cdot c \cdot \Delta T$$

Differential temperature measurement for the ATS is accomplished in a manner similar to the cooling water system. The ATS uses a series of ultra precision RTDs and custom calibrated thermistor sensors to measure the temperature difference between the air supplied to the meter box and the air in the meter box.

A TSI 4021 high performance mass flowmeter (+/- 2% of reading) is used to measure the mass flow rate of air removed from or delivered to the meter box by the ATS. The ATS flow rate measurement was commissioned by passing the airflow through a 0 to 80 SCFH rotometer in series with the TSI 4021 as illustrated in Figure 29. The meter and rotometer readings agreed to within 2% for the full range of the rotometer.

Figure 29 – Air Transfer System Commissioning

Commissioning & Calibration of Complete TM Hot Box Apparatus

Having completing the commissioning and calibration of the measurement and control subsystems, the research team undertook the commissioning and calibration of the complete TM hot box apparatus using a series of calibration panels and ideal wood-framed, fiberglass insulated test wall specimens. These activities are summarized in this portion of the report.

Air Tightness

Air movement is a major component of the TM research project. It is therefore necessary to eliminate any air movement outside of the ATS and the test wall specimen. Figure 30 shows the air leakage between the meter box and guard box for a series of 4 different tests.

Air leakage rates were measured using a CanBest window test kit. A second fan was used to pressurize/depressurize the climate box to the same pressures as the meter box to permit differentiation between the meter box air leakage and air leakage through the test wall specimen. Air pressures were measured using an Energy Conservatory DG700.

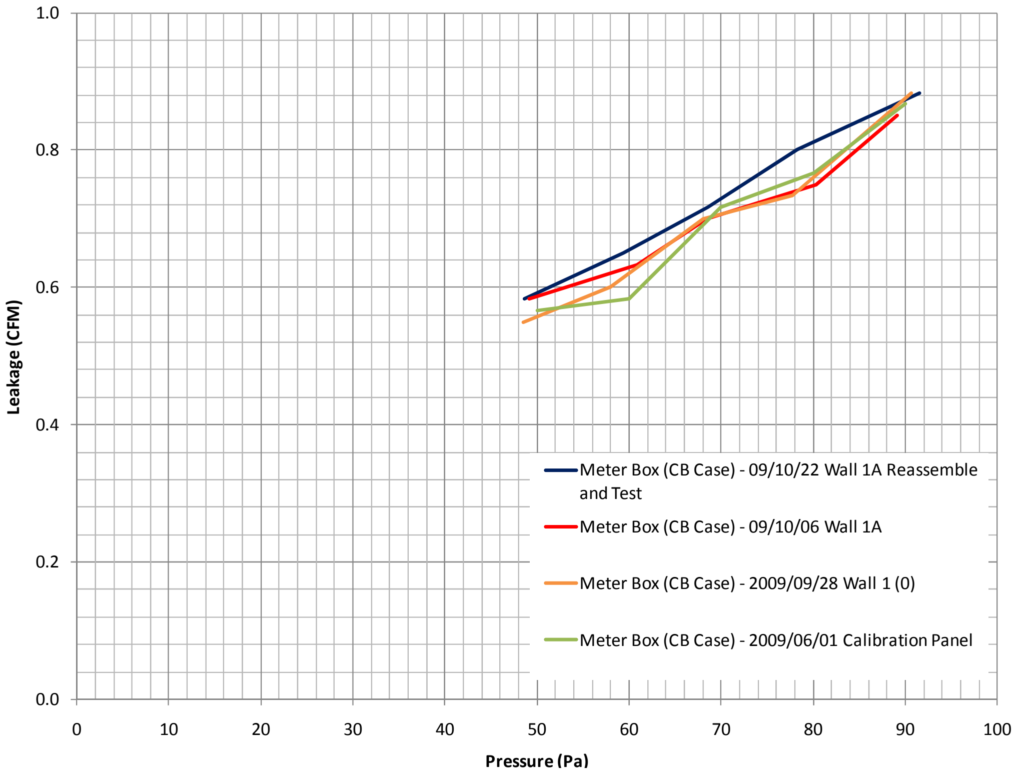


Figure 30 – Air Leakage Characterization for the Meter Box over a Series of 4 Tests

The results of the tests demonstrate the ability to repeatedly achieve a good seal between the meter box and the wall cartridge so that air leakage between the two is minimized.

It is also desirable to characterize the air leakage between the meter box and the climate box, through the test wall specimen. This was done using a similar approach: a second fan was used to balance the pressure between the meter box and the guard box to permit isolation of the air leakage through the wall assembly.

Figure 31 shows this characterization for the same series of 4 tests illustrated in Figure 30. The lowest line (green) represents a calibration panel that comprises a solid 100 mm (4 in.) thick panel of HDEPS insulation. The only leakage paths in this case exist around the perimeter of the panel where it meets the cartridge. It is therefore very tight.

The second lowest line (yellow) represents a 2x4 wood frame test wall specimen with 12 mm (1/2 in.) GWB, R13 fiberglass batt, OSB sheathing with a 3 mm (1/8 in.) horizontal joint, a Tyvek WRB and vinyl siding. The wall was constructed to be as tight as reasonably possible.

The third and fourth lines (red & blue respectively) represent a second construction of the same framed wall, but with two standard (non-airtight) electrical boxes, a 14-2 Romex cable, and without sealing the joint at the top and the bottom of the Tyvek WRB. These were constructed to be representative of standard construction practices. The clearly show more leakage than the wall represented by the yellow line and good repeatability from one test, through the removal of the calibration panel, two the reassembly of the test apparatus.

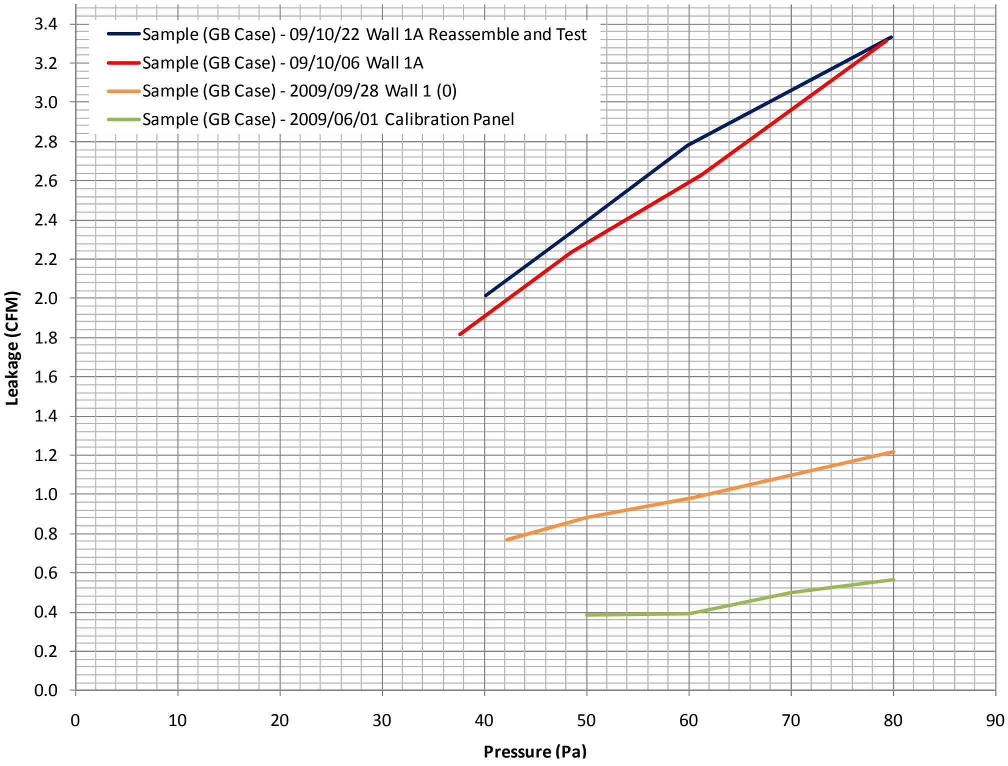


Figure 31 – Test Wall Specimen Air Leakage Characterization for a Series of 4 Tests

Calibration Panels

Three full-size calibration panels were constructed to facilitate the calibration of the complete TM hot box apparatus. The calibration panels each comprise two layers of HDEPS foam insulation, glued as pictured in Figure 32, to form a planar, solid, continuous layer of homogenous insulation. Two of the calibration panels are 100 mm (4 in.) thick while the third is 64 mm (2.5 in.) thick. The panels can be used individually or combined to permit calibration of the apparatus for testing walls with different thicknesses and apparent R-values.

Figure 32 – Fabrication of an HDEPS Calibration Panel

Upon the recommendation of several of the experienced industry partners, the surfaces of the calibration panels were painted with two coats of black latex paint. A number of 300x300 mm (12x12 in.) test samples were cut from the excess panel material to facilitate conductivity testing in BSC's ASTM 514 machine, a ThermoFox 314, pictured in Figure 33.

Figure 34 summarizes the ASTM 514 test results for 12 of the HDEPS calibration panel samples. The standard deviation of the R-value test results was less than 0.35% for all samples over the full temperature range.

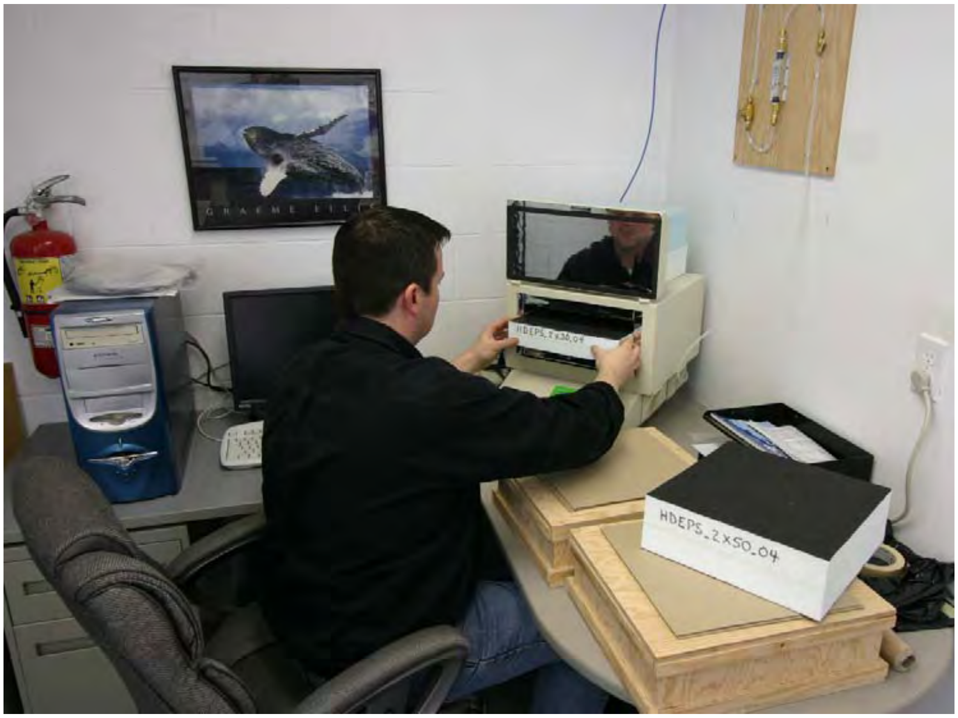


Figure 33 – Testing Calibration Panel Specimens in BSC's 514 Test Machine

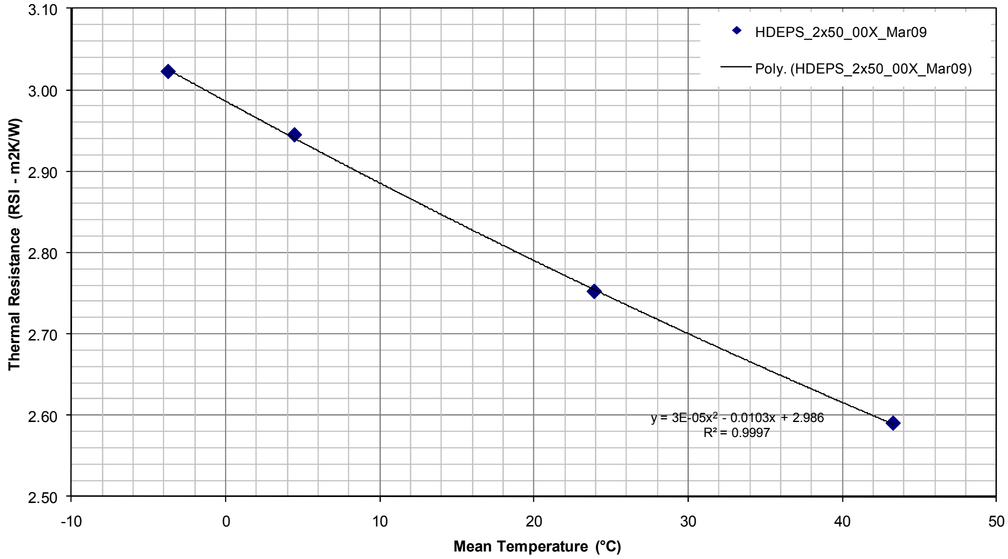


Figure 34 – Average ASTM 514 Test Results for Twelve 100 mm HDEPS Calibration Panel Samples

A similar set of test temperatures were then run in the TM hot box so the ASTM 514 results could be compared to the full-size test results. Figure 35 shows the climate side air and wall surface temperatures for a test in which the climate box was run at 2°C (35.6°F) while the meter box was maintained at 22°C (71.6°F) for an air to air temperature difference of 20°C (36°F) and a mean assembly temperature of 12°C (53.6°F).

From the graph of Figure 35 it can be seen that the climate box temperature is a little lower than the 2°C setpoint; however, it is still well within acceptable limits and shows excellent stability with less than 0.05°C standard deviation over time.

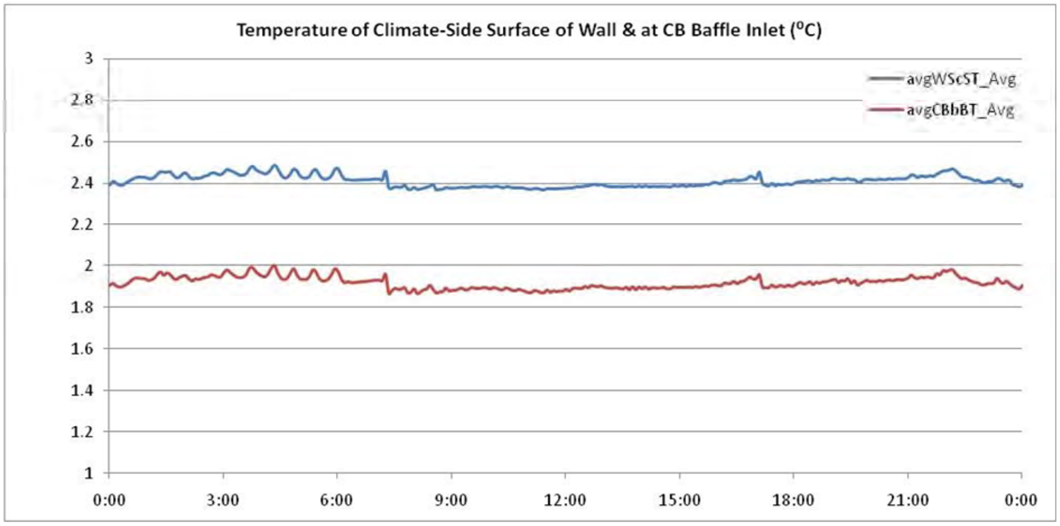


Figure 35 – Climate Box Baffle Inlet (red) and Wall Specimen Surface (blue) Temperatures

The total measured heat flow into the meter box is presented in Figure 36. The system shows excellent stability with standard deviation of less than 0.5 W.

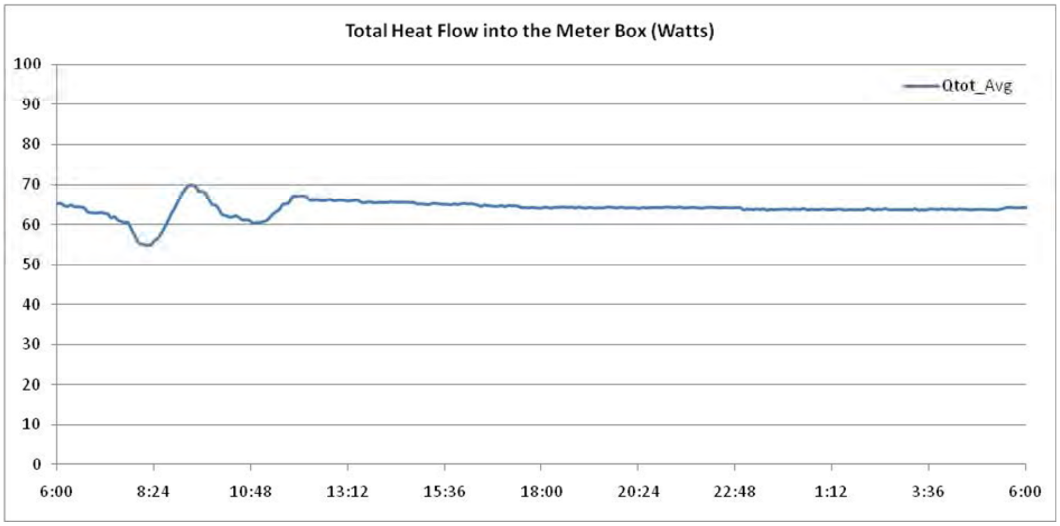


Figure 36 – Measured Total Heat Flow into the Meter Box for 100 mm HDEPS Calibration Panel, 22/2°C

Once adjustments are made for flanking losses, etc. the results of the TM hot box and the ASTM 514 test for the 100 mm (4 in.) calibration panel agree to within 3%.

Conclusions

In previous work, BSC identified the need for a more comprehensive and appropriate metric for the thermal performance of wall assemblies, especially those with higher apparent R-value. BSC followed this with a second document that proposed an apparatus and methodology for examining the problem of combined heat and airflow in wall assemblies.

BSC assembled a consortium of 6 building product manufacturers to participate in the privately-funded development of a new thermal metric through the construction and application of a new ‘Thermal Metric hot box’. This report documents the construction, commissioning and calibration of this apparatus.

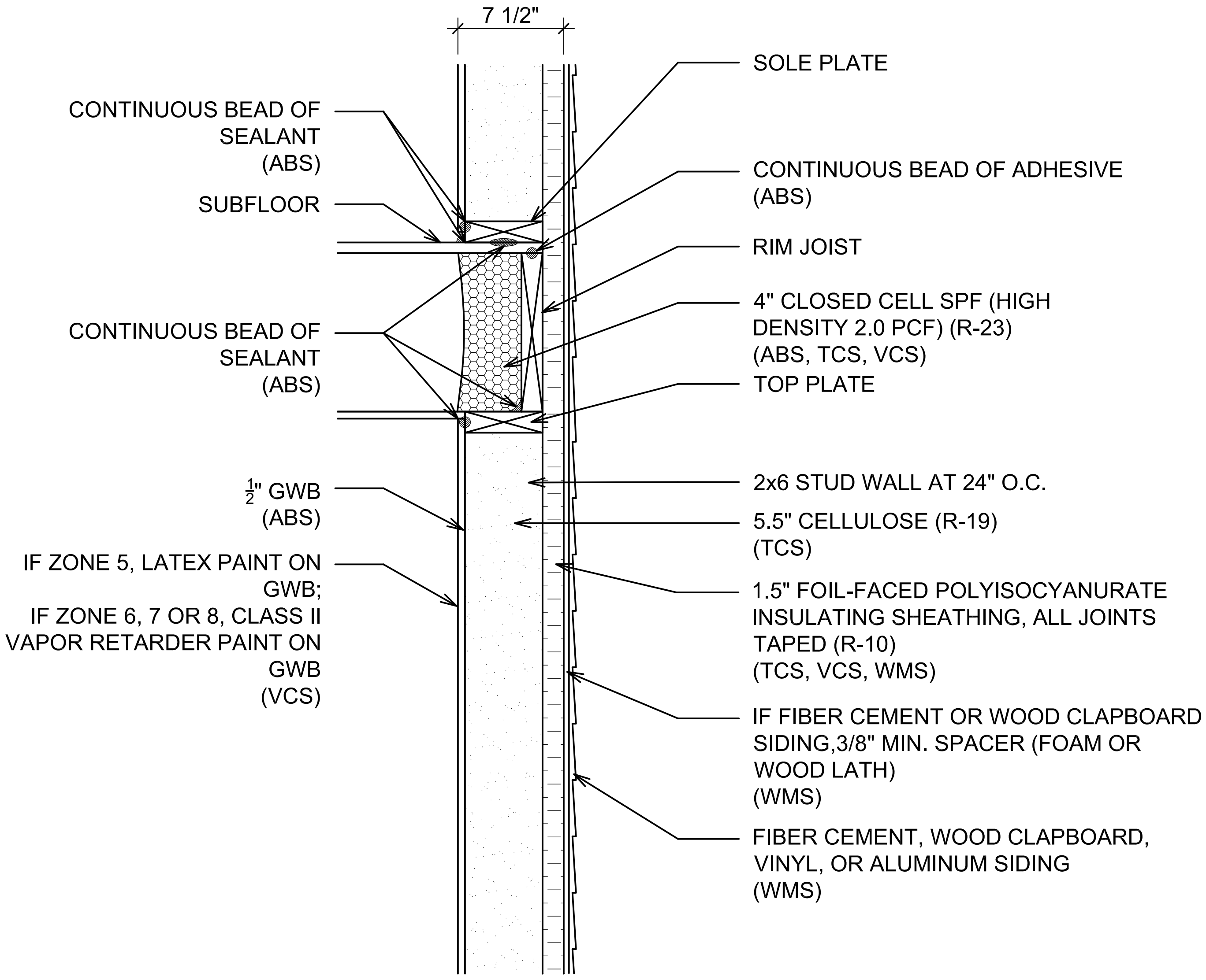
The TM hot box uses some novel systems and features to maximize its operating modes while reducing as many errors and as much noise as possible. Early calibration and testing work demonstrate that the apparatus meets the objectives laid out in BSC’s FY08 report entitled “Development of a Test Procedure and Apparatus for Measuring High Thermal Performance Walls”.

1.5.6. High R-value Enclosure Details

by Cathy Gates and BSC Staff

Framing: 2x6 STRUCTURAL STUD
Exterior Framing: VENTED LAP SIDING
Location of Insulation: CAVITY AND INSULATING SHEATHING
Location of Drainage Plane: INSULATING SHEATHING
Location of Air Barrier: AIRTIGHT DRYWALL APPROACH
Insulation Type, R-Value: 5.5" CELLULOSE + 1.5" FOIL-FACED POLYISOCYANURATE, R-29
Climate/Zone: ALL CLIMATES IN U.S.

ABS: Air Barrier System component
TCS: Thermal Control System component
VCS: Vapor Control System component
WMS: Water Management System component



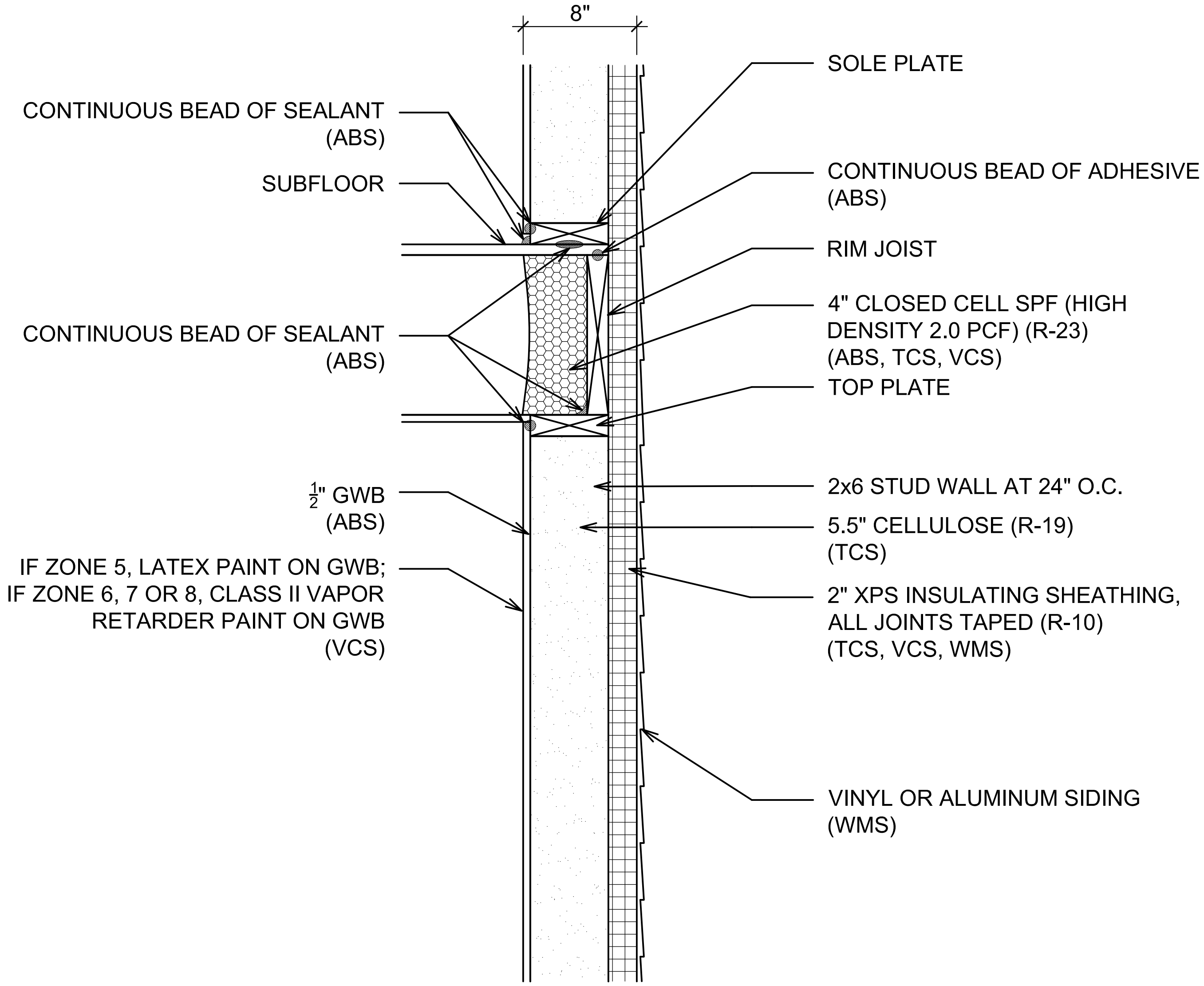
BSC with U.S.
Department of Energy
Building America

Project: High-R Enclosures
Date: 2009-09-09
Drawing Title: High-R Walls
Drawing File: HighR-Wall-02-1
Drawing Scale: 1" = 1'-0"

High-R Wall: 1 1/2" Insulating Sheathing Wall Construction

Framing: 2x6 STRUCTURAL STUD
Exterior Framing: VINYL OR ALUMINUM SIDING
Location of Insulation: CAVITY AND INSULATING SHEATHING
Location of Drainage Plane: INSULATING SHEATHING
Location of Air Barrier: AIRTIGHT DRYWALL APPROACH
Insulation Type, R-Value: 5.5" CELLULOSE + 2" XPS SHEATHING, R-29
Climate/Zone: ALL CLIMATES IN U.S.

ABS: Air Barrier System component
TCS: Thermal Control System component
VCS: Vapor Control System component
WMS: Water Management System component



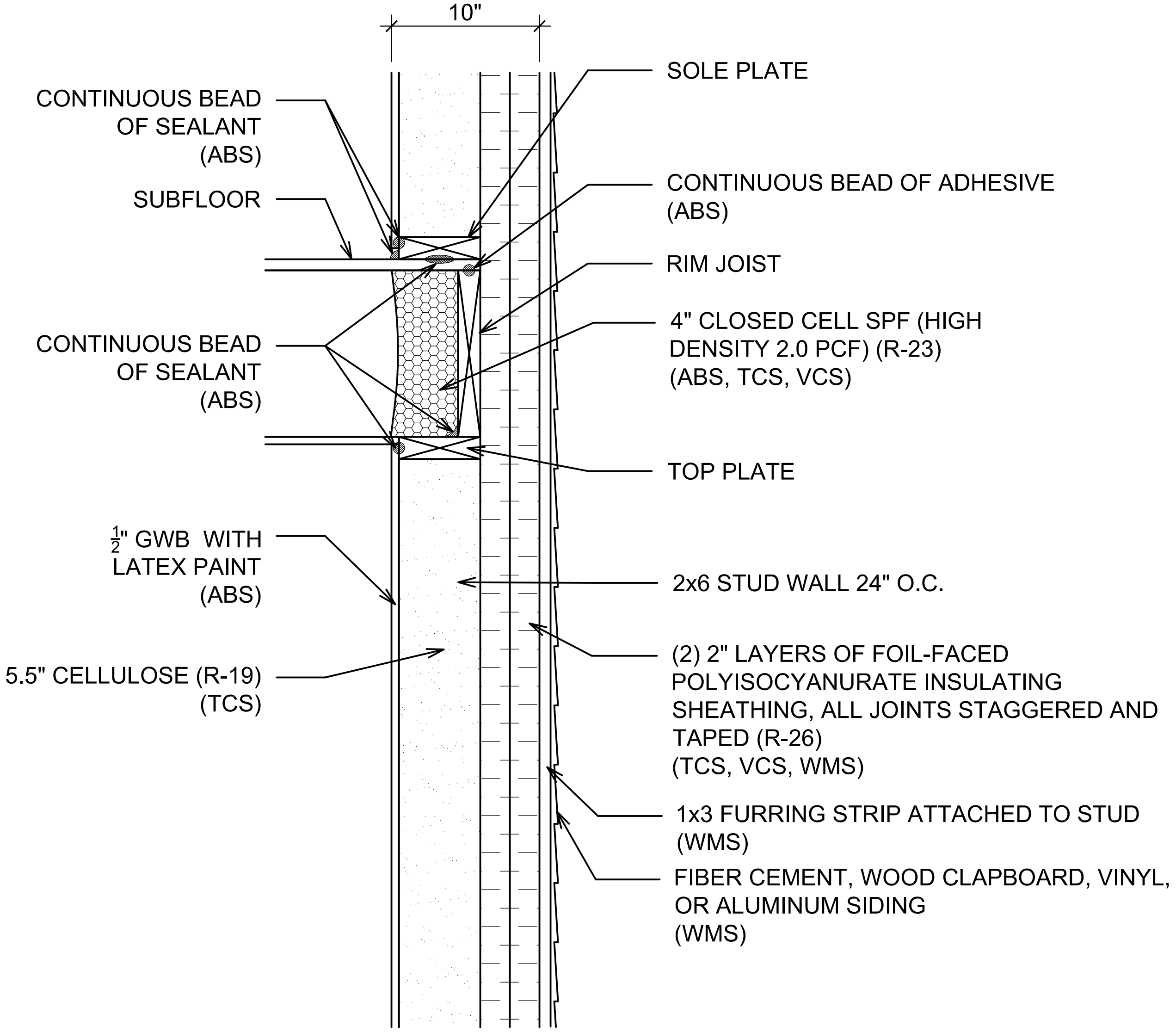
BSC with U.S.
Department of Energy
Building America

Project: High-R Enclosures
Date: 2009-09-29
Drawing Title: High-R Walls
Drawing File: HR-Wall-02-2
Drawing Scale: 1" = 1'-0"

High-R Wall: 2" Insulating Sheathing Wall Construction

Framing:	2x6 STRUCTURAL STUD
Exterior Framing:	VENTED LAP SIDING
Location of Insulation:	CAVITY AND INSULATING SHEATHING
Location of Drainage Plane:	INSULATING SHEATHING
Location of Air Barrier:	AIRTIGHT DRYWALL APPROACH
Insulation Type, R-Value:	5.5" CELLULOSE + 4" FOIL-FACED POLYISOCYANURATE, R-45
Climate/Zone:	COLD / ZONES 5, 6, 7 AND 8

ABS: Air Barrier System component
TCS: Thermal Control System component
VCS: Vapor Control System component
WMS: Water Management System component



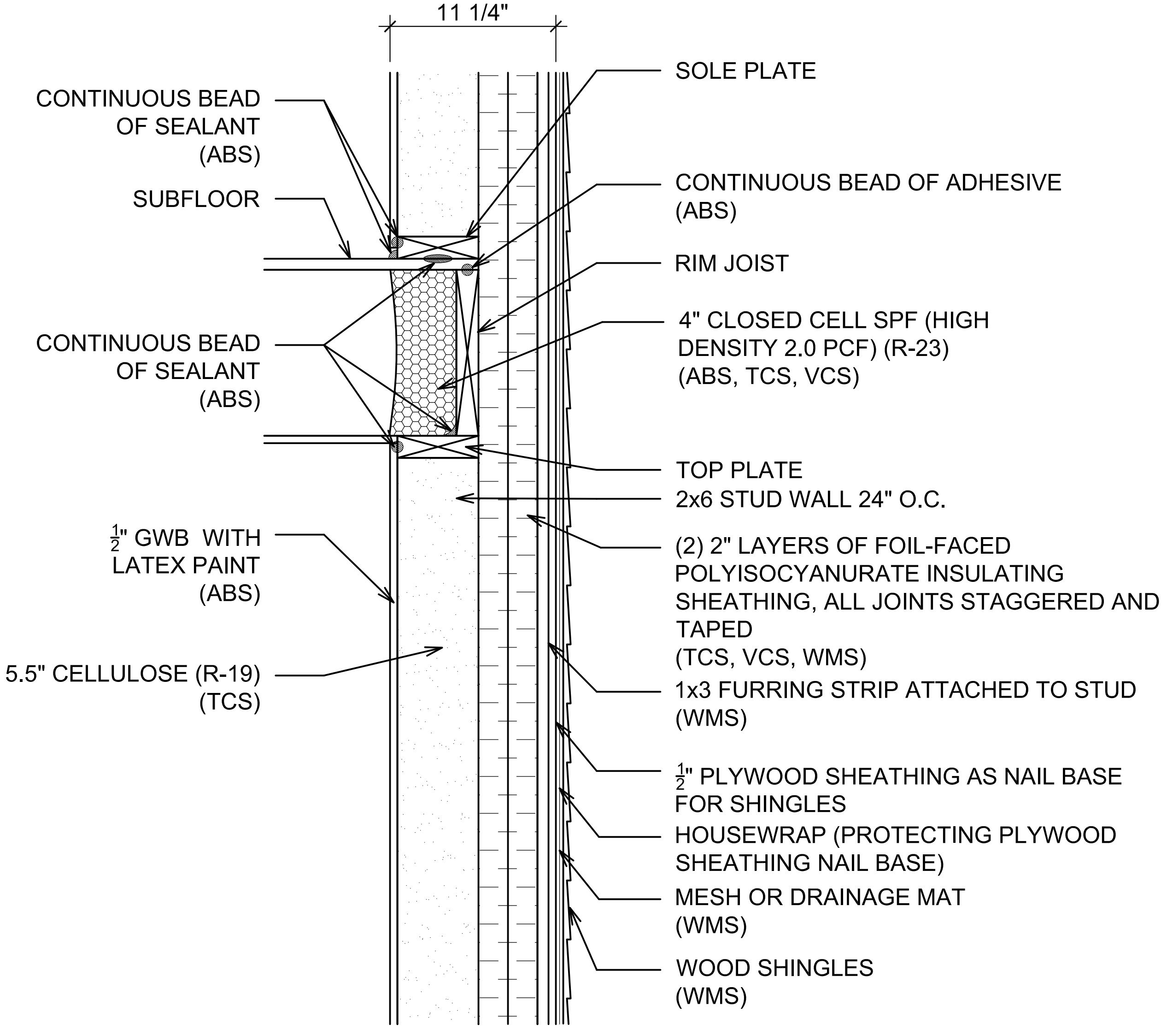
BSC with U.S.
Department of Energy
Building America

Project:	High-R Enclosures
Date:	2009-09-29
Drawing Title:	High-R Walls
Drawing File:	HighR-Wall-02-3
Drawing Scale:	1" = 1'-0"

High-R Wall: 4" Insulating Sheathing Wall Construction

Framing: 2x6 STRUCTURAL STUD
Exterior Framing: WOOD SHINGLES
Location of Insulation: CAVITY AND INSULATING SHEATHING
Location of Drainage Plane: INSULATING SHEATHING
Location of Air Barrier: AIRTIGHT DRYWALL APPROACH
Insulation Type, R-Value: 5.5" CELLULOSE + 4" FOIL-FACED POLYISOCYANURATE, R-45
Climate/Zone: COLD / ZONES 5, 6, 7 AND 8

ABS: Air Barrier System component
TCS: Thermal Control System component
VCS: Vapor Control System component
WMS: Water Management System component



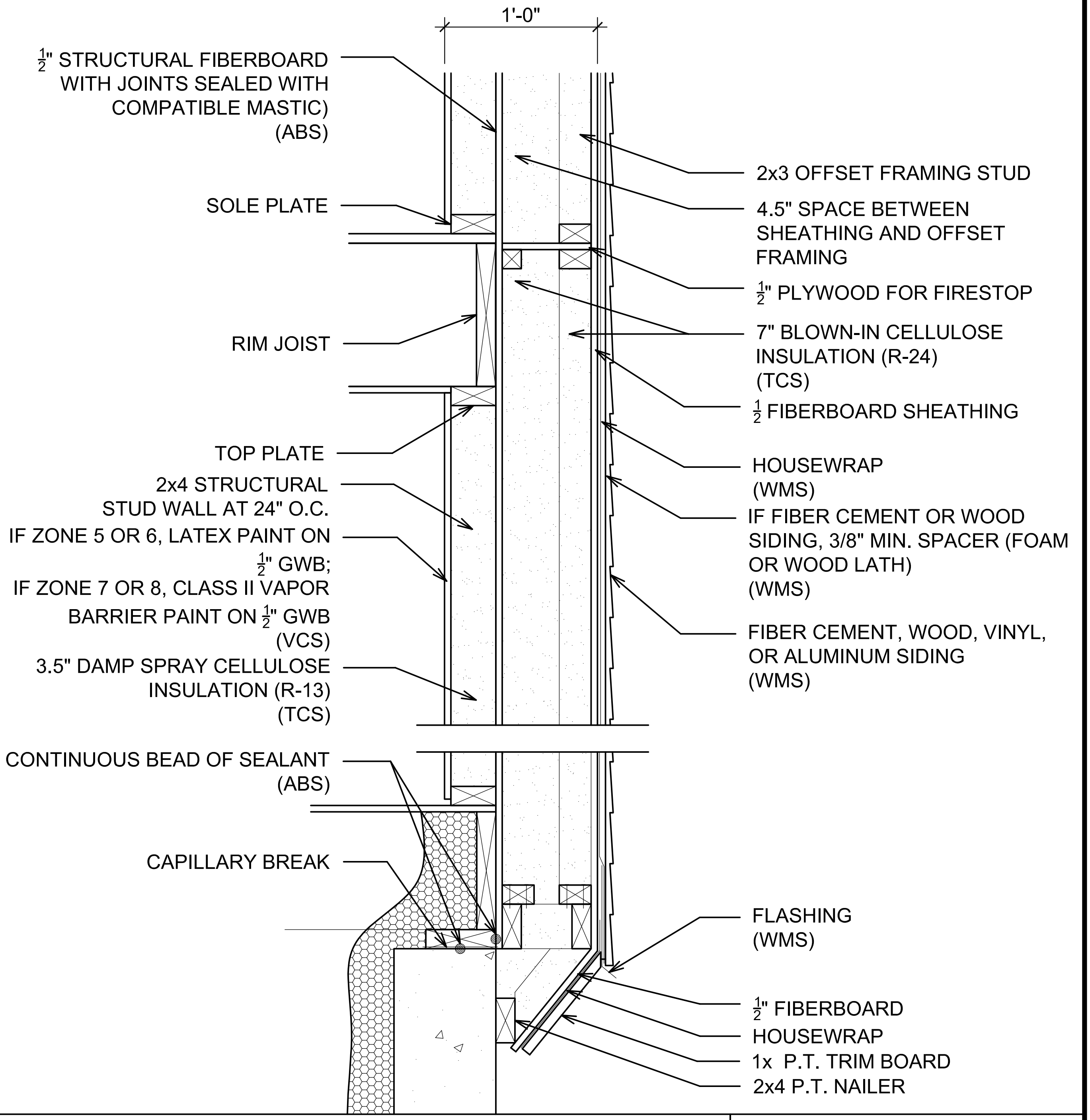
BSC with U.S.
Department of Energy
Building America

Project: High-R Enclosures
Date: 2009-09-29
Drawing Title: High-R Walls
Drawing File: HighR-Wall-02-4
Drawing Scale: 1" = 1'-0"

High-R Wall: 4" Insulating Sheathing with Shingles Wall Construction

Framing:	DOUBLE STUD WALL: 2x4 INTERIOR STUD + 2x3 EXTERIOR STUD
Exterior Framing:	VENTED LAP SIDING
Location of Insulation:	INTERIOR AND EXTERIOR WALL CAVITIES
Location of Drainage Plane:	HOUSEWRAP ON EXTERIOR SHEATHING
Location of Air Barrier:	FIBERBOARD SHEATHING ATTACHED TO INTERIOR STUD WALL
Insulation Type, R-Value:	10.5" CELLULOSE, R-37
Climate/Zone:	COLD / ZONES 5, 6, 7, AND 8

ABS: Air Barrier System component
TCS: Thermal Control System component
VCS: Vapor Control System component
WMS: Water Management System component



BSC with U.S.
Department of Energy
Building America

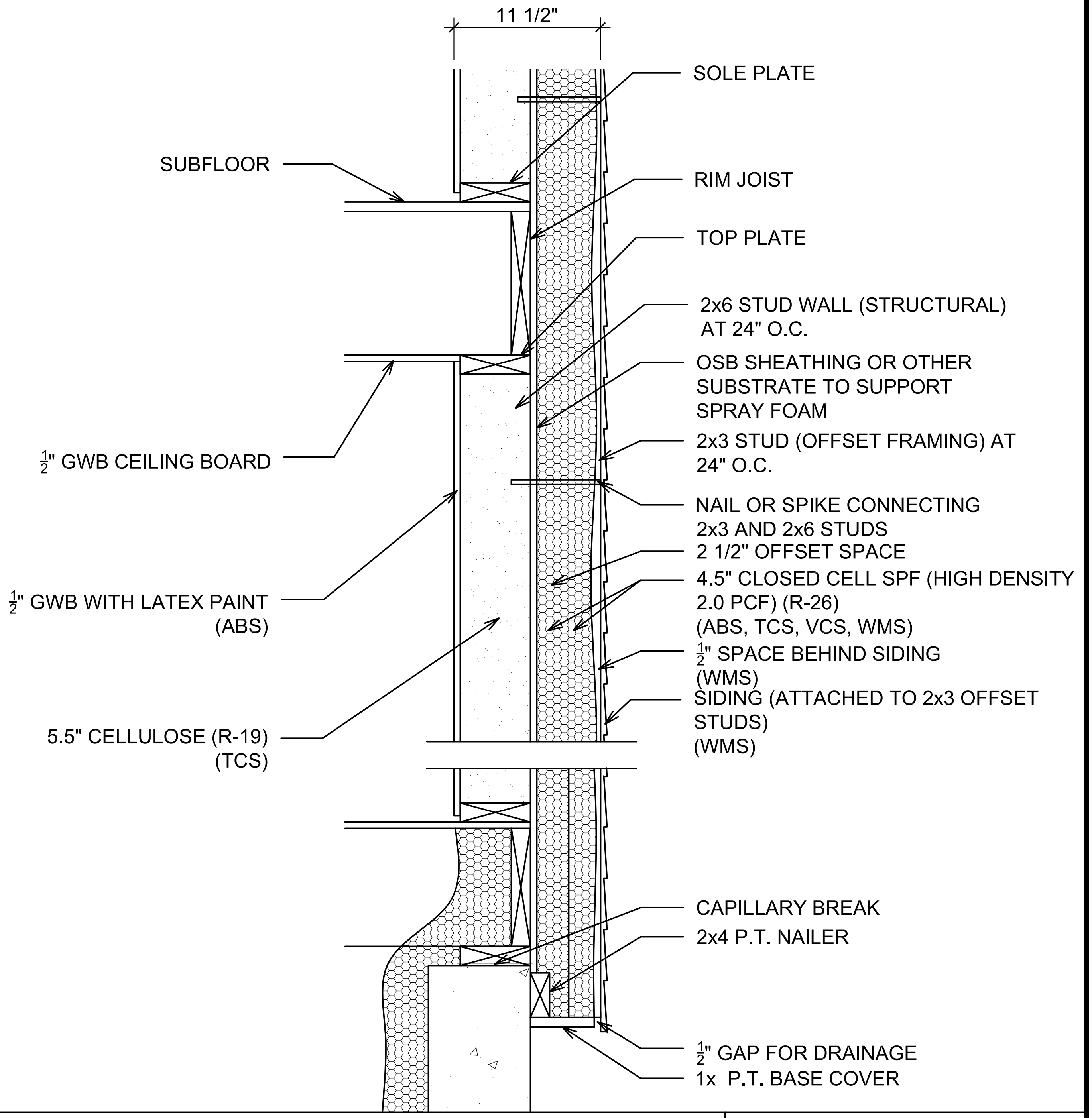
Project: High-R Enclosures
Date: 2009-09-09
Drawing Title: High-R Walls
Drawing File: HighR-Wall-04-1
Drawing Scale: 1" = 1'-0"

High-R Wall: Double Stud w/ Interior Load Bearing Wall Construction

C-264

Framing: 2x6 STRUCTURAL STUD W/ 2x3 EXTERIOR OFFSET FRAMING
Exterior Framing: VENTED LAP SIDING
Location of Insulation: CAVITY AND IN FRAMING OFFSET SPACE
Location of Drainage Plane: EXTERIOR FACE OF CLOSED CELL
Location of Air Barrier: CLOSED CELL INSULATION
Insulation Type, R-Value: 5.5" CELLULOSE + 4.5" CLOSED CELL SPF (HIGH DENSITY 2.0 PCF), R-46
Climate/Zone: COLD / ZONES 5, 6,7, AND 8

ABS: Air Barrier System component
TCS: Thermal Control System component
VCS: Vapor Control System component
WMS: Water Management System component



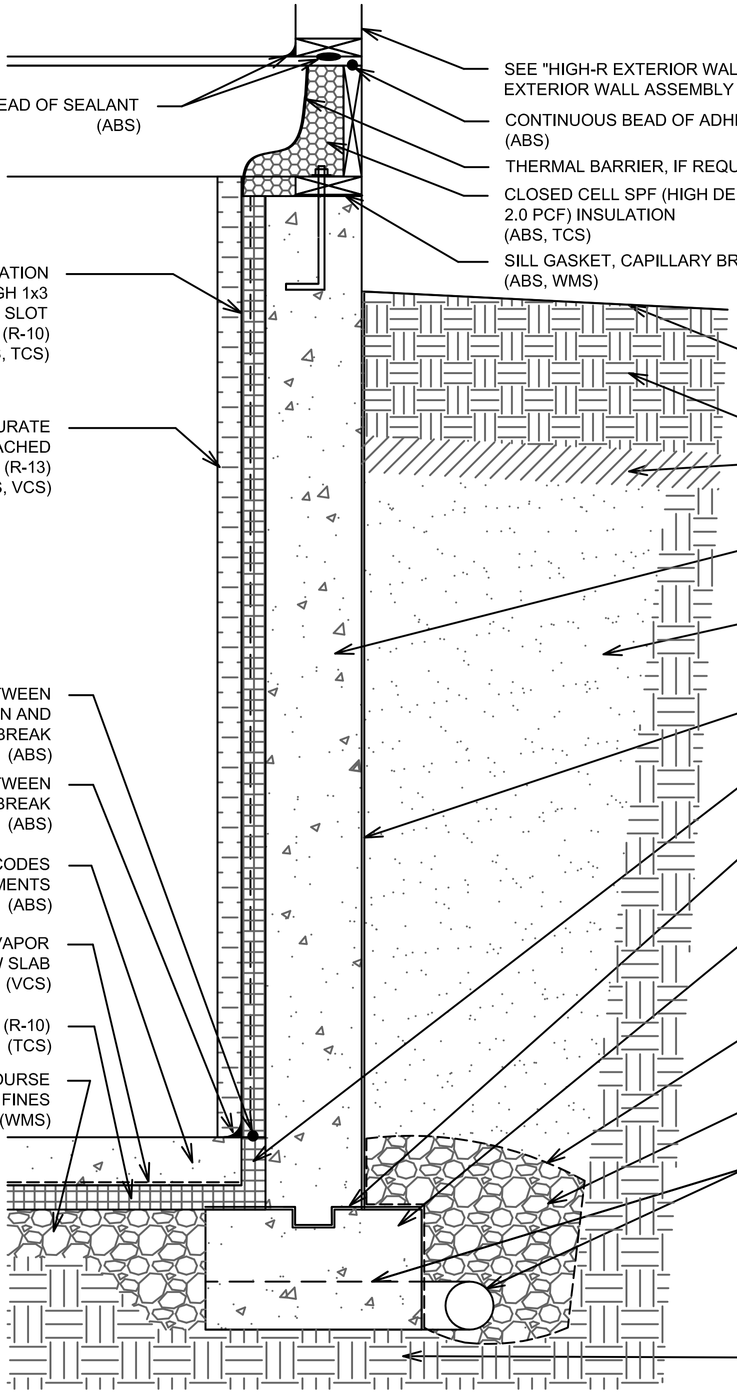
BSC with U.S.
Department of Energy
Building America

Project: High-R Enclosures
Date: 2009-09-29
Drawing Title: High-R Walls
Drawing File: HighR-Wall-11
Drawing Scale: 1" = 1'-0"

High-R Wall: Offset Framing Wall Construction

Foundation: CONCRETE
Basement: UNFINISHED
Location of Insulation: INTERIOR
Insulation Type, Insulation R-Value:
Concrete wall dries to the outside (above grade)
2" XPS + 2" FOIL-FACED POLYISOCYANURATE, R-23

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



CONTINUOUS BEAD OF SEALANT (ABS)

2" XPS SLOTTED INSULATION ATTACHED TO WALL THROUGH 1x3 FURRING STRIP PLACED IN SLOT (R-10) (ABS, TCS)

2" FOIL-FACED POLYISOCYANURATE RIGID INSULATION ATTACHED TO FURRING STRIPS (R-13) (ABS, TCS, VCS)

CONTINUOUS SEALANT BETWEEN RIGID INSULATION AND BOND BREAK (ABS)

CONTINUOUS SEALANT BETWEEN SLAB AND BOND BREAK (ABS)

4" CONCRETE SLAB; SEE LOCAL CODES FOR REINFORCING REQUIREMENTS (ABS)

6 MIL POLYETHYLENE VAPOR BARRIER BELOW SLAB (VCS)

2" XPS RIGID INSULATION (R-10) (TCS)

4" THICK BASE COURSE OF GRAVEL, NO FINES (WMS)

SEE "HIGH-R EXTERIOR WALLS" FOR EXTERIOR WALL ASSEMBLY OPTIONS

CONTINUOUS BEAD OF ADHESIVE (ABS)

THERMAL BARRIER, IF REQUIRED

CLOSED CELL SPF (HIGH DENSITY 2.0 PCF) INSULATION (ABS, TCS)

SILL GASKET, CAPILLARY BREAK (ABS, WMS)

GRADE SLOPES AT 5% AWAY FROM FOUNDATION WALL (WMS)

12" MIN. TOP SOIL

IMPERMEABLE COVER -- 3" CLAY OR MEMBRANE SKIRT -- EXTENDING MIN. 2'-0" AWAY FROM WALL (WMS)

8" CONCRETE FOUNDATION WALL; SEE LOCAL CODES FOR THICKNESS AND REINFORCING REQUIREMENTS

GW, GP, SW AND SP USCS SOIL TYPES; SEE LOCAL CODES FOR ADDITIONAL SOIL TYPE REQUIREMENTS (WMS)

DAMPPROOFING EXTENDING FROM GRADE TO FOOTING (WMS)

2" XPS BOND BREAK BETWEEN CONCRETE WALL AND SLAB

CAPILLARY BREAK -- DAMPPROOFING, CEMENTITIOUS COATING, MEMBRANE -- APPLIED TO TOP OF FOOTING (WMS)

X" x X' CONCRETE FOOTING WITH KEYWAY; SEE LOCAL CODES FOR SIZE AND REINFORCING REQUIREMENTS

FILTER FABRIC WRAPPING AROUND PERIMETER GRAVEL (WMS)

COARSE GRAVEL, NO FINES (WMS)

4" PERFORATED PERIMETER DRAIN PIPE WITH"T" CONNECTION THROUGH FOOTING TO INTERIOR DRAIN TILES; DRAIN TO INTERIOR SUMP OR TO DAYLIGHT (WMS)

UNDISTURBED SOIL

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U.S. Department of Energy
Research Toward Zero Energy Homes

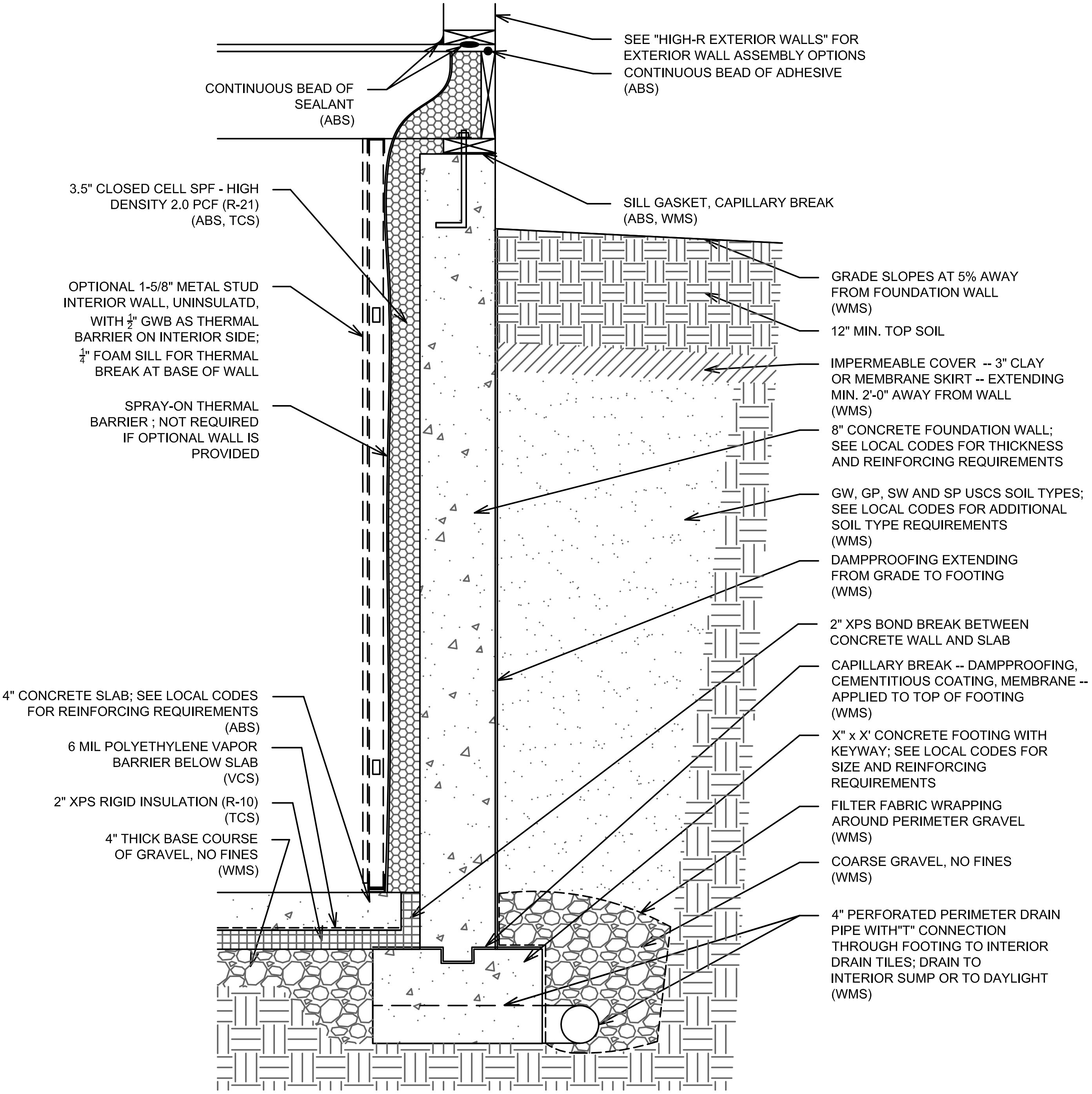
Project: High-R Foundation Walls
Date: 2009-06-03 DRAFT
Drawing Title: Foundation Walls
Drawing File: FoundationDetails.dwg
Drawing Scale: 3/4" = 1'-0"

Sheet Title:

Bsmt Type #1

Foundation: CONCRETE
Basement: UNFINISHED (OPTIONALLY FINISHED)
Location of Insulation: INTERIOR
Insulation Type, Insulation R-Value:
Concrete wall dries to the outside (above grade)
3-1/2" CLOSED CELL SPF (HIGH DENSITY 2.0 PCF),R-21

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



Project: High-R Foundation Walls
Date: 2009-06-03 DRAFT
Drawing Title: Foundation Walls
Drawing File: FoundationDetails.dwg
Drawing Scale: 3/4" = 1'-0"

Sheet Title:

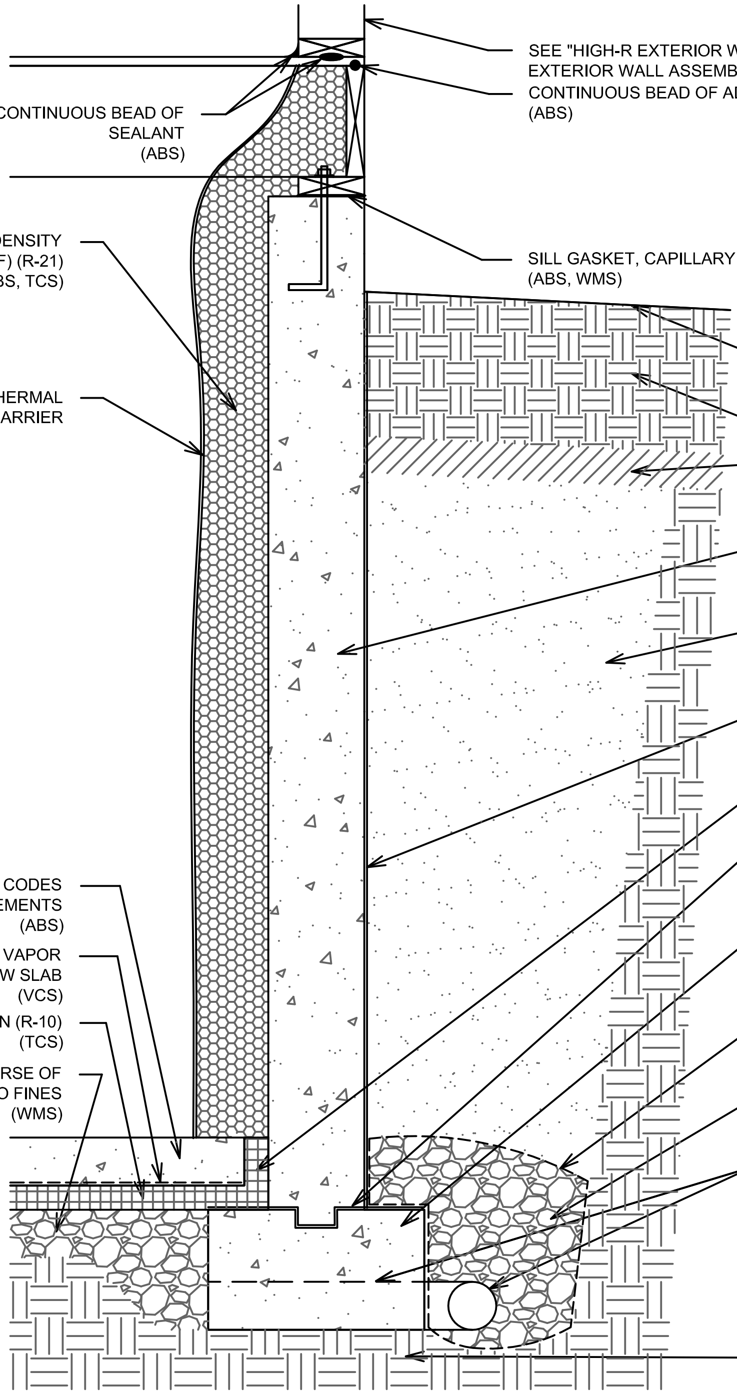
Bsmt Type #2

Foundation:	CONCRETE
Basement:	UNFINISHED
Location of Insulation:	INTERIOR
Insulation Type, Insulation R-Value:	

Concrete wall dries to the inside and outside (above grade)
6" OPEN CELL SPF (LOW DENSITY 0.5 PCF), R-21

Appropriate for Zone 5

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



CONTINUOUS BEAD OF SEALANT (ABS)

6" OPEN CELL SPF (LOW DENSITY 0.5 PCF) (R-21) (ABS, TCS)

SPRAY-ON THERMAL BARRIER

4" CONCRETE SLAB; SEE LOCAL CODES FOR REINFORCING REQUIREMENTS (ABS)

6 MIL POLYETHYLENE VAPOR BARRIER BELOW SLAB (VCS)

2" XPS RIGID INSULATION (R-10) (TCS)

4" THICK BASE COURSE OF GRAVEL, NO FINES (WMS)

SEE "HIGH-R EXTERIOR WALLS" FOR EXTERIOR WALL ASSEMBLY OPTIONS

CONTINUOUS BEAD OF ADHESIVE (ABS)

SILL GASKET, CAPILLARY BREAK (ABS, WMS)

GRADE SLOPES AT 5% AWAY FROM FOUNDATION WALL (WMS)

12" MIN. TOP SOIL

IMPERMEABLE COVER -- 3" CLAY OR MEMBRANE SKIRT -- EXTENDING MIN. 2'-0" AWAY FROM WALL (WMS)

8" CONCRETE FOUNDATION WALL; SEE LOCAL CODES FOR THICKNESS AND REINFORCING REQUIREMENTS

GW, GP, SW AND SP USCS SOIL TYPES; SEE LOCAL CODES FOR ADDITIONAL SOIL TYPE REQUIREMENTS (WMS)

DAMPPROOFING EXTENDING FROM GRADE TO FOOTING (WMS)

2" XPS BOND BREAK BETWEEN CONCRETE WALL AND SLAB

CAPILLARY BREAK -- DAMPPROOFING, CEMENTITIOUS COATING, MEMBRANE -- APPLIED TO TOP OF FOOTING (WMS)

X" x X' CONCRETE FOOTING WITH KEYWAY; SEE LOCAL CODES FOR SIZE AND REINFORCING REQUIREMENTS

FILTER FABRIC WRAPPING AROUND PERIMETER GRAVEL (WMS)

COARSE GRAVEL, NO FINES (WMS)

4" PERFORATED PERIMETER DRAIN PIPE WITH"T" CONNECTION THROUGH FOOTING TO INTERIOR DRAIN TILES; DRAIN TO INTERIOR SUMP OR TO DAYLIGHT (WMS)

UNDISTURBED SOIL

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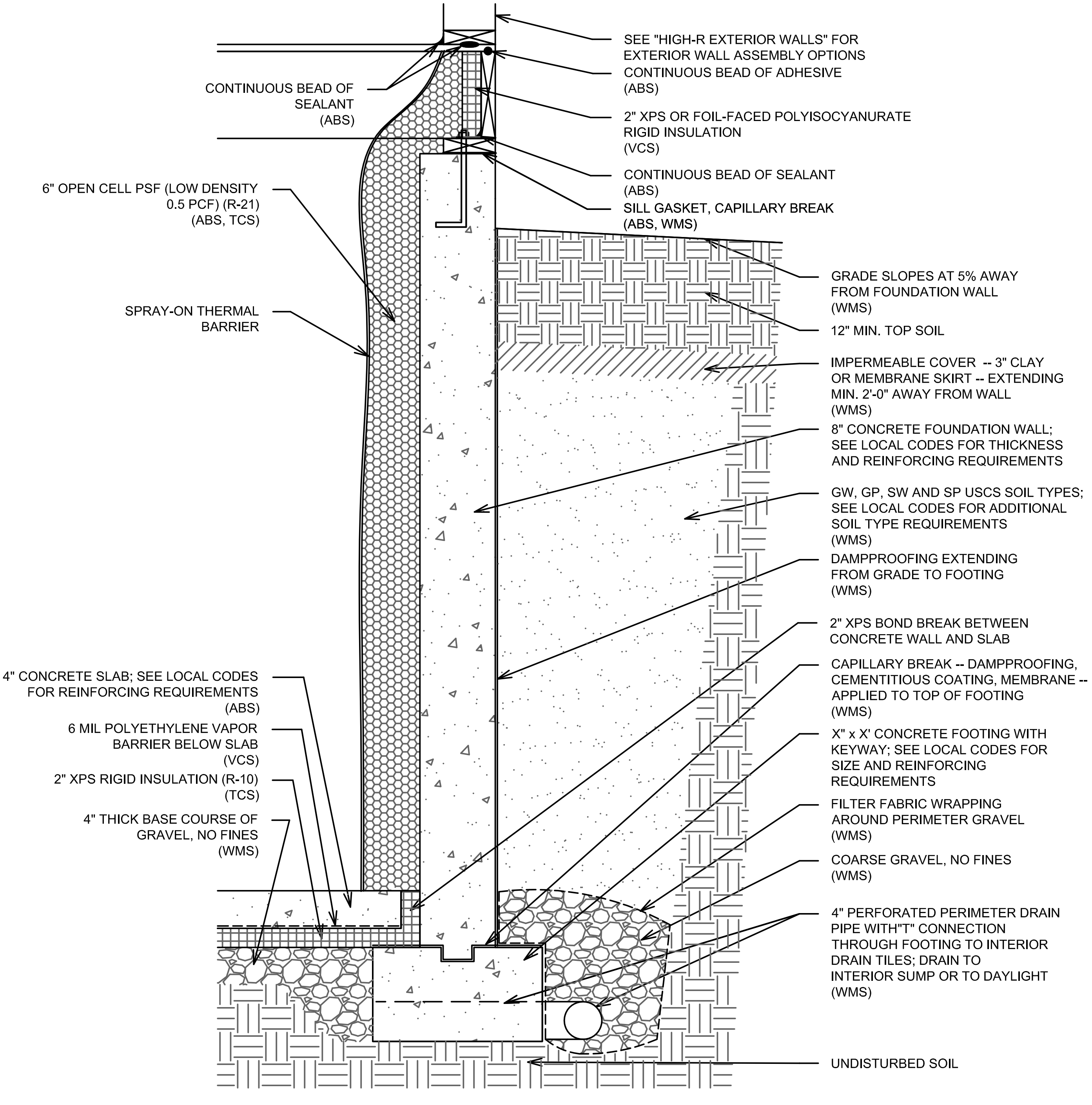
Project:	High-R Foundation Walls
Date:	2009-06-03 DRAFT
Drawing Title:	Foundation Walls
Drawing File:	FoundationDetails.dwg
Drawing Scale:	3/4" = 1'-0"

Sheet Title:

Bsmt Type #3

Foundation: CONCRETE
Basement: UNFINISHED
Location of Insulation: INTERIOR
Insulation Type, Insulation R-Value:
Concrete wall dries to the inside and outside (above grade)
6" OPEN CELL SPF (LOW DENSITY 0.5 PCF), R-21
Appropriate for Zone 6

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



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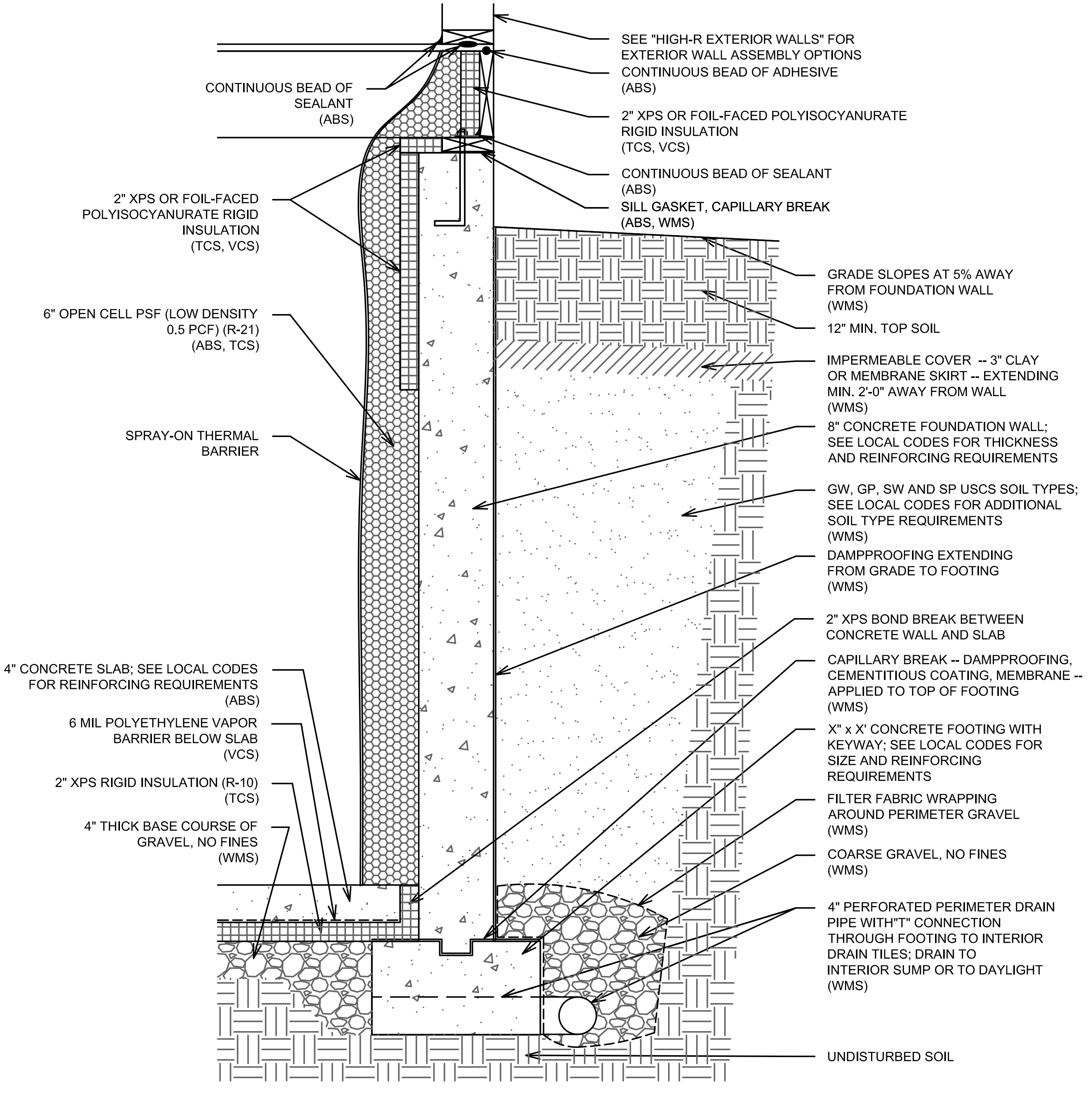
Project: High-R Foundation Walls
Date: 2009-06-03 DRAFT
Drawing Title: Foundation Walls
Drawing File: FoundationDetails.dwg
Drawing Scale: 3/4" = 1'-0"

Sheet Title:

Bsmt Type #3A

Foundation: CONCRETE
Basement: UNFINISHED
Location of Insulation: INTERIOR
Insulation Type, Insulation R-Value:
Concrete wall dries to the inside and outside (above grade)
6" OPEN CELL SPF (LOW DENSITY 0.5 PCF), R-21
Appropriate for Zone 7 and higher

ABS:	*Air Barrier System component*
TCS:	*Thermal Control System component*
VCS:	*Vapor Control System component*
WMS:	*Water Management System component*



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Project:	High-R Foundation Walls
Date:	2009-06-03 DRAFT
Drawing Title:	Foundation Walls
Drawing File:	FoundationDetails.dwg
Drawing Scale:	3/4" = 1'-0"

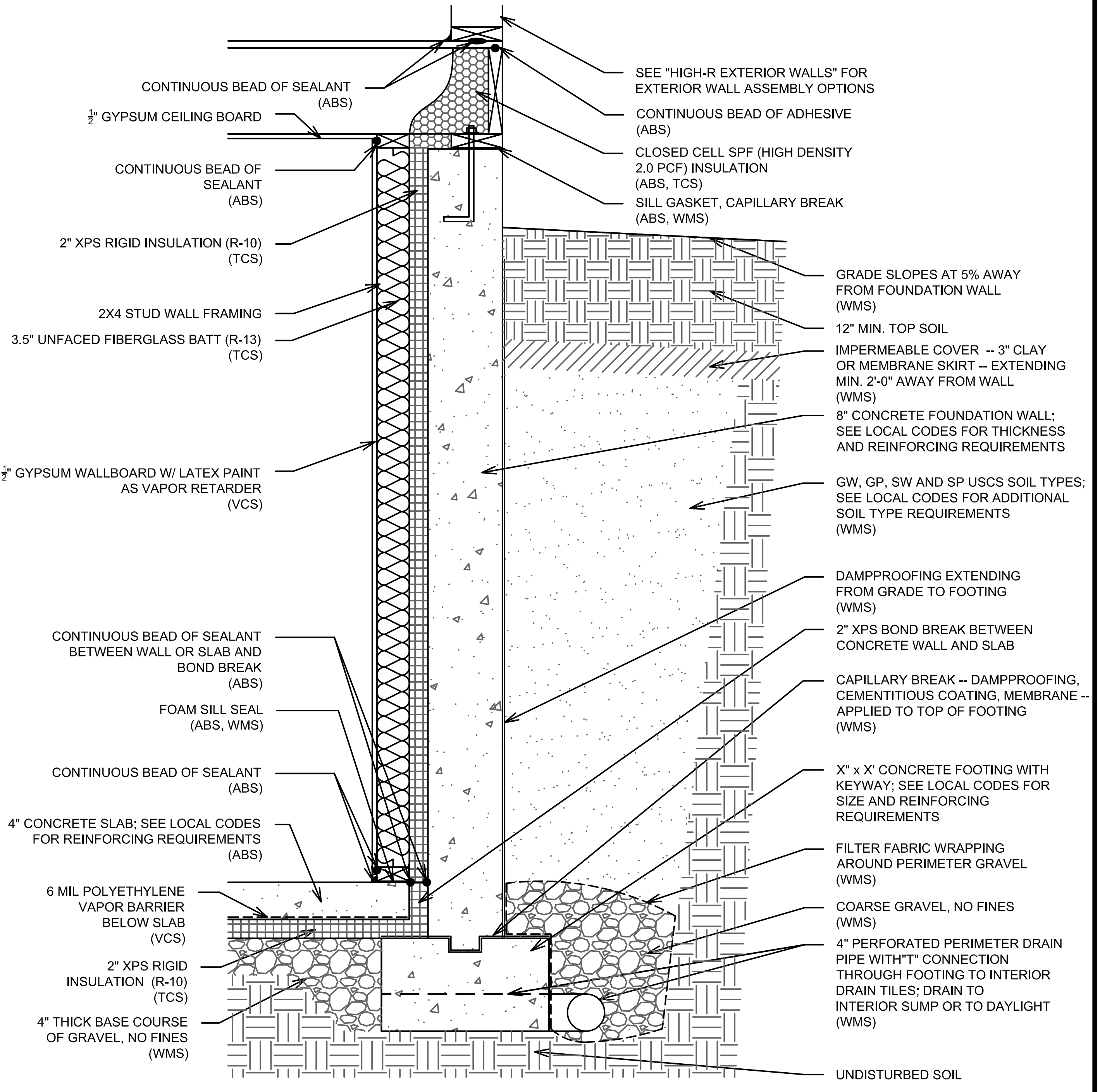
Sheet Title:

Bsmt Type #3B

Foundation:	CONCRETE
Basement:	FINISHED
Location of Insulation:	INTERIOR
Insulation Type, Insulation R-Value:	

Concrete wall dries to inside and to outside (above grade)
2" XPS + 3.5" FIBERGLASS BATT, R-23

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



with

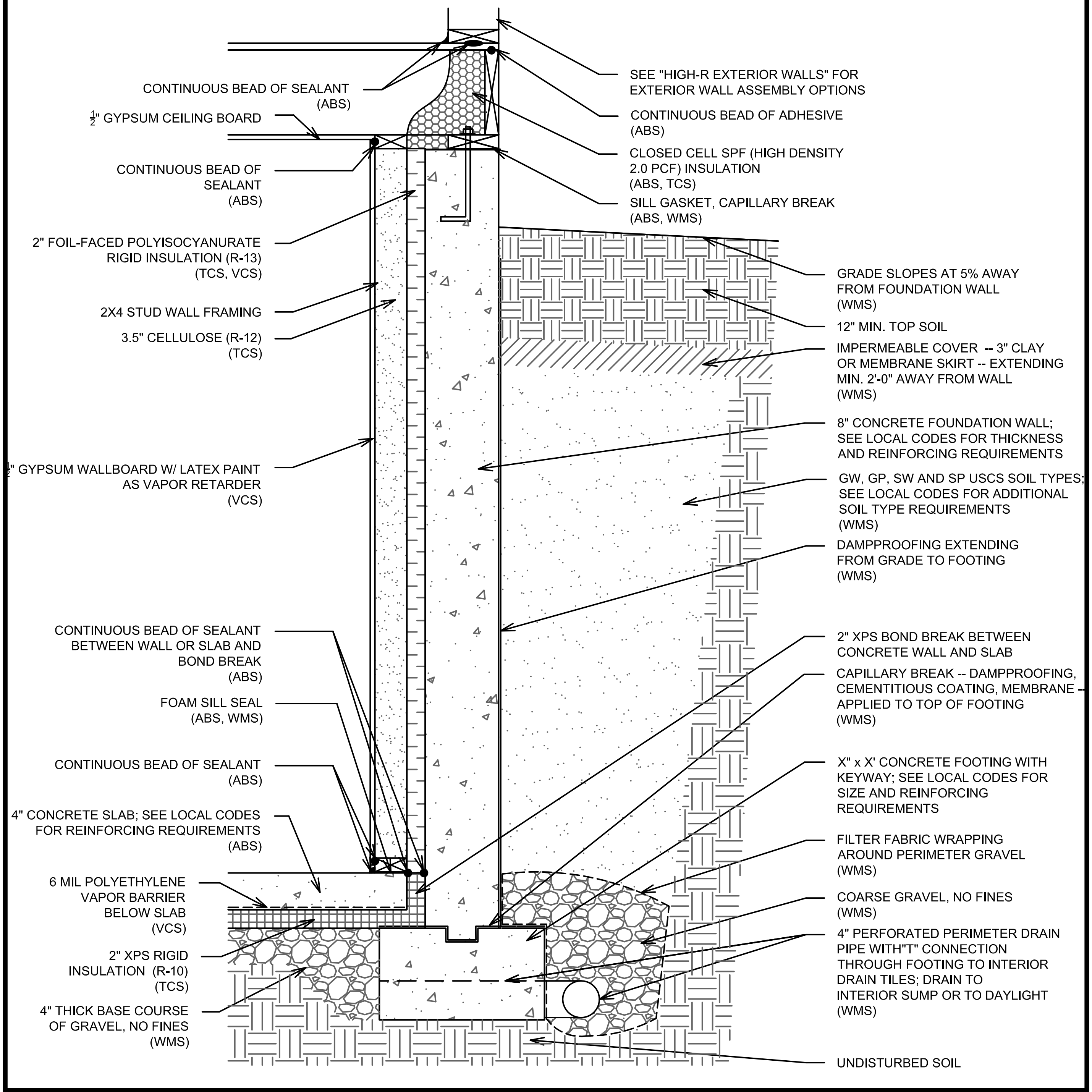
Project:	High-R Foundation Walls
Date:	2009-06-03 DRAFT
Drawing Title:	Foundation Walls
Drawing File:	FoundationDetails.dwg
Drawing Scale:	3/4" = 1'-0"

Sheet Title:

Bsmt Type #4

Foundation: CONCRETE
Basement: FINISHED
Location of Insulation: INTERIOR
Insulation Type, Insulation R-Value:
Concrete wall dries to outside (above grade)
2" FOIL-FACED POLYISOCYANURATE +
3.5" CELLULOSE, R-25

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



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Project: High-R Foundation Walls
Date: 2009-06-03 DRAFT
Drawing Title: Foundation Walls
Drawing File: FoundationDetails.dwg
Drawing Scale: 3/4" = 1'-0"

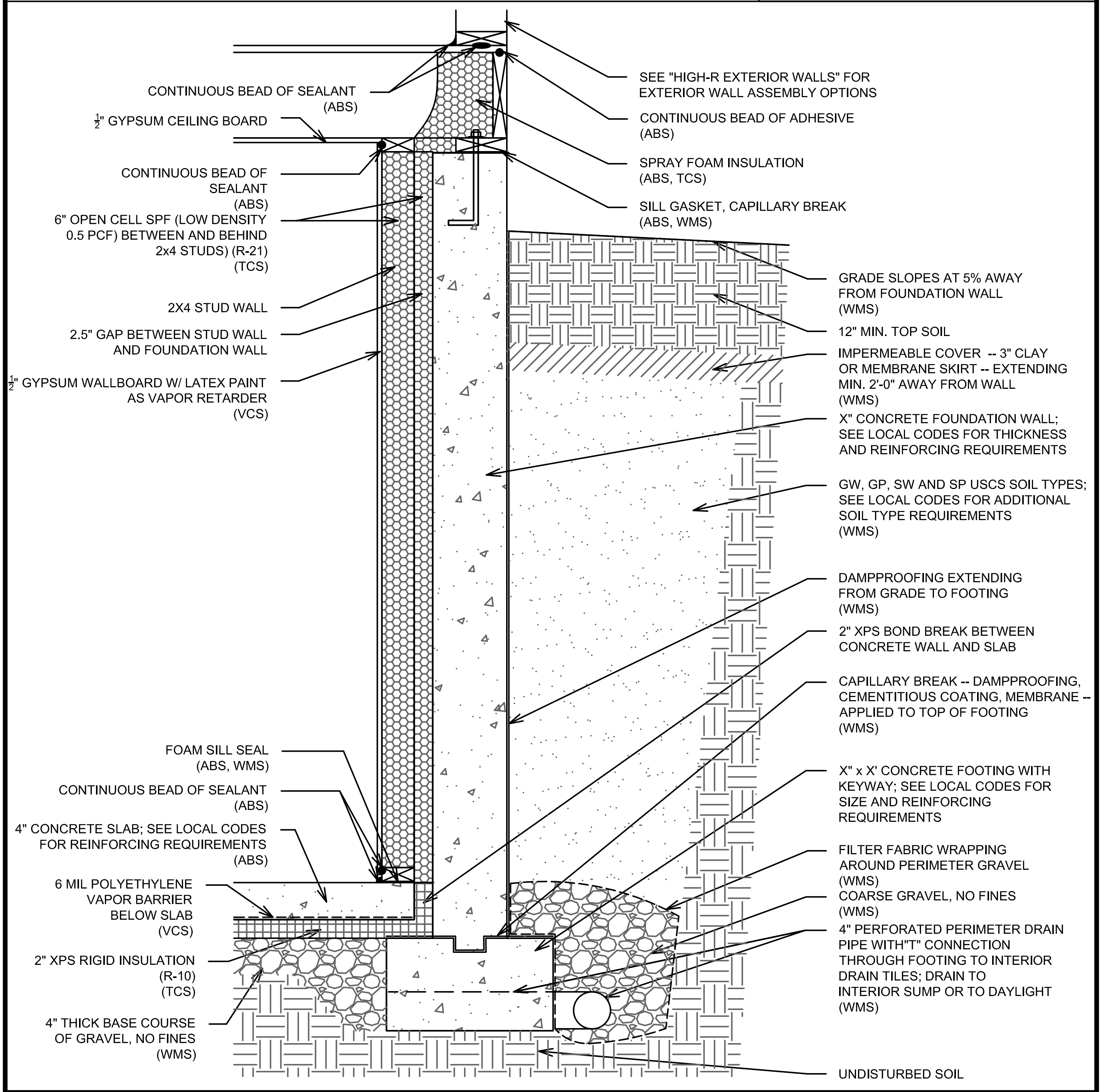
Sheet Title:

Bsmt Type #5

Foundation: CONCRETE
Basement: FINISHED
Location of Insulation: INTERIOR
Insulation Type, Insulation R-Value:
Concrete wall dries to the inside and outside (above grade)
6" OPEN CELL SPF (LOW DENSITY 0.5 PCF), R-21

Appropriate for Zone 5

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



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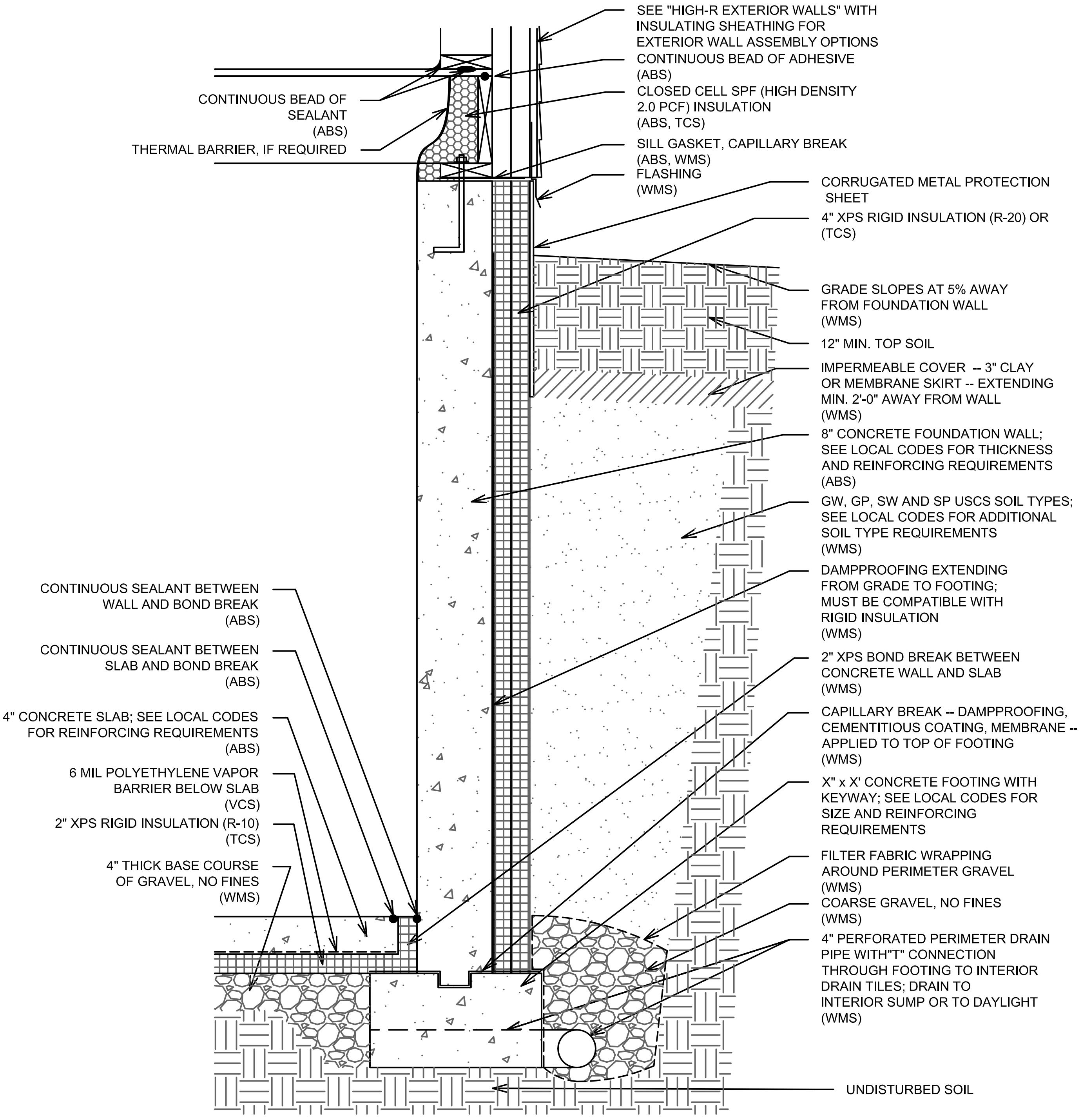
Project: High-R Foundation Walls
Date: 2009-06-03 DRAFT
Drawing Title: Foundation Walls
Drawing File: FoundationDetails.dwg
Drawing Scale: 3/4" = 1'-0"

Sheet Title:

Bsmt Type #6

Foundation: CONCRETE
Basement: UNFINISHED
Location of Insulation: EXTERIOR
Insulation Type, Insultaion R-Value:
Concrete wall dries to inside
4" XPS, R-20

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



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Project:	High-R Foundation Walls
Date:	2009-06-03 DRAFT
Drawing Title:	Foundation Walls
Drawing File:	FoundationDetails.dwg
Drawing Scale:	3/4" = 1'-0"

Sheet Title:

Bsmt Type #7

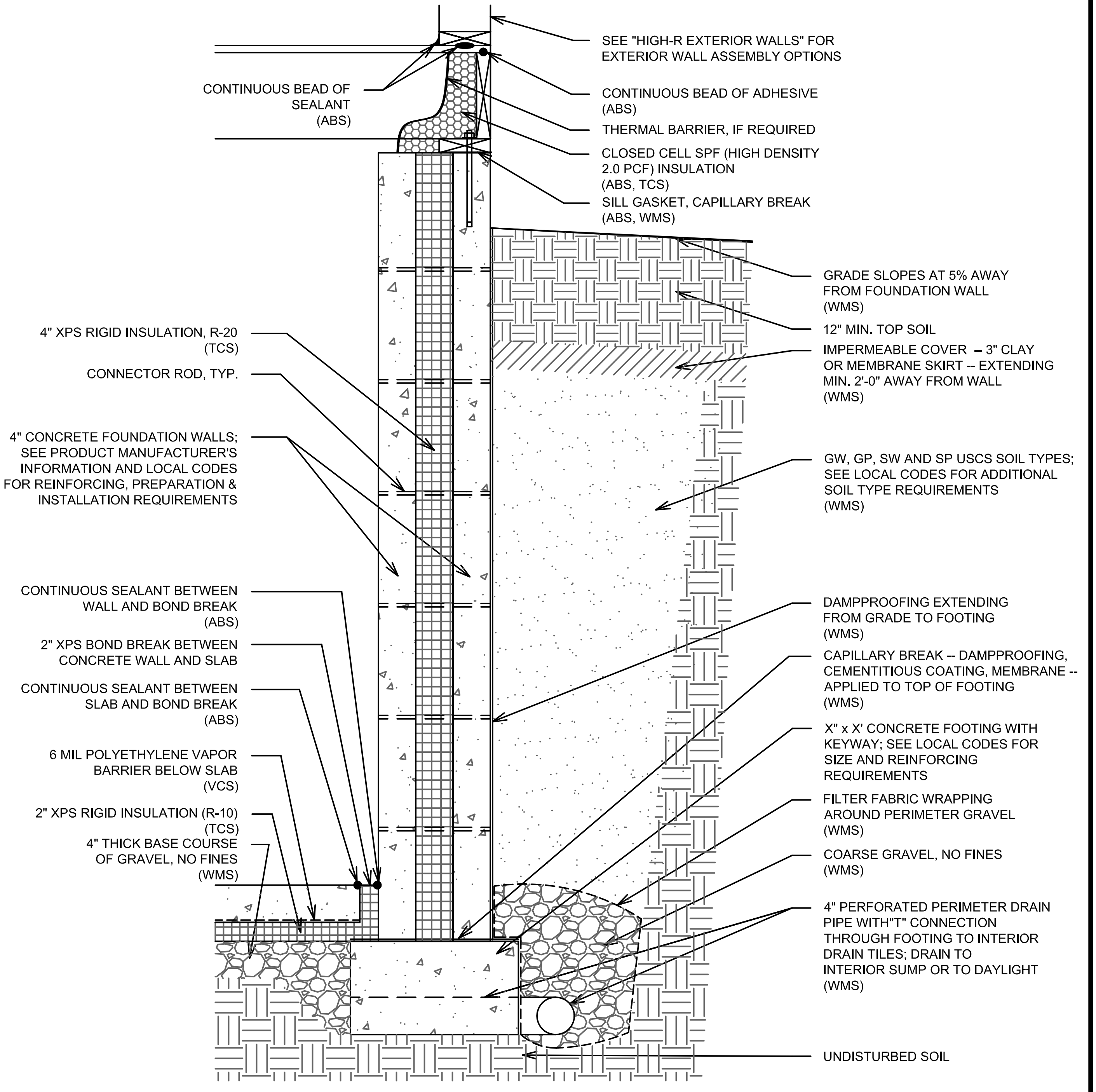
Foundation:	CONCRETE
Basement:	UNFINISHED
Location of Insulation:	MIDDLE OF WALL

Insulation Type, Insulation R-Value:

Concrete wall dries to the inside and outside (above grade)

4" XPS, R-20

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



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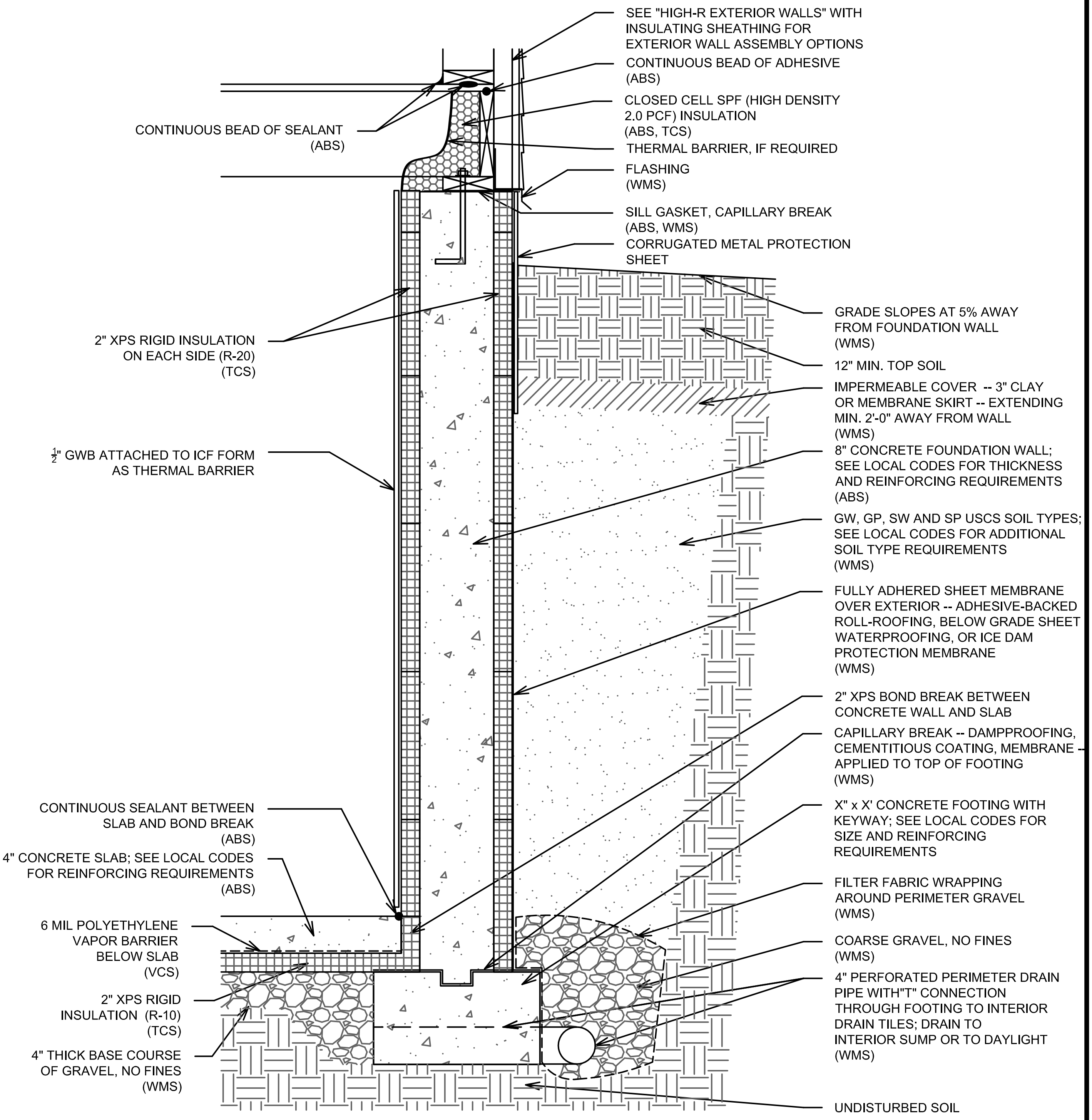
Project:	High-R Foundation Walls
Date:	2009-06-03 DRAFT
Drawing Title:	Foundation Walls
Drawing File:	FoundationDetails.dwg
Drawing Scale:	3/4" = 1'-0"

Sheet Title:

Bsmt Type #8

Foundation: CONCRETE (ICF)
Basement: UNFINISHED
Location of Insulation: INTERIOR AND EXTERIOR
Insulation Type, Insulation R-Value:
Concrete wall dries to the inside and outside (above grade)
4" XPS, R-20

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



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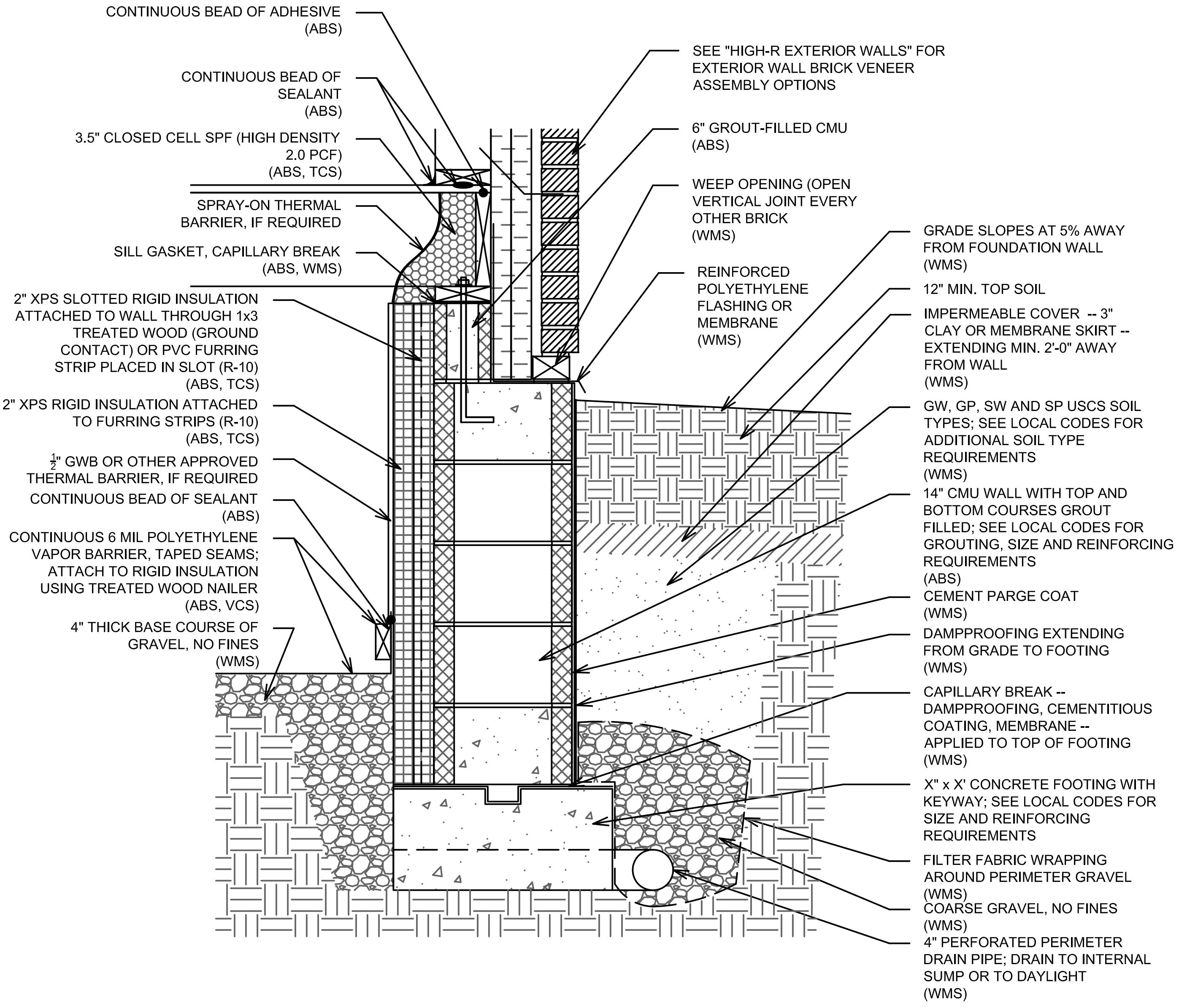
Project: High-R Foundation Walls
Date: 2009-06-03 DRAFT
Drawing Title: Foundation Walls
Drawing File: FoundationDetails.dwg
Drawing Scale: 3/4" = 1'-0"

Sheet Title:

Bsmt Type #9

Foundation: 14" CMU WALL WITH BRICK VENEER
Crawl Space: UNVENTED
Ground Cover: CONTINUOUS POLYETHYLENE VAPOR BARRIER
Location of Insulation: INTERIOR OF FOUNDATION WALL
Drying: WALL DRIES TO OUTSIDE (ABOVE GRADE);
Insulation Type, Insulation R-Value:
4" XPS RIGID INSULATION, R-20

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



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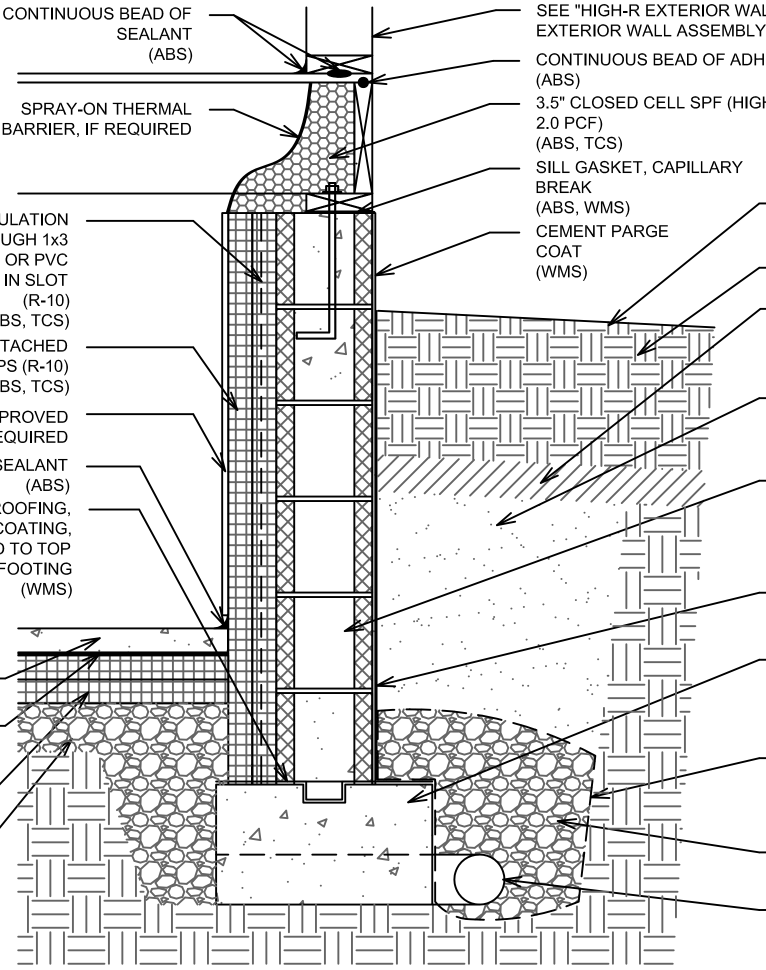
Project: High-R Foundation Walls
Date: 2009-06-03 DRAFT
Drawing Title: Foundation Walls
Drawing File: FoundationDetails.dwg
Drawing Scale: 3/4 = 1'-0"

Sheet Title:
CS Type #1

Foundation: 8" CMU WALL
Crawl Space: UNVENTED
Ground Cover: 2" CONCRETE SLAB
Location of Insulation: INTERIOR OF FOUNDATION WALLS AND UNDER SLAB
Drying: WALL DRIES TO OUTSIDE (ABOVE GRADE);
SLAB DRIES TO INTERIOR
Insulation Type, Insulation R-Value:
4" XPS RIGID INSULATION, R-20

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



CONTINUOUS BEAD OF SEALANT (ABS)

SPRAY-ON THERMAL BARRIER, IF REQUIRED

2" XPS SLOTTED RIGID INSULATION ATTACHED TO WALL THROUGH 1x3 P.T. (GROUND CONTACT) OR PVC FURRING STRIP PLACED IN SLOT (R-10) (ABS, TCS)

2" XPS RIGID INSULATION ATTACHED TO FURRING STRIPS (R-10) (ABS, TCS)

½" GWB OR OTHER APPROVED THERMAL BARRIER, IF REQUIRED

CONTINUOUS BEAD OF SEALANT (ABS)

CAPILLARY BREAK -- DAMPPROOFING, CEMENTITIOUS COATING, MEMBRANE -- APPLIED TO TOP OF FOOTING (WMS)

2" MIN. CONCRETE SLAB (ABS)

6 MIL POLYETHYLENE VAPOR BARRIER (VCS)

4" XPS RIGID INSULATION (TCS)

4" THICK BASE COURSE OF GRAVEL, NO FINES (WMS)

SEE "HIGH-R EXTERIOR WALLS" FOR EXTERIOR WALL ASSEMBLY OPTIONS

CONTINUOUS BEAD OF ADHESIVE (ABS)

3.5" CLOSED CELL SPF (HIGH DENSITY 2.0 PCF) (ABS, TCS)

SILL GASKET, CAPILLARY BREAK (ABS, WMS)

CEMENT PARGE COAT (WMS)

GRADE SLOPES AT 5% AWAY FROM FOUNDATION WALL (WMS)

12" MIN. TOP SOIL

IMPERMEABLE COVER -- 3" CLAY OR MEMBRANE SKIRT -- EXTENDING MIN. 2'-0" AWAY FROM WALL (WMS)

GW, GP, SW AND SP USCS SOIL TYPES; SEE LOCAL CODES FOR ADDITIONAL SOIL TYPE REQUIREMENTS (WMS)

8" CMU WALL WITH TOP 2 COURSES AND BOTTOM COURSE GROUT FILLED; SEE LOCAL CODES FOR GROUTING, THICKNESS AND REINFORCING REQUIREMENTS

DAMPPROOFING EXTENDING FROM GRADE TO FOOTING (WMS)

X" x X' CONCRETE FOOTING WITH KEYWAY; SEE LOCAL CODES FOR SIZE AND REINFORCING REQUIREMENTS

FILTER FABRIC WRAPPING AROUND PERIMETER GRAVEL (WMS)

COARSE GRAVEL, NO FINES (WMS)

4" PERFORATED PERIMETER DRAIN PIPE; DRAIN TO INTERNAL SUMP OR TO DAYLIGHT (WMS)

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Project: High-R Foundation Walls
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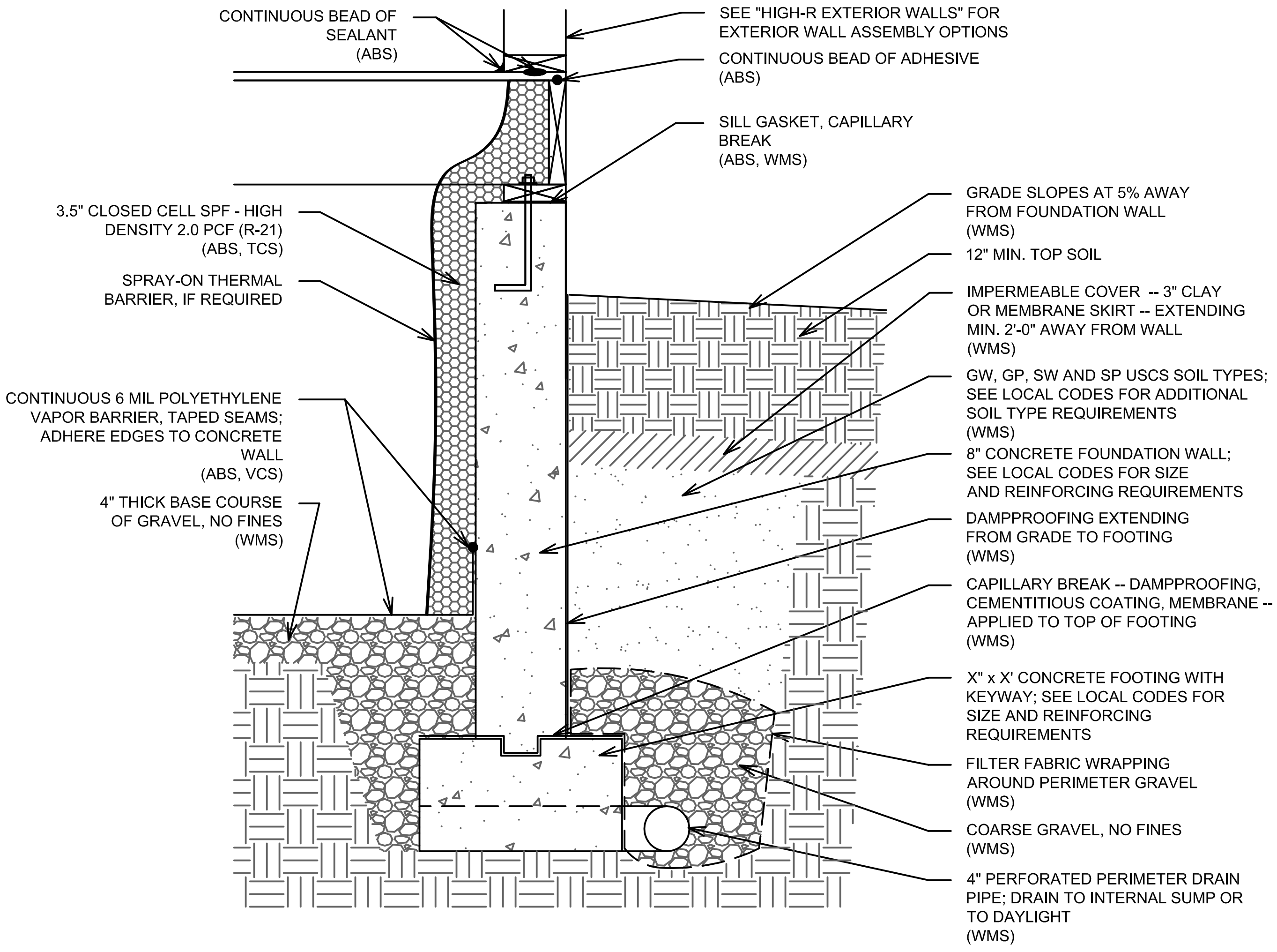
Drawing Scale: 3/4 = 1'-0"

Sheet Title:

CS Type #2

Foundation: 8" CONCRETE WALL
Crawl Space: UNVENTED
Ground Cover: CONTINUOUS POLYETHYLENE VAPOR BARRIER
Location of Insulation: INTERIOR OF FOUNDATION WALL
Drying: WALL DRIES TO OUTSIDE (ABOVE GRADE)
Insulation Type, Insulation R-Value:
3.5" CLOSED CELL SPF (HIGH DENSITY 2.0 PCF), R-21

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



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Date: 2009-06-03 DRAFT
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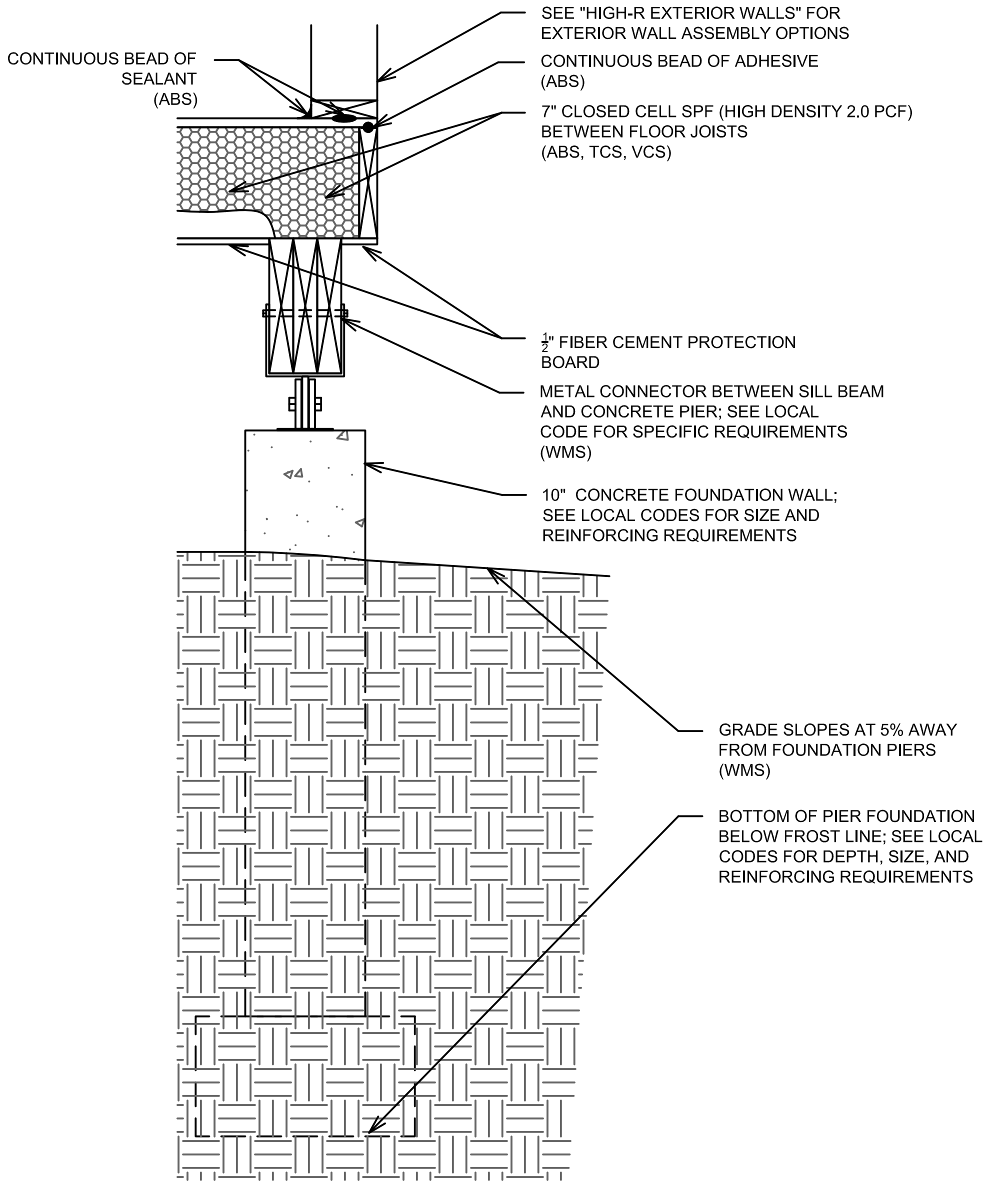
Drawing File: FoundationDetails.dwg
Drawing Scale: 3/4" = 1'-0"

Sheet Title:

CS Type #3

Foundation: CONCRETE PIERS
Crawl Space: VENTED
Ground Cover: NONE
Location of Insulation: INSIDE FLOOR JOISTS
Drying: N/A
Insulation Type, Insulation R-Value:
7" CLOSED CELL SPF (HIGH DENSITY 2.0 PCF), R-42

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



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Project: High-R Foundation Walls
Date: 2009-06-03 DRAFT
Drawing Title: Foundation Walls
Drawing File: FoundationDetails.dwg
Drawing Scale: 3/4" = 1'-0"

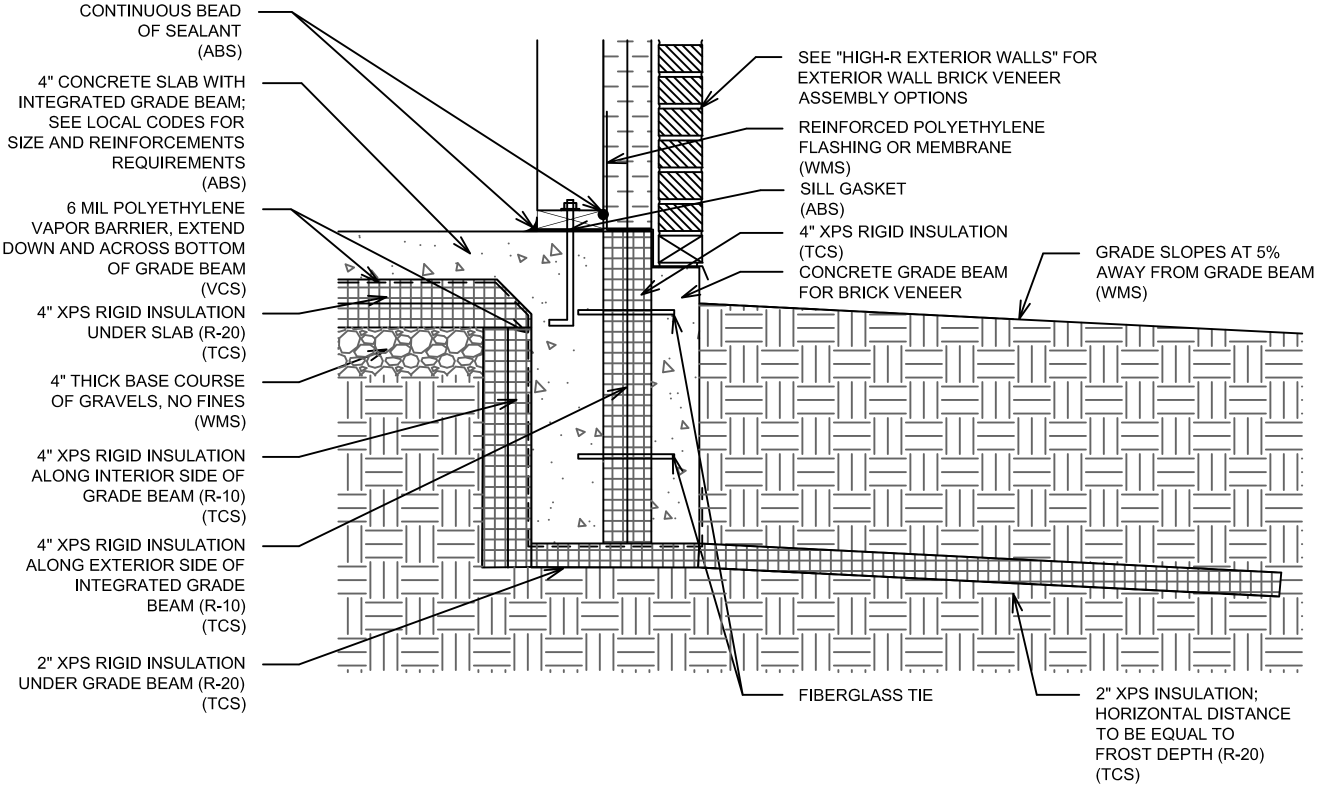
Sheet Title:

CS Type #4

Foundation: CONCRETE GRADE BEAM INTEGRAL WITH SLAB
Slab on Grade Type: MONOLITHIC SLAB
Location of Insulation: BELOW SLAB, ENCLOSING GRADE BEAM, AND HORIZONTAL FROST PROTECTION
Drying: TO INTERIOR
Insulation Type, Insulation R-Value:
BELOW SLAB: 4" XPS RIGID INSULATION, R-20
INTERIOR OF GRADE BEAM: 4" XPS RIGID INSULATION, R-20
EXTERIOR OF GRADE BEAM, 4" XPS RIGID INSULATION, R-10
BELOW GRADE BEAM: 2" XPS RIGID INSULATION, R-10
FROST PROTECTION: 2" XPS RIGID INSULATION, R-10

Appropriate for Cold Climates

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



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Project: High-R Foundation Walls
Date: 2009-06-05 DRAFT
Drawing Title: Foundation Walls
Drawing File: FoundationDetails.dwg
Drawing Scale: 3/4" = 1'-0"

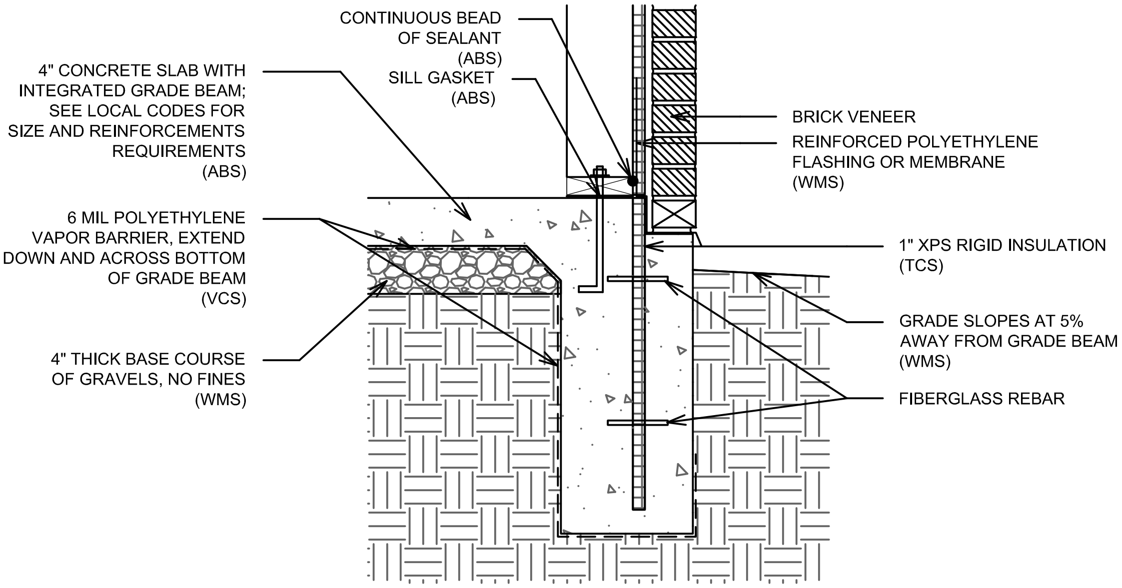
Sheet Title:

SG Type #1A

Foundation: CONCRETE GRADE BEAM INTEGRAL WITH SLAB
Slab on Grade Type: MONOLITHIC SLAB
Location of Insulation: WITHIN GRADE BEAM
Drying: TO INTERIOR
Insulation Type, Insulation R-Value:
1" XPS IN GRADE BEAM

Appropriate for Mixed-Humid Climates

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



CONTINUOUS BEAD

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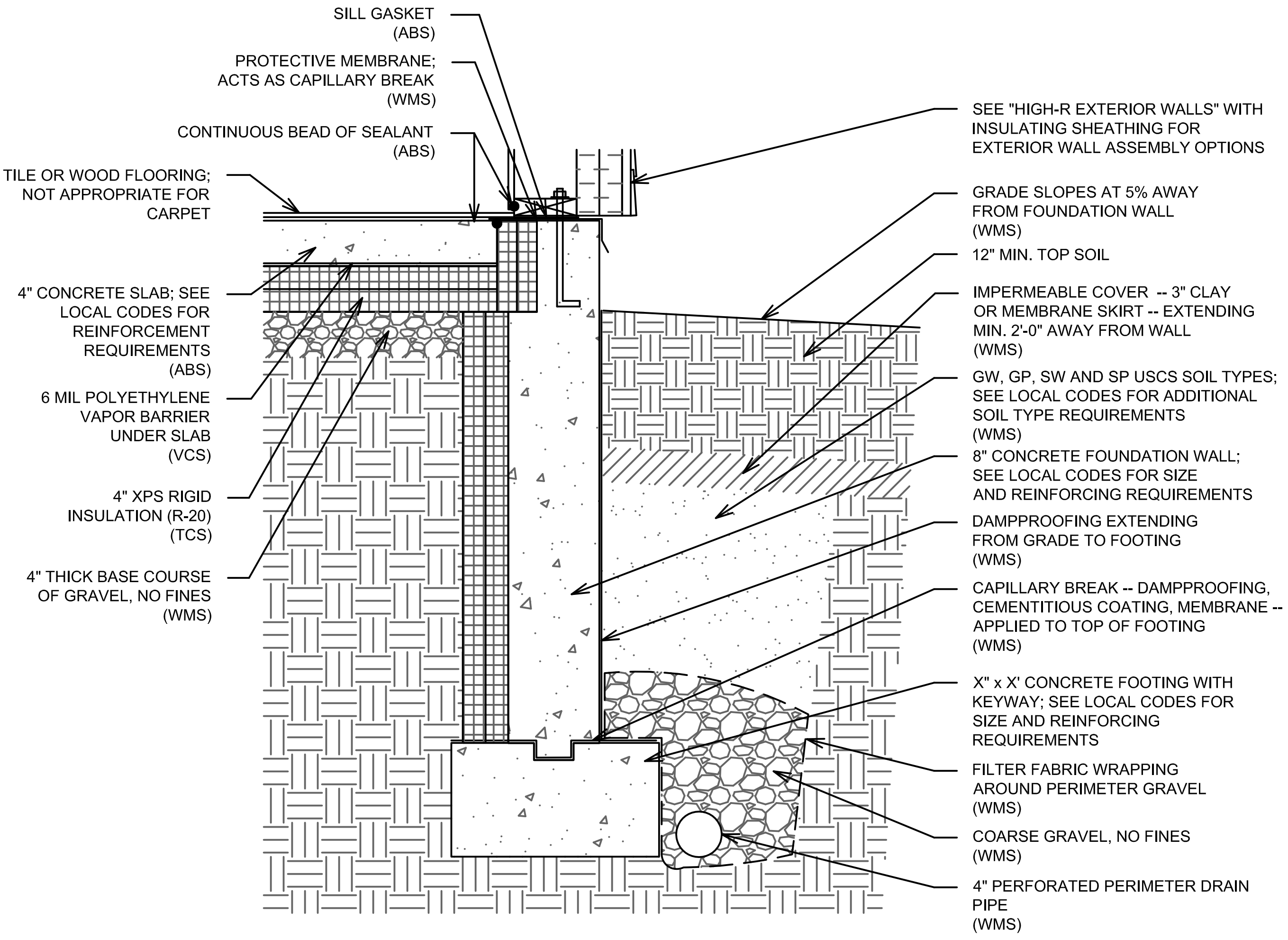
Project: High-R Foundation Walls
Date: 2009-06-05 DRAFT
Drawing Title: Foundation Walls
Drawing File: FoundationDetails.dwg
Drawing Scale: 3/4" = 1'-0"

Sheet Title:

SG Type #1B

Foundation: CONCRETE
Slab on Grade Type: INDEPENDENT 4" SLAB ON GRADE
Location of Insulation: BELOW SLAB, ON PERIMETER OF SLAB, AND ON INTERIOR OF FOUNDATION WALL
Drying: SLAB: TO INTERIOR;
FOUNDATION WALL: TO OUTSIDE (ABOVE GRADE)
Insulation Type, Insulation R-Value:
BELOW SLAB: 4" XPS RIGID INSULATION, R-20
PERIMETER OF SLAB: 4" XPS RIGID INSULATION, R-20
INTERIOR OF WALL: 4" XPS RIGID INSULATION, R-20

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



SILL GASKET (ABS)

PROTECTIVE MEMBRANE; ACTS AS CAPILLARY BREAK (WMS)

CONTINUOUS BEAD OF SEALANT (ABS)

TILE OR WOOD FLOORING; NOT APPROPRIATE FOR CARPET

4" CONCRETE SLAB; SEE LOCAL CODES FOR REINFORCEMENT REQUIREMENTS (ABS)

6 MIL POLYETHYLENE VAPOR BARRIER UNDER SLAB (VCS)

4" XPS RIGID INSULATION (R-20) (TCS)

4" THICK BASE COURSE OF GRAVEL, NO FINES (WMS)

SEE "HIGH-R EXTERIOR WALLS" WITH INSULATING SHEATHING FOR EXTERIOR WALL ASSEMBLY OPTIONS

GRADE SLOPES AT 5% AWAY FROM FOUNDATION WALL (WMS)

12" MIN. TOP SOIL

IMPERMEABLE COVER -- 3" CLAY OR MEMBRANE SKIRT -- EXTENDING MIN. 2'-0" AWAY FROM WALL (WMS)

GW, GP, SW AND SP USCS SOIL TYPES; SEE LOCAL CODES FOR ADDITIONAL SOIL TYPE REQUIREMENTS (WMS)

8" CONCRETE FOUNDATION WALL; SEE LOCAL CODES FOR SIZE AND REINFORCING REQUIREMENTS

DAMPPROOFING EXTENDING FROM GRADE TO FOOTING (WMS)

CAPILLARY BREAK -- DAMPPROOFING, CEMENTITIOUS COATING, MEMBRANE -- APPLIED TO TOP OF FOOTING (WMS)

X" x X' CONCRETE FOOTING WITH KEYWAY; SEE LOCAL CODES FOR SIZE AND REINFORCING REQUIREMENTS

FILTER FABRIC WRAPPING AROUND PERIMETER GRAVEL (WMS)

COARSE GRAVEL, NO FINES (WMS)

4" PERFORATED PERIMETER DRAIN PIPE (WMS)

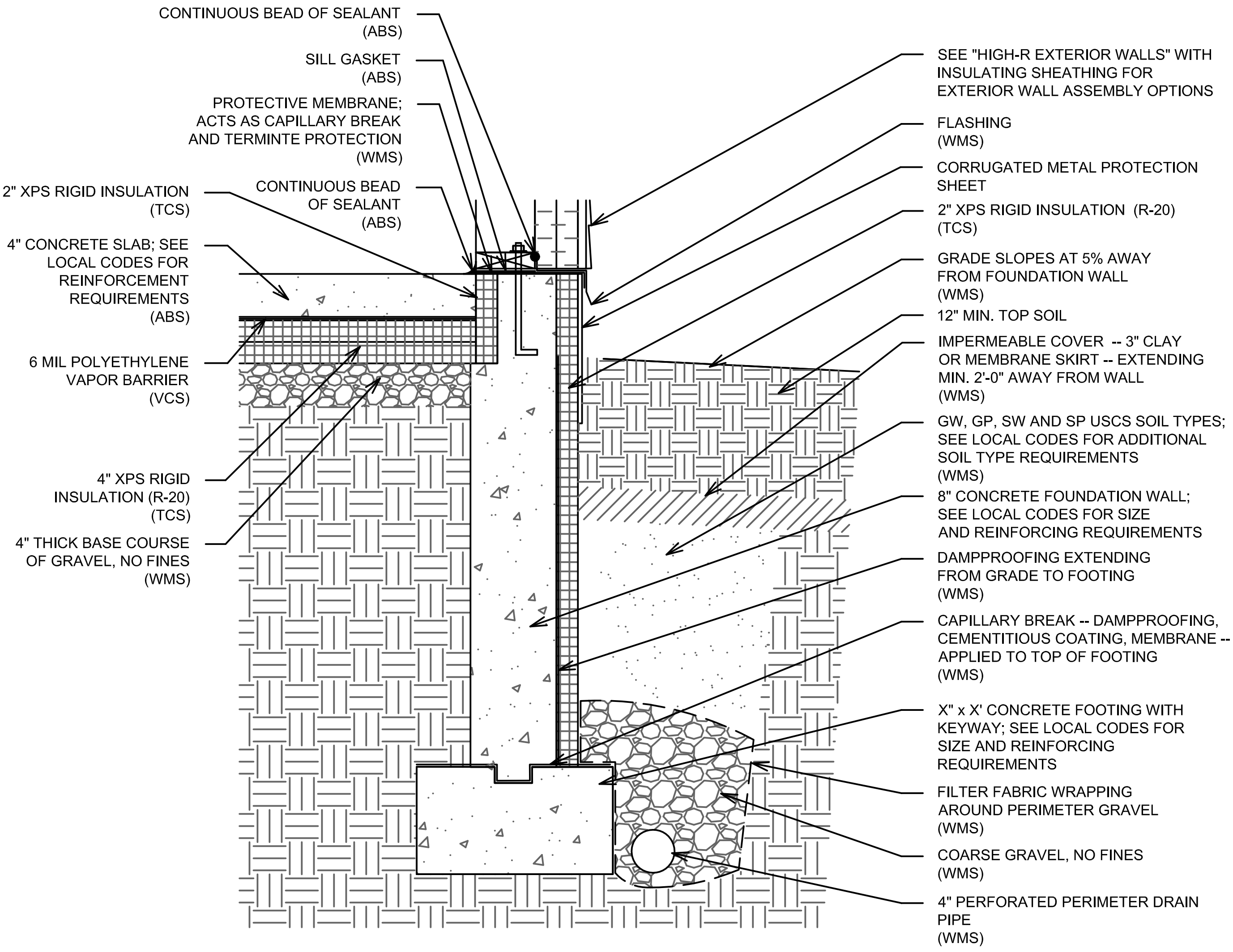
bsc *with* Building America
U.S. Department of Energy
Research Toward Zero Energy Homes

Project: High-R Foundation Walls
Date: 2009-06-05 DRAFT
Drawing Title: Foundation Walls
Drawing File: FoundationDetails.dwg
Drawing Scale: 3/4" = 1'-0"

Sheet Title:
SG Type #2

Foundation: CONCRETE
Slab on Grade Type: INDEPENDENT 4" SLAB ON GRADE
Location of Insulation: BELOW SLAB AND ON EXTERIOR OF FOUNDATION WALL
Drying: SLAB: TO INTERIOR;
FOUNDATION WALL: TO INSIDE AND OUTSIDE (ABOVE GRADE
Insulation Type, Insulation R-Value:
BELOW SLAB: 4" XPS RIGID INSULATION, R-20
EXTERIOR OF WALL: 2" XPS RIGID INSULATION, R-10

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



bsc with Building America U.S. Department of Energy *Research Toward Zero Energy Homes*

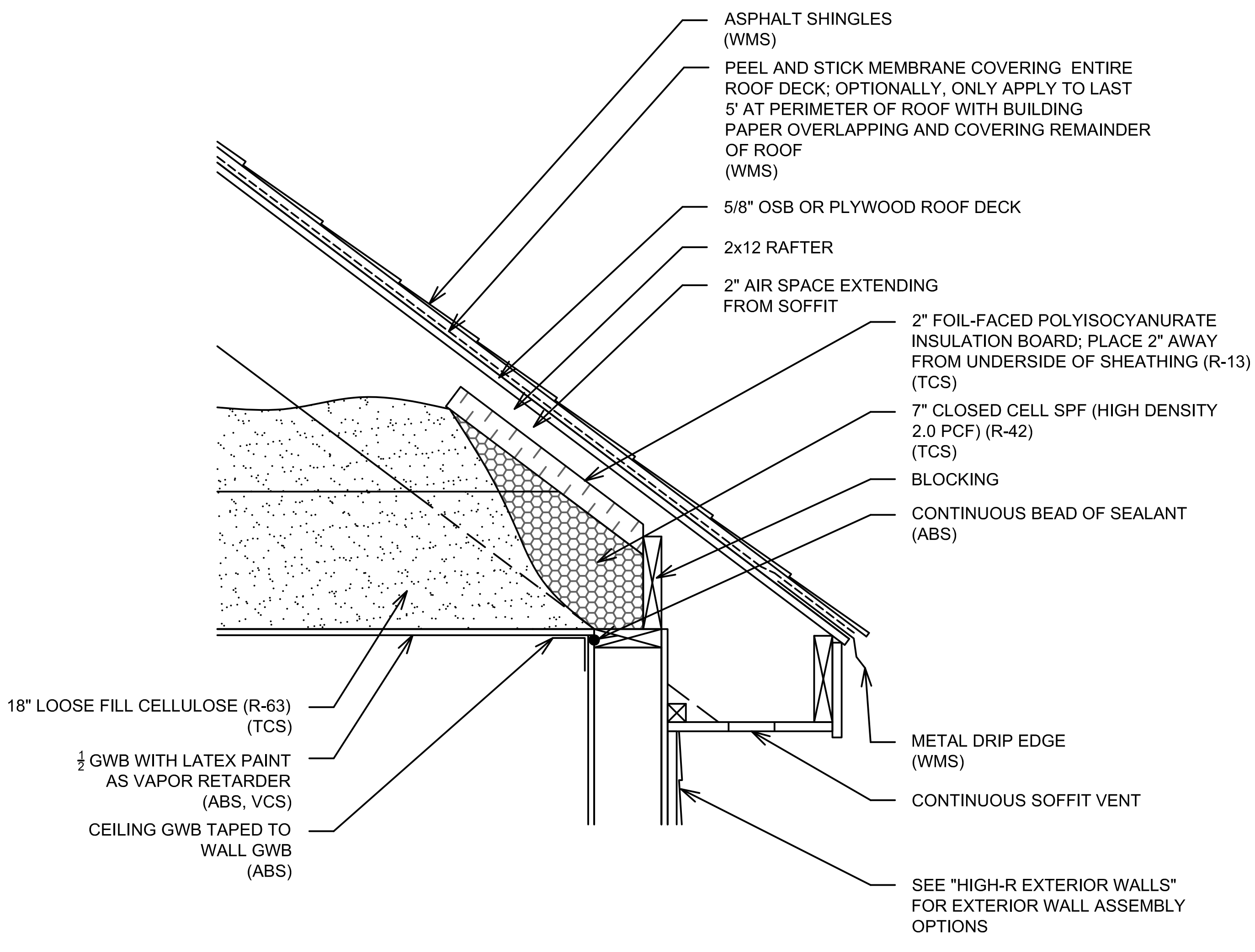
Project: High-R Foundation Walls
Date: 2009-06-05 DRAFT
Drawing Title: Foundation Walls
Drawing File: FoundationDetails.dwg
Drawing Scale: 3/4" = 1'-0"

Sheet Title:

SG Type #3

Roof Structure: 2X12 RAFTER
Vented or Unvented: VENTED
Attic or Cathedral: ATTIC
Location of Insulation: PERIMETER + WITHIN (AND ABOVE) ATTIC FLOOR JOISTS
Insulation Type, Insulation R-Value:
PERIMETER: 2" FOIL-FACED POLYISOCYANURATE + 7.5" CLOSED CELL SPF (HIGH DENSITY 2.0 PCF) , R-55
ATTIC FLOOR: 18" LOOSE FILL CELLULOSE, R-63

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



bsc with Building America U.S. Department of Energy Research Toward Zero Energy Homes

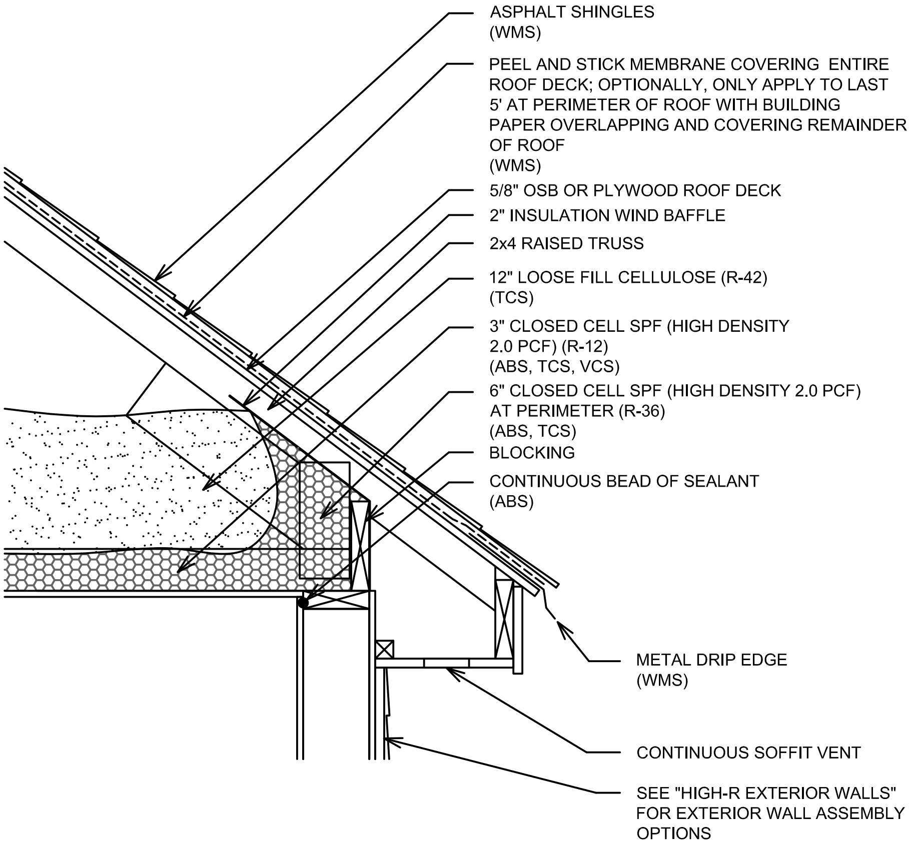
Project: High-R Assemblies
Date: 2009-07-03 DRAFT
Drawing Title: Roof Assemblies
Drawing File: RoofDetails.dwg
Drawing Scale: 3/4" = 1'-0"

Sheet Title:

Roof Type #1

Roof Structure:	2X4 RAISED TRUSS
Vented or Unvented:	VENTED
Attic or Cathedral:	ATTIC
Location of Insulation:	PERIMETER + AT ATTIC FLOOR
Insulation Type, Insulation R-Value:	
	PERIMETER: 3" CLOSED CELL SPF (HIGH DENSITY 2.0 PCF), R-18
	ATTIC FLOOR: 3" CLOSED CELL + 12" LOOSE FILL CELLULOSE, R-60

ABS:	*Air Barrier System component*
TCS:	*Thermal Control System component*
VCS:	*Vapor Control System component*
WMS:	*Water Management System component*



bsc with Building America® U.S. Department of Energy Research Toward Zero Energy Homes

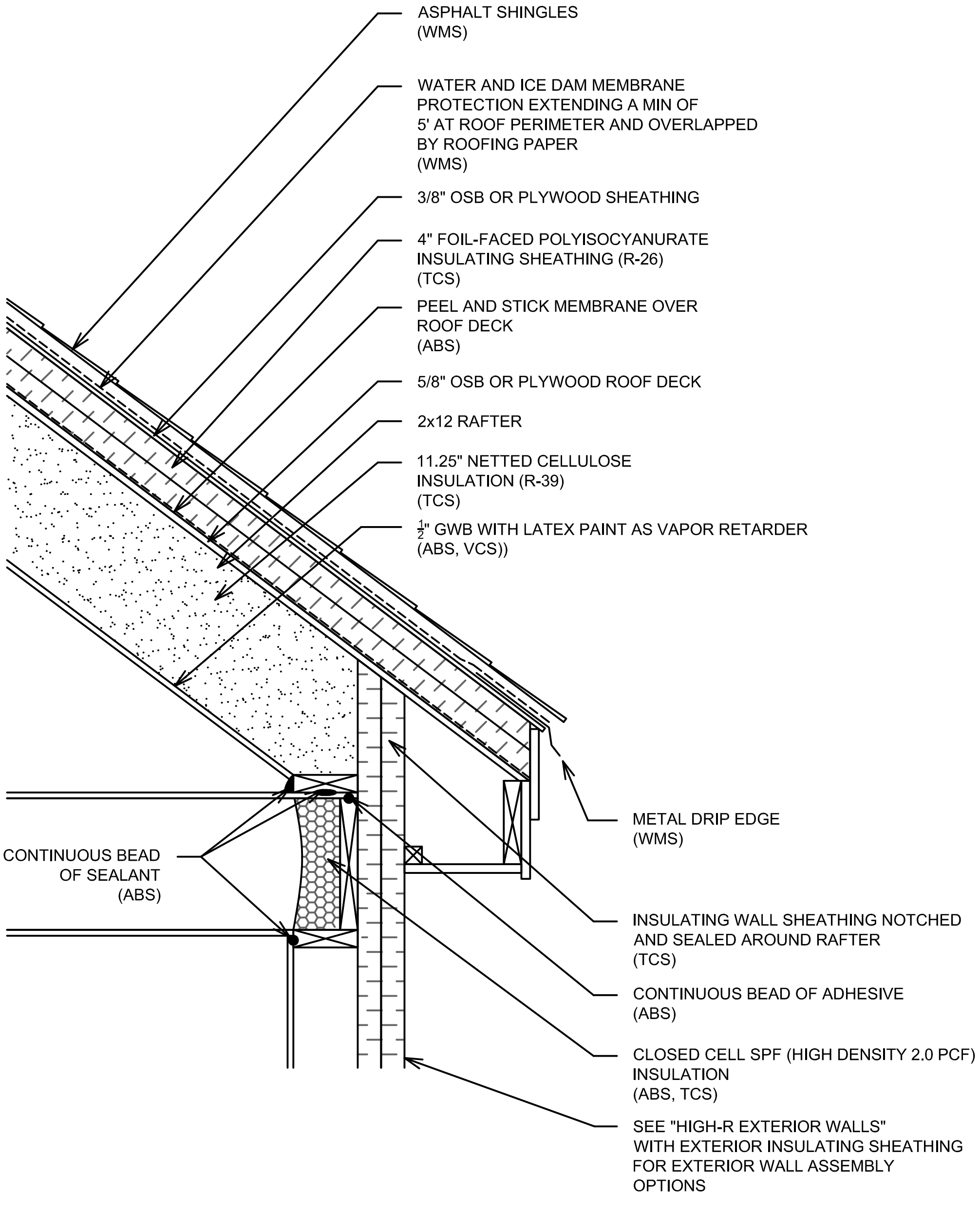
Project:	High-R Assemblies
Date:	2009-07-03 DRAFT
Drawing Title:	Roof Assemblies
Drawing File:	RoofDetails.dwg
Drawing Scale:	3/4" = 1'-0"

Sheet Title:

Roof Type #2

Roof Structure: 2X12 RAFTER
Vented or Unvented: UNVENTED
Attic or Cathedral: CATHEDRAL
Location of Insulation: ABOVE ROOF DECK AND IN RAFTER CAVITY
Insulation Type, Insulation R-Value:
4" FOIL-FACED POLYISOCYANURATE ABOVE ROOF DECK + 11.25" CELLULOSE IN RAFTER CAVITY, R-65
Climate/Zone: *Cold Climate/up to Zone 6*

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



bsc with Building America U.S. Department of Energy *Research Toward Zero Energy Homes*

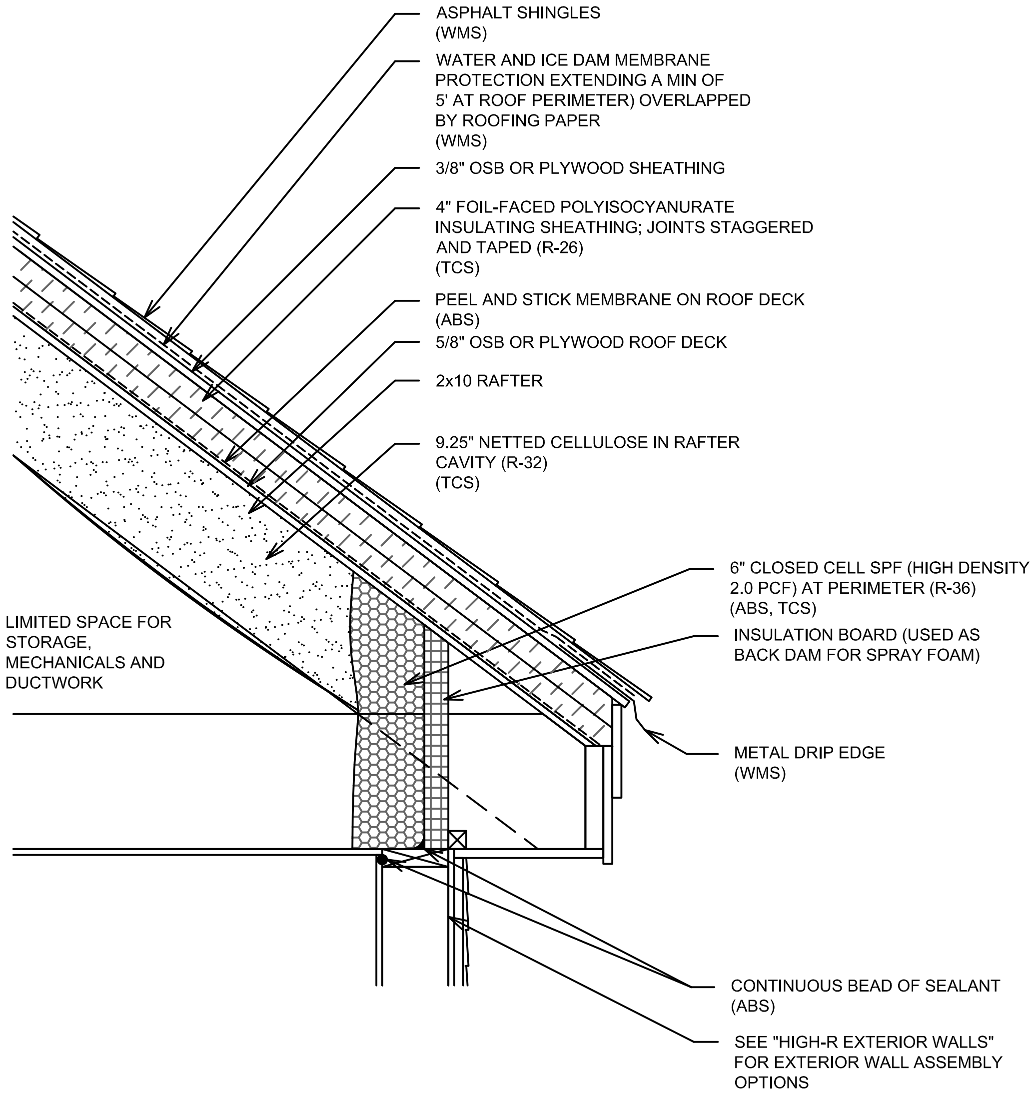
Project: High-R Assemblies
Date: 2009-07-03 DRAFT
Drawing Title: Roof Assemblies
Drawing File: RoofDetails.dwg
Drawing Scale: 3/4" = 1'-0"

Sheet Title:

Roof Type #3

Roof Structure: 2X10 RAFTER
Vented or Unvented: UNVENTED
Attic or Cathedral: ATTIC
Location of Insulation: ABOVE ROOF DECK AND IN RAFTER CAVITY
Insulation Type, Insulation R-Value:
ROOF: 4" FOIL-FACED POLYISOCYANURATE ABOVE ROOF DECK + 9.25" CELLULOSE IN RAFTER CAVITY, R-58
PERIMETER: 6" CLOSED CELL SPF (HIGH DENSITY 2.0 PCF), R-36
Climate/Zone: Cold Climate/up to Zone 6

ABS:	*Air Barrier System component*
TCS:	*Thermal Control System component*
VCS:	*Vapor Control System component*
WMS:	*Water Management System component*



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Research Toward Zero Energy Homes

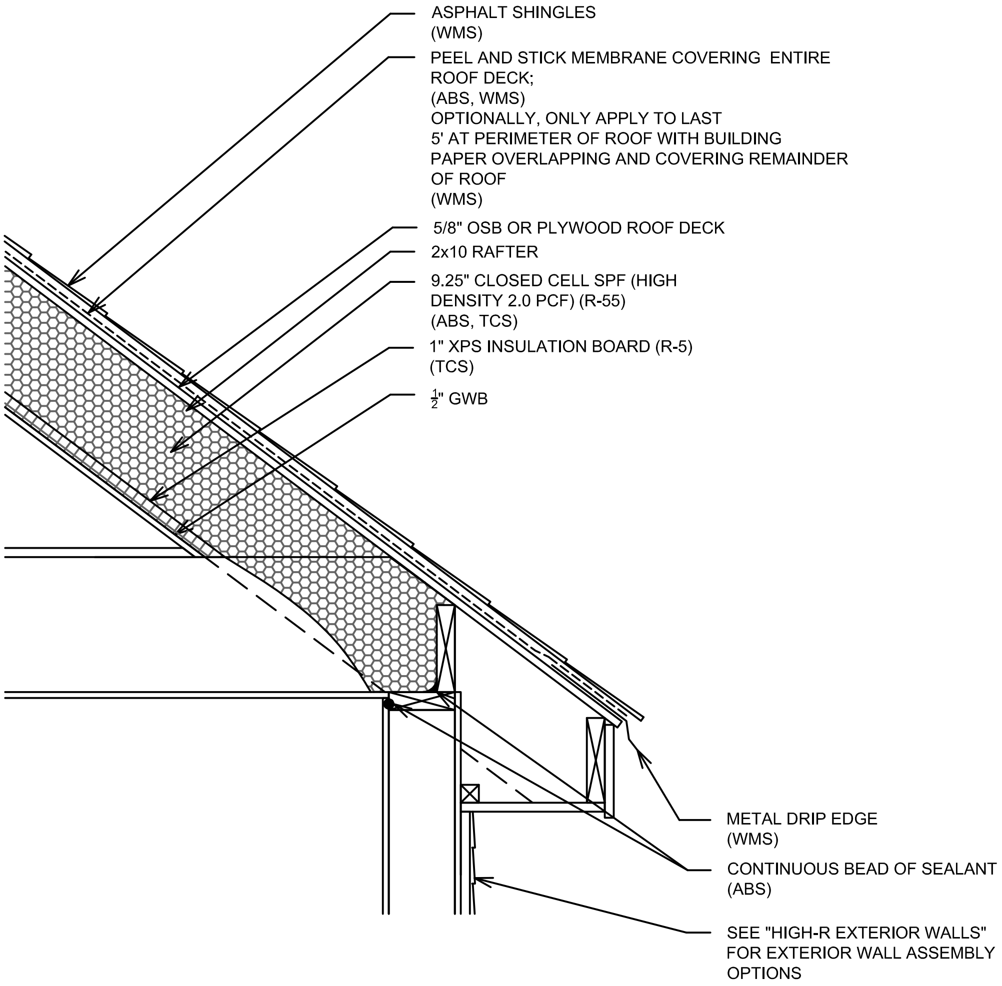
Project: High-R Assemblies
Date: 2009-07-03 DRAFT
Drawing Title: Roof Assemblies
Drawing File: RoofDetails.dwg
Drawing Scale: 3/4" = 1'-0"

Sheet Title:

Roof Type #4

Roof Structure: 2X10 RAFTER
Vented or Unvented: UNVENTED
Attic or Cathedral: CATHEDRAL
Location of Insulation: RAFTER CAVITY
Insulation Type, Insulation R-Value:
9.25" CLOSED CELL SPF (HIGH DENSITY 2.0 PCF) + 1" RIGID INSULATION UNDER RAFTER, R-60

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



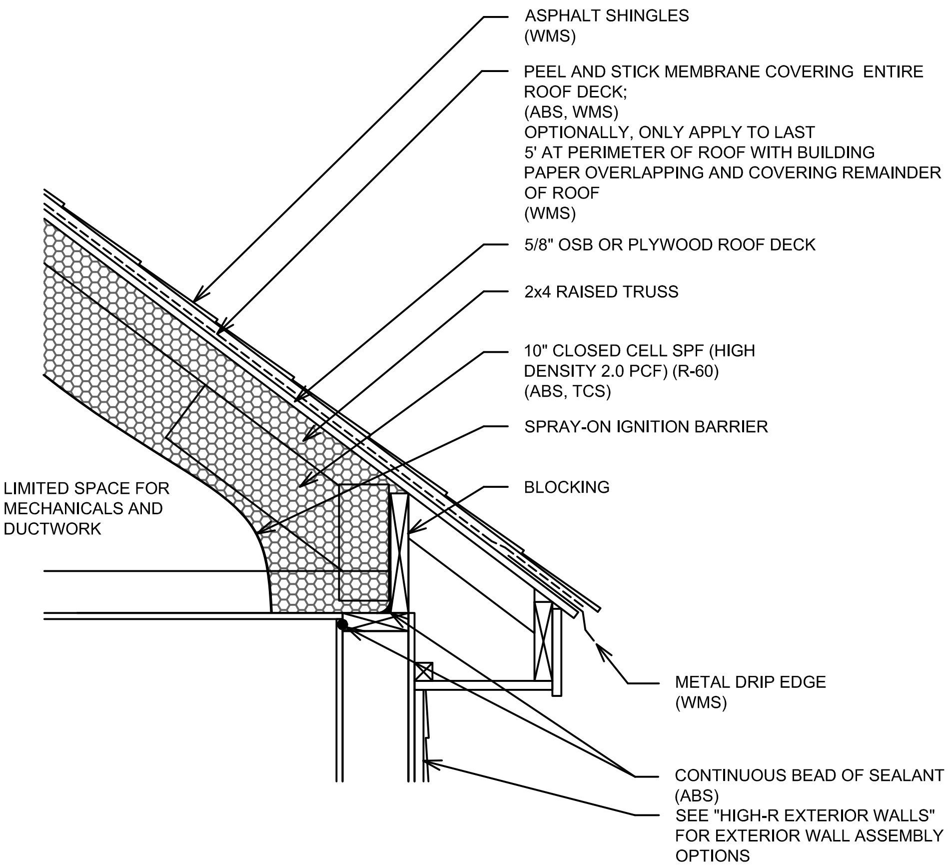
Project: High-R Assemblies
Date: 2009-07-03 DRAFT
Drawing Title: Roof Assemblies
Drawing File: RoofDetails.dwg
Drawing Scale: 3/4" = 1'-0"

Sheet Title:

Roof Type #5

Roof Structure: 2x4 RAISED TRUSS
Vented or Unvented: UNVENTED
Attic or Cathedral: ATTIC
Location of Insulation: BELOW ROOF DECK
Insulation Type, Insulation R-Value:
10" CLOSED CELL SPF (HIGH DENSITY 2.0 PCF), R-60

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



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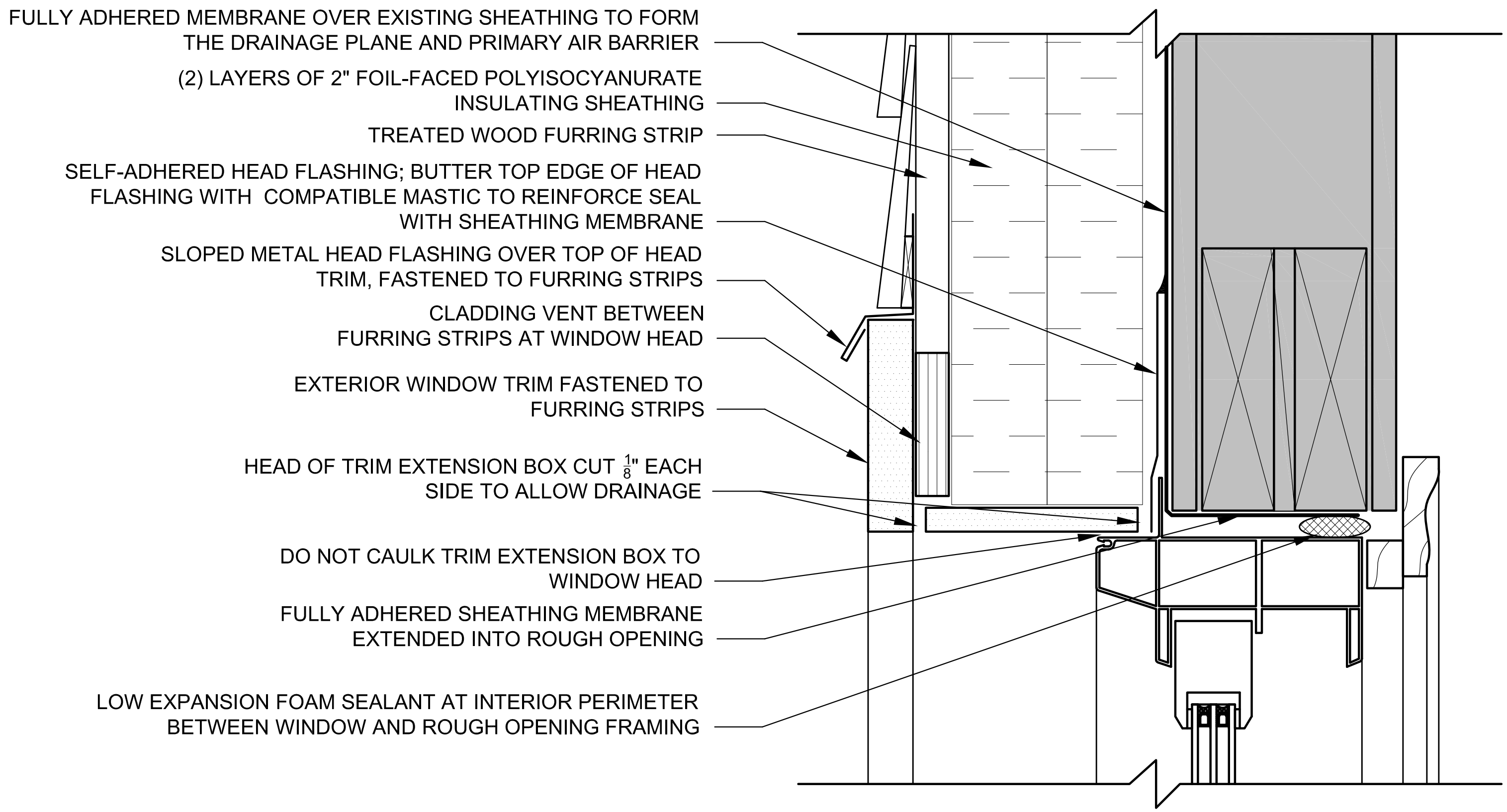
Project: High-R Assemblies
Date: 2009-07-03 DRAFT
Drawing Title: Roof Assemblies
Drawing File: RoofDetails.dwg
Drawing Scale: 3/4" = 1'-0"

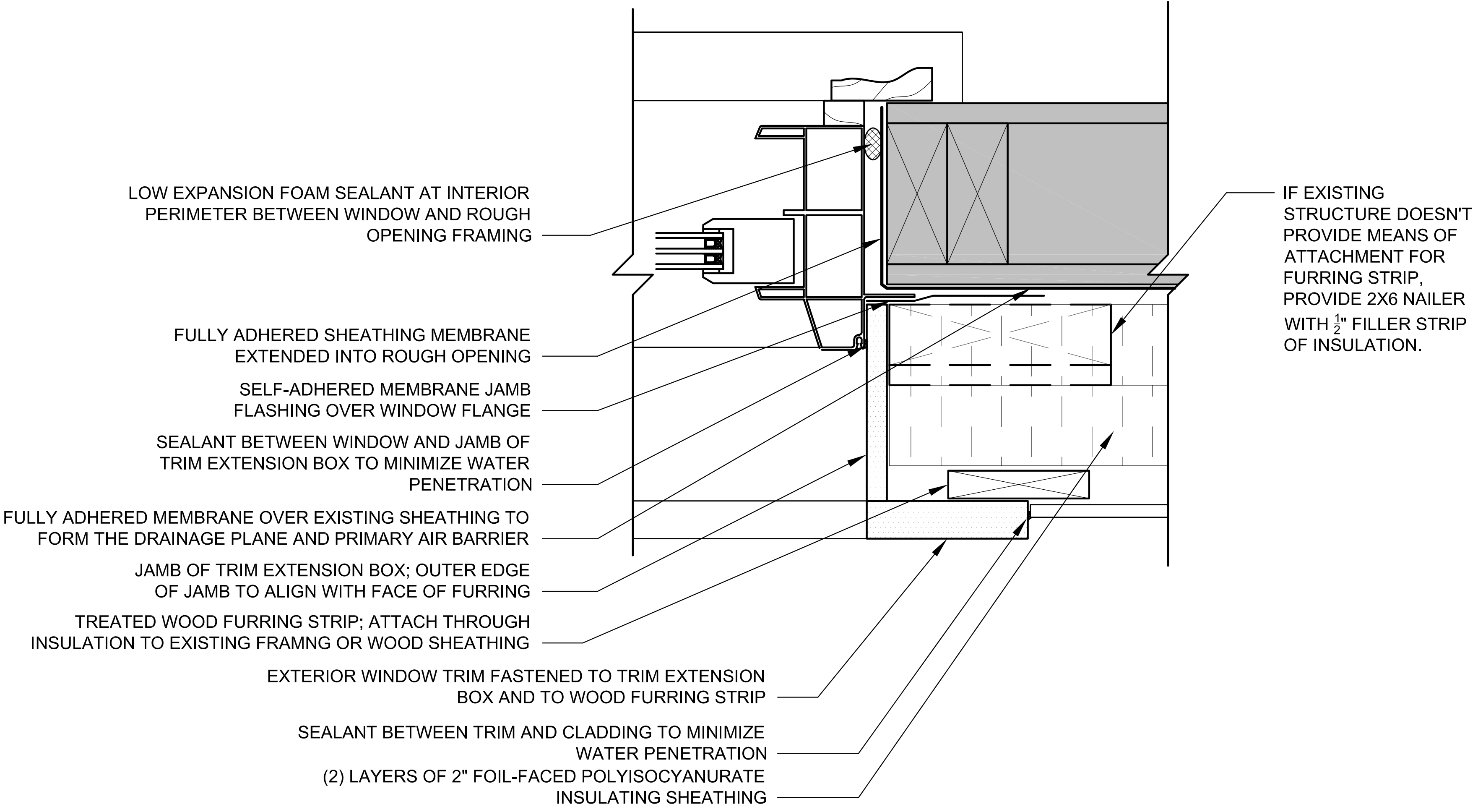
Sheet Title:

Roof Type #6



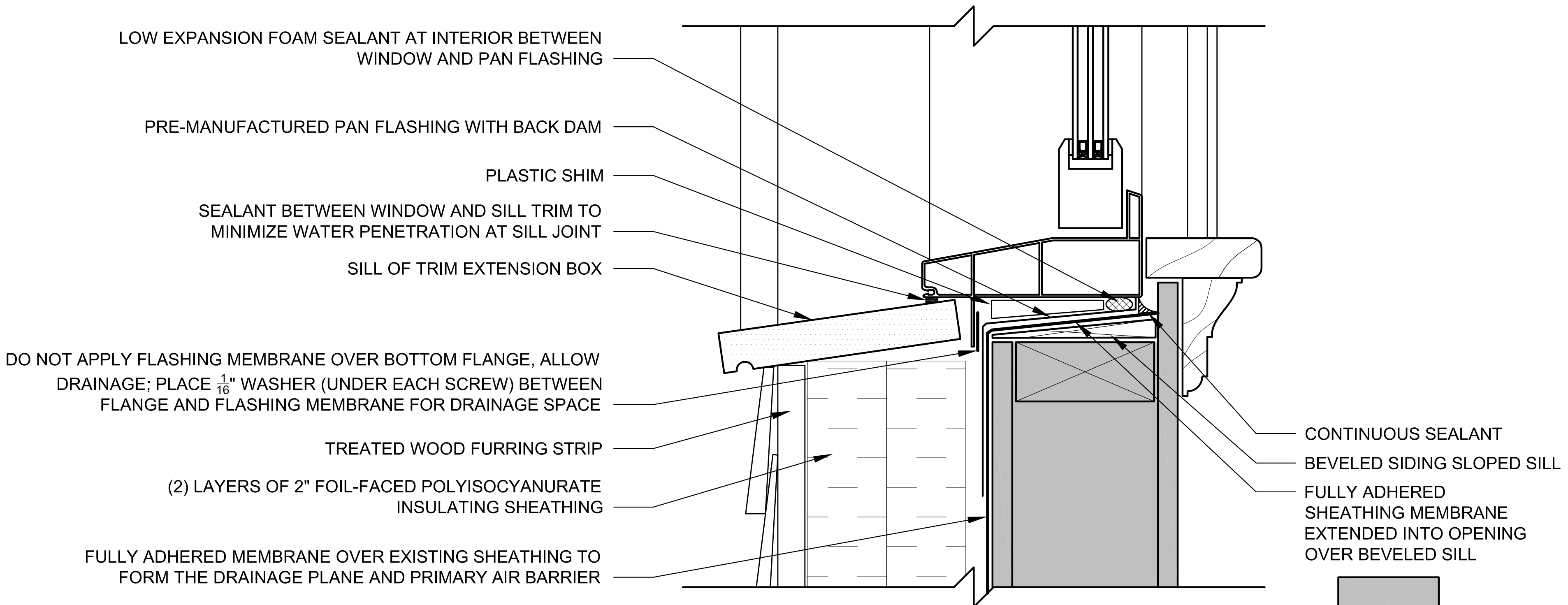
3 WINDOW HEAD DETAIL

SCALE: 3" = 1'-0"



2 WINDOW JAMB DETAIL

SCALE: 3" = 1'-0"



1 WINDOW SILL DETAIL

SCALE: 3" = 1'-0"

▨ GRAY TONE INDICATES EXISTING STRUCTURE

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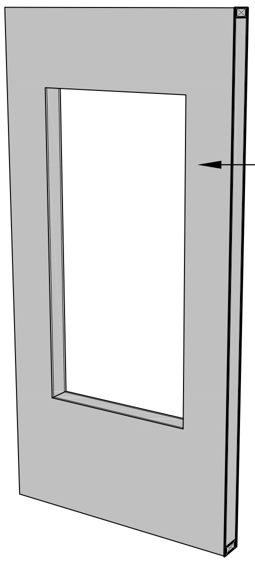
U.S. Department of Energy
Research Toward Zero Energy Homes

Project:	Deep Energy Retrofit
Date:	2009-08-28 DRAFT
Drawing Title:	Window Details
Drawing File:	InnerRetrofitDetails.dwg
Drawing Scale:	3" = 1'-0"

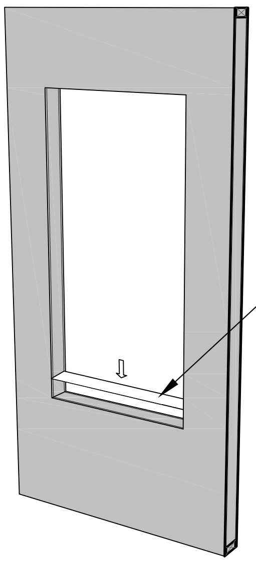
Sheet Title:

Win-1



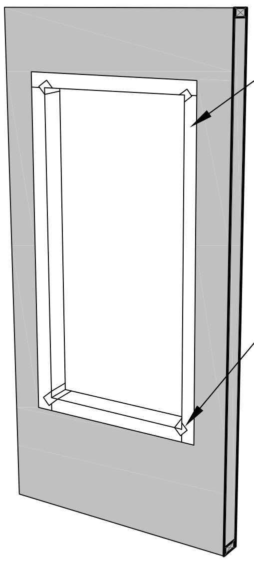
EXISTING FRAMED AND SHEATHED WALL WITH WINDOW ROUGH OPENING

STEP 1



INSTALL BEVELED SIDING TO FORM SLOPED SILL

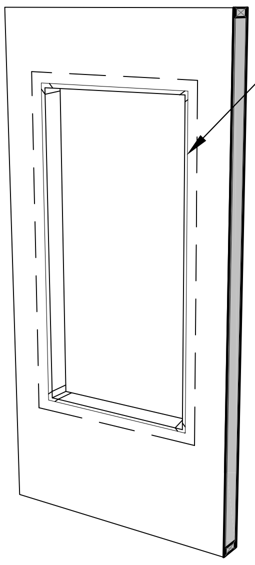
STEP 2



APPLY SELF ADHERED MEMBRANE STRIPS AROUND AND EXTEND INTO OPENING.

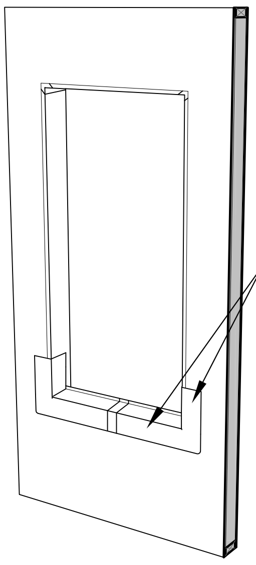
INSTALL CORNER FLASHING PATCHES AT EACH CORNER

STEP 3



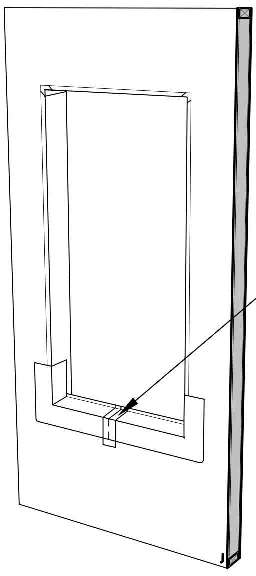
INSTALL FULLY ADHERED MEMBRANE OVER EXISTING SHEATHING TO FORM AIR BARRIER AND DRAINAGE PLANE; OVERLAP MEMBRANE STRIPS

STEP 4



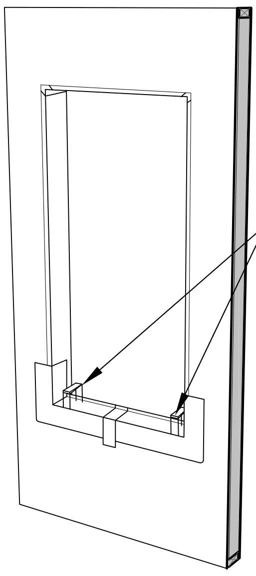
INSTALL PRE-MANUFACTURED SILL PAN WITH BACK DAM

STEP 5



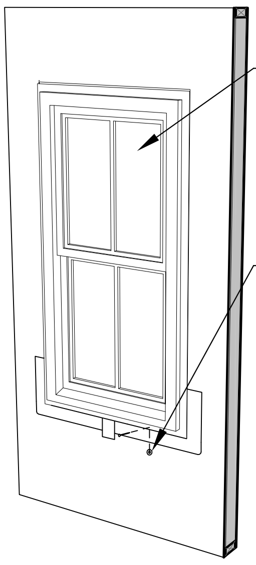
TAPE OR FLASH SILL PAN AT SILL JOINT

STEP 6



INSTALL PLASTIC SHIMS NEAR ENDS OF SILL; LEAVE DRAINAGE GAP AT CORNERS

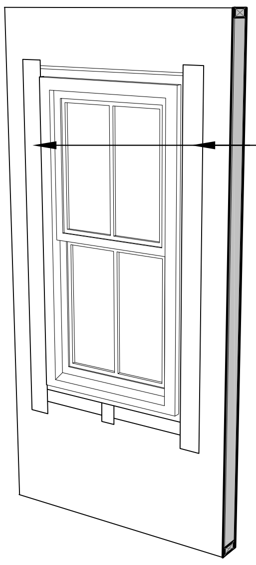
STEP 7



INSTALL WINDOW, ENSURE PLUMB, LEVEL AND SQUARE, SHIM AS REQUIRED

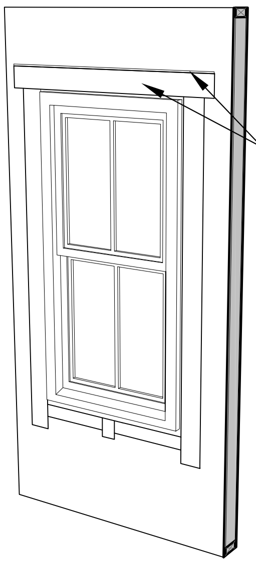
PLACE $\frac{1}{16}$" WASHER BETWEEN BOTTOM WINDOW FLANGE AND SILL PAN AT EACH FASTENER TO MAINTAIN DRAINAGE GAP

STEP 8



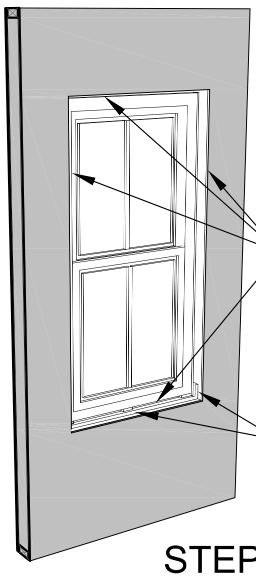
INSTALL SELF ADHERED JAMB FLASHING, BOTH SIDES

STEP 9



INSTALL SELF ADHERED HEAD FLASHING; BUTTER TOP EDGE OF FLASHING WITH COMPATIBLE MASTIC TO REINFORCE SEAL

STEP 10



INTERIOR SIDE OF WALL

PROVIDE LOW EXPANSION FOAM AT PERIMETER OF WINDOW, ALL 4 SIDES

APPLY CONTINUOUS SEALANT ACROSS SILL AND UP SIDE OF OPENING AT BACK DAM OF SILL PAN; SEALANT MUST BE COMPATIBLE WITH FULLY ADHERED MEMBRANE

STEP 11

▨ GRAY TONE INDICATES EXISTING STRUCTURE

1 WINDOW INSTALLATION SEQUENCE

N.T.S.

bsc with Building America U.S. Department of Energy Research Toward Zero Energy Homes

Project:	Deep Energy Retrofit
Date:	2009-08-20 DRAFT
Drawing Title:	Window Installation Sequence
Drawing File:	InnerRetrofitDetails.dwg
Drawing Scale:	N.T.S.

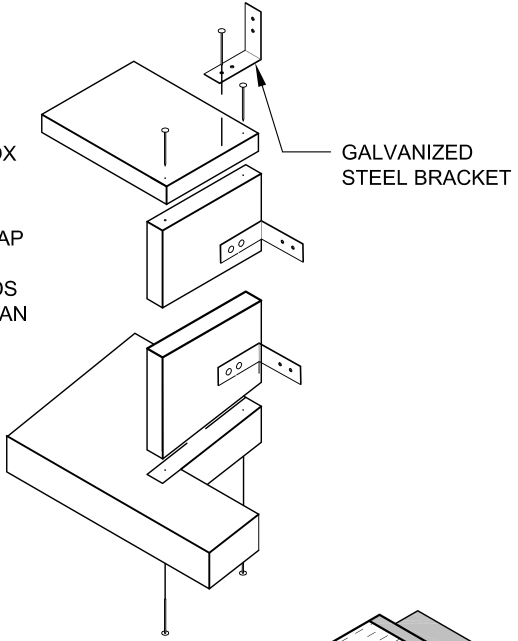
Sheet Title:

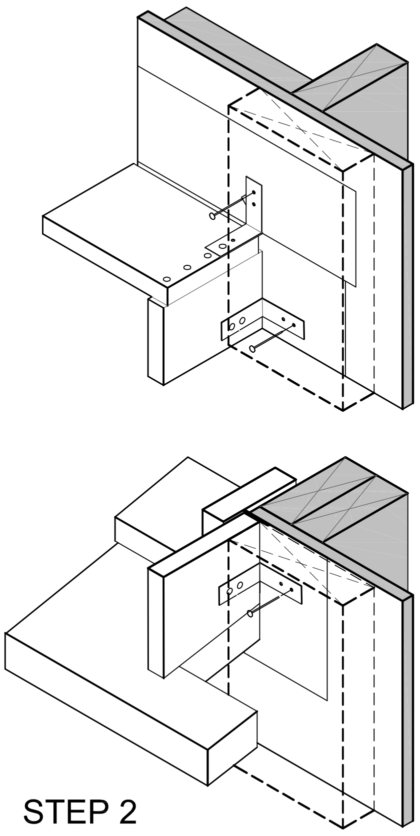
Win-2

C-292

STEP 1

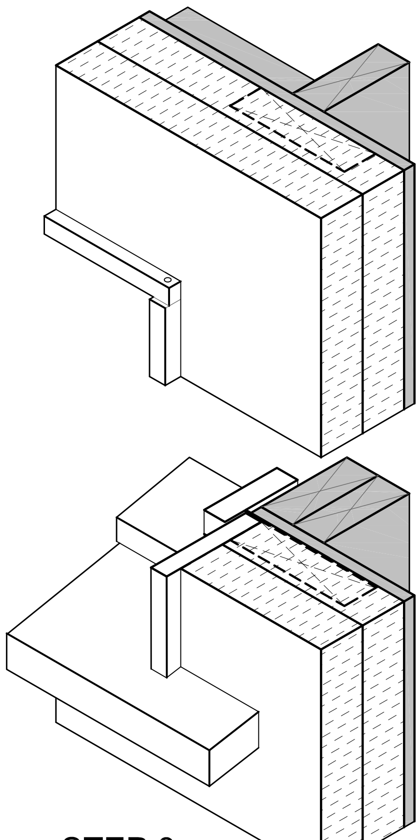
PREASSEMBLE TRIM EXTENSION BOX USING WATER-RESISTANT TRIM MATERIAL; CUT HEAD PIECE $\frac{1}{4}$" NARROW TO ALLOW $\frac{1}{8}$" DRAINAGE GAP TO EITHER SIDE; SLOPE SILL PIECE FOR DRAINAGE; NOTCH SILL AT ENDS SO THAT INSULATING SHEATHING CAN BE PLACED BEHIND IT.





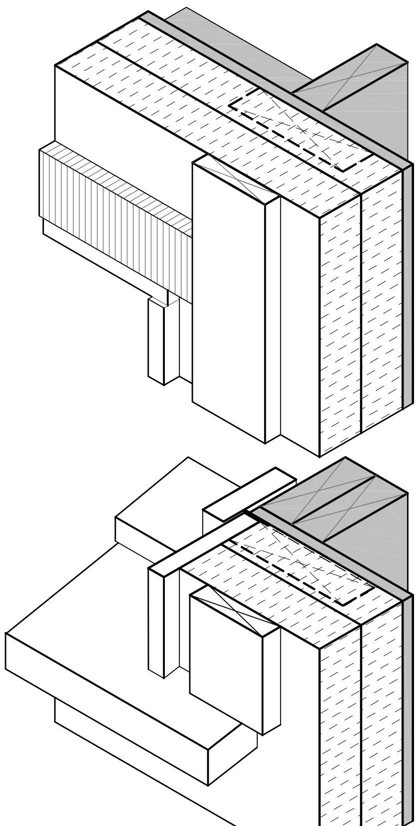
STEP 2

ATTACH TRIM EXTENSION BOX AFTER WINDOW IS INSTALLED AND INTEGRATED INTO DRAINAGE PLANE; IF OPTIONAL NAILER IS NEEDED, ATTACH EXTENSION BOX DIRECTLY TO NAILER



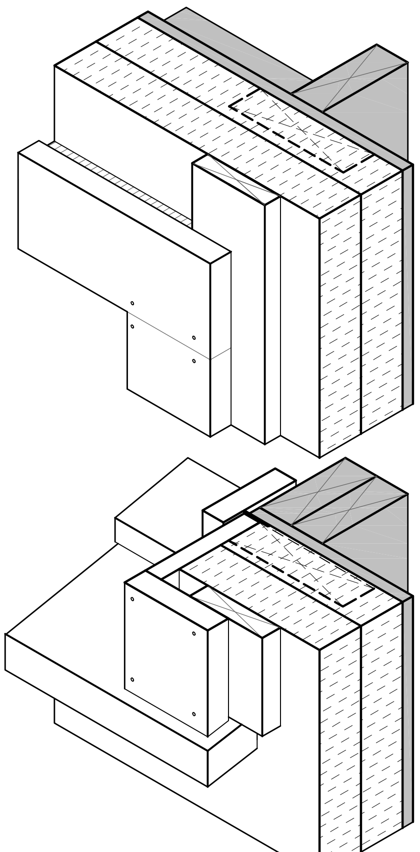
STEP 3

INSTALL INSULATING SHEATHING UP TIGHT TO THE TRIM EXTENSION BOX



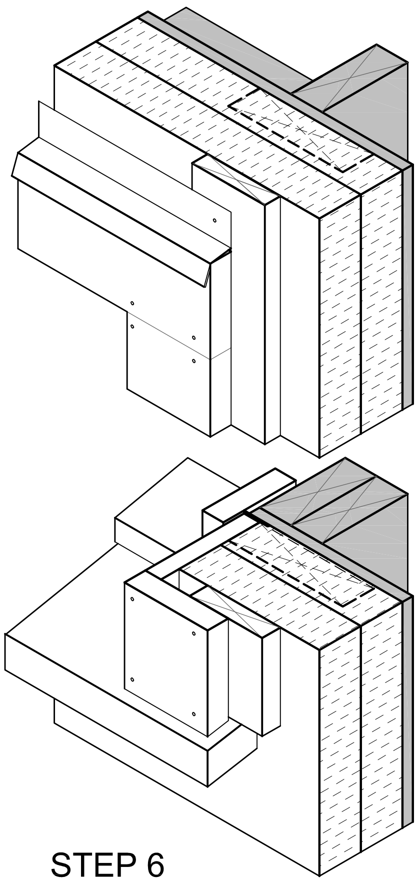
STEP 4

INSTALL 1 x 4 FURRING TO SUPPORT WINDOW TRIM AND CLADDING. INSTALL CLADDING VENT BETWEEN FURRING STRIPS AT WINDOW HEAD



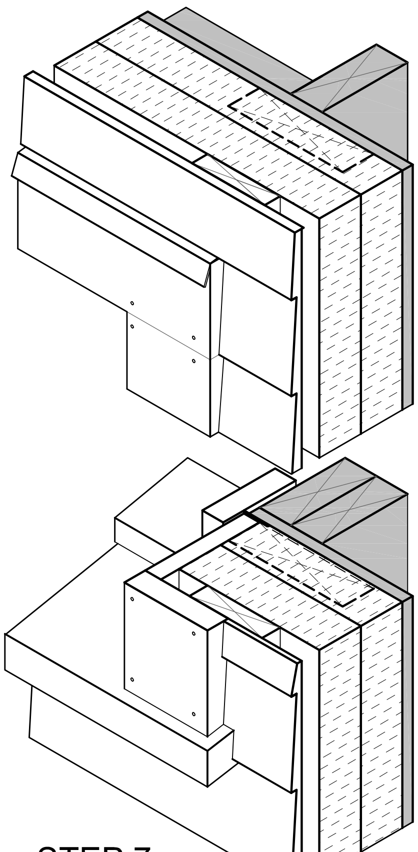
STEP 5

INSTALL WINDOW TRIM; FASTEN TO TRIM EXTENSION BOX AND TO FURRING



STEP 6

INSTALL SLOPED METAL HEAD FLASHING OVER HEAD TRIM, FASTEN TO FURRING STRIPS



STEP 7

INSTALL CLADDING

▨ GRAY TONE INDICATES EXISTING STRUCTURE

① WINDOW TRIM INSTALLATION SEQUENCE

N.T.S.

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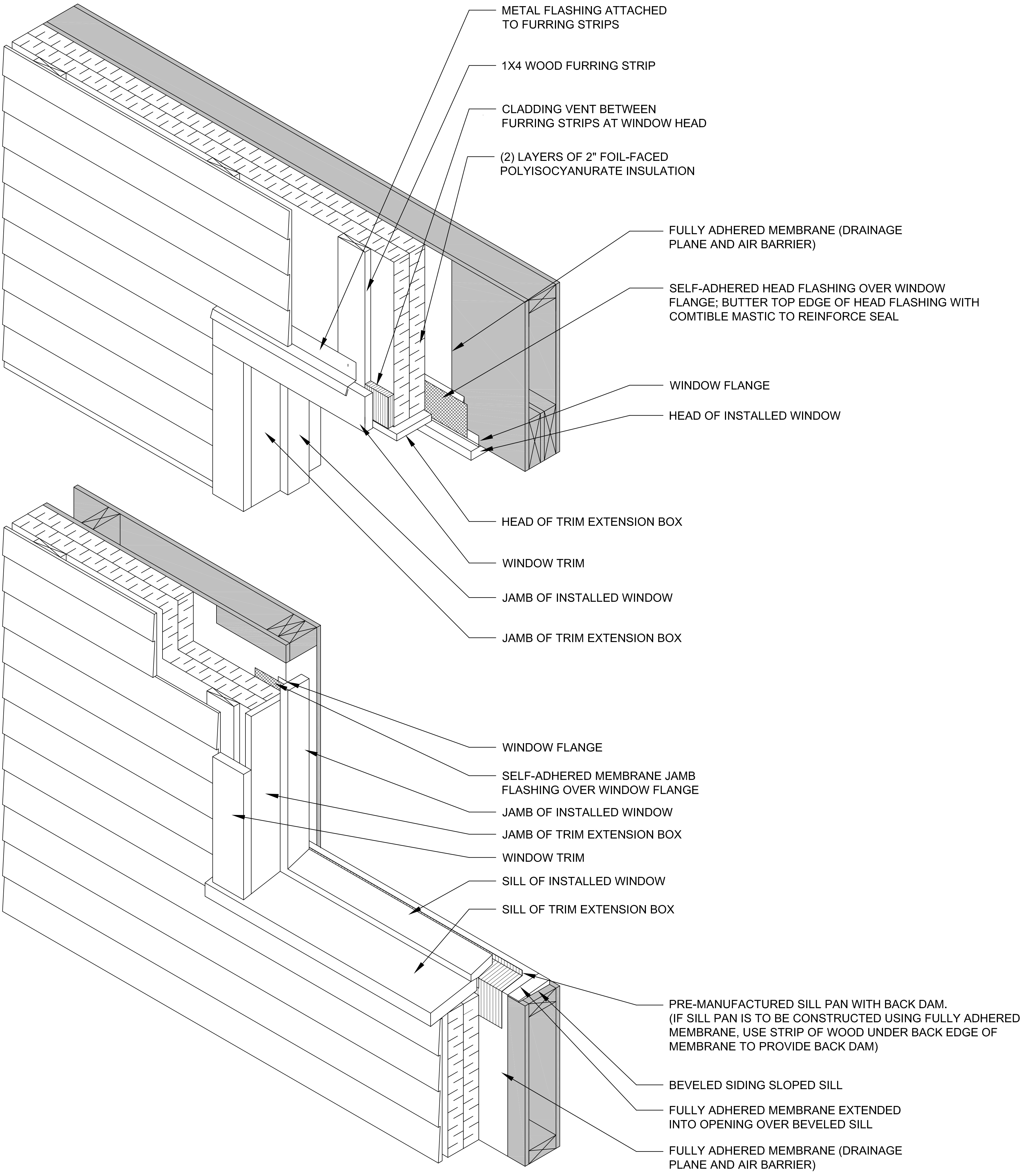
Project: Deep Energy Retrofit
Date: 2009-08-20 DRAFT
Drawing Title: Window Trim Installation Sequence
Drawing File: InnerRetrofitDetails.dwg
Drawing Scale: N.T.S.

Sheet Title:
Win-3



▨ GRAY TONE INDICATES EXISTING STRUCTURE

1

ENCLOSURE ASSEMBLY WITH WINDOW OPENING

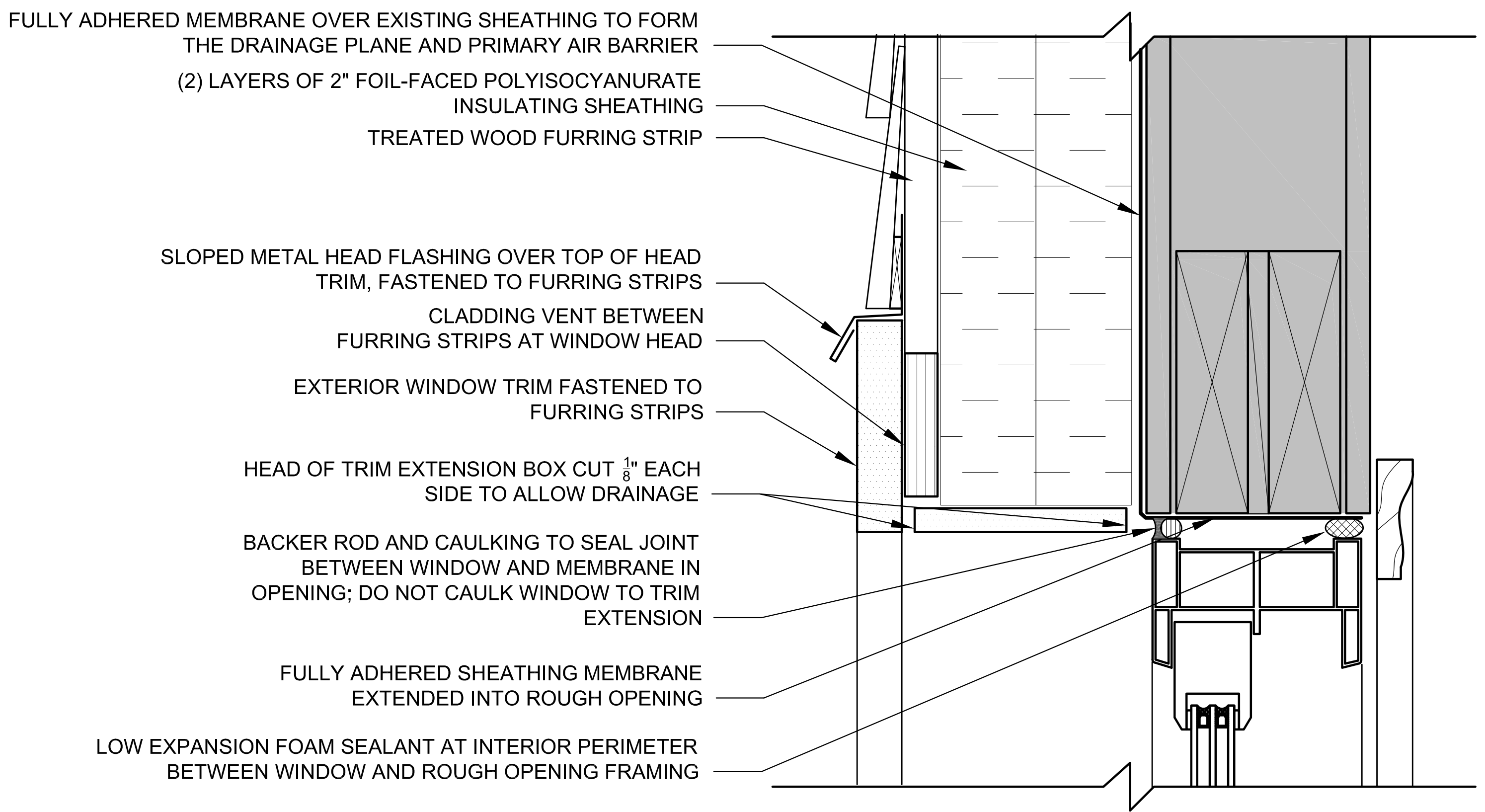
N.T.S.

bsc with Building America U.S. Department of Energy Research Toward Zero Energy Homes

Project: Deep Energy Retrofit
Date: 2009-08-20 DRAFT
Drawing Title: Enclosure Assembly with Window Opening
Drawing File: InnerRetrofitDetails.dwg
Drawing Scale: N.T.S.

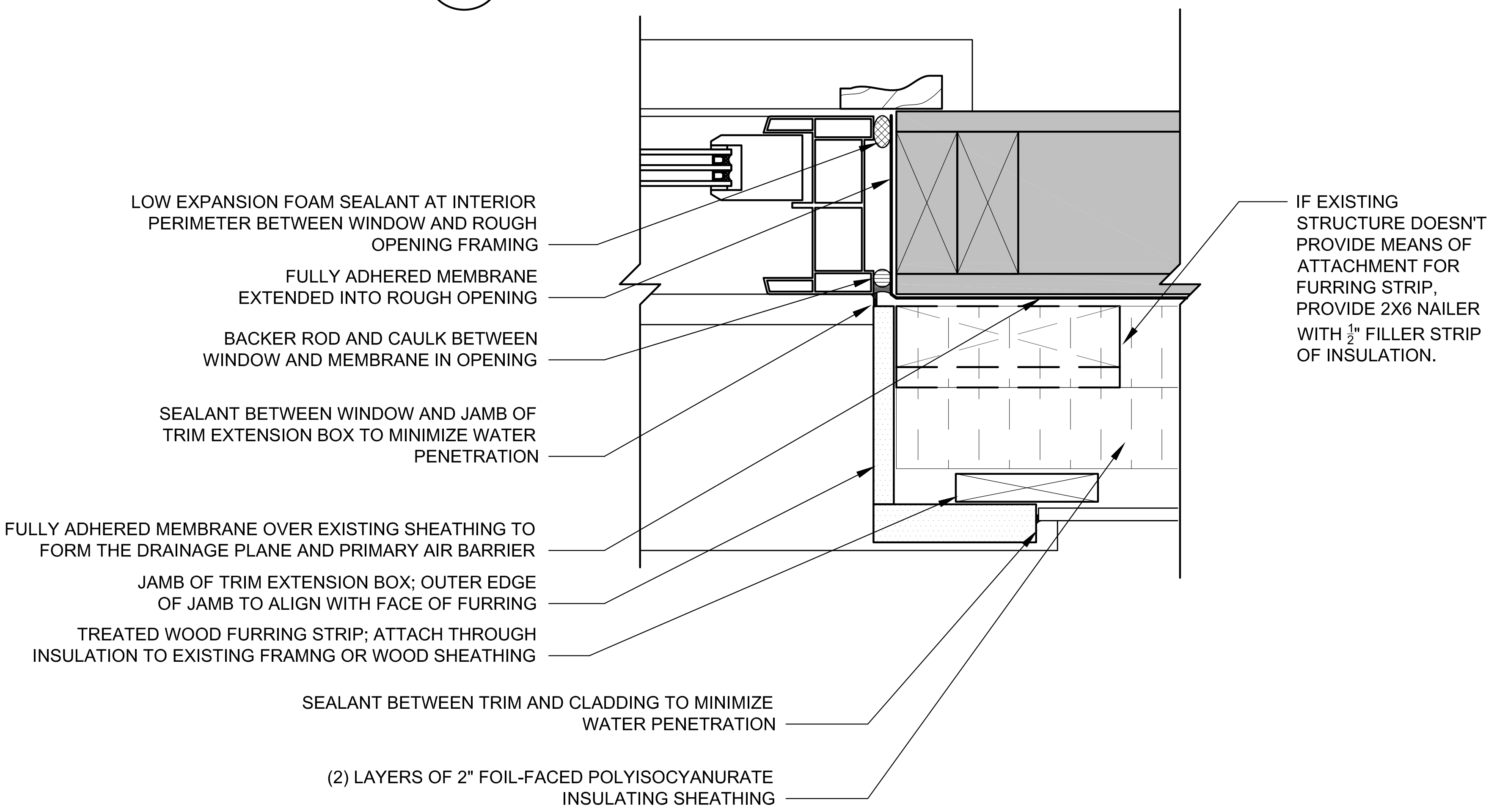
Sheet Title:

Win-4



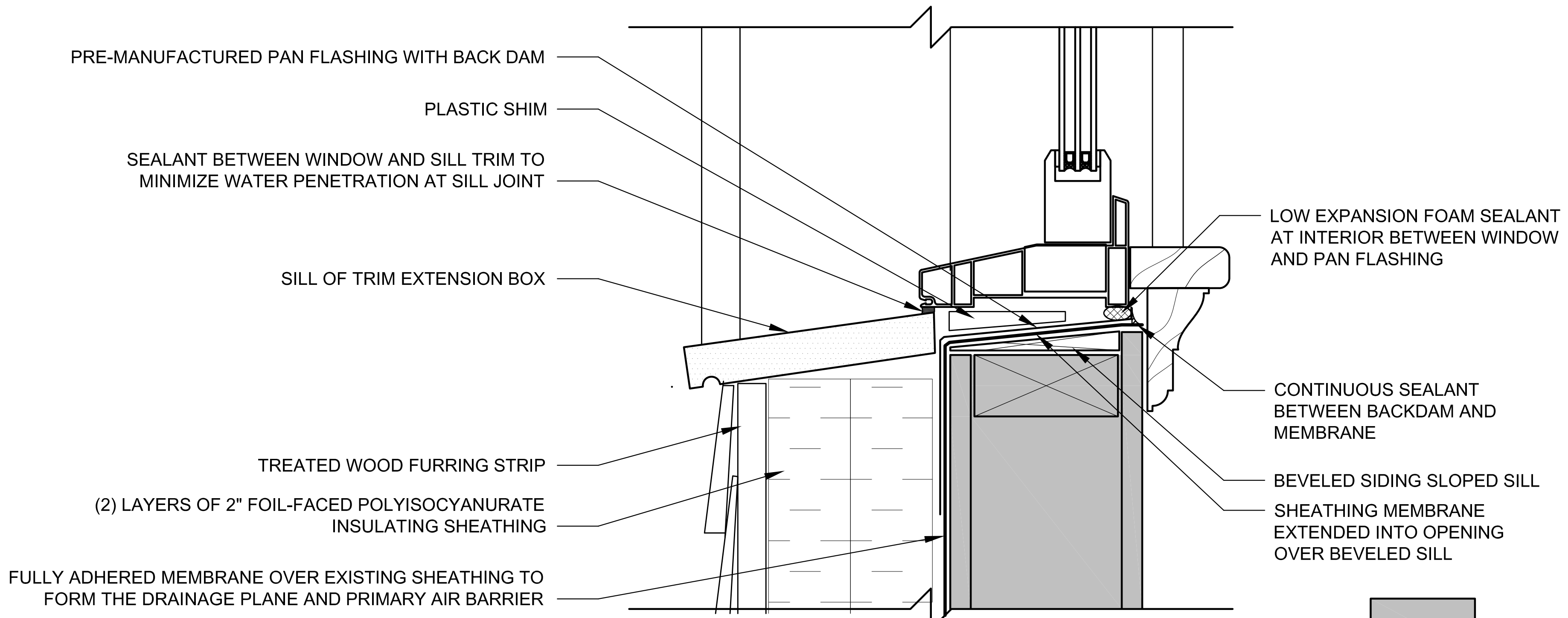
3 WINDOW HEAD DETAIL- NO FLANGE

SCALE: 3" = 1'-0"



2 WINDOW JAMB DETAIL - NO FLANGE

SCALE: 3" = 1'-0"



1 WINDOW SILL DETAIL - NO FLANGE

SCALE: 3" = 1'-0"

▨ GRAY TONE INDICATES EXISTING STRUCTURE

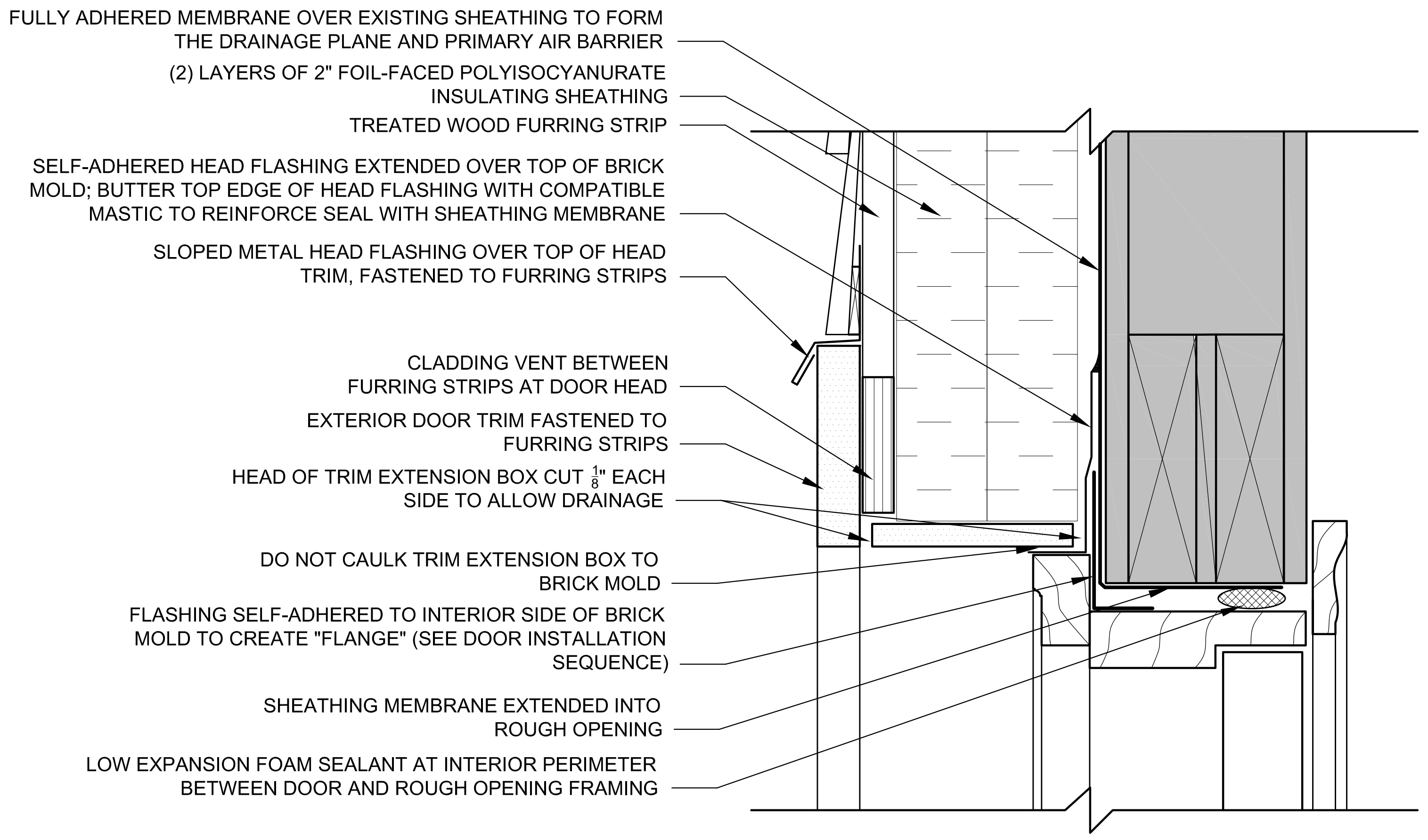
with

U.S. Department of Energy
Research Toward Zero Energy Homes

Project:	Deep Energy Retrofit
Date:	2009-08-28 DRAFT
Drawing Title:	Window Details
Drawing File:	InnerRetrofitDetails.dwg
Drawing Scale:	3" = 1'-0"

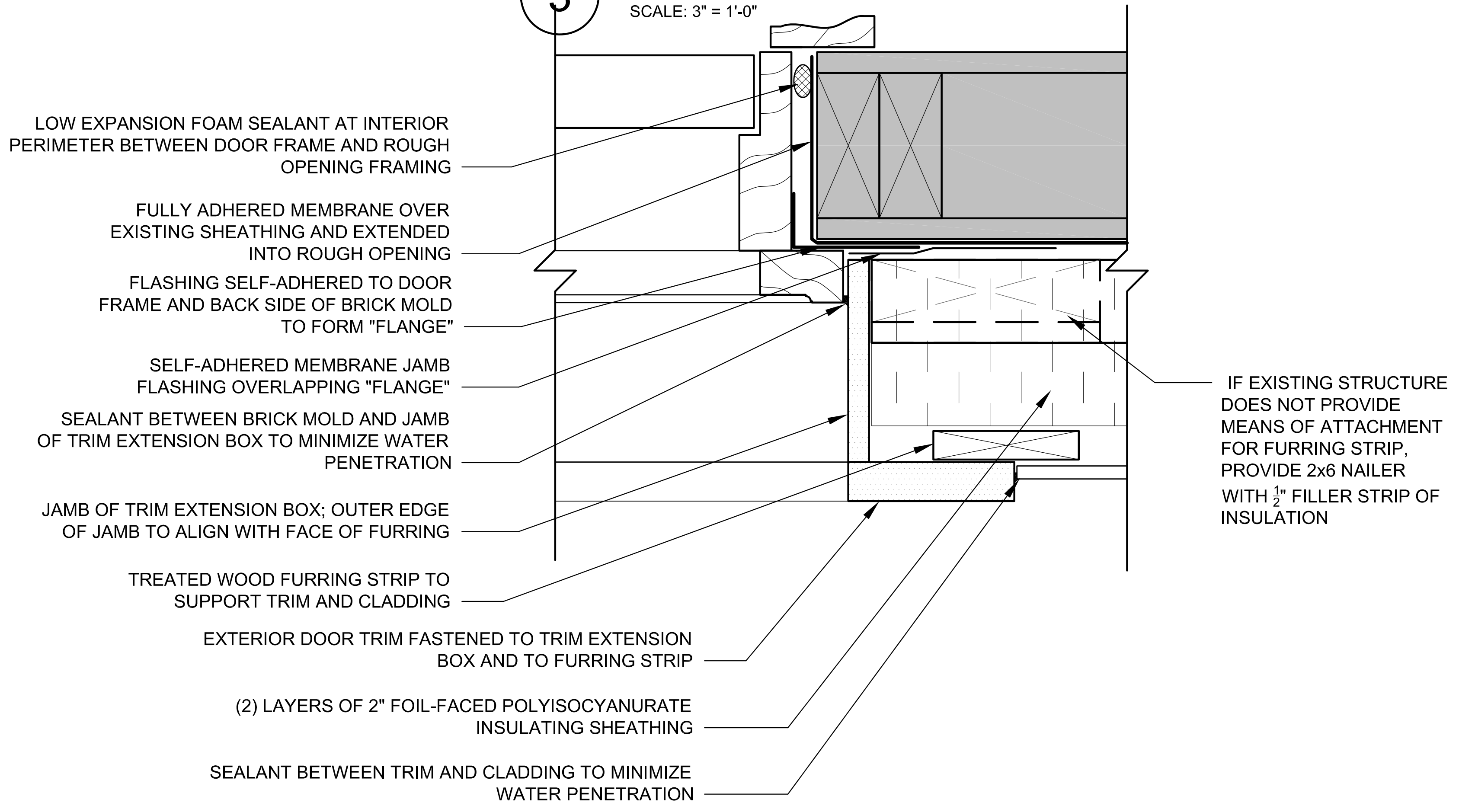
Sheet Title:

Win-1A



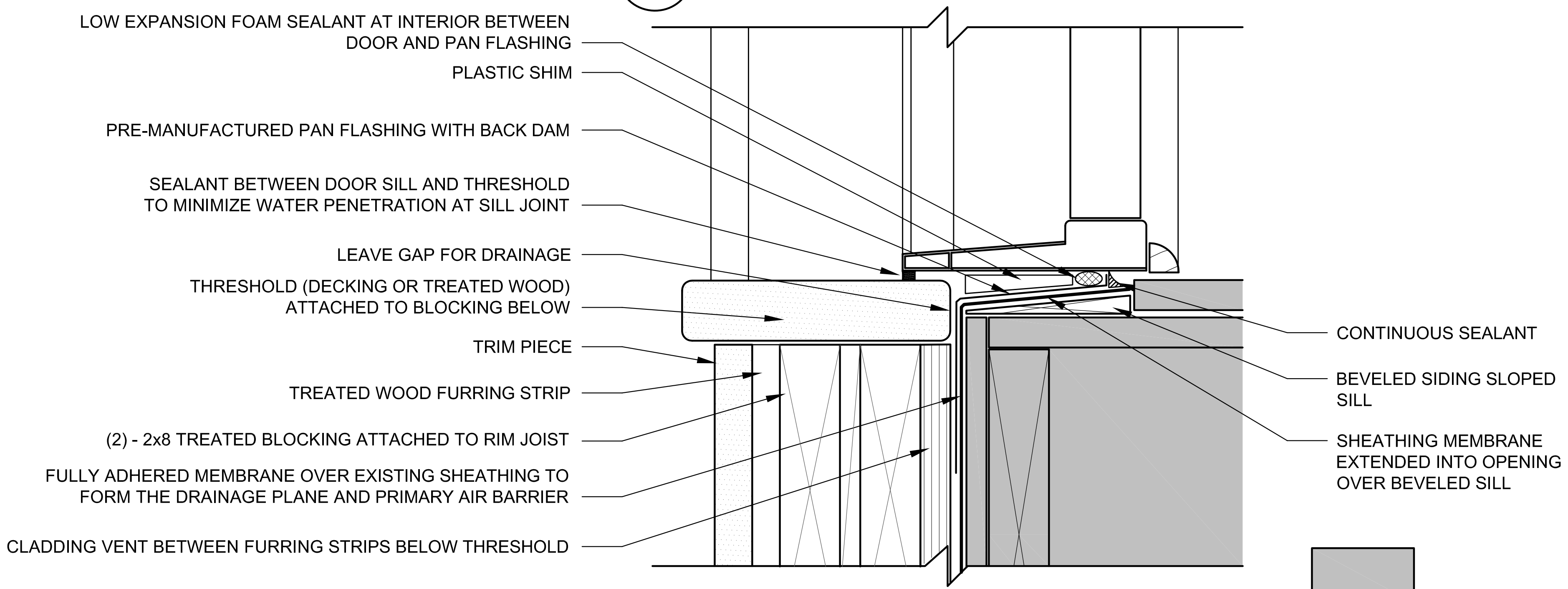
3 DOOR HEAD DETAIL

SCALE: 3" = 1'-0"



2 DOOR JAMB DETAIL

SCALE: 3" = 1'-0"



▨ GRAY TONE INDICATES EXISTING STRUCTURE

1 DOOR SILL DETAIL

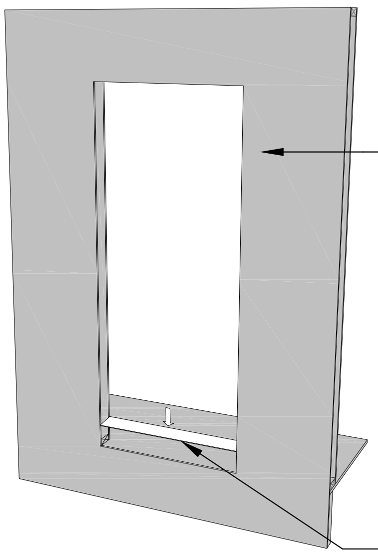
SCALE: 3" = 1'-0"

bsc with Building America U.S. Department of Energy Research Toward Zero Energy Homes

Project:	Deep Energy Retrofit
Date:	2009-08-20 DRAFT
Drawing Title:	Door Details
Drawing File:	InnerRetrofitDetails.dwg
Drawing Scale:	3" = 1'-0"

Sheet Title:

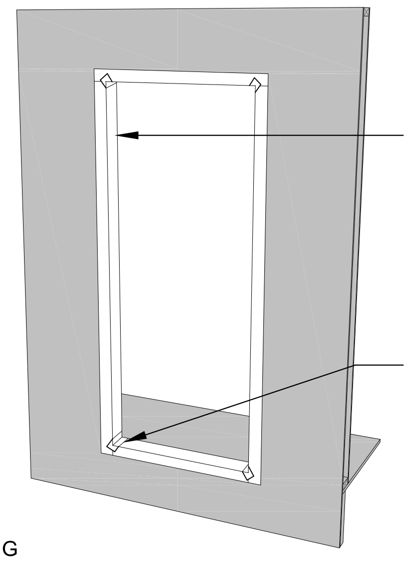
Door-1



EXISTING FRAMED AND SHEATHED WALL WITH DOOR ROUGH OPENING

INSTALL BEVELED SIDING TO FORM SLOPED SILL

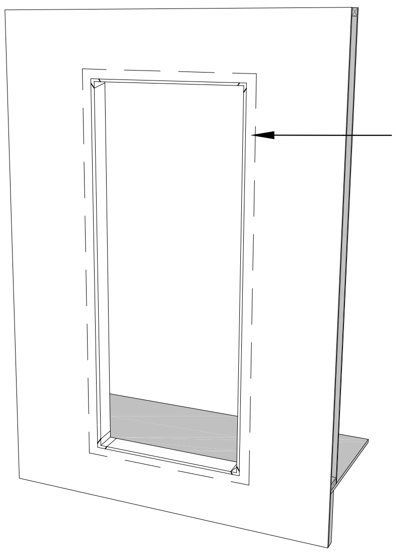
STEP 1



APPLY SELF-ADHERED MEMBRANE STRIPS AROUND AND EXTEND INTO OPENING (ALL 4 SIDES)

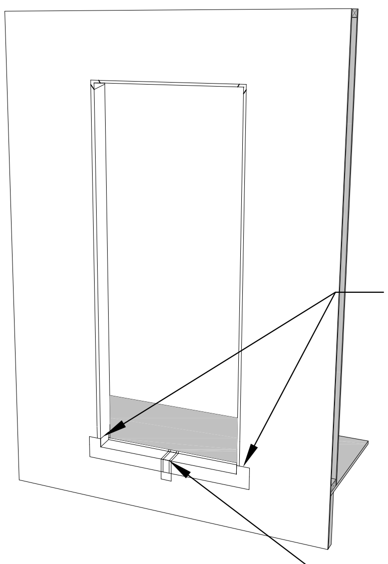
INSTALL CORNER FLASHING PATCHES AT EACH CORNER

STEP 2



APPLY FULLY ADHERED MEMBRANE OVER EXISTING SHEATHING TO FORM AIR BARRIER AND DRAINAGE PLANE; OVERLAP MEMBRANE STRIPS

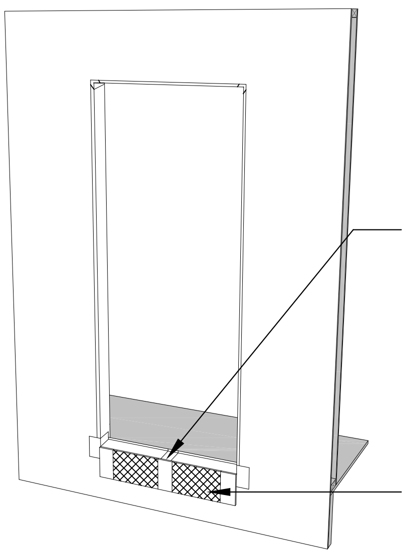
STEP 3



INSTALL PRE-MANUFACTURED SILL PAN

TAPE OR FLASH SILL PAN AT SILL JOINT

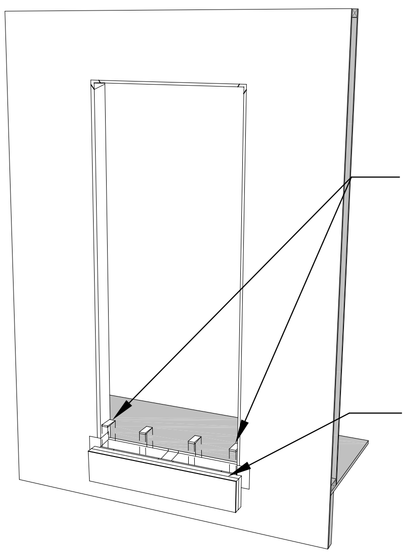
STEP 4



INSTALL $\frac{1}{2}$" TREATED FURRING STRIPS

INSTALL CLADDING VENT BETWEEN FURRING

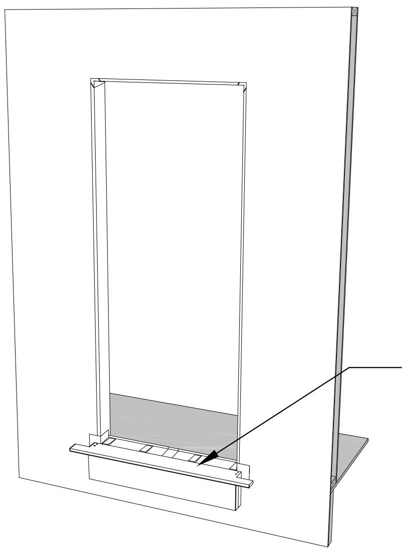
STEP 5



INSTALL PLASTIC SHIMS, LEAVE DRAINAGE GAP AT CORNERS

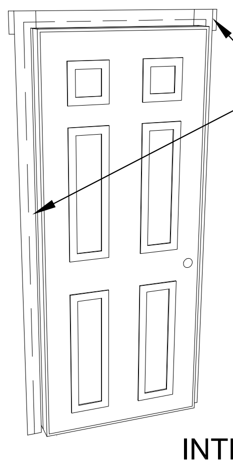
INSTALL (2)-2x8 BLOCKING TO SUPPORT THRESHOLD EXTENSION

STEP 6



ATTACH THRESHOLD TO BLOCKING; THRESHOLD ENDS ARE NOTCHED TO ALLOW INSULATING SHEATHING BEHIND

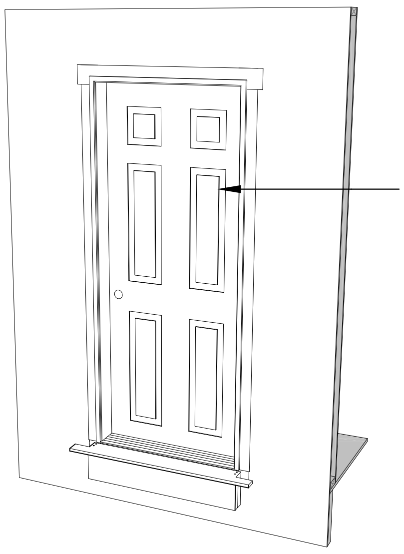
STEP 7



APPLY SELF-ADHERING FLASHING TO INTERIOR SIDE OF BRICK MOLD TO CREATE "FLANGES" AT HEAD AND JAMBS OF DOOR

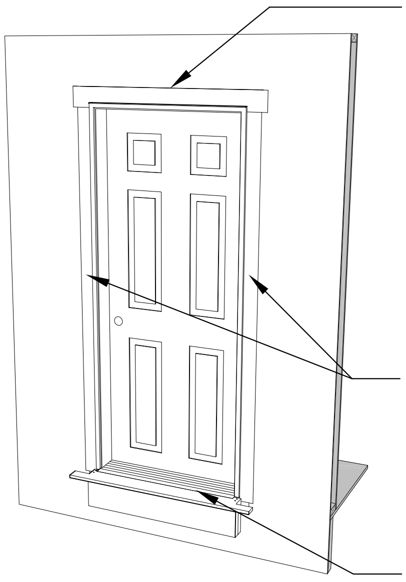
INTERIOR SIDE OF DOOR

STEP 8 (REVERSE VIEW)



INSTALL DOOR, ENSURE PLUMB, LEVEL AND SQUARE, SHIM AS REQUIRED

STEP 9

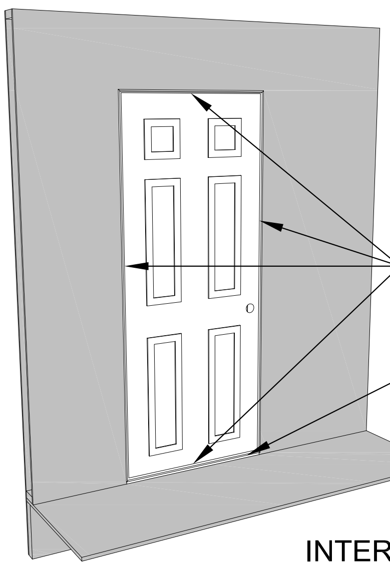


2) INSTALL HEAD FLASHING OVER "FLANGE" OVERLAPPING JAMB FLASHING; BUTTER TOP EDGE OF FLASHING WITH COMPATIBLE MASTIC

1) INSTALL JAMB FLASHING OVER "FLANGES", BOTH SIDES

3) INSTALL SILL EXTENSION

STEP 10



PROVIDE LOW EXPANSION FOAM AT PERIMETER OF DOOR, ALL 4 SIDES

APPLY CONTINUOUS SEALANT ACROSS OPENING AT BACKDAM OF SILL PAN; SEALANT TO BE COMPATIBLE WITH FULLY ADHERED MEMBRANE

INTERIOR VIEW

STEP 11 (REVERSE VIEW)

▨ GRAY TONE INDICATES EXISTING STRUCTURE

1 DOOR INSTALLATION SEQUENCE

N.T.S.

bsc with Building America U.S. Department of Energy Research Toward Zero Energy Homes

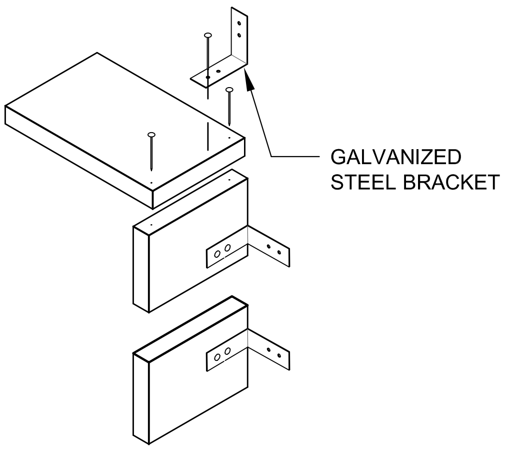
Project:	Deep Energy Retrofit
Date:	2009-08-20 DRAFT
Drawing Title:	Door Installation Sequence
Drawing File:	InnerRetrofitDetails.dwg
Drawing Scale:	N.T.S.

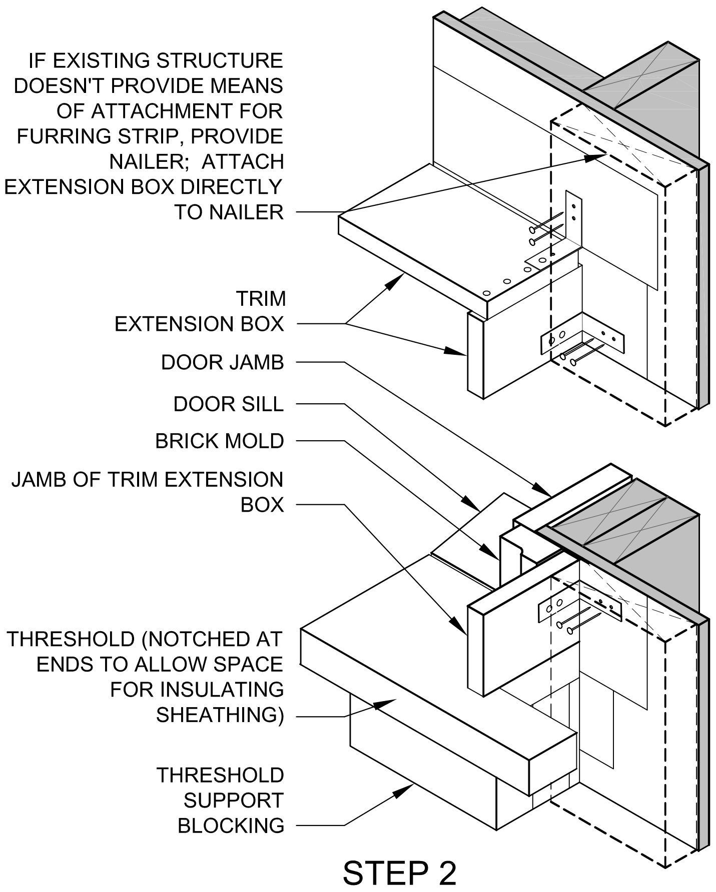
Sheet Title:

Door-2

STEP 1

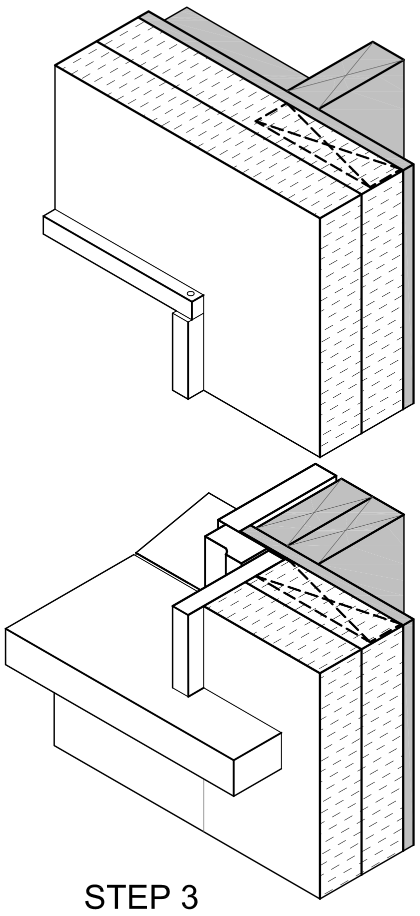
PREASSEMBLE TRIM EXTENSION BOX USING WATER-RESISTANT TRIM MATERIAL; CUT HEAD PIECE ¼" NARROW TO ALLOW ⅛" DRAINAGE GAP TO EITHER SIDE; TRIM EXTENSION BOX CONSISTS OF HEAD AND JAMBS WHICH FIT AROUND THE BRICK MOLD AND REACH DOWN TO THE THRESHOLD. THE THRESHOLD AND THRESHOLD SUPPORT ARE ATTACHED DURING DOOR INSTALLATION.





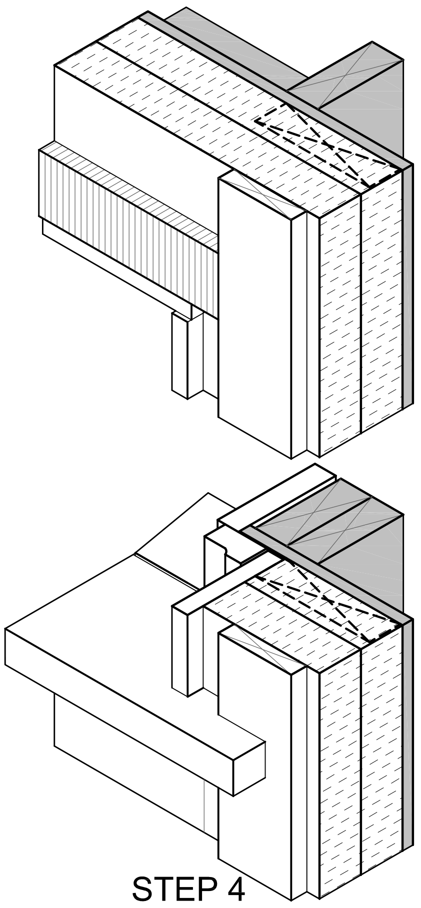
STEP 2

ATTACH TRIM EXTENSION BOX AFTER DOOR IS INSTALLED AND INTEGRATED INTO DRAINAGE PLANE



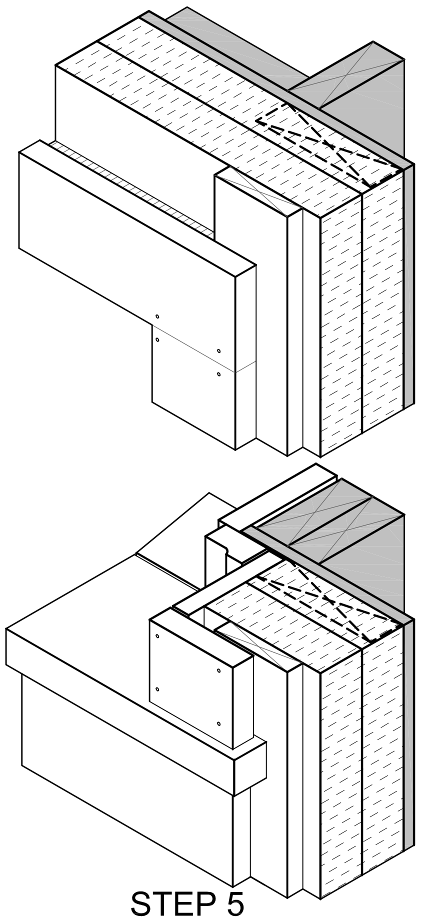
STEP 3

INSTALL INSULATING SHEATHING UP TIGHT TO THE TRIM EXTENSION BOX, THE THRESHOLD, AND THE BLOCKING UNDER THRESHOLD



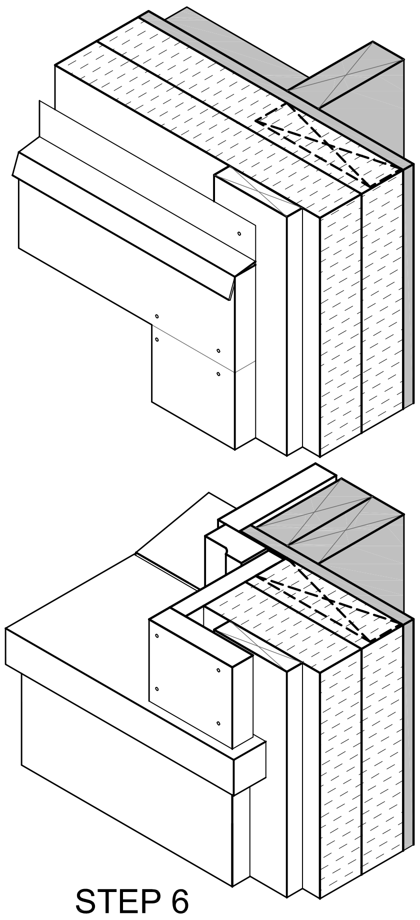
STEP 4

INSTALL 1 x 4 FURRING TO SUPPORT DOOR TRIM AND CLADDING. INSTALL CLADDING VENT BETWEEN FURRING STRIPS AT DOOR HEAD



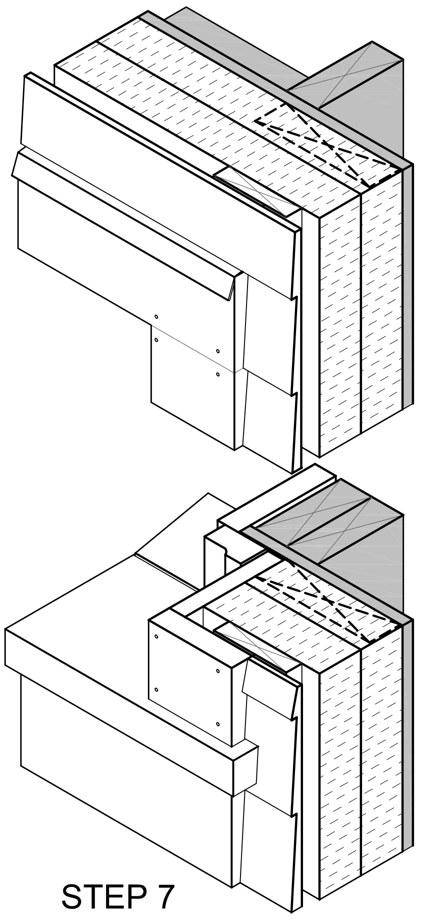
STEP 5

INSTALL DOOR TRIM, FASTEN TO TRIM EXTENSION BOX AND FURRING



STEP 6

INSTALL SLOPED METAL HEAD FLASHING OVER HEAD TRIM, FASTEN TO FURRING STRIPS



STEP 7

INSTALL CLADDING

▨ GRAY TONE INDICATES EXISTING STRUCTURE

1 DOOR TRIM INSTALLATION SEQUENCE

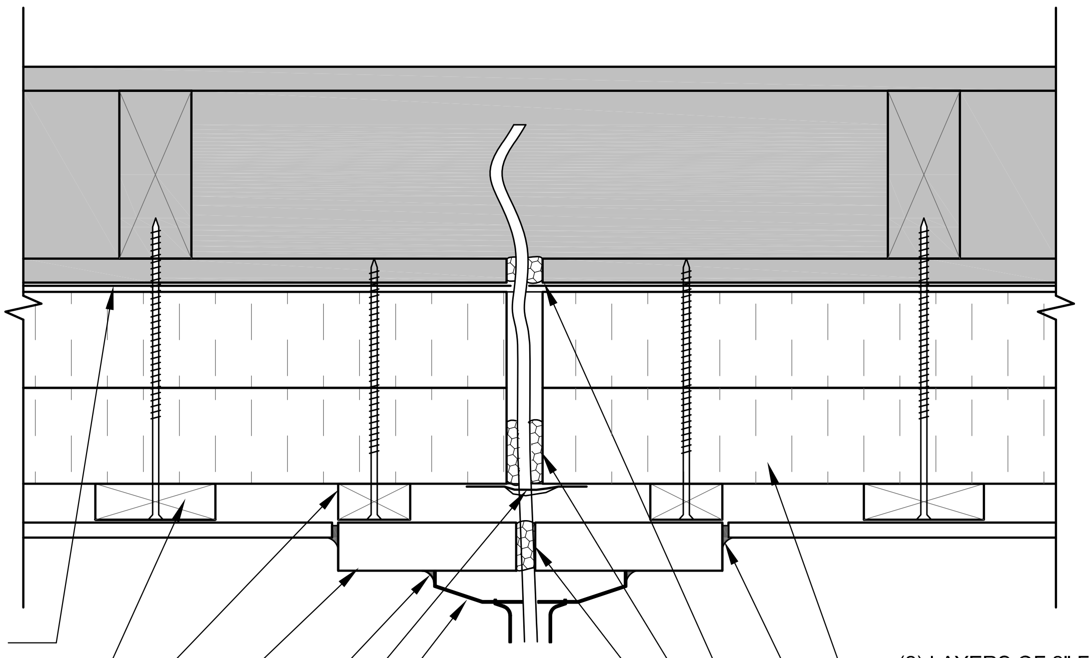
N.T.S.

bsc with Building America U.S. Department of Energy Research Toward Zero Energy Homes

Project: Deep Energy Retrofit
Date: 2009-08-20 DRAFT
Drawing Title: Door Trim Installation Sequence
Drawing File: InnerRetrofitDetails.dwg
Drawing Scale: N.T.S.

Sheet Title:

Door-3



FULLY ADHERED MEMBRANE OVER EXISTING SHEATHING TO FORM DRAINAGE PLANE AND PRIMARY AIR BARRIER

FURRING ATTACHED BACK TO EXISTING SHEATHING OR FRAMING THROUGH INSULATION

LIGHTING FIXTURE TRIM / MOUNTING BLOCK

APPLY CAULKING AROUND FIXTURE BASE TOP AND SIDES (NOT BOTTOM)

APPLY TAPE OVER PENETRATION THROUGH INSULATING SHEATHING

FIXTURE ATTACHMENT

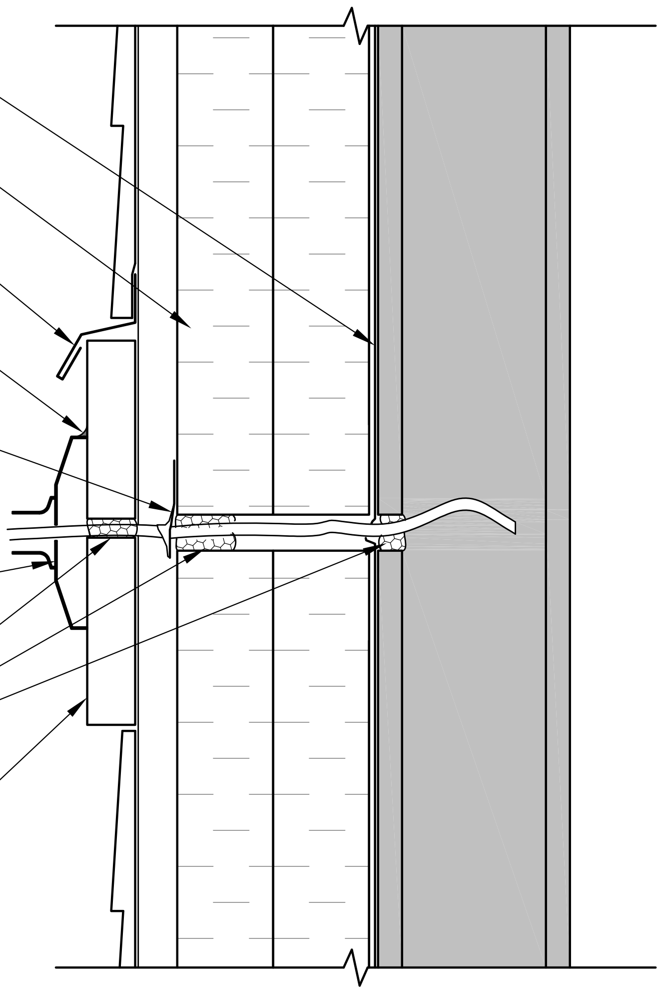
(2) LAYERS OF 2" FOIL-FACED POLYISOCYANURATE INSULATING SHEATHING

APPLY CAULKING OVER JOINT BTW CLADDING AND TRIM / MOUNTING BLOCK

APPLY URETHANE FOAM SEALANT AROUND WIRE PENETRATION AT SHEATHING, INSULATING SHEATHING AND AT TRIM / MOUNTING BLOCK

2 EXTERIOR LIGHT FIXTURE PLAN DETAIL

SCALE: 3" = 1'-0"



FULLY ADHERED MEMBRANE APPLIED TO EXISTING SHEATHING TO FORM DRAINAGE PLANE AND PRIMARY AIR BARRIER

(2) LAYERS OF 2" FOIL-FACED POLYISOCYANURATE INSULATING SHEATHING

METAL CAP FLASHING

APPLY CAULKING AROUND FIXTURE BASE TOP AND SIDES

APPLY TAPE OVER PENETRATION THROUGH INSULATING SHEATHING

FIXTURE ATTACHMENT

APPLY URETHANE FOAM SEALANT AROUND WIRE PENETRATION AT SHEATHING, INSULATING SHEATHING, AND AT TRIM / MOUNTING BLOCK

LIGHTING FIXTURE TRIM / MOUNTING BLOCK

1 EXTERIOR LIGHT FIXTURE SECTION DETAIL

SCALE: 3" = 1'-0"

▨ GRAY TONE INDICATES EXISTING STRUCTURE

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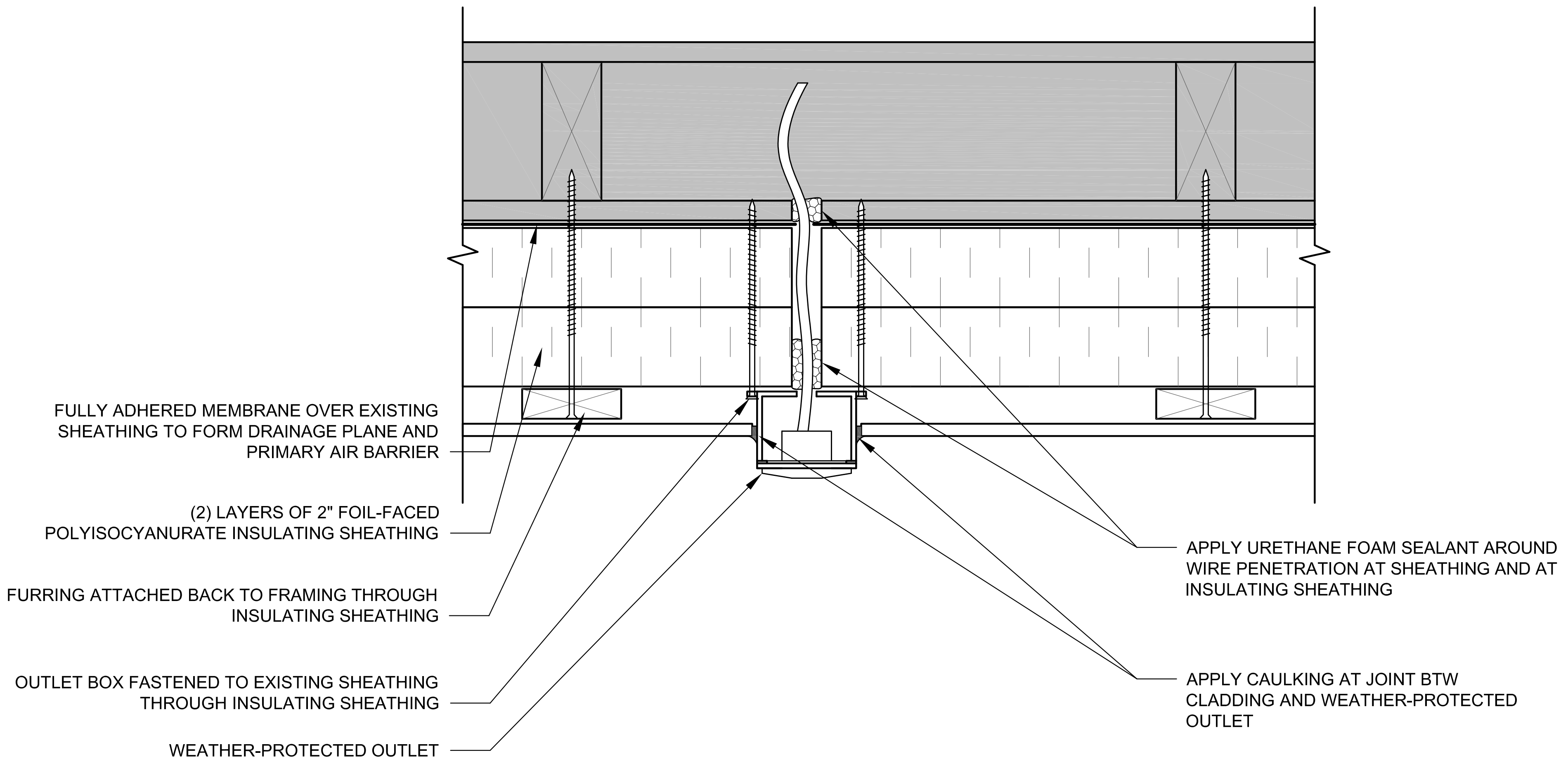
Project:	Deep Energy Retrofit
Date:	2009-08-20 DRAFT
Drawing Title:	Penetration Details
Drawing File:	InnerRetrofitDetails.dwg
Drawing Scale:	3" = 1'-0"

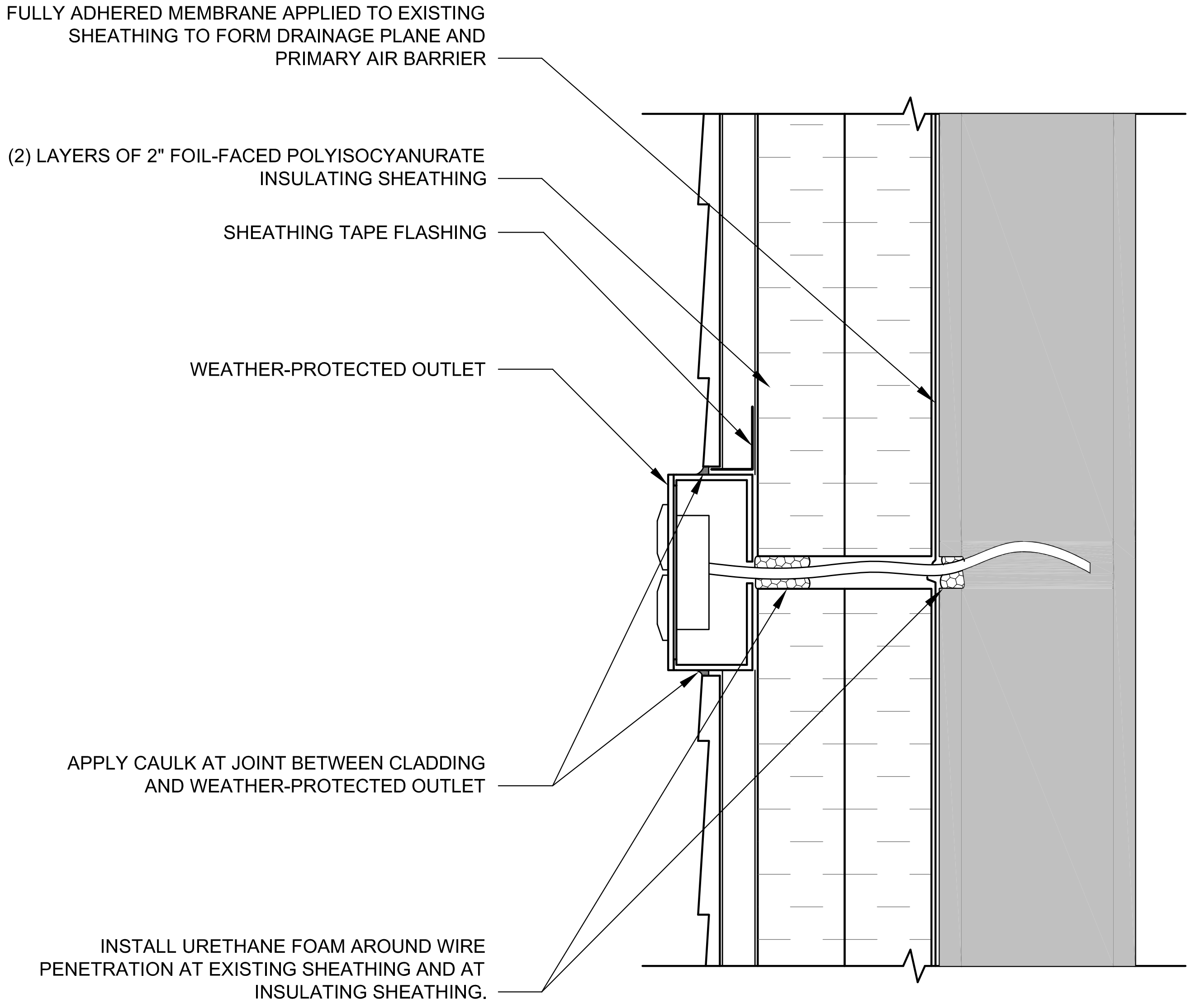
Sheet Title:

Pen-1



2 EXTERIOR ELECTRIC BOX PLAN DETAIL

SCALE: 3" = 1'-0"



1 EXTERIOR ELECTRIC BOX SECTION DETAIL

SCALE: 3" = 1'-0"

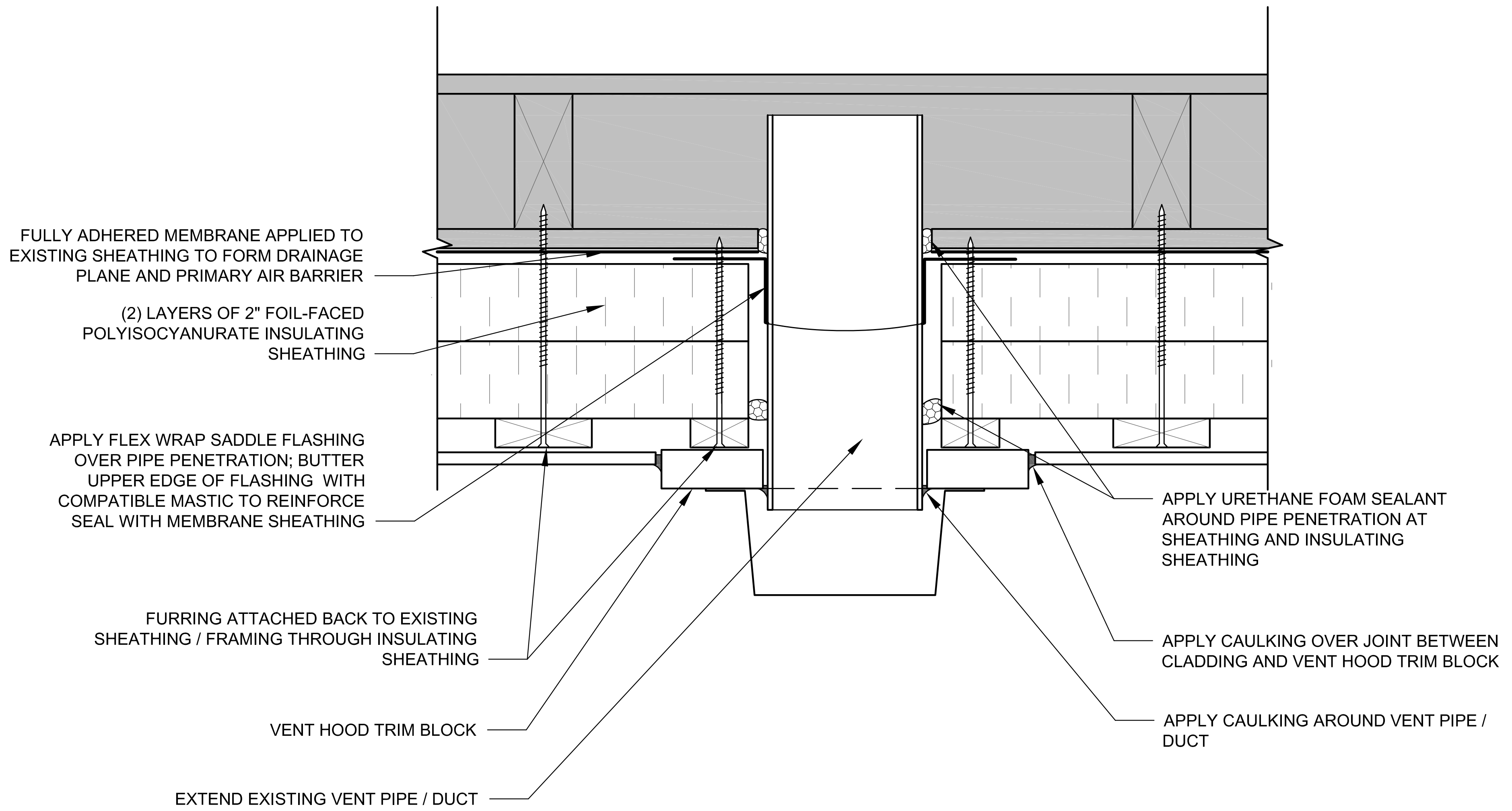
▨ GRAY TONE INDICATES EXISTING STRUCTURE

bsc with Building America U.S. Department of Energy Research Toward Zero Energy Homes

Project:	Deep Energy Retrofit
Date:	2009-08-20 DRAFT
Drawing Title:	Penetration Details
Drawing File:	InnerRetrofitDetails.dwg
Drawing Scale:	3" = 1'-0"

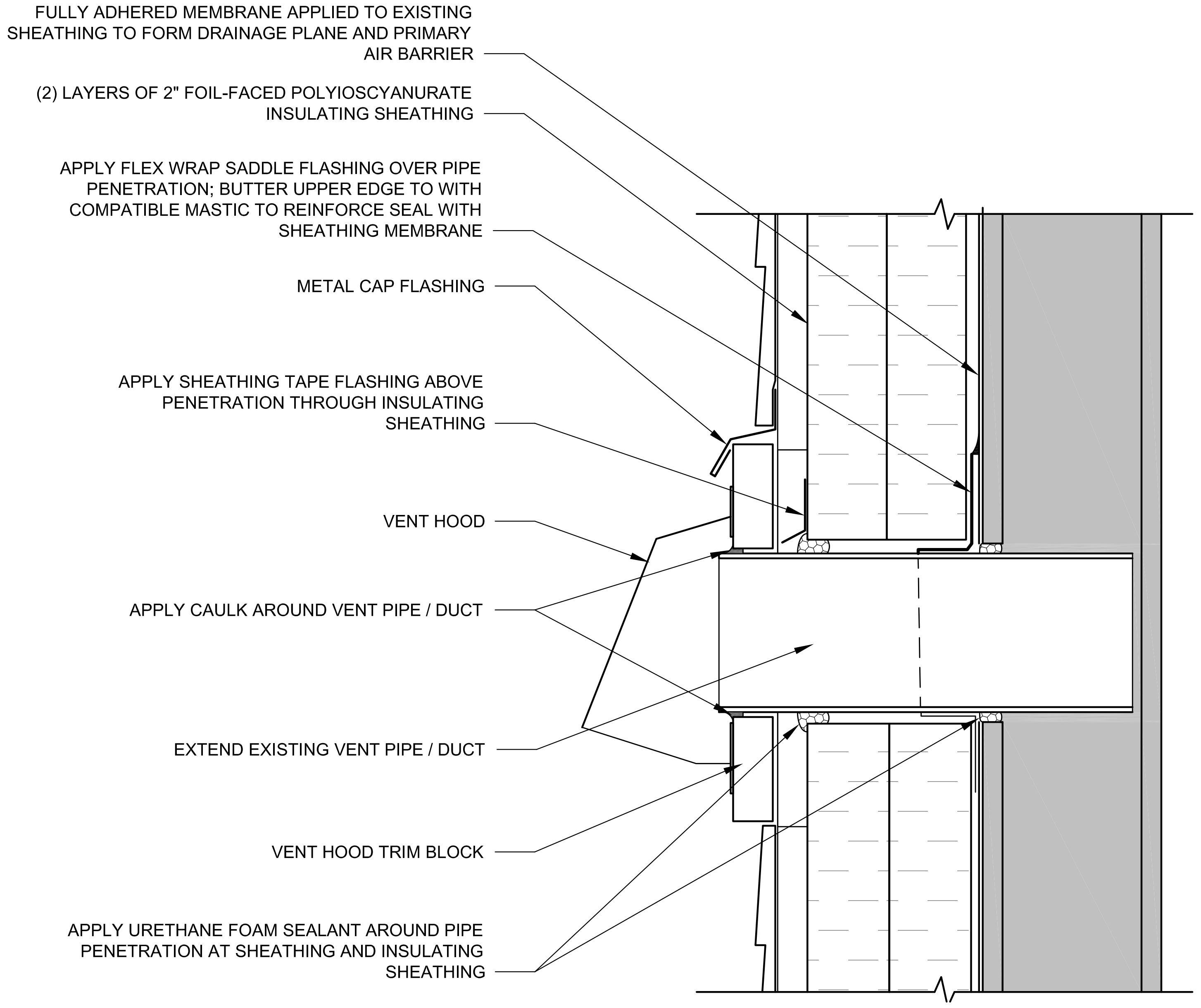
Sheet Title:

Pen-2



2 VENT PIPE/DUCT PLAN DETAIL

SCALE: 3" = 1'-0"



1 VENT PIPE/DUCT SECTION DETAIL

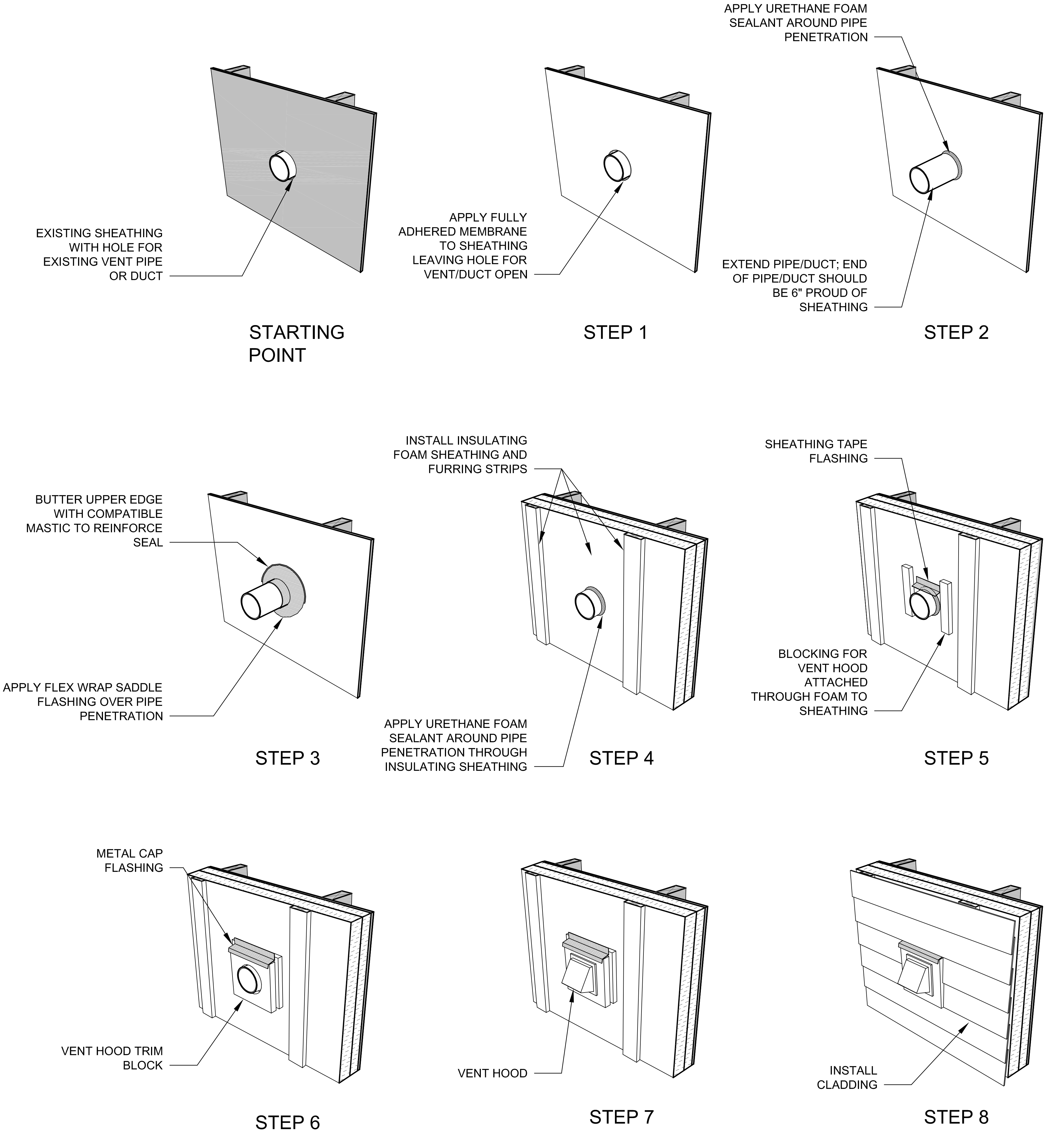
SCALE: 3" = 1'-0"

▨ GRAY TONE INDICATES EXISTING STRUCTURE

bsc with Building America U.S. Department of Energy Research Toward Zero Energy Homes

Project: Deep Energy Retrofit
Date: 2009-08-20 DRAFT
Drawing Title: Penetration Details
Drawing File: InnerRetrofitDetails.dwg
Drawing Scale: 3" = 1'-0"

Sheet Title:
Pen-3



EXISTING SHEATHING WITH HOLE FOR EXISTING VENT PIPE OR DUCT

STARTING POINT

APPLY FULLY ADHERED MEMBRANE TO SHEATHING LEAVING HOLE FOR VENT/DUCT OPEN

STEP 1

APPLY URETHANE FOAM SEALANT AROUND PIPE PENETRATION

EXTEND PIPE/DUCT; END OF PIPE/DUCT SHOULD BE 6" PROUD OF SHEATHING

STEP 2

BUTTER UPPER EDGE WITH COMPATIBLE MASTIC TO REINFORCE SEAL

APPLY FLEX WRAP SADDLE FLASHING OVER PIPE PENETRATION

STEP 3

INSTALL INSULATING FOAM SHEATHING AND FURRING STRIPS

APPLY URETHANE FOAM SEALANT AROUND PIPE PENETRATION THROUGH INSULATING SHEATHING

STEP 4

SHEATHING TAPE FLASHING

BLOCKING FOR VENT HOOD ATTACHED THROUGH FOAM TO SHEATHING

STEP 5

METAL CAP FLASHING

VENT HOOD TRIM BLOCK

STEP 6

VENT HOOD

STEP 7

INSTALL CLADDING

STEP 8

1 VENT PIPE/DUCT INSTALLATION SEQUENCE

N.T.S.

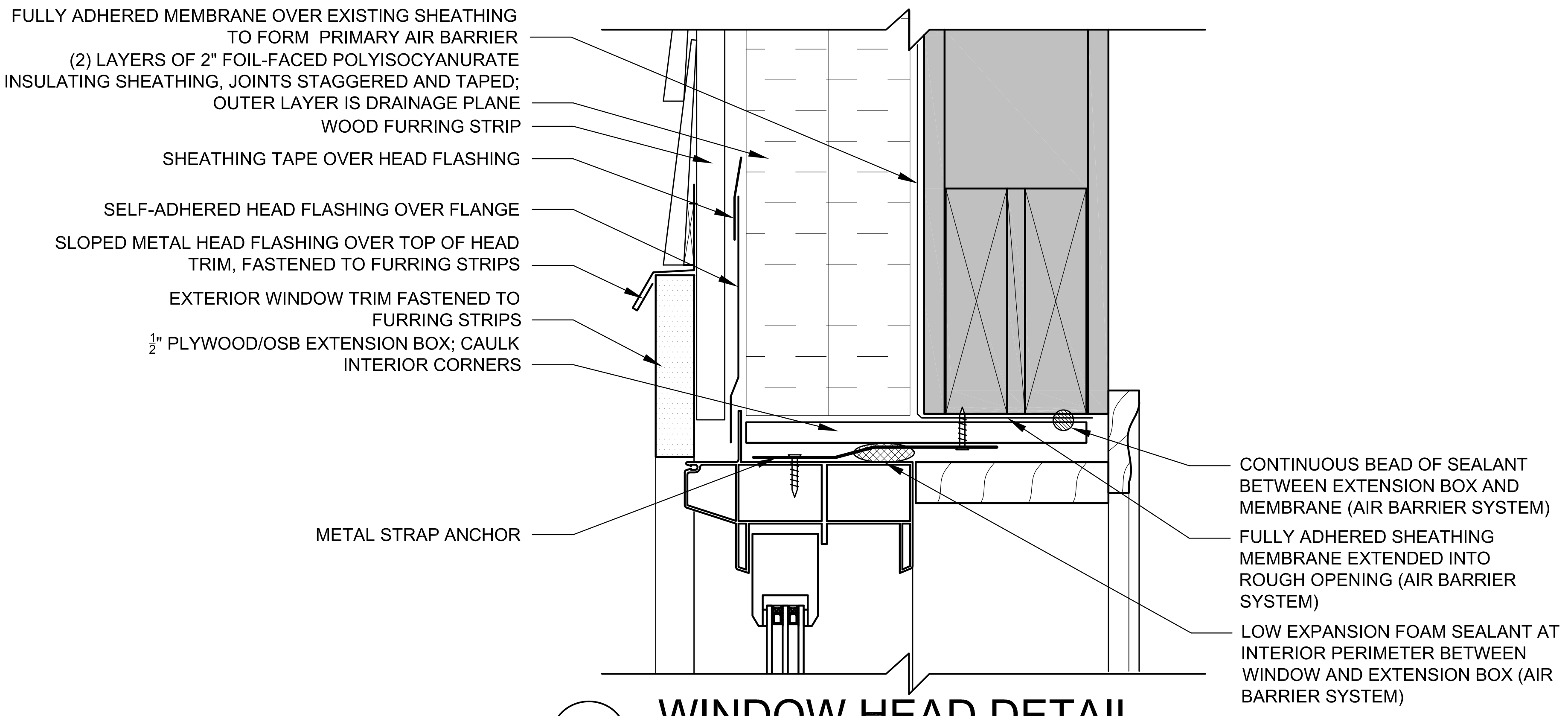
▨ GRAY TONE INDICATES EXISTING STRUCTURE

bsc with Building AMERICA U.S. Department of Energy Research Toward Zero Energy Homes

Project:	Deep Energy Retrofit
Date:	2009-08-20 DRAFT
Drawing Title:	Penetration Details
Drawing File:	InnerRetrofitDetails.dwg
Drawing Scale:	N.T.S.

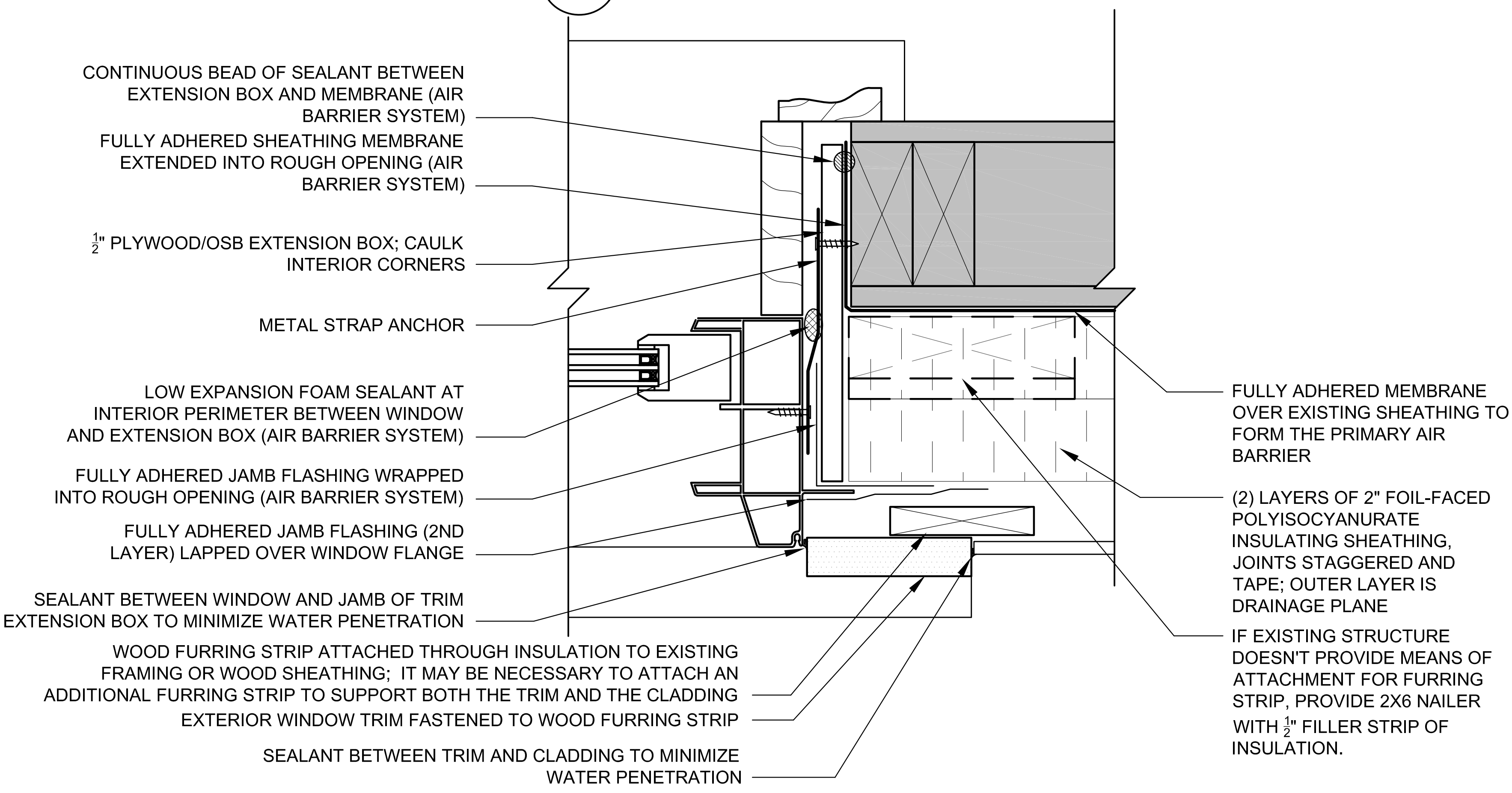
Sheet Title:

Pen-4



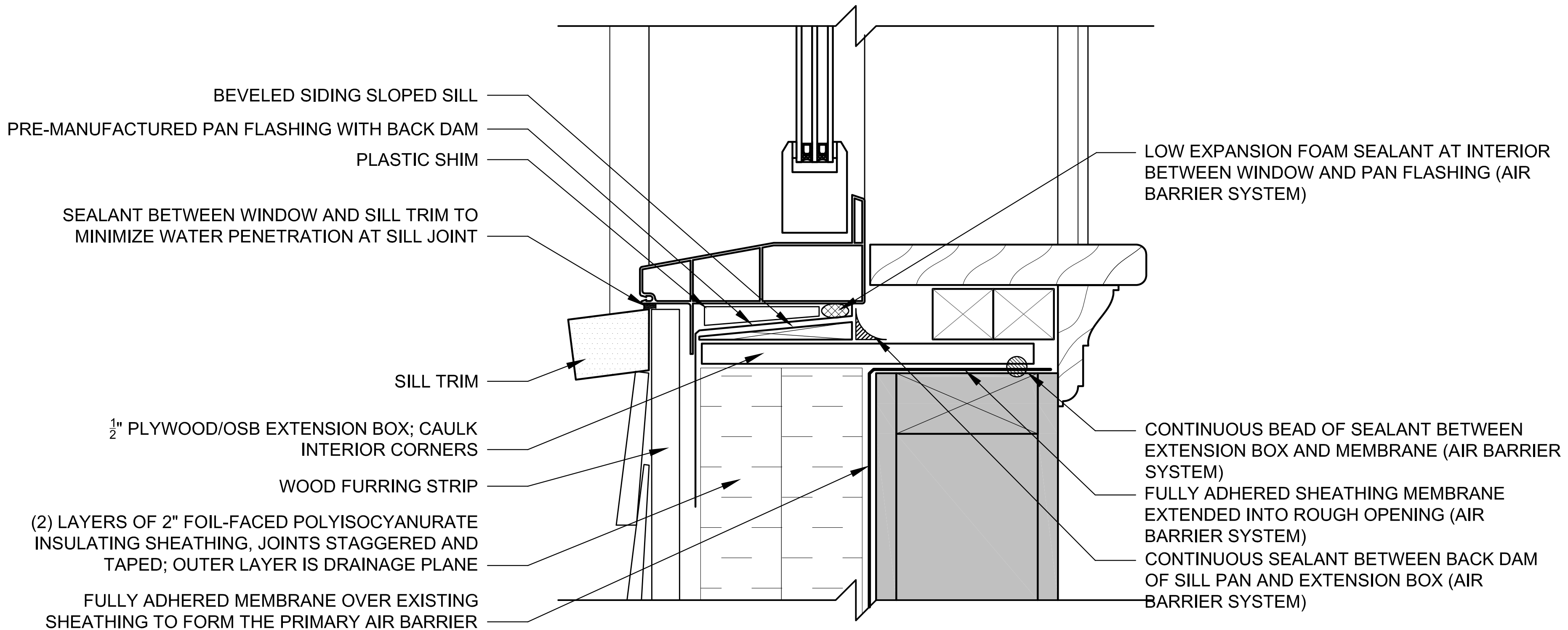
3 WINDOW HEAD DETAIL

SCALE: 3" = 1'-0"



2 WINDOW JAMB DETAIL

SCALE: 3" = 1'-0"



1 WINDOW SILL DETAIL

SCALE: 3" = 1'-0"

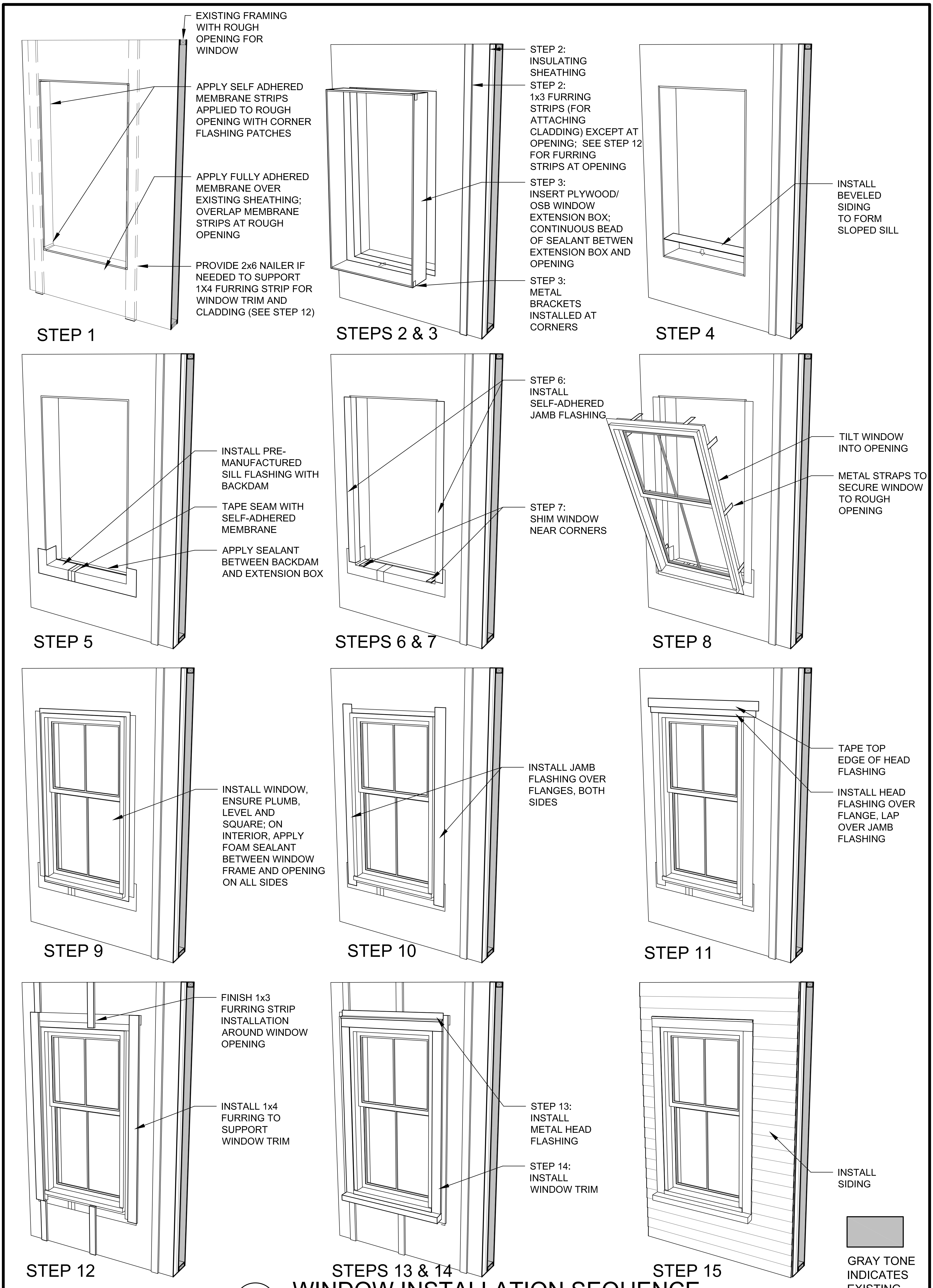
▨ GRAY TONE INDICATES EXISTING STRUCTURE

bsc with Building America U.S. Department of Energy
Research Toward Zero Energy Homes

Project:	Deep Energy Retrofit
Date:	2009-09-01-DRAFT
Drawing Title:	Window Details
Drawing File:	OuterRetrofitDetails.dwg
Drawing Scale:	3"=1'-0"

Sheet Title:

Win-1



STEP 1

EXISTING FRAMING WITH ROUGH OPENING FOR WINDOW

APPLY SELF ADHERED MEMBRANE STRIPS APPLIED TO ROUGH OPENING WITH CORNER FLASHING PATCHES

APPLY FULLY ADHERED MEMBRANE OVER EXISTING SHEATHING; OVERLAP MEMBRANE STRIPS AT ROUGH OPENING

PROVIDE 2x6 NAILER IF NEEDED TO SUPPORT 1X4 FURRING STRIP FOR WINDOW TRIM AND CLADDING (SEE STEP 12)

STEPS 2 & 3

STEP 2: INSULATING SHEATHING

STEP 2: 1x3 FURRING STRIPS (FOR ATTACHING CLADDING) EXCEPT AT OPENING; SEE STEP 12 FOR FURRING STRIPS AT OPENING

STEP 3: INSERT PLYWOOD/ OSB WINDOW EXTENSION BOX; CONTINUOUS BEAD OF SEALANT BETWEN EXTENSION BOX AND OPENING

STEP 3: METAL BRACKETS INSTALLED AT CORNERS

STEP 4

INSTALL BEVELED SIDING TO FORM SLOPED SILL

STEP 5

INSTALL PRE-MANUFACTURED SILL FLASHING WITH BACKDAM

TAPE SEAM WITH SELF-ADHERED MEMBRANE

APPLY SEALANT BETWEEN BACKDAM AND EXTENSION BOX

STEPS 6 & 7

STEP 6: INSTALL SELF-ADHERED JAMB FLASHING

STEP 7: SHIM WINDOW NEAR CORNERS

STEP 8

TILT WINDOW INTO OPENING

METAL STRAPS TO SECURE WINDOW TO ROUGH OPENING

STEP 9

INSTALL WINDOW, ENSURE PLUMB, LEVEL AND SQUARE; ON INTERIOR, APPLY FOAM SEALANT BETWEEN WINDOW FRAME AND OPENING ON ALL SIDES

STEP 10

INSTALL JAMB FLASHING OVER FLANGES, BOTH SIDES

STEP 11

TAPE TOP EDGE OF HEAD FLASHING

INSTALL HEAD FLASHING OVER FLANGE, LAP OVER JAMB FLASHING

STEP 12

FINISH 1x3 FURRING STRIP INSTALLATION AROUND WINDOW OPENING

INSTALL 1x4 FURRING TO SUPPORT WINDOW TRIM

STEPS 13 & 14

STEP 13: INSTALL METAL HEAD FLASHING

STEP 14: INSTALL WINDOW TRIM

STEP 15

INSTALL SIDING

▨ GRAY TONE INDICATES EXISTING STRUCTURE

① WINDOW INSTALLATION SEQUENCE

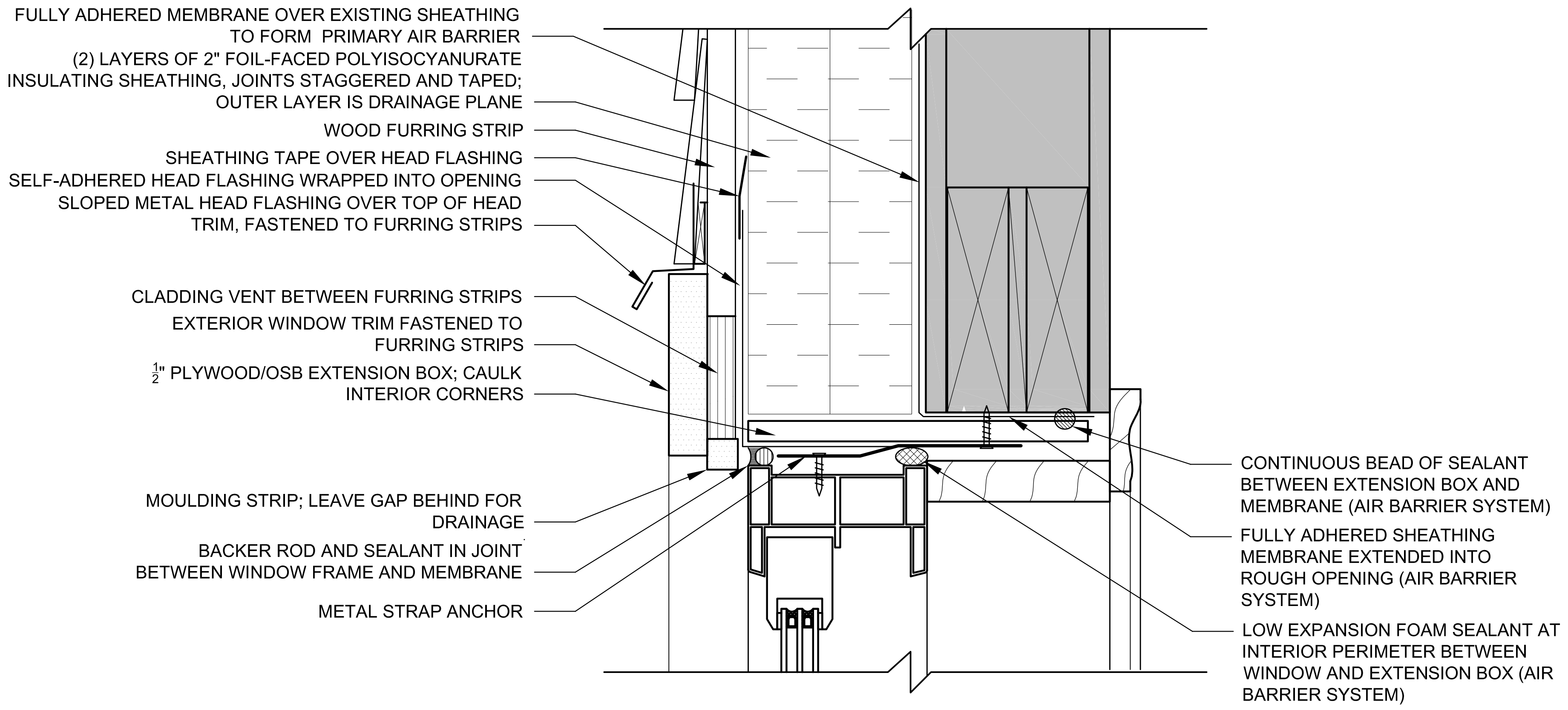
N.T.S.

bsc with Building AMERICA U.S. Department of Energy Research Toward Zero Energy Homes

Project:	Deep Energy Retrofit
Date:	2009-09-04-DRAFT
Drawing Title:	Window Installation Sequence
Drawing File:	OuterRetrofitDetails.dwg
Drawing Scale:	N.T.S.

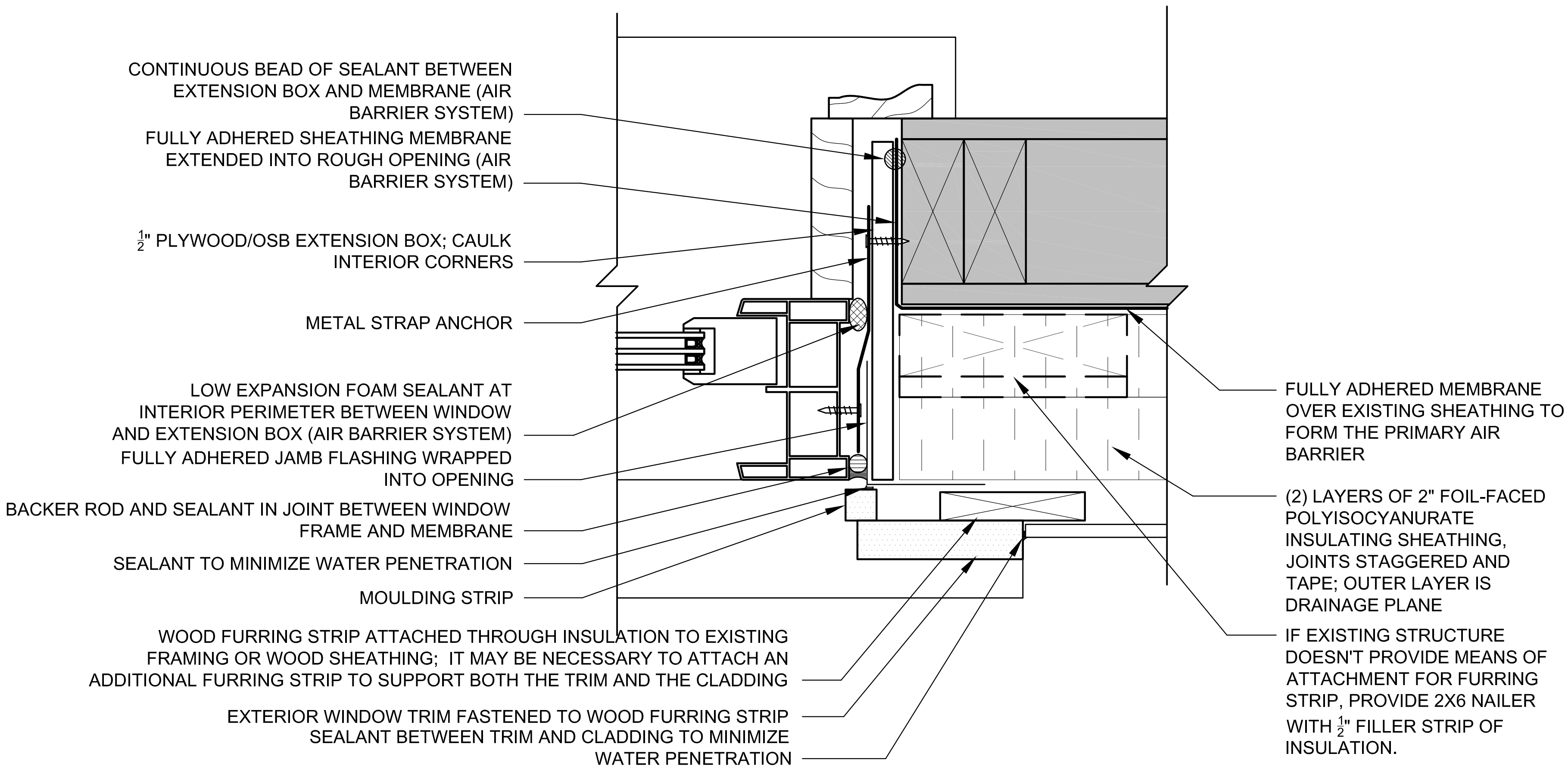
Sheet Title:

Win-2



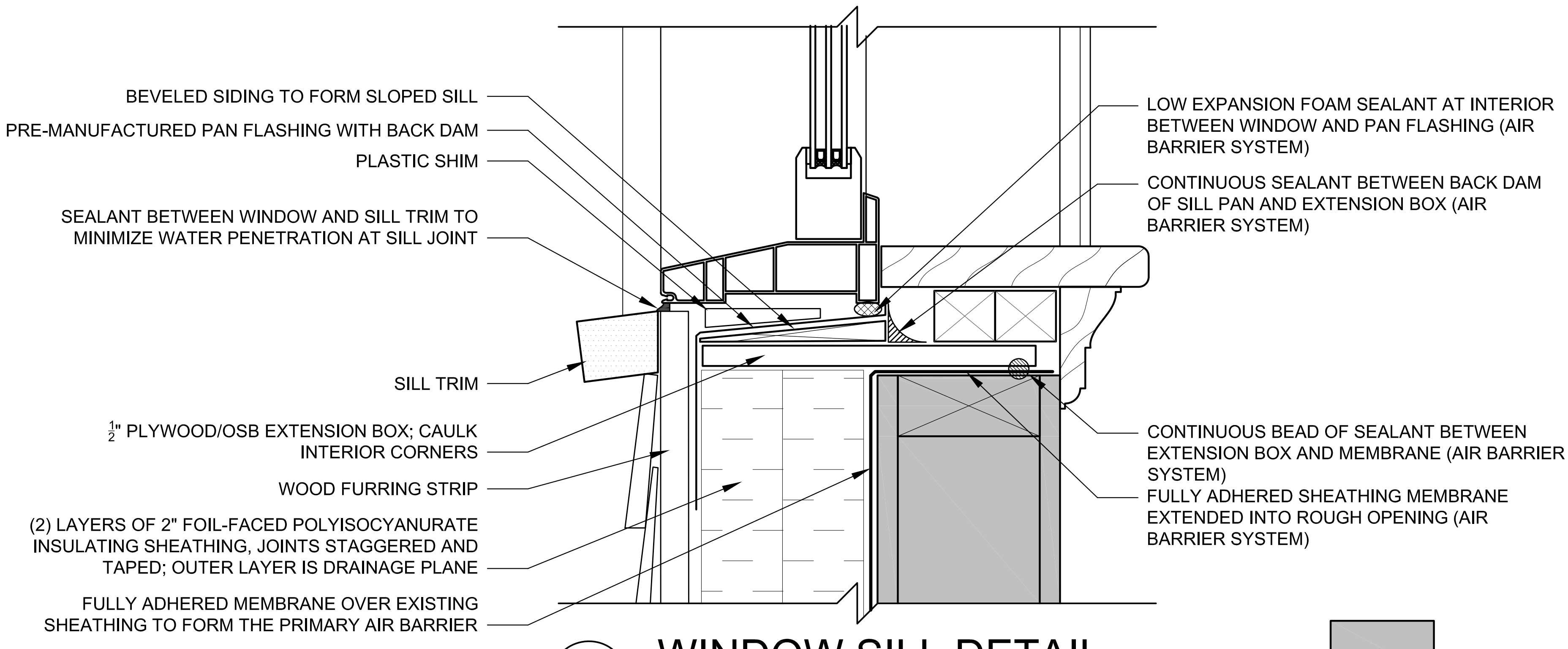
3 WINDOW HEAD DETAIL

SCALE: 3" = 1'-0"



2 WINDOW JAMB DETAIL

SCALE: 3" = 1'-0"



1 WINDOW SILL DETAIL

SCALE: 3" = 1'-0"

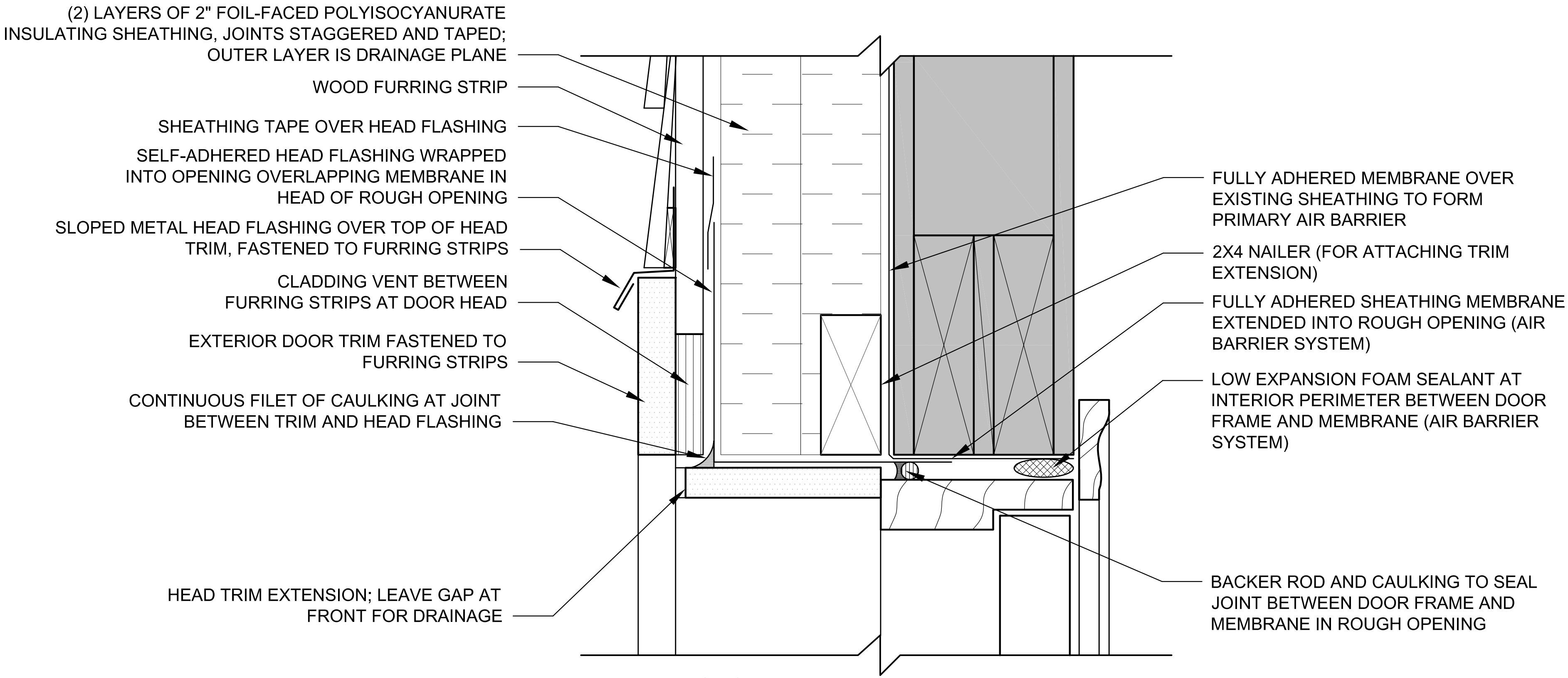
▨ GRAY TONE INDICATES EXISTING STRUCTURE

bsc with Building America U.S. Department of Energy Research Toward Zero Energy Homes

Project:	Deep Energy Retrofit
Date:	2009-09-04-DRAFT
Drawing Title:	Window Details
Drawing File:	OuterRetrofitDetails.dwg
Drawing Scale:	3"=1'-0"

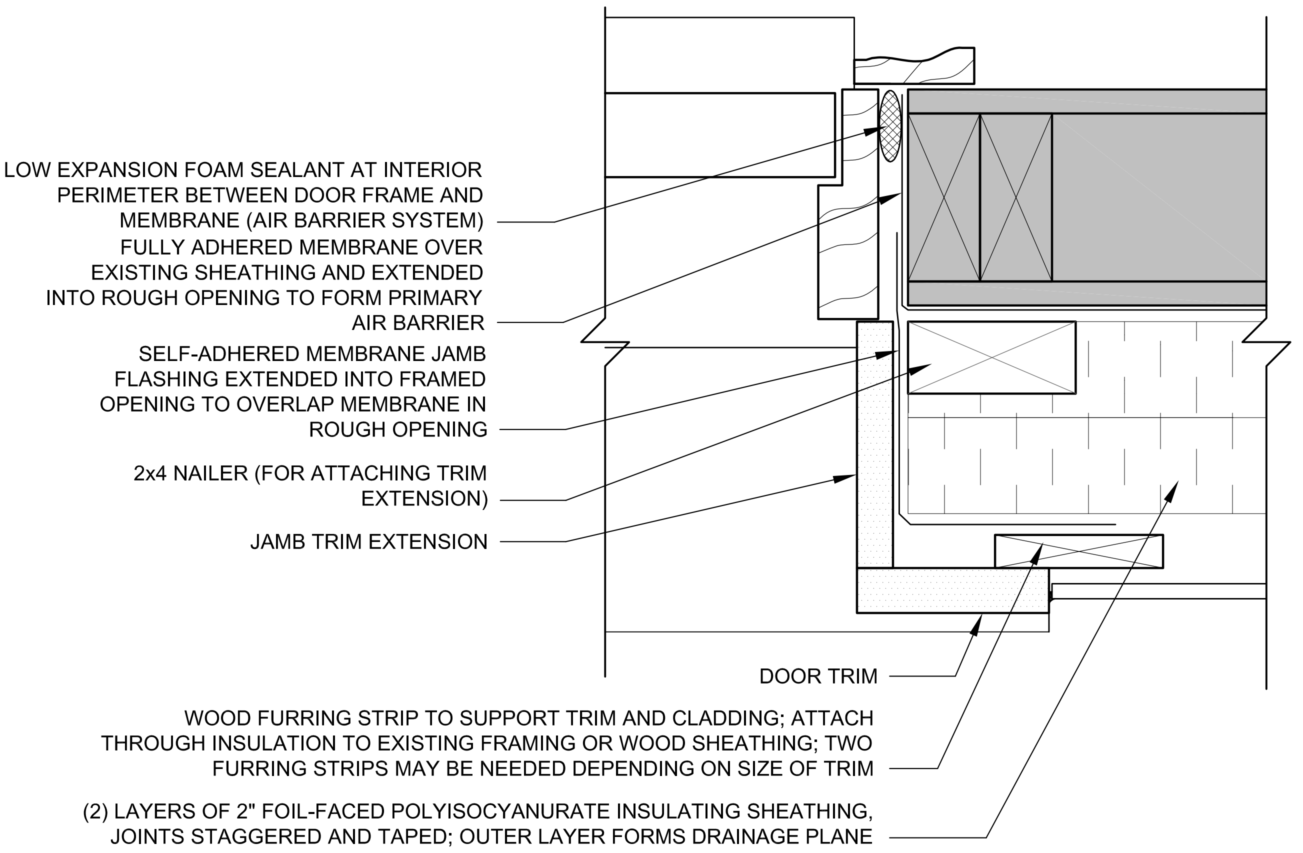
Sheet Title:

Win-1A



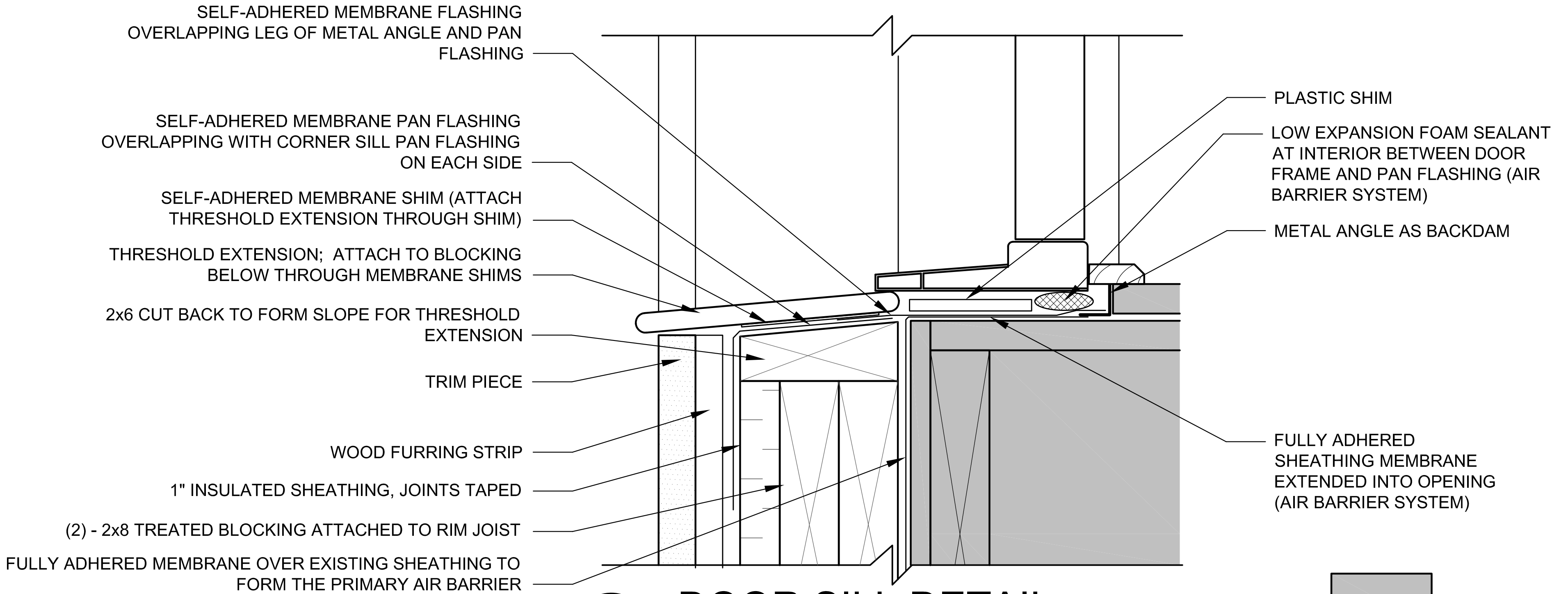
3 DOOR HEAD DETAIL

SCALE: 3" = 1'-0"



2 DOOR JAMB DETAIL

SCALE: 3" = 1'-0"



1 DOOR SILL DETAIL

SCALE: 3" = 1'-0"

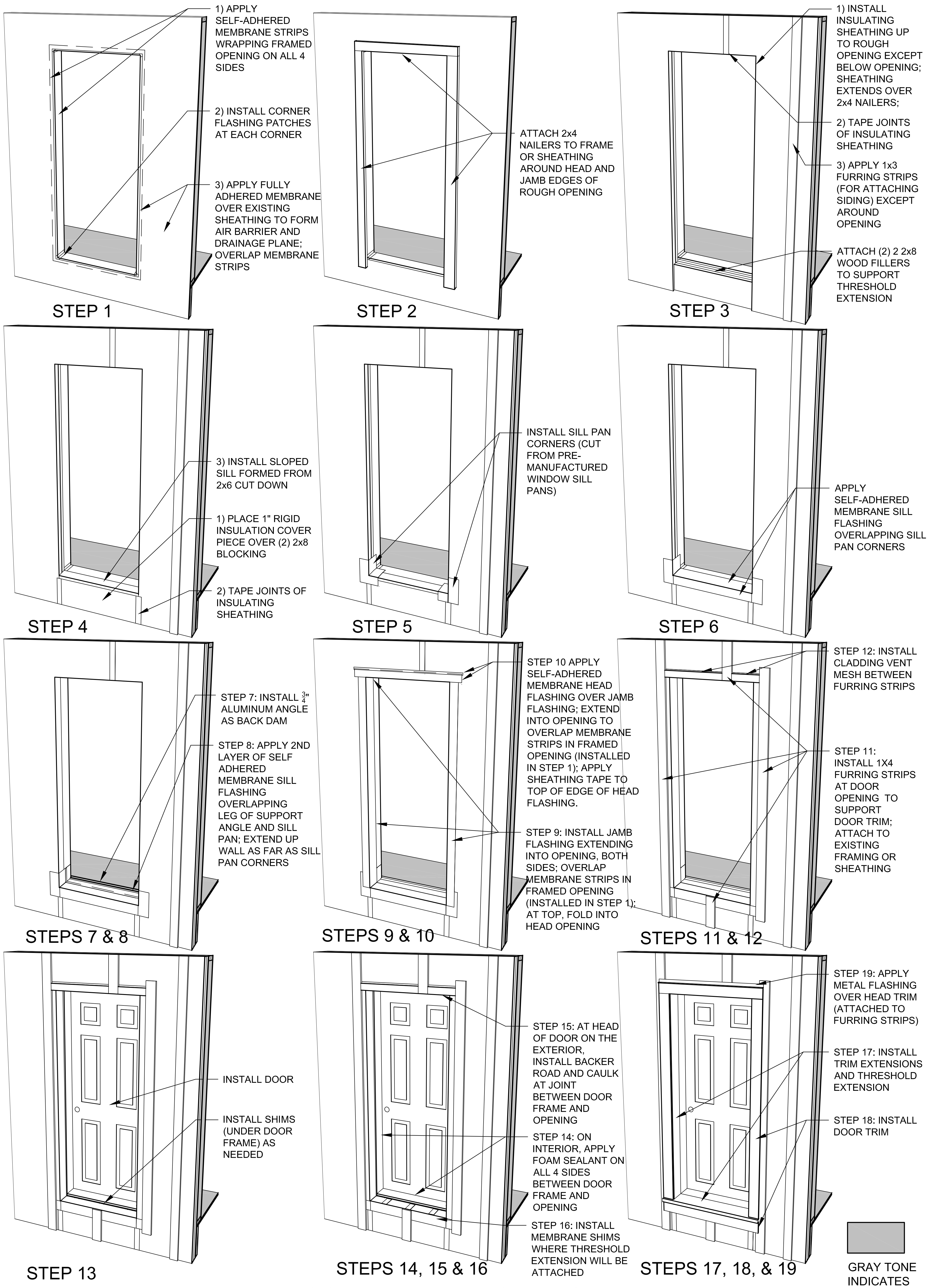
▨ GRAY TONE INDICATES EXISTING STRUCTURE

bsc with Building America U.S. Department of Energy Research Toward Zero Energy Homes

Project: Deep Energy Retrofit
Date: 2009-09-03-DRAFT
Drawing Title: Door Details
Drawing File: OuterRetrofitDetails.dwg
Drawing Scale: 3"=1'-0"

Sheet Title:

Door-1



STEP 1

1) APPLY SELF-ADHERED MEMBRANE STRIPS WRAPPING FRAMED OPENING ON ALL 4 SIDES

2) INSTALL CORNER FLASHING PATCHES AT EACH CORNER

3) APPLY FULLY ADHERED MEMBRANE OVER EXISTING SHEATHING TO FORM AIR BARRIER AND DRAINAGE PLANE; OVERLAP MEMBRANE STRIPS

STEP 2

ATTACH 2x4 NAILERS TO FRAME OR SHEATHING AROUND HEAD AND JAMB EDGES OF ROUGH OPENING

STEP 3

1) INSTALL INSULATING SHEATHING UP TO ROUGH OPENING EXCEPT BELOW OPENING; SHEATHING EXTENDS OVER 2x4 NAILERS;

2) TAPE JOINTS OF INSULATING SHEATHING

3) APPLY 1x3 FURRING STRIPS (FOR ATTACHING SIDING) EXCEPT AROUND OPENING

ATTACH (2) 2 2x8 WOOD FILLERS TO SUPPORT THRESHOLD EXTENSION

STEP 4

3) INSTALL SLOPED SILL FORMED FROM 2x6 CUT DOWN

1) PLACE 1" RIGID INSULATION COVER PIECE OVER (2) 2x8 BLOCKING

2) TAPE JOINTS OF INSULATING SHEATHING

STEP 5

INSTALL SILL PAN CORNERS (CUT FROM PRE-MANUFACTURED WINDOW SILL PANS)

STEP 6

APPLY SELF-ADHERED MEMBRANE SILL FLASHING OVERLAPPING SILL PAN CORNERS

STEPS 7 & 8

STEP 7: INSTALL $\frac{3}{4}$" ALUMINUM ANGLE AS BACK DAM

STEP 8: APPLY 2ND LAYER OF SELF ADHERED MEMBRANE SILL FLASHING OVERLAPPING LEG OF SUPPORT ANGLE AND SILL PAN; EXTEND UP WALL AS FAR AS SILL PAN CORNERS

STEPS 9 & 10

STEP 10 APPLY SELF-ADHERED MEMBRANE HEAD FLASHING OVER JAMB FLASHING; EXTEND INTO OPENING TO OVERLAP MEMBRANE STRIPS IN FRAMED OPENING (INSTALLED IN STEP 1); APPLY SHEATHING TAPE TO TOP OF EDGE OF HEAD FLASHING.

STEP 9: INSTALL JAMB FLASHING EXTENDING INTO OPENING, BOTH SIDES; OVERLAP MEMBRANE STRIPS IN FRAMED OPENING (INSTALLED IN STEP 1); AT TOP, FOLD INTO HEAD OPENING

STEPS 11 & 12

STEP 12: INSTALL CLADDING VENT MESH BETWEEN FURRING STRIPS

STEP 11: INSTALL 1X4 FURRING STRIPS AT DOOR OPENING TO SUPPORT DOOR TRIM; ATTACH TO EXISTING FRAMING OR SHEATHING

STEP 13

INSTALL DOOR

INSTALL SHIMS (UNDER DOOR FRAME) AS NEEDED

STEPS 14, 15 & 16

STEP 15: AT HEAD OF DOOR ON THE EXTERIOR, INSTALL BACKER ROAD AND CAULK AT JOINT BETWEEN DOOR FRAME AND OPENING

STEP 14: ON INTERIOR, APPLY FOAM SEALANT ON ALL 4 SIDES BETWEEN DOOR FRAME AND OPENING

STEP 16: INSTALL MEMBRANE SHIMS WHERE THRESHOLD EXTENSION WILL BE ATTACHED

STEPS 17, 18, & 19

STEP 19: APPLY METAL FLASHING OVER HEAD TRIM (ATTACHED TO FURRING STRIPS)

STEP 17: INSTALL TRIM EXTENSIONS AND THRESHOLD EXTENSION

STEP 18: INSTALL DOOR TRIM

▨ GRAY TONE INDICATES EXISTING STRUCTURE

1 DOOR INSTALLATION SEQUENCE

N.T.S.

bsc with Building America U.S. Department of Energy Research Toward Zero Energy Homes

Project:	Deep Energy Retrofit
Date:	2009-09-04-DRAFT
Drawing Title:	Door Installation Sequence
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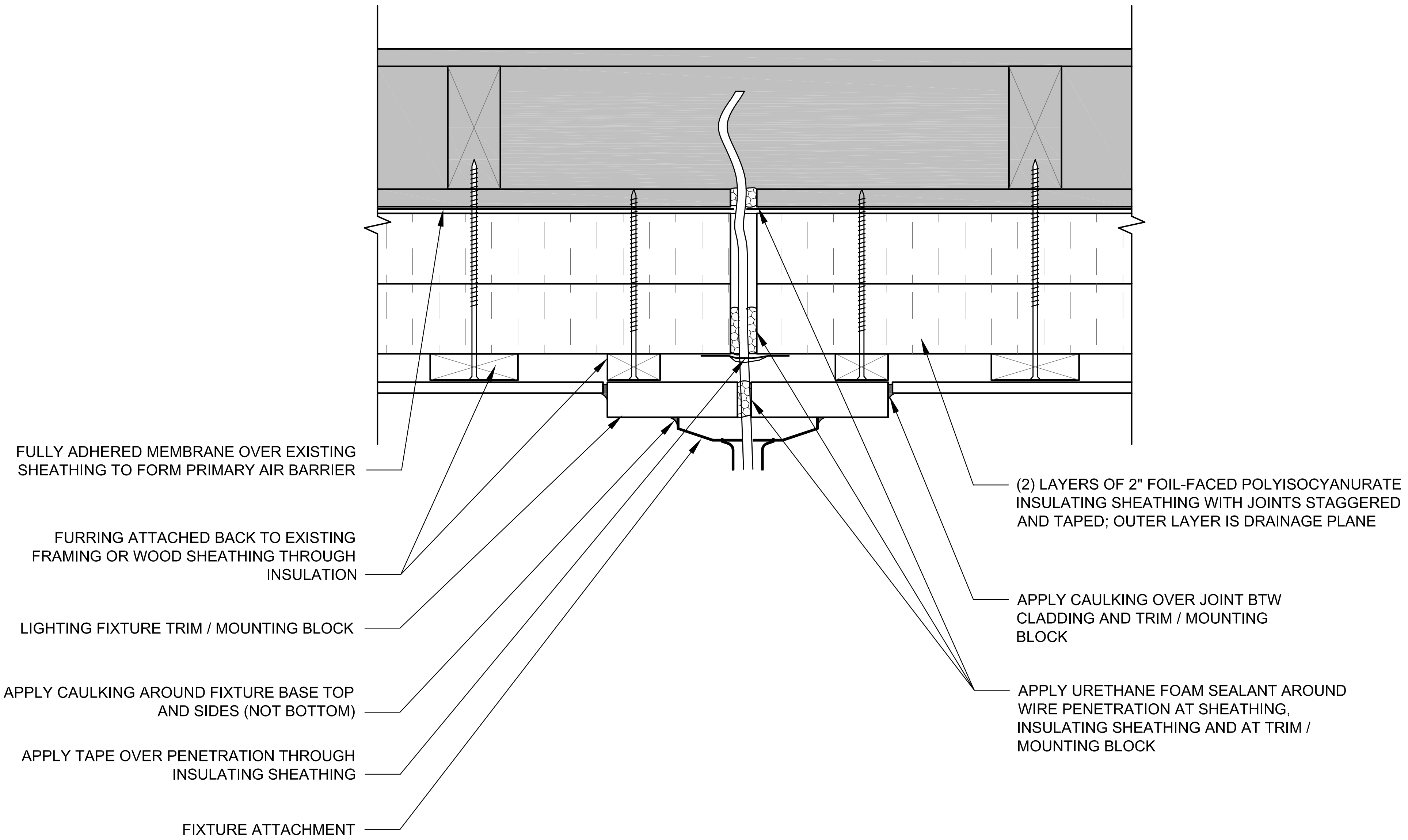
Drawing Scale:	N.T.S.

Sheet Title:

Door-2



2 EXTERIOR LIGHT FIXTURE PLAN DETAIL

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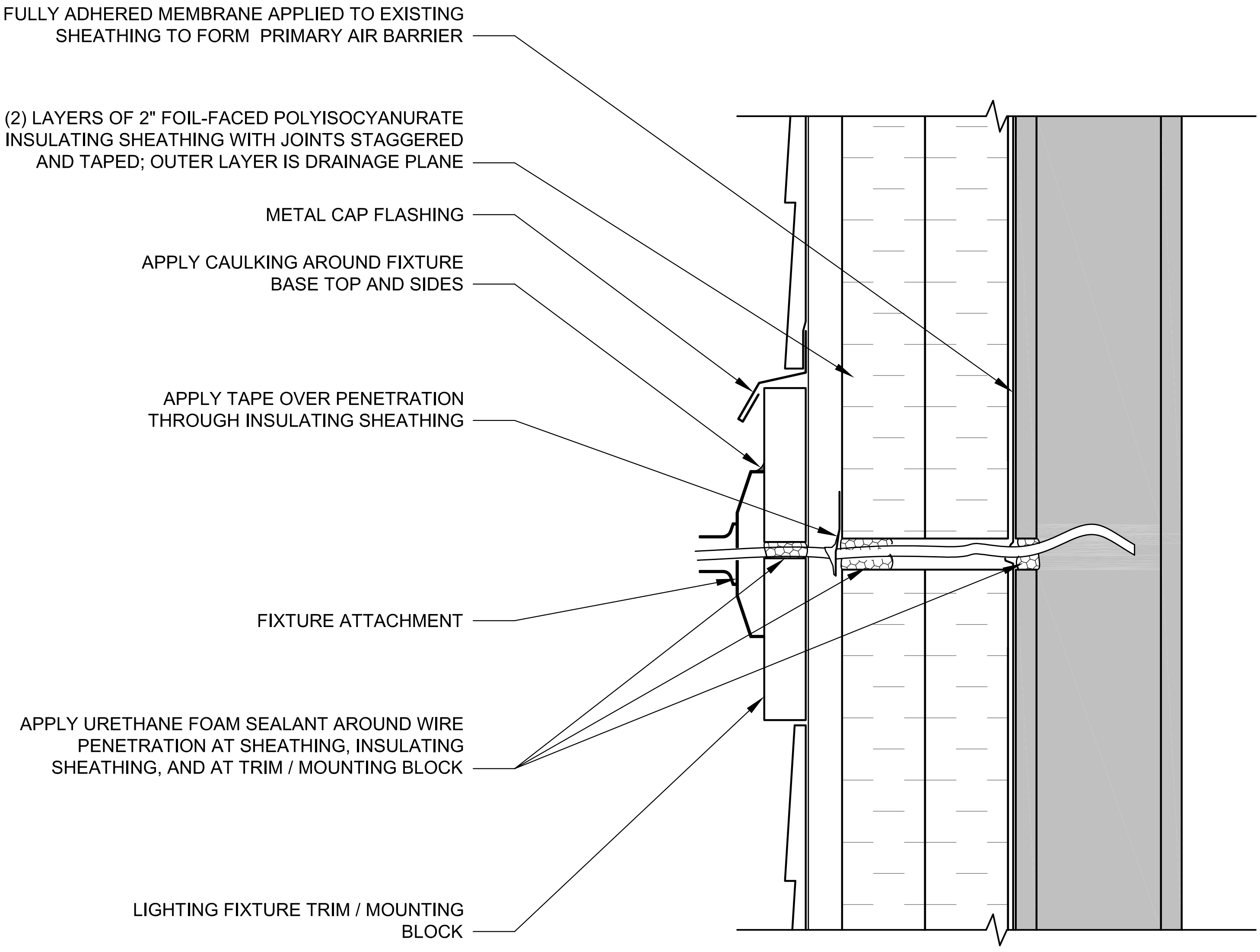


1 EXTERIOR LIGHT FIXTURE SECTION DETAIL

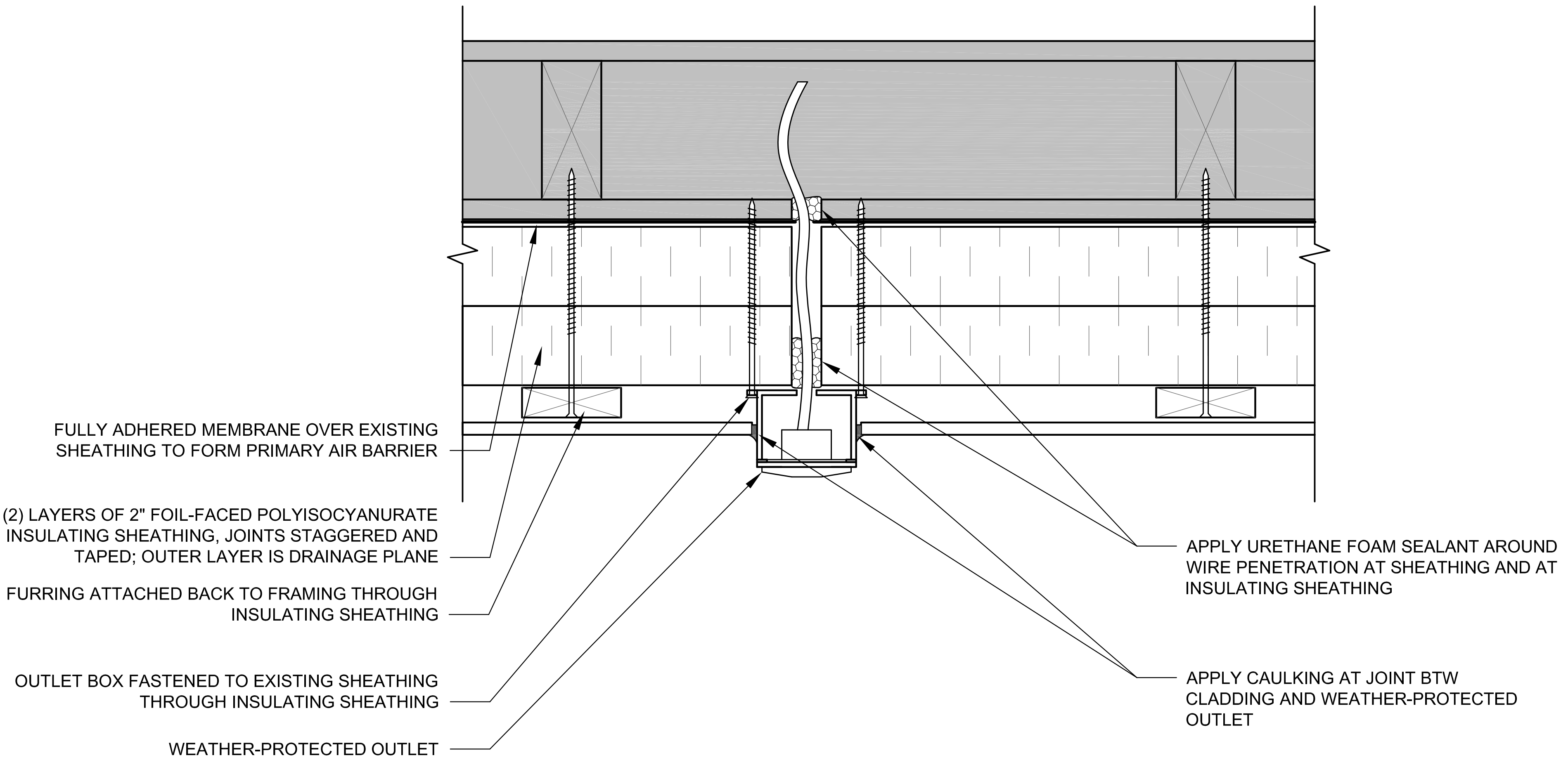
SCALE: 3" = 1'-0"

▨ GRAY TONE INDICATES EXISTING STRUCTURE

bsc with Building America U.S. Department of Energy Research Toward Zero Energy Homes

Project: Deep Energy Retrofit
Date: 2009-08-20-DRAFT
Drawing Title: Penetration Details
Drawing File: OuterRetrofitDetails.dwg
Drawing Scale: 3"=1'-0"

Sheet Title:
Pen-1



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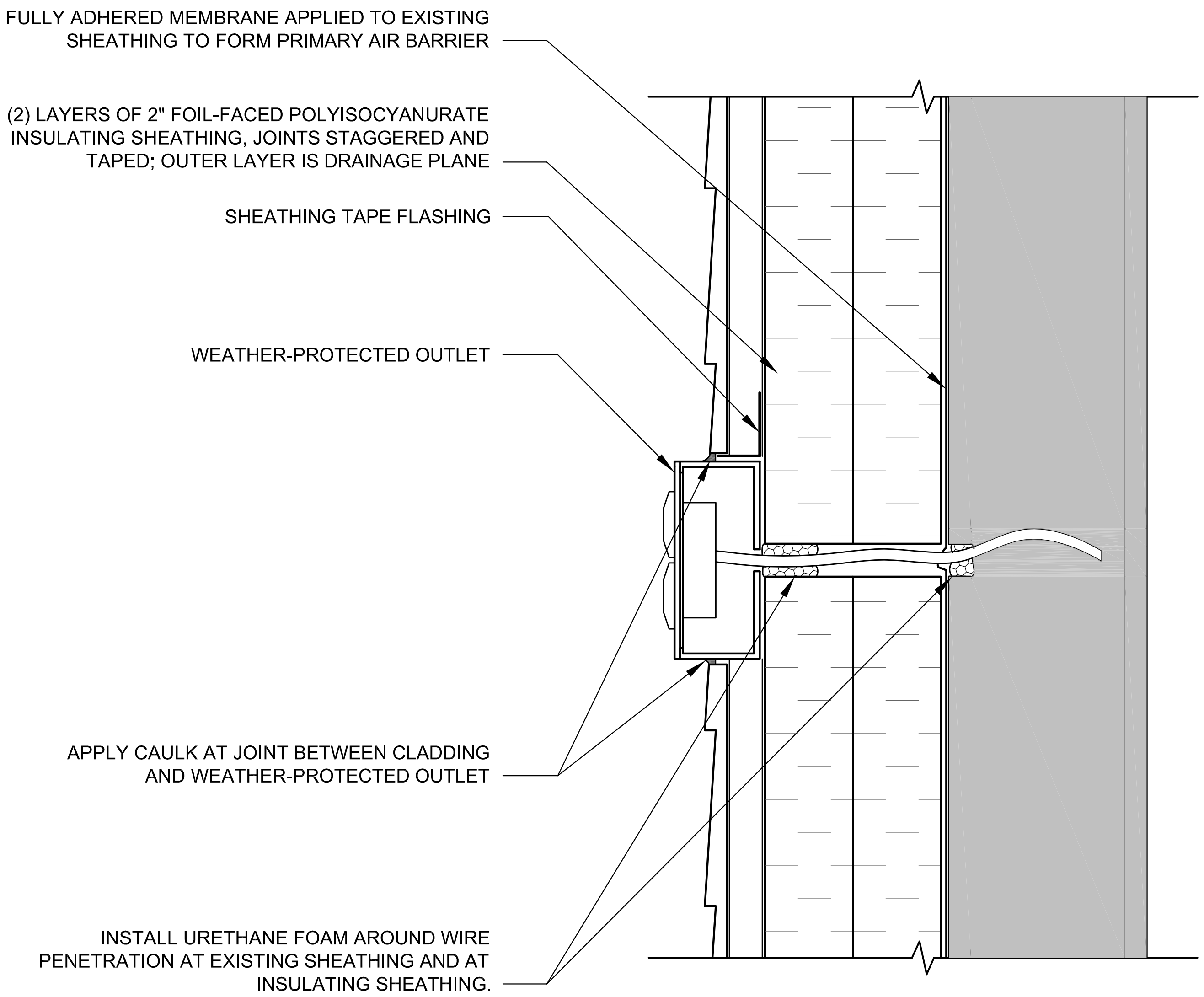


1 EXTERIOR ELECTRIC BOX SECTION DETAIL

SCALE: 3" = 1'-0"

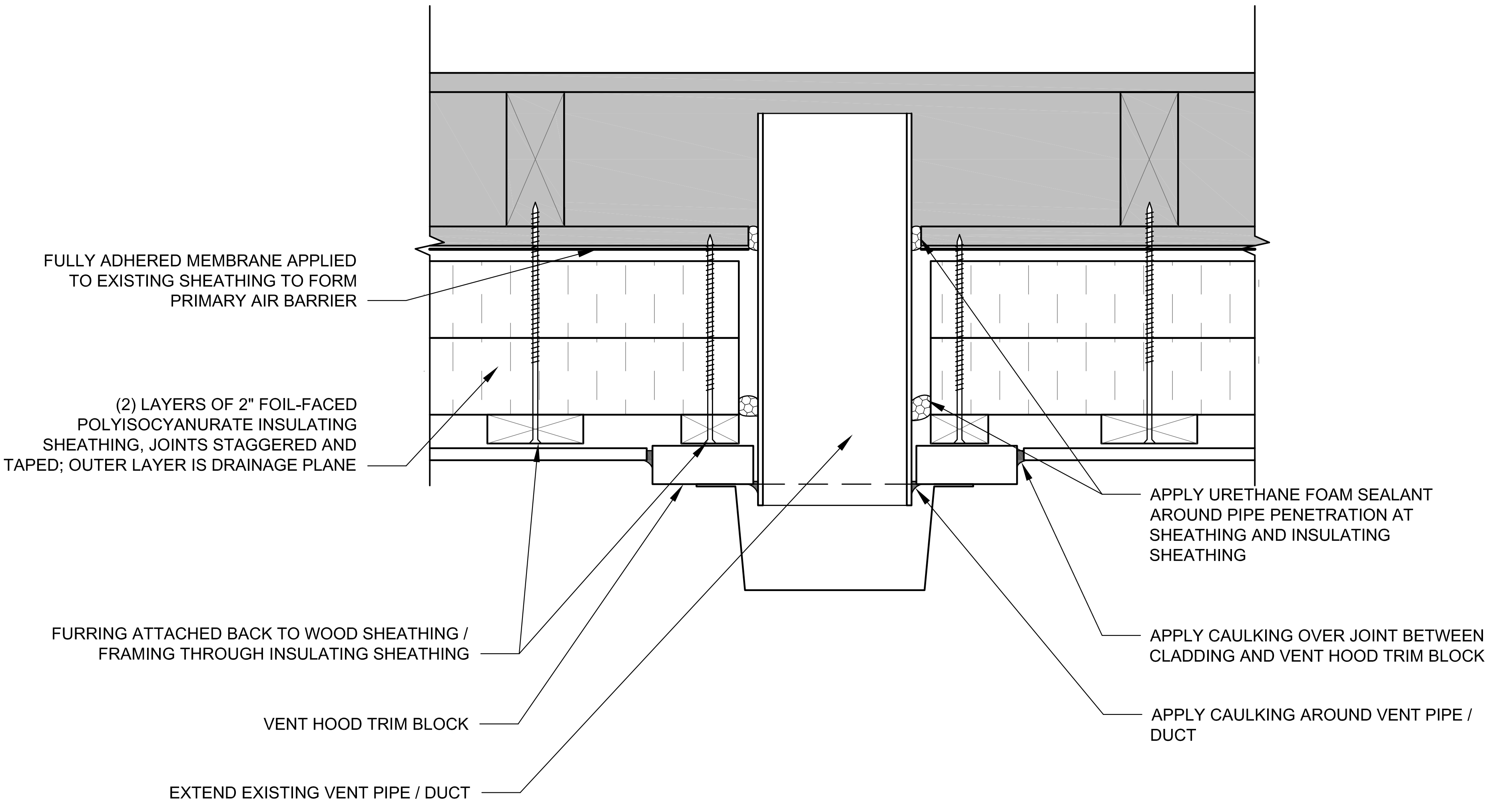
▨ GRAY TONE INDICATES EXISTING STRUCTURE

bsc with Building America U.S. Department of Energy Research Toward Zero Energy Homes

Project:	Deep Energy Retrofit
Date:	2009-08-20-DRAFT
Drawing Title:	Penetration Details
Drawing File:	OuterRetrofitDetails.dwg
Drawing Scale:	3"=1'-0"

Sheet Title:

Pen-2



2 VENT PIPE/DUCT PLAN DETAIL

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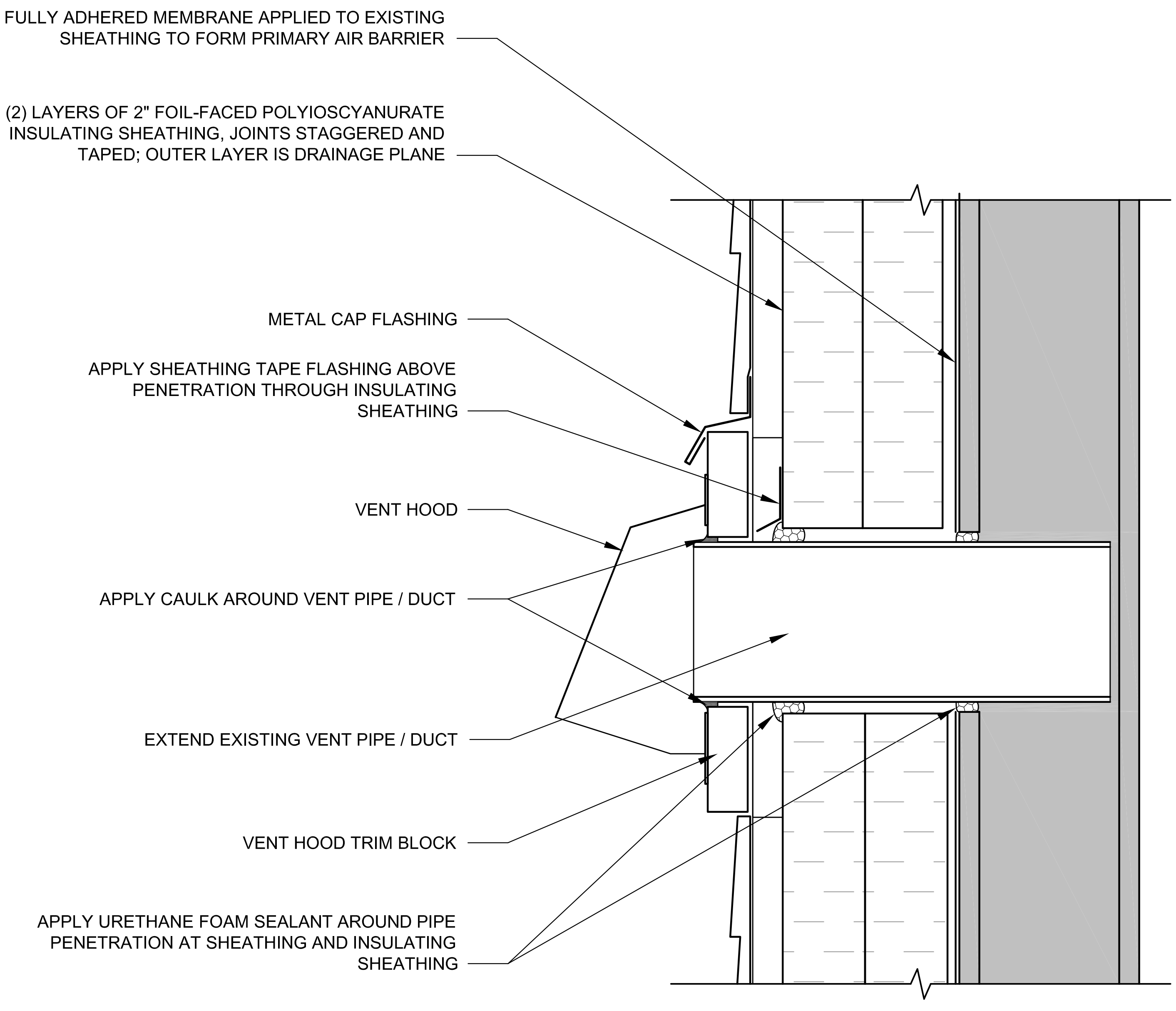


1 VENT PIPE/DUCT SECTION DETAIL

SCALE: 3" = 1'-0"

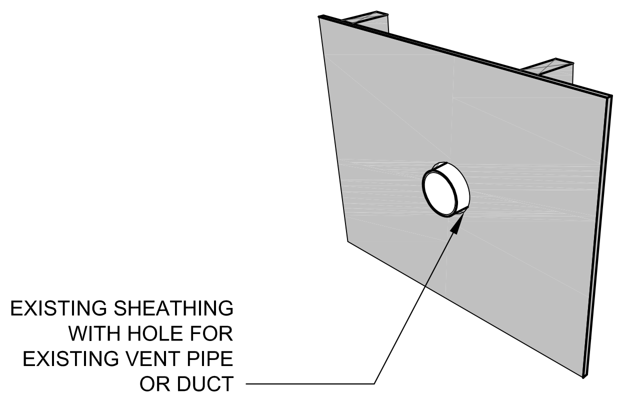
▨ GRAY TONE INDICATES EXISTING STRUCTURE

bsc with Building America U.S. Department of Energy Research Toward Zero Energy Homes

Project:	Deep Energy Retrofit
Date:	2009-08-20-DRAFT
Drawing Title:	Penetration Details
Drawing File:	OuterRetrofitDetails.dwg
Drawing Scale:	3"=1'-0"

Sheet Title:

Pen-3



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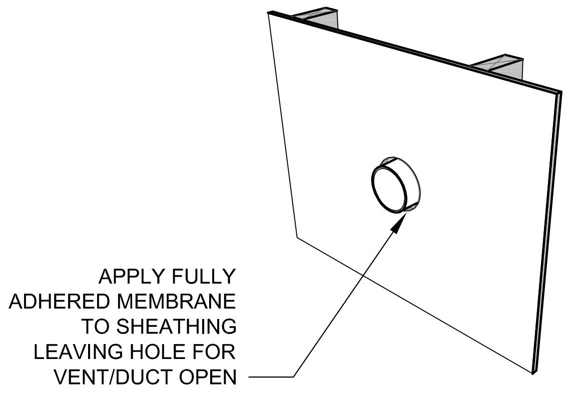
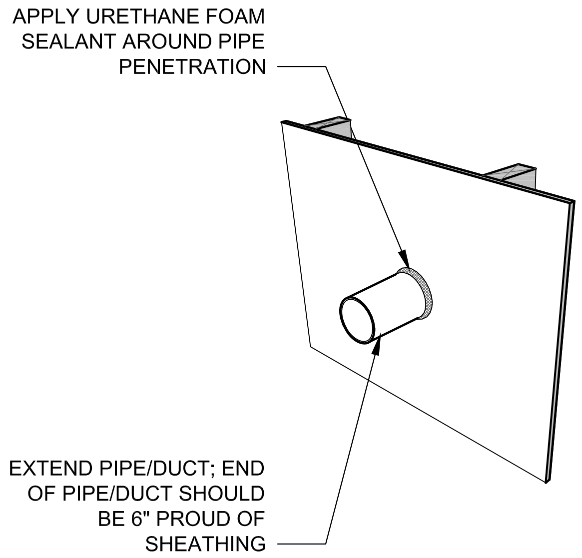


STEP 1



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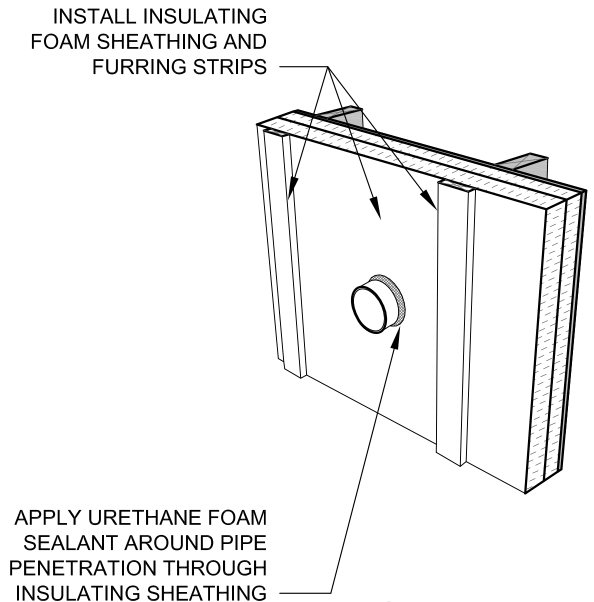

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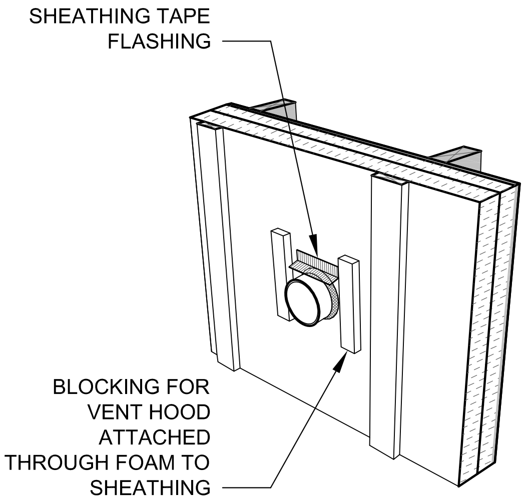

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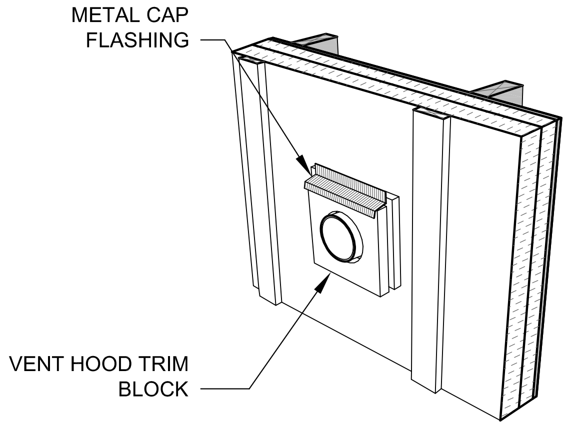

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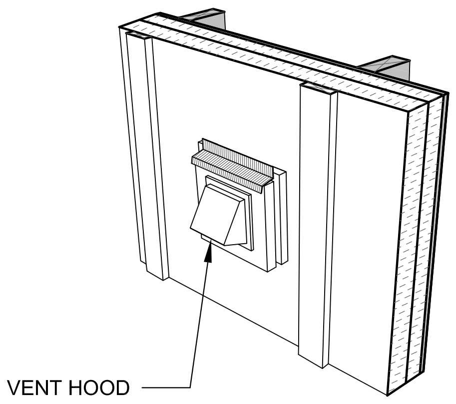
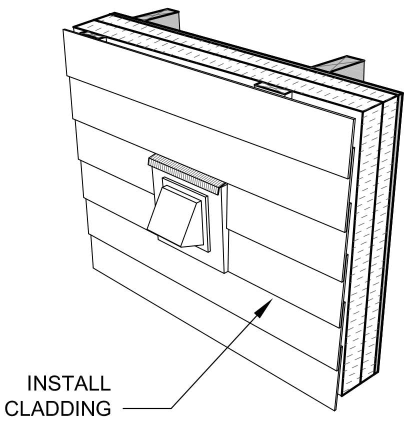


STEP 6



STEP 7

1 VENT PIPE/DUCT INSTALLATION SEQUENCE

N.T.S.

▨ GRAY TONE INDICATES EXISTING STRUCTURE

bsc with Building America U.S. Department of Energy Research Toward Zero Energy Homes

Project:	Deep Energy Retrofit
Date:	2009-08-20-DRAFT
Drawing Title:	Penetration Details
Drawing File:	OuterRetrofitDetails.dwg
Drawing Scale:	N.T.S.

Sheet Title:

Pen-4

1.5.7. Advanced Framing Deployment – Interim Report

by Joseph Lstiburek and Aaron Grin, December 2009

Building America High R-value Enclosures Research Project:

Advanced Framing Deployment Interim Report

Joseph Lstiburek, Ph.D., P.Eng.
Aaron Grin, M.A.Sc.

Building Science Corporation, Somerville, MA

December 2009

Abstract:

This report investigates the implementation of advanced framing in both production and prototype built homes built in a variety of climate regions across the USA.The current industry standard wall is being replaced by a 2×6 frame at 24 in. centers with single top plates, two-stud corners, no jack studs, no cripples and single headers (and in many cases no headers at all). The advanced framing system is cheaper because it uses 5% to 10% less board feet of lumber, and it is faster because it uses 30% fewer pieces. It saves energy because it provides a 60% deeper cavity (which allows 60% more cavity insulation) and because it reduces the framing factor from 25% to 15%. Advanced framing can save energy, greenhouse gas emissions, and money if properly implemented. Through BSC's experience we have found that builders can save $1000 per house on advanced framing. To maximize cost savings and energy savings for the homeowner, the builder financial savings are best shifted to implementing more energy saving measures. In 2010 BSC will continue deployment of advanced framing wherever possible with its Building America partners.

Advanced Framing Deployment - Interim Report

History and Background

The current industry standard wall—a 2×4 frame at 16 in. (400 mm) centers with double top plates, three stud corners, jack studs, cripples and double headers— is being replaced by a 2×6 frame at 24 in. (600 mm) centers with single top plates, two-stud corners, no jack studs, no cripples and single headers (and in many cases no headers at all). The advanced framing system is cheaper because it uses 5% to 10% less lumber (board-feet), and it is faster because it uses 30% fewer pieces. It saves energy because it provides a 60% deeper cavity (which allows 60% more cavity insulation) and because it reduces the framing factor from 25% to 15%.

The framing elements are farther apart allowing easier installation of services—everything fits easier making the trades happier—the electrician drills fewer holes and the insulator insulates faster because there are fewer cavities, even though the cavities are wider and deeper. Everything lines up so the load paths are direct, leading to fewer but stronger connections. The lines are cleaner, so it just looks and feels better.

Some of the advanced frame technology goes back to the beginnings of framing—“in-line” framing or “stack” framing where everything lines up is not new (Figure 1). But, the real innovations came from a magnificent collaboration between the U.S. Department of Housing and Urban Development (HUD) and the National Association of Home Builders Research Foundation (NAHB Research Foundation) in the 1970s. Out of a HUD initiative called Operation Breakthrough the NAHB Research Foundation delivered “optimum value engineering framing” or OVE framing. Today, this is referred to as “Advanced Framing.”

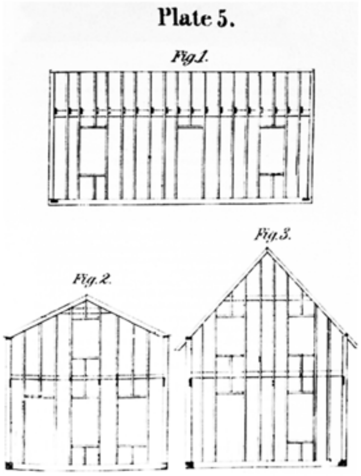


Figure 1 - In-line Framing. (Bullock, 1854)

Figure 2 shows the current expression of advanced framing. Everything lines up so that double top plates are not necessary. No headers in non load-bearing walls. Window openings are clean without jack studs and cripples. Exterior corners have two studs. Gypsum board is supported with drywall clips. And all of this is code accepted by the model building codes because of the foresight of HUD and the NAHB. Although it’s in the code, most code officials are not aware of it and even fewer builders.

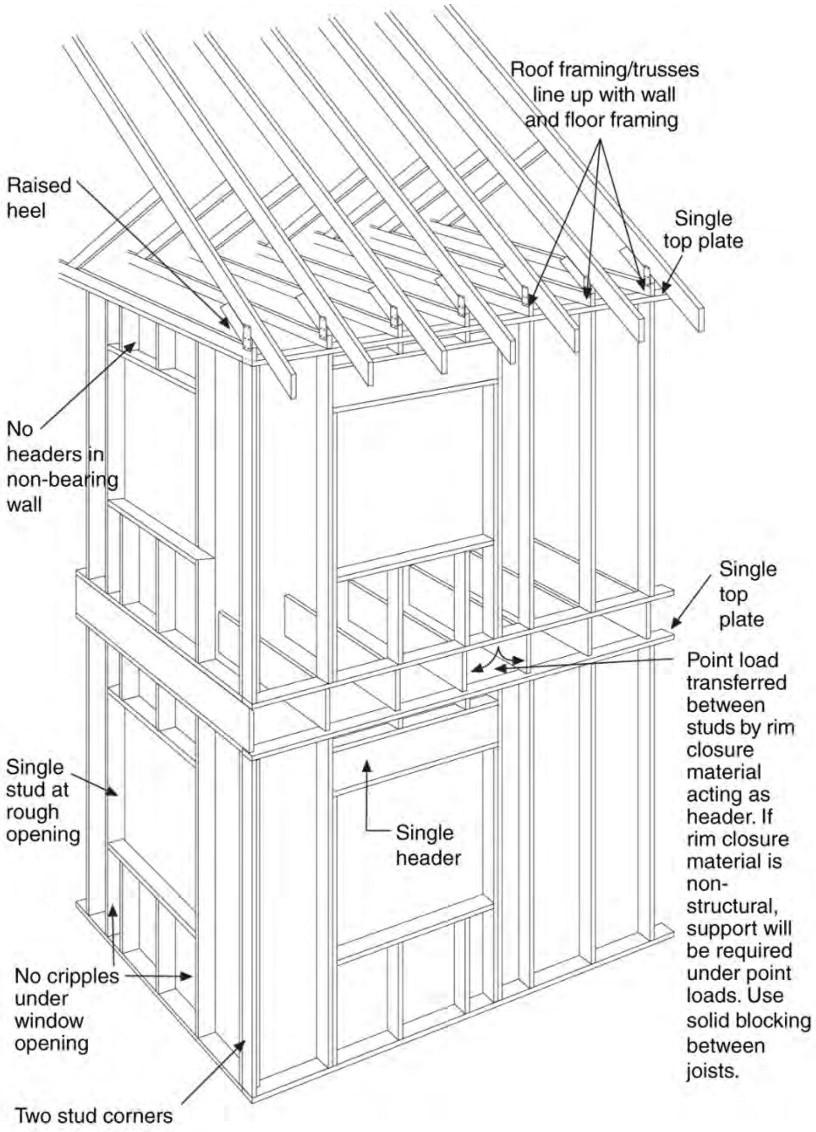


Figure 2: Advanced framing

One of the biggest pushback's from builders and code officials comes from corner support for gypsum board and trim. "Floating corners" reduce drywall cracking and, therefore, are an improvement. Wood always moves because of changing moisture contents. Gypsum board does not want to move. When you attach something that is always moving to something that does not want to move you get cracking. The key to reducing drywall cracking is to attach it less, the easiest drywall clip in the past was to cut a piece of corner bead into 2 in. (51 mm) lengths.

Single top plates seem to be the biggest problem. Not from a structural perspective or from a constructability perspective but from a perception perspective. There are two ways of making a connection: with a metal plate or with a wood splice. The approach taken is purely one based on preference by the framer.

The real change involving single top plates is that when you are framing an 8 ft (2.4 m) wall the studs have to be 1.5 in. (38 mm) longer. Standard "pre-cuts" don't work. You need 94 inches (2.39 m) not

92.5 inches (2.35 m). Load-bearing walls need headers and advanced framing typically involves using single headers with the header pushed to the exterior of the wall. This keeps the header away from the gypsum board so that boarders can't attach to it, therefore, shrinkage in the header does not result in a crack in the drywall.

The most significant change is the fact that the walls are thicker and we have to figure out what to do with the additional 4 in. (100 mm). Do we make the foundation wider? Do we lose 4 in. (102 mm) to the interior? Do we keep the foundation the same, but cantilever the walls? These are not trivial. In production housing interior dimensions are a big deal and can mess up kitchen layouts, hallways and stairs. Site setbacks must be considered as well. It typically means that the drawings have to be redone. Taking existing floor plans and redrawing them is a $1,000 to $1,500 hit per plan for a production builder. This is the biggest knock against advanced framing. Of course, this is not a problem if the plans are drawn up from scratch to be advanced frame.

The floor framing is now on 24 in. (600 mm) centers, and that means the floor sheathing has to be thicker. The savings in the floor framing covers the cost of the thicker floor sheathing. The interior walls are also framed on 24 in. (600 mm) centers using 2×4s. Almost all of them are not load bearing hence the connections are pretty much non-structural.

Things get interesting when we add insulating sheathing, althoughit is not part of advanced framing. Many builders that use advanced framing today also incorporate insulating sheathing. With insulating sheathing the water control layer is the exterior face of the insulating sheathing taped. Insulating sheathing provides no "racking resistance" or "shear" properties. For that OSB or plywood is required creating "braced wall panels" and most builders build them into corners.

Techniques and Components of Advanced Framing

Advanced framing consists of a base set of framing features which allows the builder to use 5% to 10% less board feet of wood, use 30% fewer pieces of wood, creating fewer thermal bridges all while reducing costs. BSC recommends the following features:

- Exterior Walls
    - 2" x 6" Studs
    - 24" Stud Spacing
    - 2-Stud Corners
    - Single Top Plate
    - Stacked Framing
    - Single King Studs
    - Single Jack Studs
    - Non-Load Bearing Headers Removed
- Interior Partitions
    - 24" Stud Spacing
    - Single Top Plate
    - Non-Load Bearing Headers Removed
- Floor Framing
    - 24" Spacing
- Roof Framing
    - 24" Spacing

The following figures are photographs from a variety of homes that have implemented advanced framing measures. These details are also documented the drawings provided in Appendix 1.

Figure: Exterior Walls 2" x 6" Studs 24" Stud Spacing

Figure 3 - Exterior Walls 2-Stud Corners

Figure 4 - Exterior Walls Single Top Plate and Stacked Framing

Figure 5: Exterior Walls Single King Studs without Jack Studs

Figure 6: Exterior Walls Non-Load Bearing Headers Removed

BSC Advanced Framing Research

Building Science Corporation incorporates advanced framing in a large number of its Building America homes. The following table summarizes the number of homes built in various climate regions.

Table 1 - Advanced Framed Homes per Climate Region in 2009

	Number of Homes
Cold, 4A	1
Cold, 5A	9
Hot-Humid, 2A	85
Marine, 3C	1
Mixed-Humid, 3A	29
Mixed-Humid, 4A	1
Grand Total	126

The Hot-Humid and Mixed-Humid regions contain entire communities of advanced framed homes as well as a few prototypes. The other climate regions consist primarily of prototypes and small groups of homes with advanced framing. This can also be presented in terms of builders. Table 2 contains the number of homes built by each BSC BA builder.

Table 2 - Advanced Framed Homes per Builder in 2009

	Number of Homes
Ark Ventures, LLC	1
C.Nelson	7
Colter Construction	1
David Weekley Homes	77
Greencraft LLC.	5
Moser Builders	1
Project Home Again	32
Synergy Companies Construction LLC	1
Zeta Communities	1
Grand Total	126

David Weekley Homes and Project Home Again have taken the lessons learned from early prototypes and have fully embraced advanced framing. David Weekley Homes is in the process of trials and adoption of advanced framing company-wide, in all divisions, in all climate regions. Although the community builders produce the most total square feet, the prototypes also add to the overall total and provide important implementation lessons for the project. Table 3 summarizes the total square feet built per climate region.

Table 3 - Square Feet Built per Climate Region in 2009

	Square Feet Built
Cold, 4A	3782
Cold, 5A	27419
Hot-Humid, 2A	199034
Marine, 3C	1561
Mixed-Humid, 3A	45714
Mixed-Humid, 4A	1280
Grand Total	278790

In total for 2009, over ¼ million square feet of residential floor area have been constructed incorporating advanced framing techniques under the supervision of BSC staff. Many homes include the entire advanced framing package, but some do not include all of the recommended features. This is summarized in Figure 4.

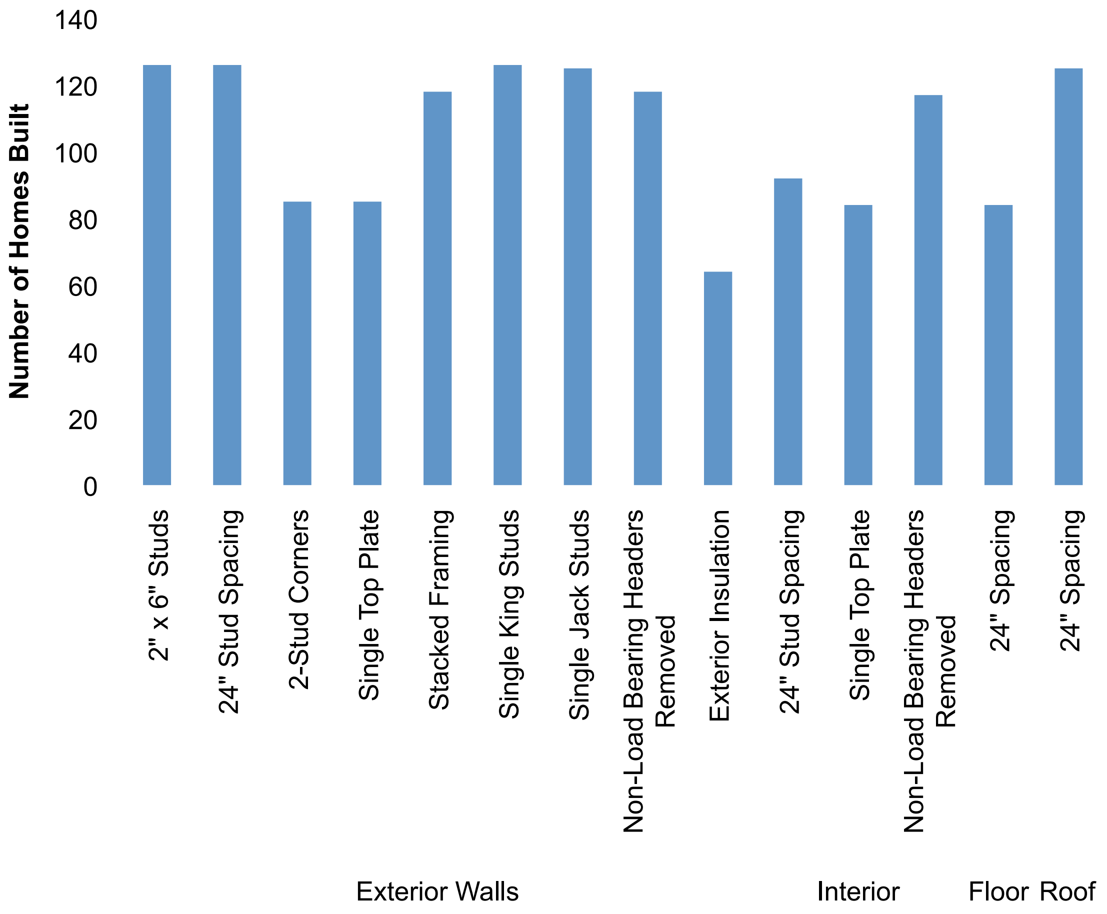


Figure 2 - Advanced Framing Features

The most common advanced framing features adopted are the 2×6 frame at 24 in. (600 mm) centers with stacked framing (where possible), single king studs, single jack studs and removal of non-load bearing headers. Full adoption of advanced framing would include all of the items shown in Figure 4 except the exterior insulation. The exterior insulation data is shown for comparison to demonstrate the high adoption percentage when advanced framing is utilized. It is not always possible to incorporate 24” spacing of the floor joists, which leads to the requirement of using double top plates in the walls because the walls and floors are now framed at different spacing. To realize the full benefits and up-front cost savings of advanced framing, the builder and designer(s) should make the decision to adopt advanced framing early in the design process. Early adoption and acceptance of the full framing package allows the designer to select framing systems (joists, trusses, beams, headers etc) that can be used at 24” O.C. and remain within the relevant building code requirements.

Energy Analysis

Advanced framing has the added benefit of reduced thermal bridging, reduced heat loss and hence energy and cost savings for the occupant. The annual site energy savings associated to adopting advanced framing with and without exterior insulating sheathing are shown in Table 4 and Table 5.

Table 4 - Annual Site Energy Savings with Exterior Insulation

	Avg. Annual Site Energy Savings (MBtu)
Cold, 4A	2.78
Cold, 5A	4.52
Hot-Humid, 2A	unknown
Marine, 3C	0.99
Mixed-Humid, 3A	5.28
Mixed-Humid, 4A	1.19
Average	2.95
	Avg. Annual Energy Savings ($)
Cold, 4A	$43
Cold, 5A	$90
Hot-Humid, 2A	unknown
Marine, 3C	$38
Mixed-Humid, 3A	$180
Mixed-Humid, 4A	$28
Average	$76

Table 5 - Annual Site Energy Savings without Exterior Insulation

	Avg. Annual Site Energy Savings (MBtu)
Cold, 4A	unknown
Cold, 5A	2.50
Hot-Humid, 2A	2.11
Marine, 3C	unknown
Mixed-Humid, 3A	unknown
Mixed-Humid, 4A	unknown
Average	2.31
	Avg. Annual Energy Savings ($)
Cold, 4A	unknown
Cold, 5A	$36
Hot-Humid, 2A	$68
Marine, 3C	unknown
Mixed-Humid, 3A	unknown
Mixed-Humid, 4A	unknown
Average	$52

The data presented in Table 5 is that of a smaller sample than that in Table 4. This is due to the fact that a large number of BSC BA builders adopting advanced framing also adopt exterior insulating sheathing. The exterior insulation significantly improves the performance of the building enclosure. This can be seen in the annual energy savings as well as annual energy cost savings. On average the advanced framing package saves approximately $60 annually. Although the greenhouse gas emissions are not modeled, because less energy is being used, fewer emissions are being released at the power plants. The site energy savings and cost savings are greatly affected by the climate region. Increased thermal performance only reduces annual energy costs associated to heating and cooling. If the heating and cooling loads are very small, as they would be in a mild climate such as Marine 3C, only a small savings is realized both in terms of energy and cost. Some of the data necessary to complete these tables was left as ‘unknowns’ for 2009 as this data was not available. It is anticipated that homes built in 2010 will have this data available and it will be included in the final report.

Cost and Constructability

Regardless of the energy and green house gas emissions savings, construction is a business, and businesses must be run based on the financials. There is little incentive for builders to incorporate advanced framing measures based on the annual energy savings values alone. Since the builders do not operate the houses for any significant period of time, the builders themselves to do not receive the financial energy savings benefit from incorporating these measures. In certain instances with prototype homes these financial values are very difficult to determine. This is because most trade crews must learn on at least 5 homes before proficiency with advanced framing is realized and most prototype homes do not cost analyze and compare each step. Only when a plan has been built a number of times to a base standard and then changes are made to that plan and built a number of times again incorporating advanced framing can the true value of the savings be estimated. In a production based build, the cost of engineering can also be spread over a large sample of homes instead of just one prototype. In 2010, BSC will provide additional information about these cost savings.

Incorporating the advanced framing design changes from the inception of a design does not generally require additional design fees, but re-drawing existing drawings can be costly. For the builder the cost savings of building with advanced framing is associated to reduced board feet of lumber, increased speed of framing (after a brief learning period), increased speed of other trades such as plumbers, electricians and insulators, and simplified construction. The combination of these time savings in conjunction with a well planned and executed construction schedule can significantly reduce the required build time. If each trade can spend less time in a home, more homes can be built in a given time period.

There are many cost trade-offs associated to upgrading to advanced framing. For instance increasing the spacing from 16” to 24” of floor joists requires that the floor sheathing be thicker. In BSC’s experience this increase in sheathing thickness has an associated cost that roughly matches the cost savings in reducing the board feet of floor joists required. Due to code requirements, some locations also require different sheathing for the exterior shear panels in walls if 24” stud spacing is used. Again, the associated cost increase of additional, rearranged or thicker sheathing is taken away from the savings associated with fewer board feet of exterior wall studs. Interior partitions can be framed at 24" O.C. and with single top and bottom plates can have a net positive material and cost savings. In certain circumstances, as with the David Weekley Homes Charleston division, a cost savings associated with insulating to R19 over R14 was found. The R19 fiberglass insulation package actually cost less than the R14 insulation package. Upgrading only the exterior walls to 24" O.C. is a step in the correct direction, but likely will not yield significant savings. The largest savings can be seen if all features of the advanced framing package are utilized. BSC's past experience shows that a builder can save $1,000 per home by implementing advanced framing.

Advanced framing has the possibility to be a cost shifting advantage. The energy savings is relatively low, but the upfront cost savings is relatively high for the builder. The savings from advanced framing can be used to fund other efficiency options, increasing energy efficiency even further. The cost shifting creates a home that costs the same, but is significantly more energy efficient.

Although framing at 24" OC is not new, there are still hurdles to overcome for it to be implemented nationally. There are issues getting stucco installed over 7/16" OSB on advanced framing, this is not a code compliance or structural issue, it is a matter of completing testing to prove that it is possible. Recently another advanced framing hurdle was overcome in recent Baltimore code hearings. The code for allowing the use of single headers passed the committee stage. Many other perceived issues are code compliant. Appendix A contains a summary of the compliance of advanced framing to the IRC of 2000 and 2003. Currently 24" 2x6" stud spacing, single top plates, removal of headers in non-load bearing walls and drywall clips are all code approved with specified application stipulations.

Preliminary Conclusions and Future Research Plans

Advanced framing can save energy, greenhouse gas emissions, and money if properly implemented. Through BSC's experience we have found that builders can save $1000 per house on advanced framing. To maximize cost savings and energy savings for the homeowner, the builder financial savings are best shifted to implementing more energy saving measures. The cost shifting creates a home that costs the same, but is significantly more energy efficient. Code compliance hurdles, in the few cases they actually exist, have been or are in the process of being overcome. Further testing is required in many cases, although code approved, to demonstrate that advanced framing is possible and functional.

In 2010 BSC will continue deployment of advanced framing wherever possible with its Building America partners. David Weekley Homes is to continue production and this will allow BSC to gather both energy and cost data from production levels of construction. Smaller scale implementation will be completed with other BA builders in a variety of other climate zones. The data gathered from BSC's production and prototype builders will allow further cost and energy savings analysis during 2010. We expect that this information will be included in the FY2010 final report.

References

Bullock, J. “The American Cottage Builder”, Stringer and Townsend, 1854

Neuhauser, K. “David Weekley Homes Comparative Wall Framing Analysis”, Building Science Corporation, 2008

Bazeck. “Advanced Framing”, Presentation – EEBA Conference 2001

Built Green. “Advanced Framing Builds on Love of Wood”, http://www.builtgreen.org, 2007

ENERGY STAR Builder Guide, “Reduce Framing Costs with Advanced Framing Techniques”, Unknown, Unknown

Department of Energy - Technology Fact Sheet, “Advanced Wall Framing”, Office of Building Technology, State and Community Programs Energy Efficiency and Renewable Energy - Department of Energy, 2000

Partnership for Advancing Technology in Housing, “Advanced Framing Techniques”, www.pathnet.org, unknown

Appendix 1 – BSC Advanced Framing Detail Drawings and Code Review