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

Research Report - 1003

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Jonathan Smegal and John Straube

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. 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 control in colder climates while enhancing moisture control, health, and comfort.

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High-R Foundations Case Study Analysis

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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 control in colder climates while enhancing moisture control, health, and comfort.

The 2009 IRC (Table N1102.1) and 2009 IECC (Table 402.27) require basements in DOE climate zones four and greater to 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 approach or exceed a true R-value of 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
- Resist soil pressures
- Keep the groundwater out
- Keep the soil gas out
- Keep the water vapor out
- Allow any water vapor in the wall to leave
- Keep the heat in during the winter
- Keep the heat out during the summer

Basement failures occur often due to flooding, or condensation, both of which may result in mould or dust mite problems. However, building physics and extensive field experience has shown that the majority of all basement moisture and comfort issues can be avoided by proper design and material selection.

This study compares over a dozen basement and foundation enclosure designs including historical construction strategies, code minimum construction and highly insulated construction. This report 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 durable, 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 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 with poly
- Case 3 : 3.5 inches fiberglass batt in 2x4 SPF wood framed wall with poly
- Case 4 : 1 inch XPS + 3.5 inches fiberglass batt in 2x4 SPF wood framed wall
- Case 5 : 2 inches XPS + 2 inches polyisocyanurate with R10 under slab
- Case 6 : 3.5 inches 2.0 cc pcf spray foam with R10 under slab
- Case 7 : 6 inches 0.5 oc pcf spray foam with R10 under slab
- Case 8 : 2 inches XPS + 3.5 inches fiberglass batt in 2x4 SPF wood framed wall with R10 under slab
- Case 9 : 2 inches polyisocyanurate +3.5 inches cellulose in 2x4 SPF wood framed wall with R10 under slab
- Case 10 : 6 inches 0.5 oc 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 fiberglass 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/drying)	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						
Case 15: 4" PIC, 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, 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.

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 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 Print

NRCan/RNCan , 20122001

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)
- Basement wall area – 118 m^2 (1270 ft^2)
- Basement floor slab area – 140 m^2 (1506 ft^2)
- Basement perimeter – 48.5 m^2 (159 ft^2)

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 typical residential construction is the exterior above grade brick cladding sitting on the outside edge of the foundation wall.

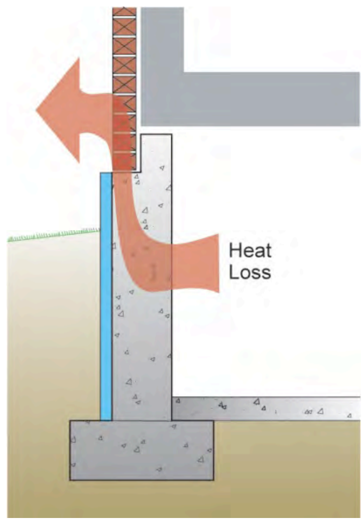

Figure 2 : Typical construction thermal bridging through foundation and brick cladding

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. In typical construction with brick veneer, there is a significant thermal bridge between the interior and exterior when the brick cladding is installed on the exterior edge of the concrete foundation wall. It was assumed that there was no significant thermal bridge at the top of the foundation wall.

All of the Basecalc results are presented in units of MBtus. For clarification 1 MBtu and its equivalent energy in other common units of measure are shown 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
Megajoules	1,057
Kilowatt hours	293.6

A common way to explain energy savings to homeowners is often in dollars saved since the value of a dollar is well 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). As a comparison, natural gas at $1.50/therm burnt in a 90% efficient furnace costs $16.70/MBtu. The cost of energy is likely to rise, even though the rate of increase is unknown, so dollar savings are likely to be higher in the future.

2.1.1. Building Code Requirements

According to the 2009 IECC in climate zones 4 or higher, the building code requires a minimum of R10 continuous insulation (e.g. fiberglass roll batt) or R13 discontinuous (e.g. framed wall with R13 fiberglass batt) unless it is an unconditioned basement and the floor overhead is insulated in accordance with IRC Sections N1102.1 and N1102.2.6. Adding this required amount of insulation makes a significant difference from an energy perspective as shown in Figure 3, but may not adequately address the comfort, moisture and health concerns that occur in basements. Case 1 in this study is an un-insulated basement as many such cases can be found in 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 3 shows the improvements in annual energy loss by insulating the full height of the basement wall with different insulation values compared to an un-insulated basement. The most significant improvement is achieved by adding the first 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/). The energy savings should be considered when determining the cost of adding insulation, and whether or not it is cost effective.

The basement wall has an area of approximately 1270 ft^2 and R5 foam insulation costs approximately 50-75 ¢/sf plus installation. Using R10 rigid foam insulation over the entire basement in this case would cost in the range of $1270 to $1905, and would save a predicted $1372/year.

Figure 3 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 odors, and storage of moisture sensitive materials on the floor 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.

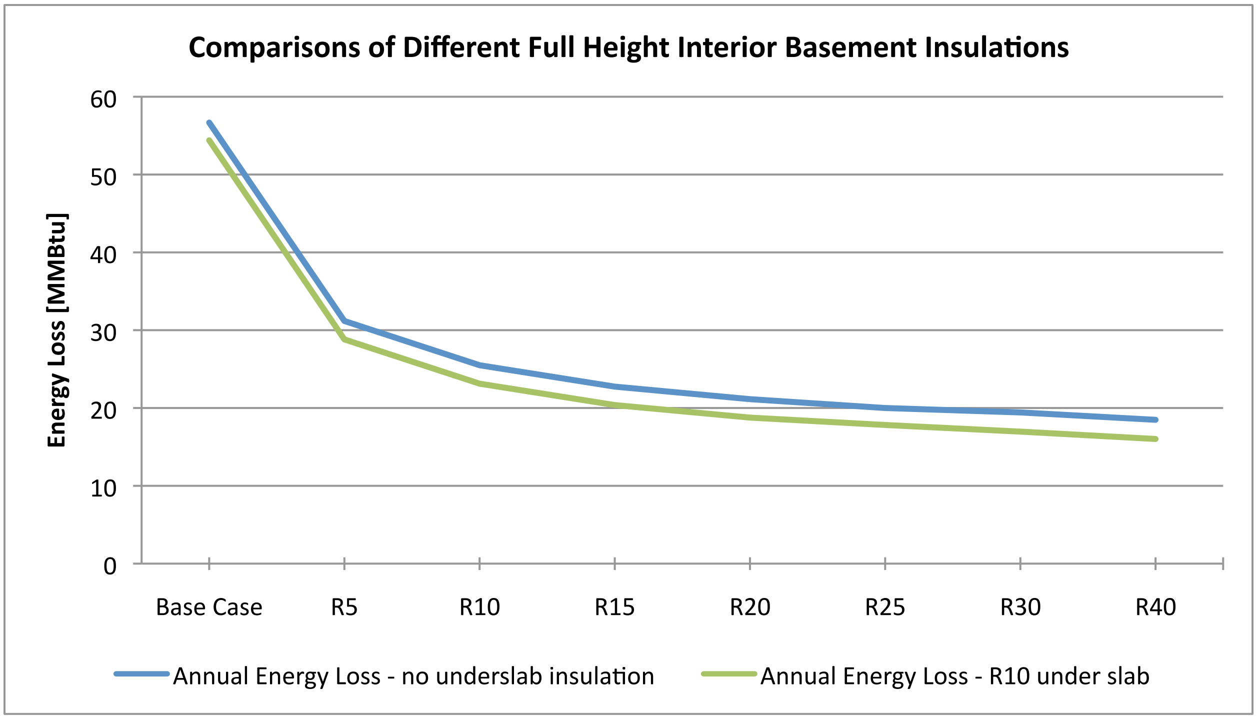

Figure 3 : Reduction in Energy Loss with the Addition of Full Height Foundation Wall Insulation

Two different underslab insulation strategies are compared in Figure 4, 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.

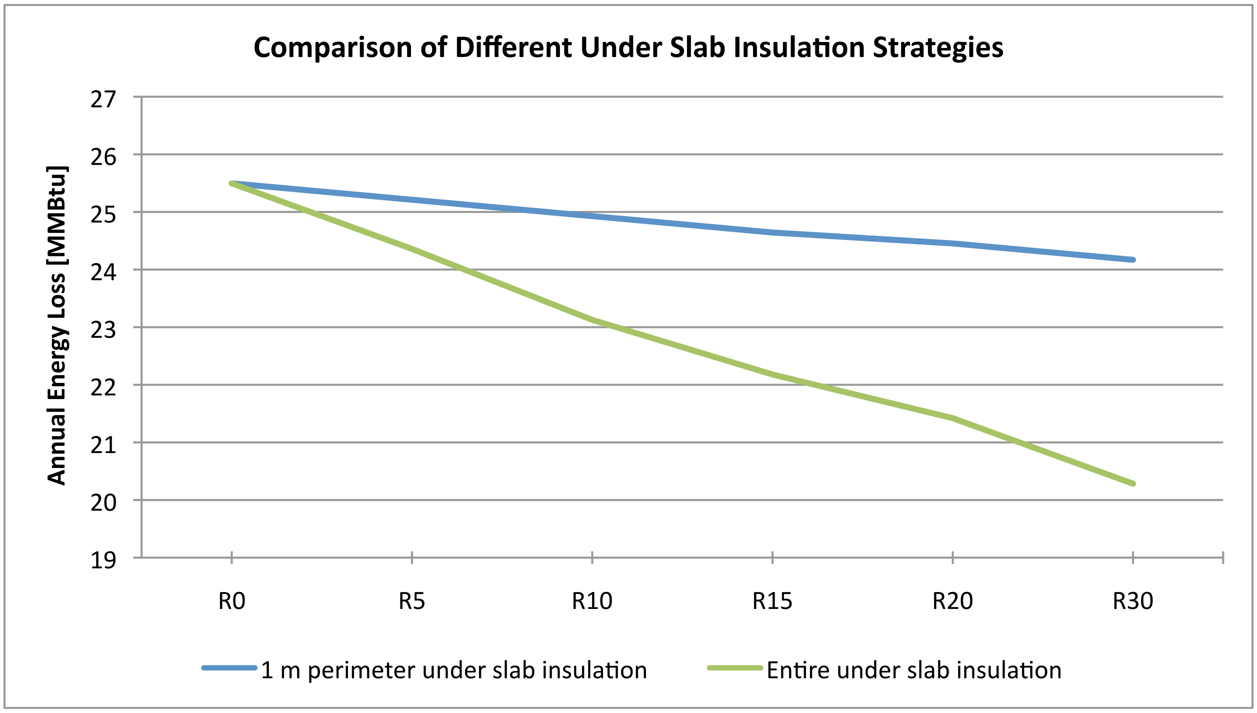

Figure 4 : Comparison of Different Underslab Insulation Techniques with R10 on foundation walls

In typical construction, there is a significant thermal break at the connection of the basement slab to the foundation footing and it also allows capillary movement of water. 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 of 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 5 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.

A savings of 1.8 MBtus for a perimeter of 48.5m (159ft) has a very short payback period.

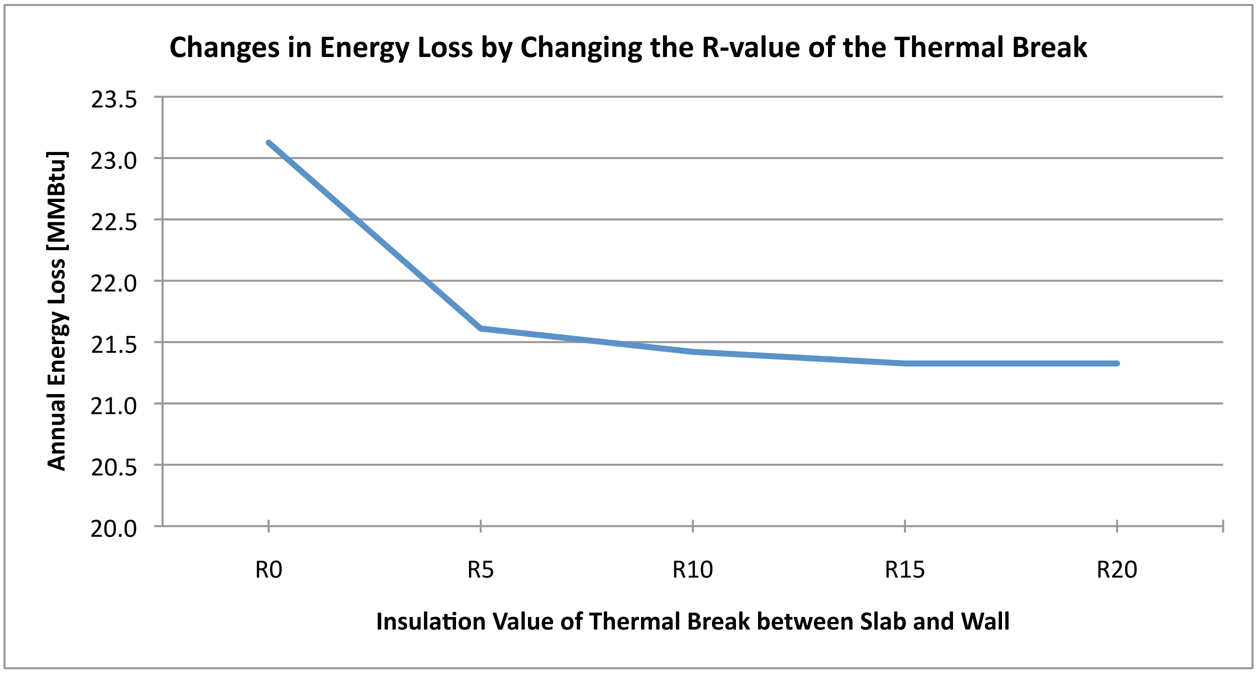

Figure 5 : Energy Savings From Thermal Break Insulation Between Concrete Footing and Slab

2.1.2. Case Study – Westford Prototype House

Recently, Building Science Corporation designed and monitored construction of a Building America prototype home in Westford Mass with an approximate area of 23' x 33' with 740 ft² of floor area and 885 ft² of foundation wall.[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.**)**

[1] Information on this project can be found at http://www.buildingscience.com/documents/case-studies/cs-ba13_MA_Westford_HFH/

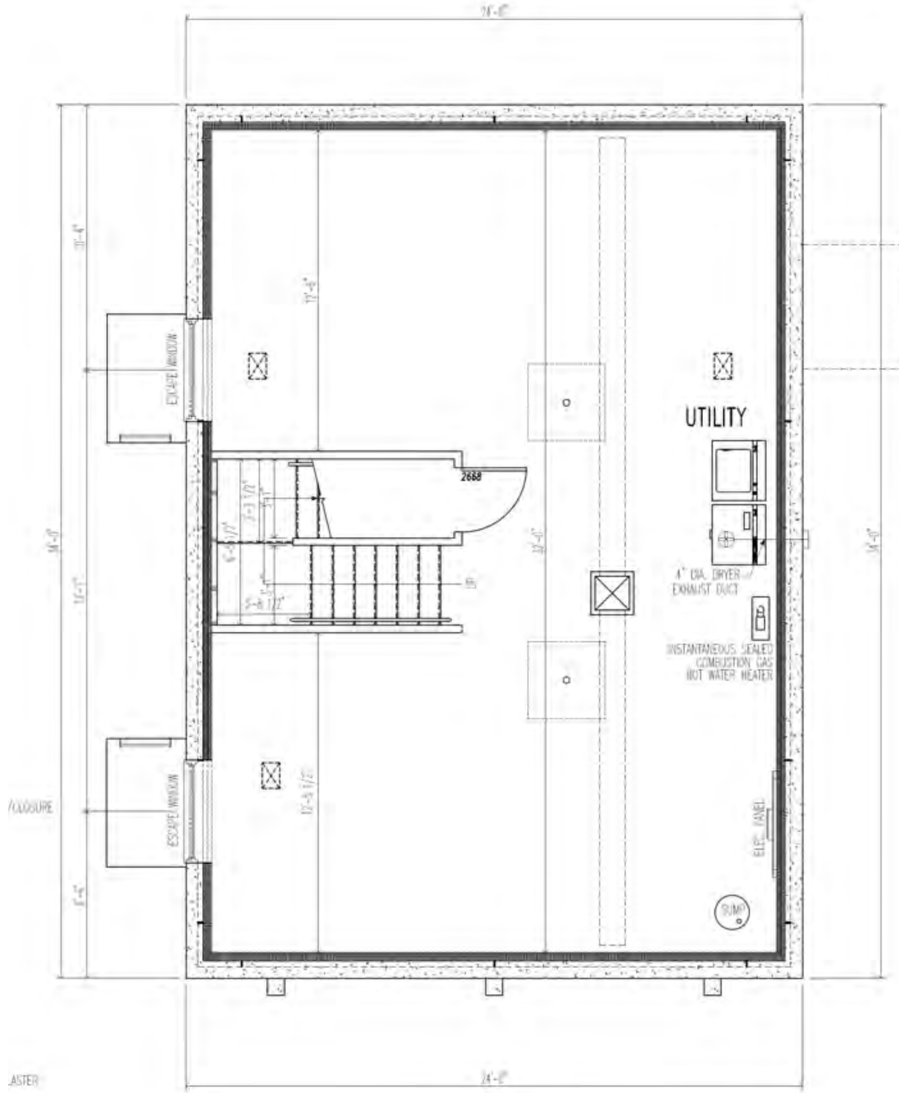

Figure 6 : Basement Floorplan of BA Westford Prototype House

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.

In this study, 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 using Basecalc, 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

	Predicted Basement Energy Losses [MBtu]	Change in Basement Energy Losses [MBtu]	Change in Whole House Energy Losses [%]
Removing Underslab insulation	8.4	1.3	4.8%
R10 under slab	7.1	0	0
R20 under slab	6.2	- 0.9	- 3.4%
R30 under slab	5.7	- 1.4	- 5.0%

Table 3 shows that 1.3 MBtus were saved by adding R10 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 become much less significant. To save another approximately 5% of the entire house's heating energy losses, another R20 is required above the original R10 insulation.

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

	Predicted Basement Energy Loses [MBtu]	Change in Basement Energy Losses [MBtu]	Change in Whole House Energy Losses [%]
R10 code minimum foundation wall insulation	10.4	3.3	11.9%
R26 foundation wall insulation	7.1	0	0
R40 foundation wall insulation	6.2	- 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. At $1.20/sf, this insulation would cost $1062, and would save 0.9 MBtu/year.

2.1.3. Basement Wall Analysis

The fourteen different walls listed previously were simulated in Basecalc, and the heating energy losses were estimated. Some of the proposed wall systems had continuous insulation and the R-values were assumed to be equal to their rating. 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 that builders will install underslab insulation when only minimal foundation wall insulation is present.

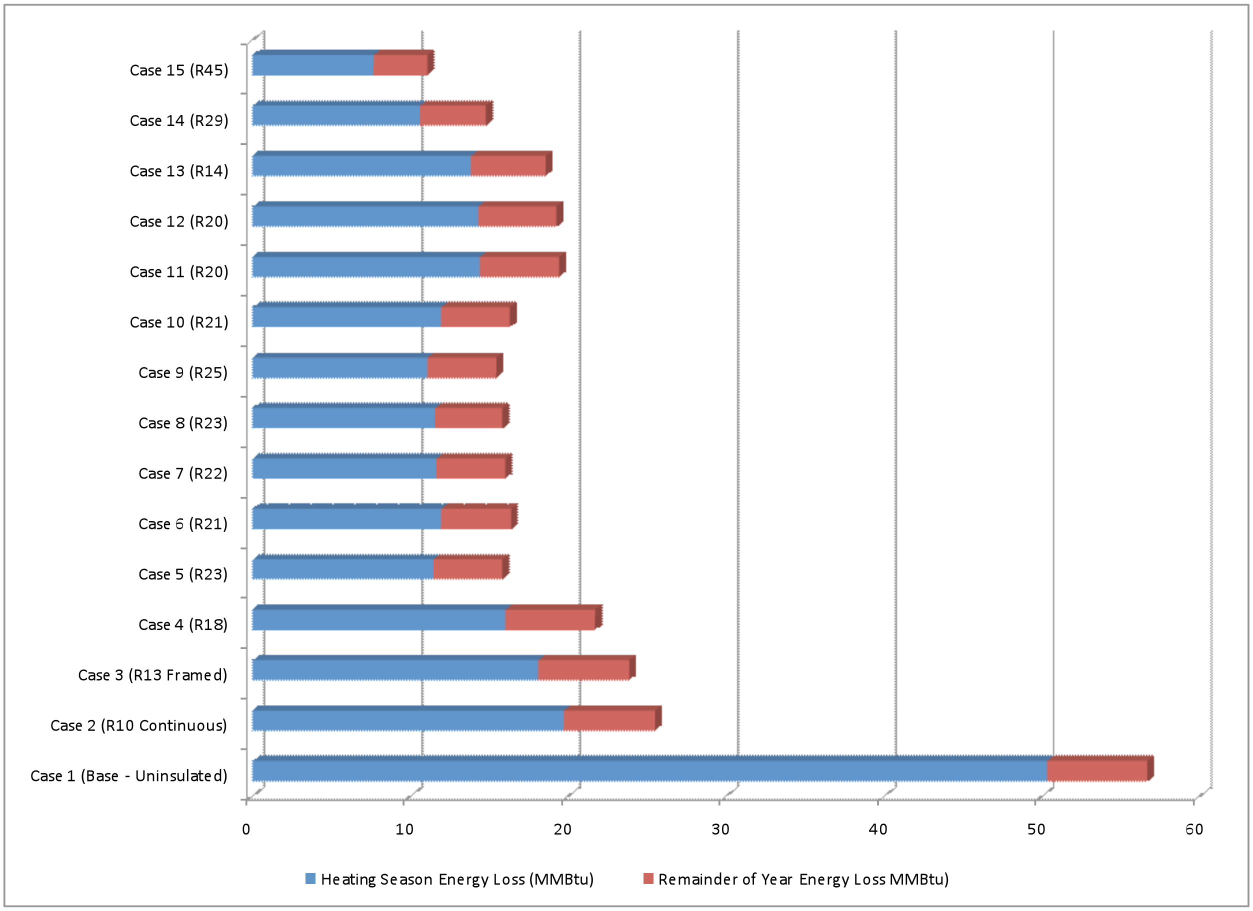

Figure 7 : Comparison of Heating Energy Losses for all Cases

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 for the specific house examined. Cases 5-10, 13, and 14 have essentially identical performance. The value of these 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 (more detail by Joseph Lstiburek 2006).

There are four main wetting mechanisms in foundations and basements. They are:

- Bulk water penetration from the exterior
- Capillary wicking or "rising damp"
- Vapor diffusion and air leakage condensation (from exterior or interior)
- Plumbing issues on the interior (not considered in this analysis)

The greatest amount of damage in the shortest time will be caused by a bulk water penetration from the exterior or interior plumbing related issues. 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 (Figure 7). 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 or thaw 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. Additional information regarding the retrofit of basements is available in Pettit(2005).

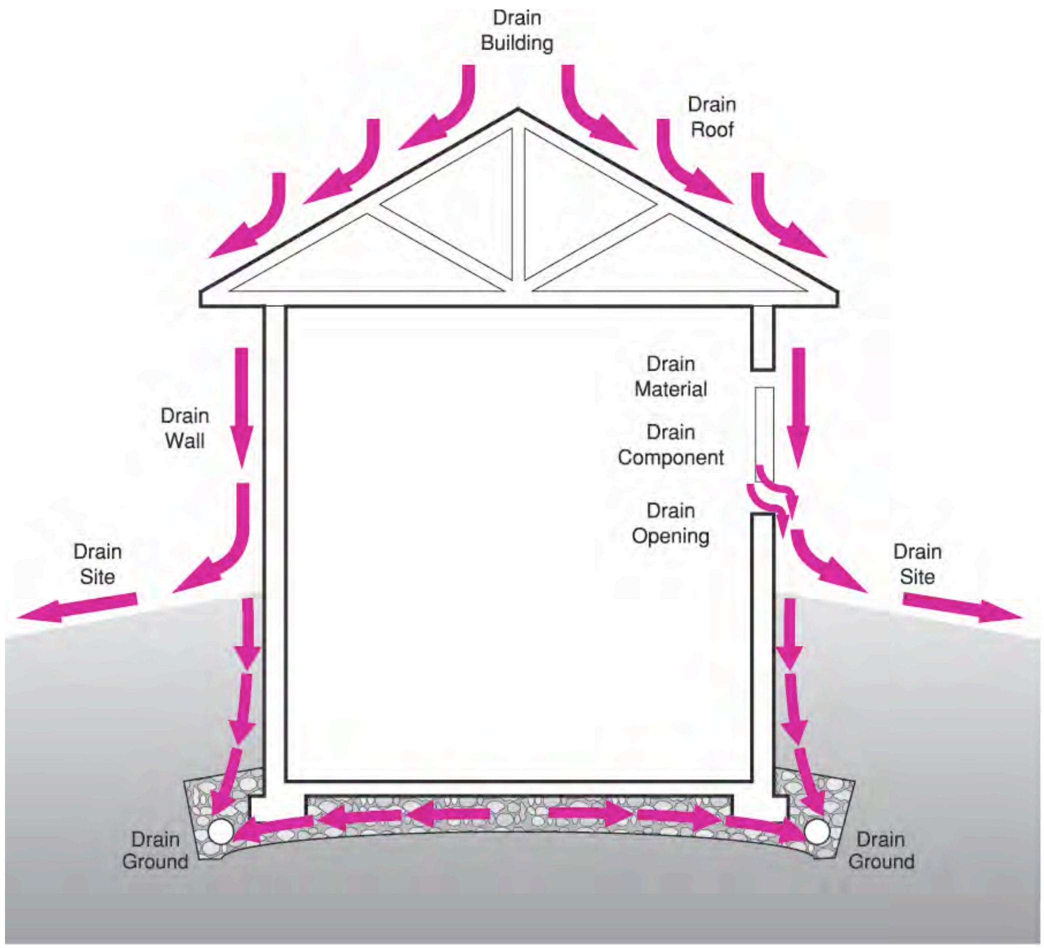

Figure 8 : Drainage details to minimize foundation moisture issues

The second source of moisture in the basement enclosure is moisture transported from wet soil by capillary 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 capillary absorption through the foundation wall. The floor slab is often poured over gravel which, if it has no fines, 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 top of 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 (Figure 9), 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 local building code. Some builders who have learned from past experience will remove a section of the polyethylene vapor barrier at the bottom 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. Alternatively, a moisture tolerant interior foam layer can reduce the flow to the interior sufficiently to avoid damage (if no additional vapor barrier is added).

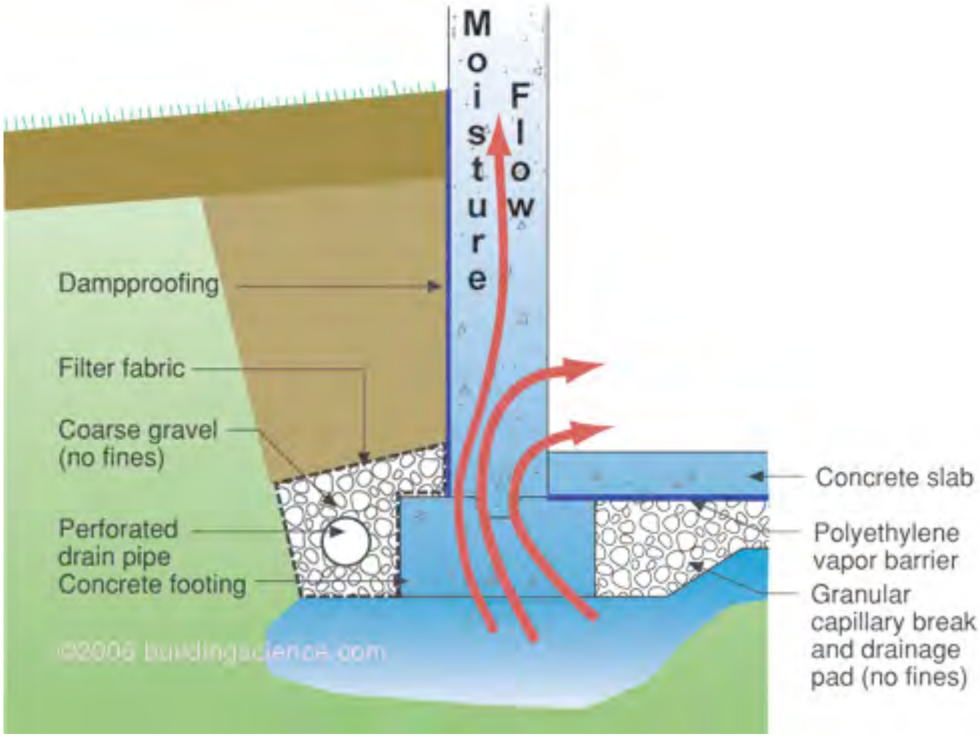

Figure 9 : Capillary rise through basement footing

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 (Figure 9). 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.

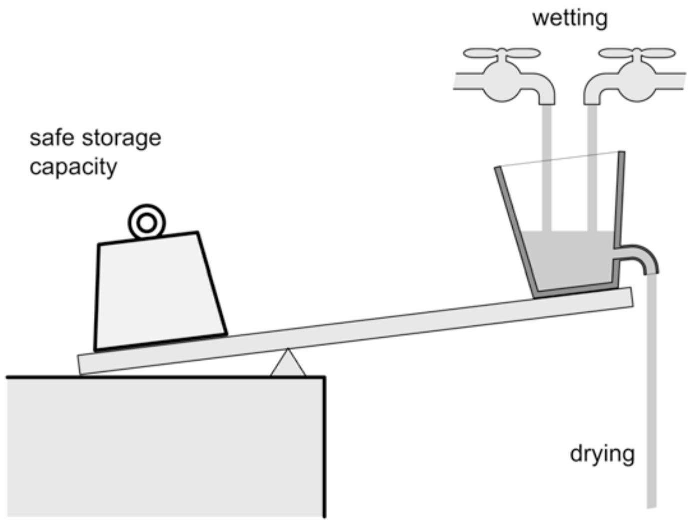

Figure 10 : Moisture balance

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, so that the below and above grade portions of a foundation wall experience different moisture and temperature regimes. 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 11. The above grade temperatures for Minneapolis are included in the weather data for WUFI.

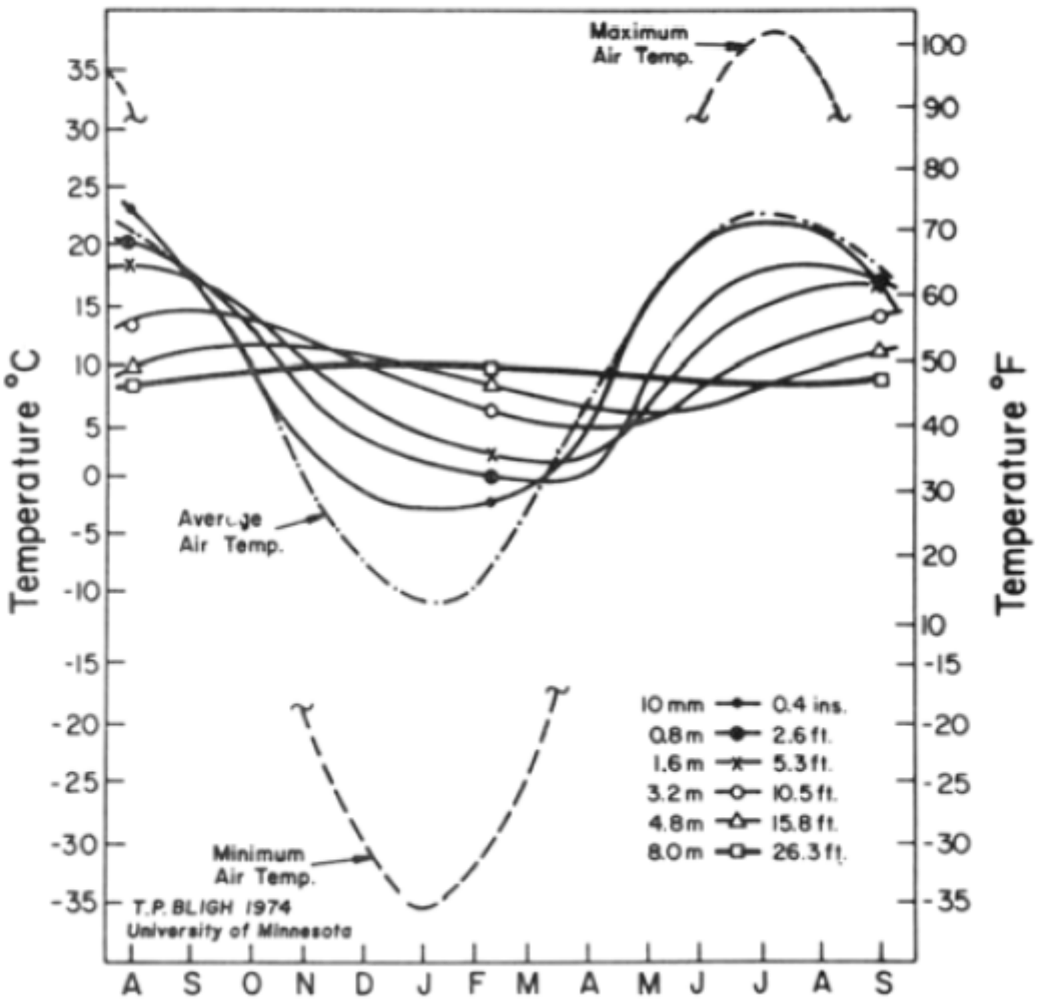

Figure 11 : Monthly temperature variation with soil depth, St.Paul, MN (Bligh 1975)

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 and it was assumed that the foundation wall and slab were not in contact with liquid water. 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. This would significantly increase the moisture loads above the predicted values where there is not capillary break installed in the foundation enclosure system.

Interior temperature and relative humidities were chosen to represent a slightly higher than average moisture load for a cold climate house (Figure 12). These boundary conditions were simulated for 10 years to ensure that the foundation system was at equilibrium with both the exterior and interior environments.

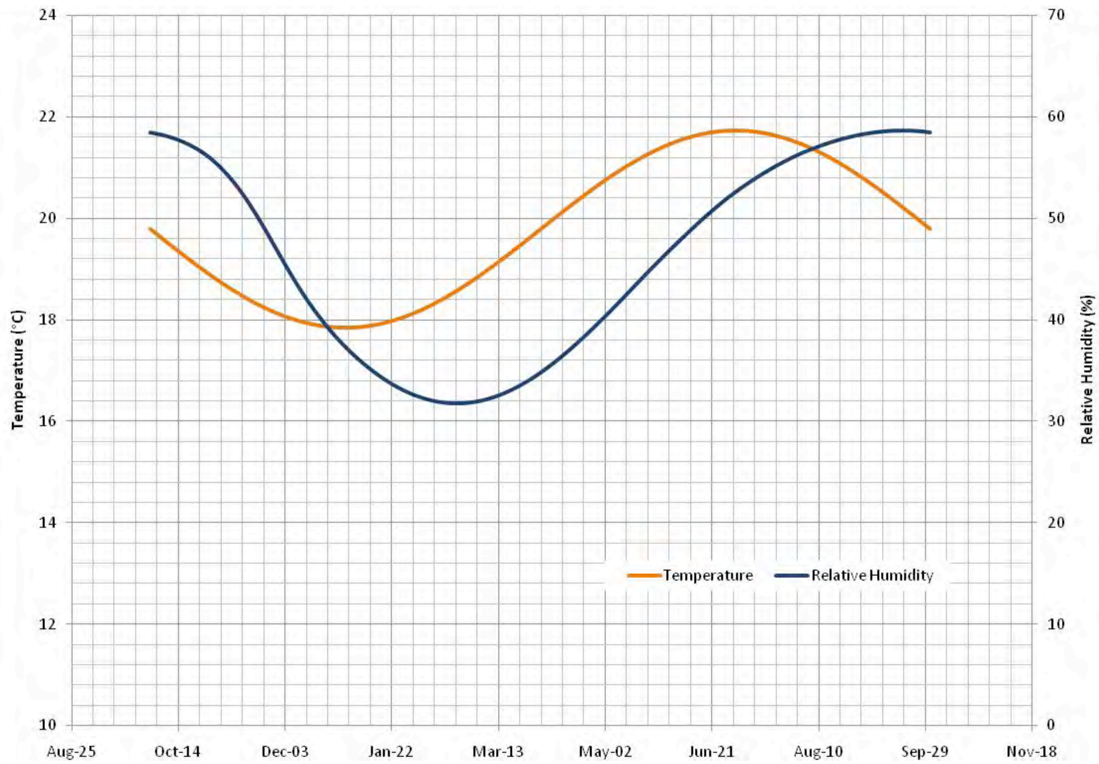

Figure 12 : Interior Temperature and Relative Humidity for Hygrothermal Simulations

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 cold climate basements in the past, but now, with increased understanding about the moisture physics of basements and below grade walls, the IRC (International Residential Code) states that Class I and II vapor retarders are not required on any below grade wall or basements (IRC 2009 Table R601.3.1).

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 13 shows the moisture behavior 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.

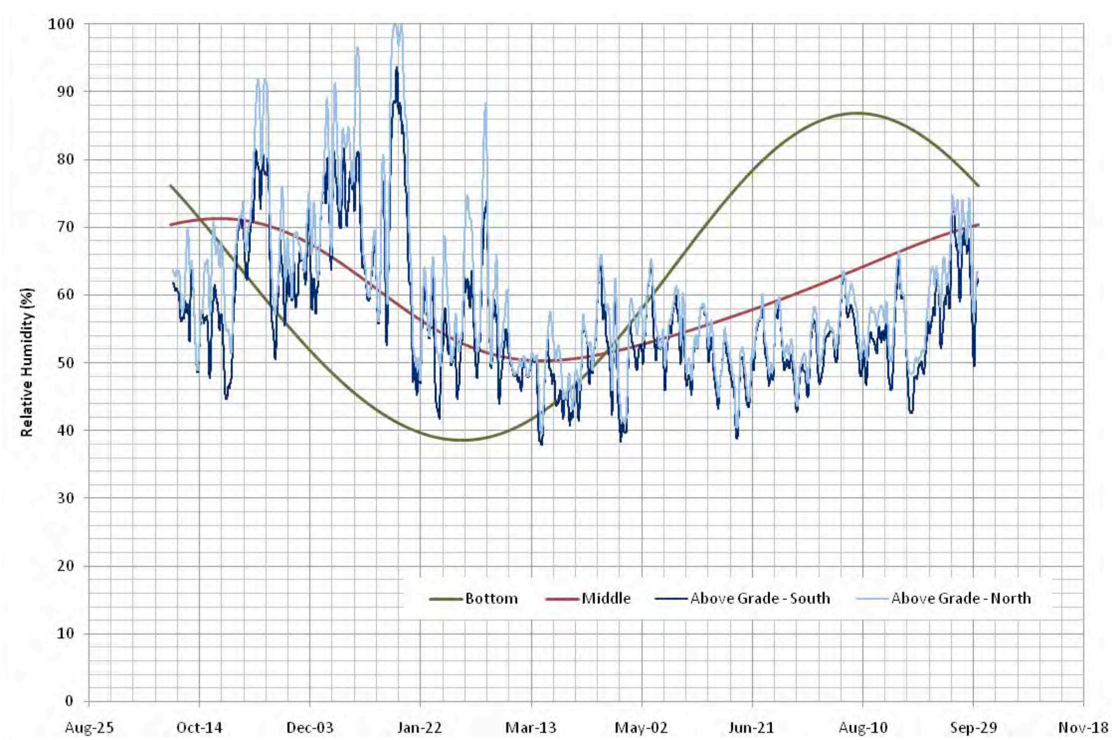

Figure 13 : Predicted RH at the Interior Surface of the Concrete Foundation Wall for Case 1

The predicted surface temperatures of the foundation wall and the dewpoint of the interior air are shown in Figure 14. 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 31% in the winter and 58% in the summer (Figure 12). 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 14 : Condensation Potential for Interior air on the Surface of the Concrete Foundation Wall

2.2.5. Case 3 - Code compliant 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 states in R601.3.1, 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 15 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.

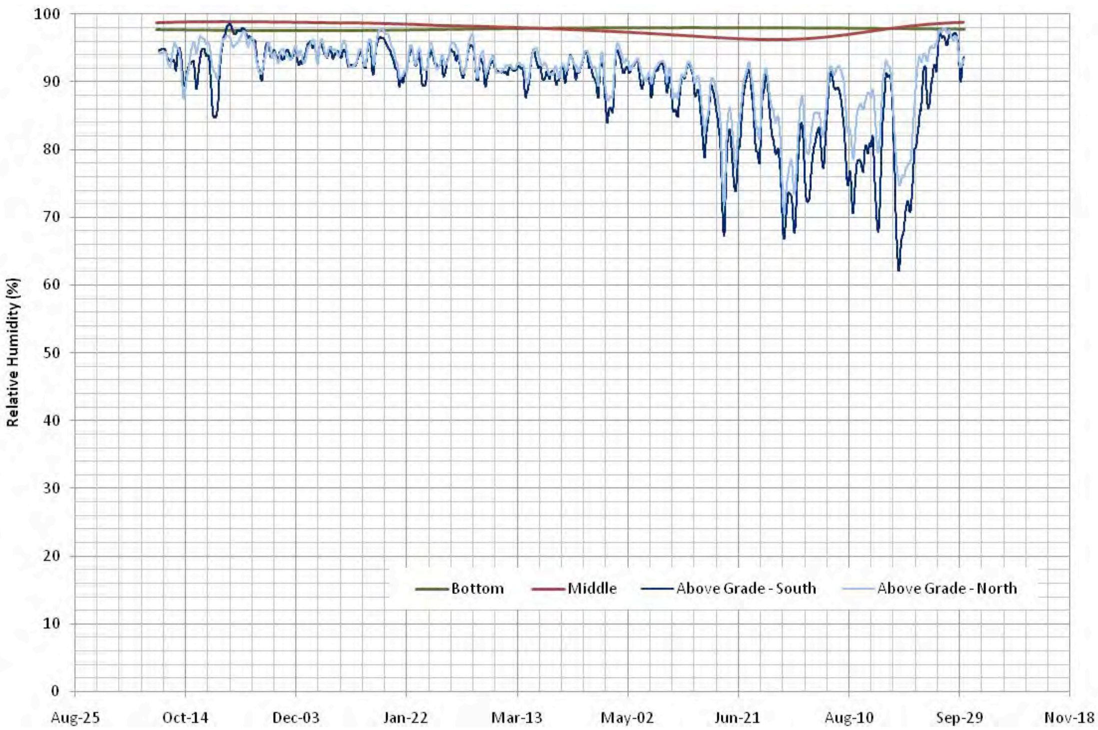

Figure 15 : Predicted Relative Humidity at the Surface of the Concrete Foundation Wall for Case 3

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 16 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.

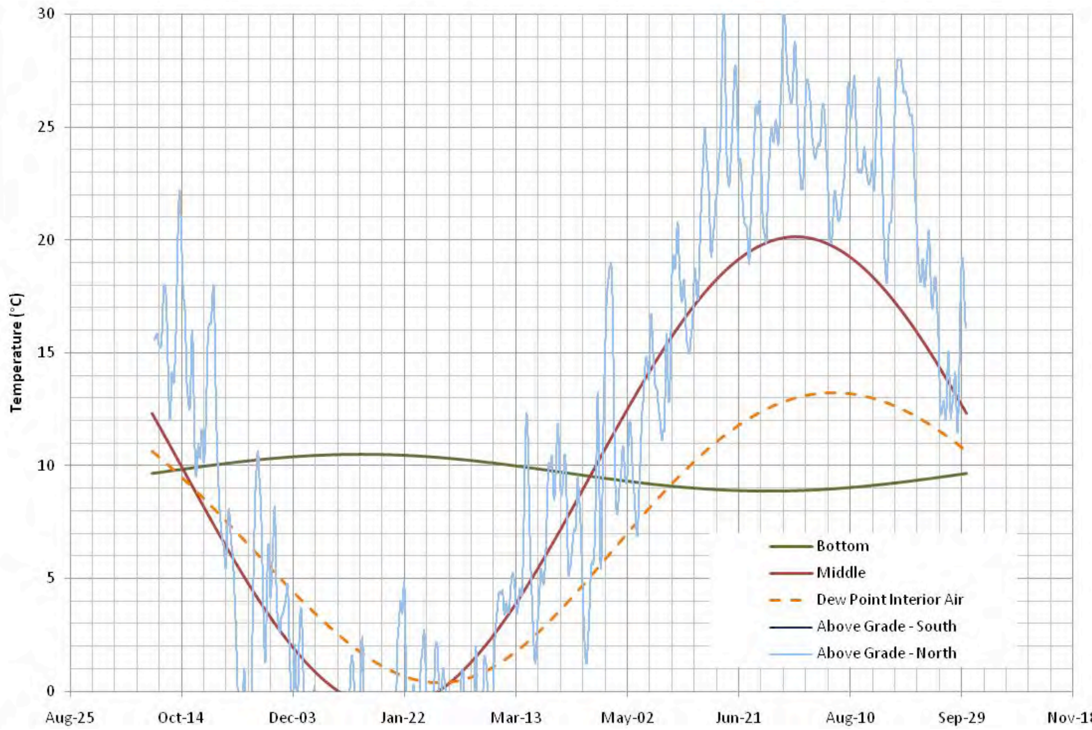

Figure 16 : Interior Air Leakage Condensation Potential for Case 3 Code Minimum Wall

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 17 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.

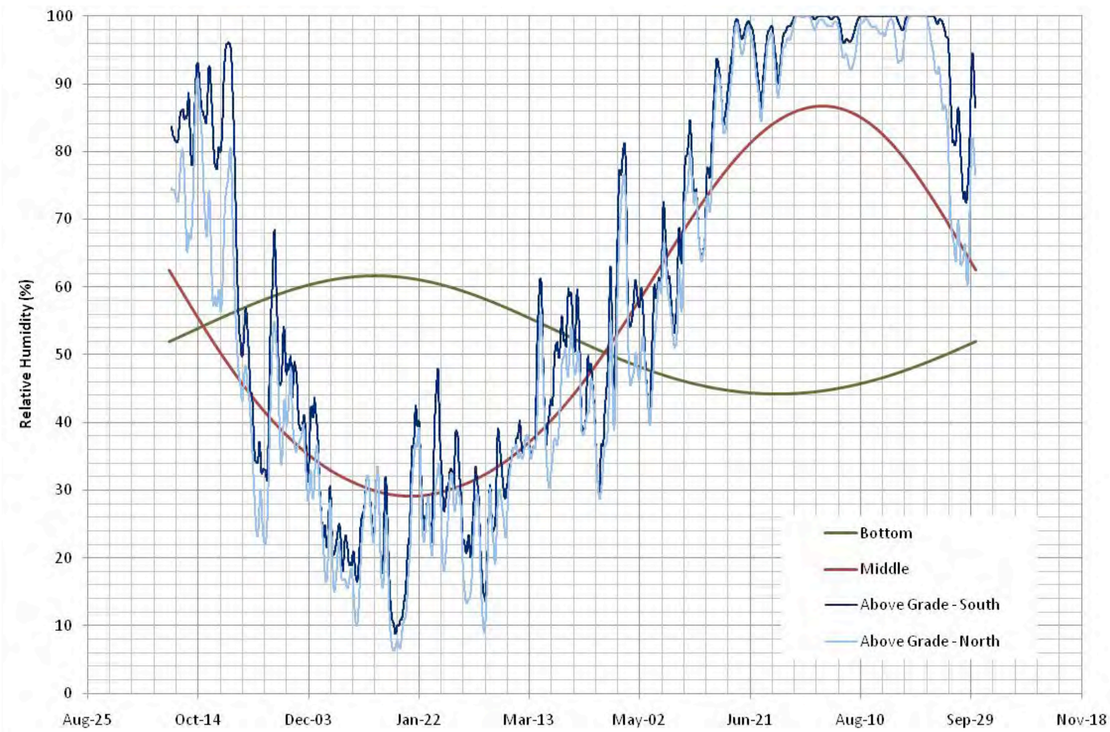

Figure 17 : Predicted Relative Humidity at the Surface of the Polyethylene Vapor Barrier for Case 3

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 be required to assess the durability of substituting EPS for XPS.

Figure 18 shows the predicted relative humidity at the interior surface of the XPS insulation 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 on the drywall, the relative humidity reaches approximately 100% at the top in the winter and at the bottom in the summer. By using a vapor retarding paint (approximately 1 perm) on the drywall, the relative humidity in both the winter and summer improved.

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. Increasing the R-value by using R-10 foam insulation reduces the moisture risks (See Case 8).

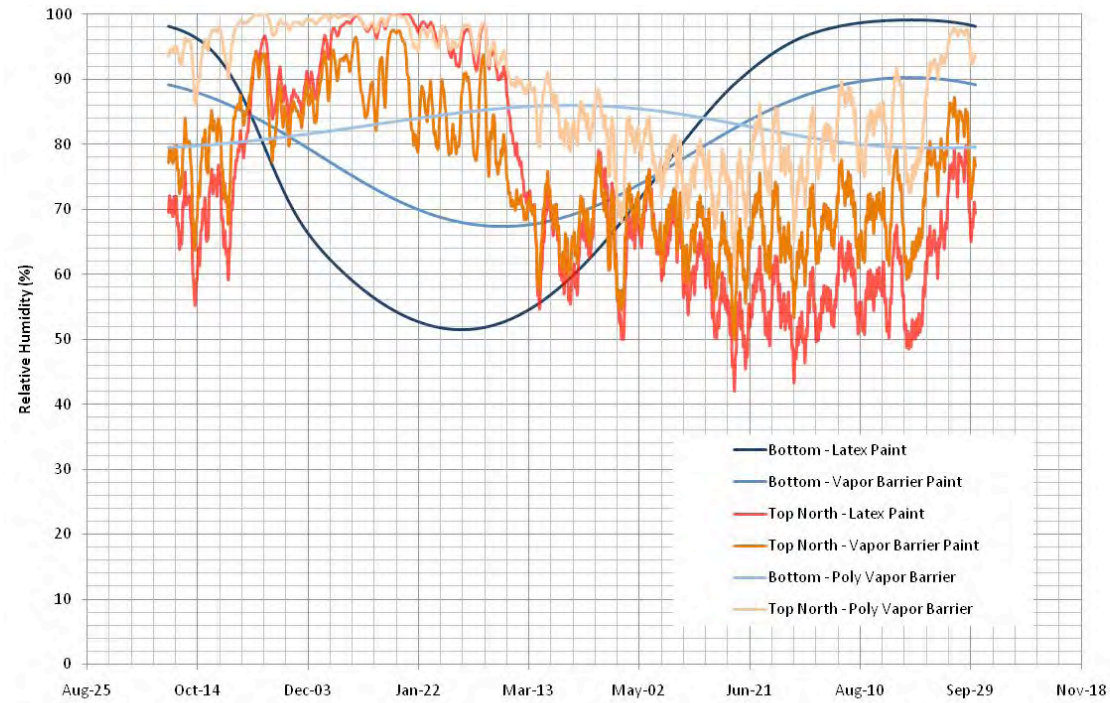

Figure 18 : Predicted Relative Humidity at the Interior Surface of XPS for Case 4

The air leakage condensation potential of Case 4 was much improved over Cases 2 and 3 as shown in Figure 19. There is still air leakage condensation potential so the drywall must be made as air tight as possible.

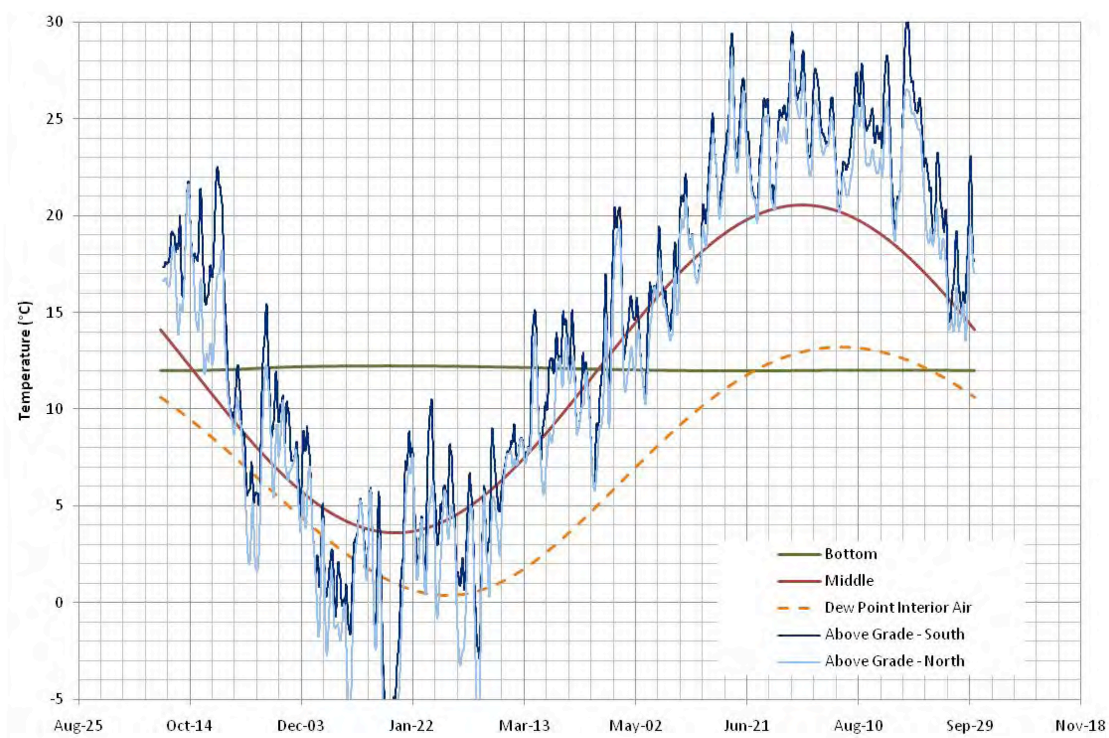

Figure 19 : Interior Air Leakage Condensation Potential for Case 4

Figure 20 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.

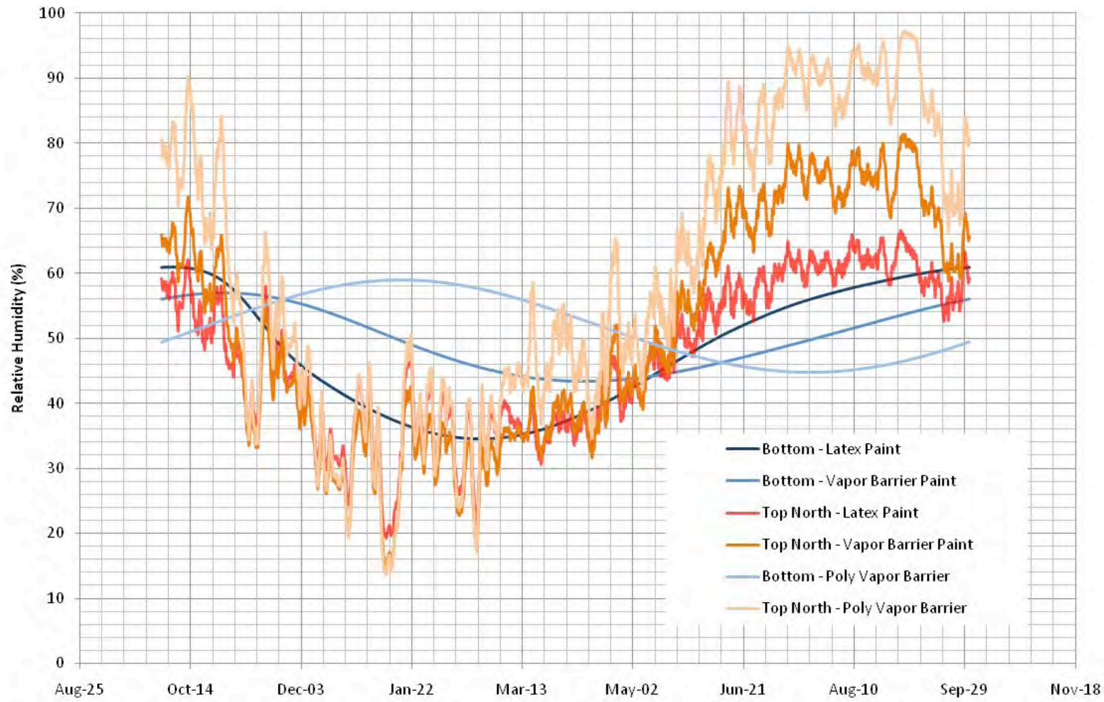

Figure 20 : Predicted Relative Humidity at the Exterior Surface of the Gypsum Board for Case 4

2.2.1. Case 5 - 2” XPS, 2” foil face 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.

2.2.2. Case 6 - 3.5” 2.0 pcf closed cell (cc) 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. A simulation was conducted to show the relative humidity at the interface between the spray foam and the concrete foundation wall (Figure 21). 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.

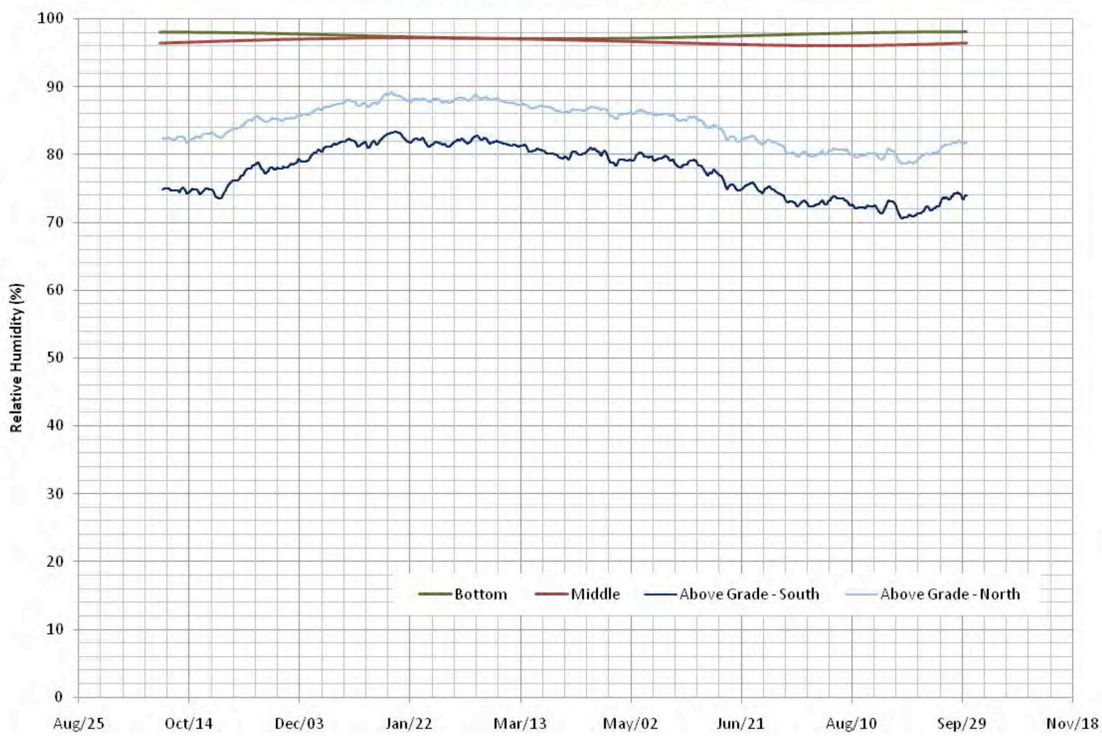

Figure 21 : Predicted Relative Humidity in the Interior Surface of the Foundation Wall of Closed Cell Spray Foam Case 6

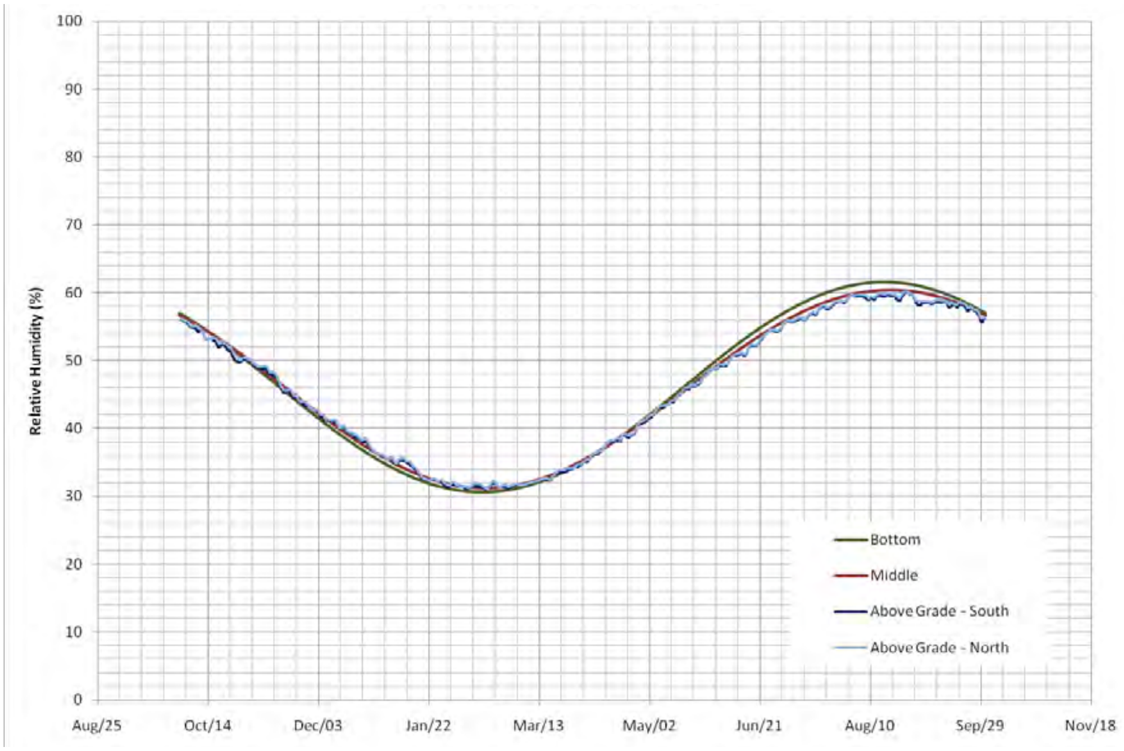

Figure 22 : Predicted Relative Humidity at the Interior Surface of Closed Cell Spray Foam Case 6

2.2.3. Case 7 - 6" 0.5 pcf open cell (oc) 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 was conducted in the interface of the foam and foundation wall after the system reaches equilibrium (Figure 23). Because neither concrete nor the spray foam is susceptible to moisture, there are no moisture related risks for this system, provided the interior surface is vapor permeable.

Figure 23 : Predicted Relative Humidity at the Interior Surface of the Foundation Wall of Open Cell Spray Foam Case 7

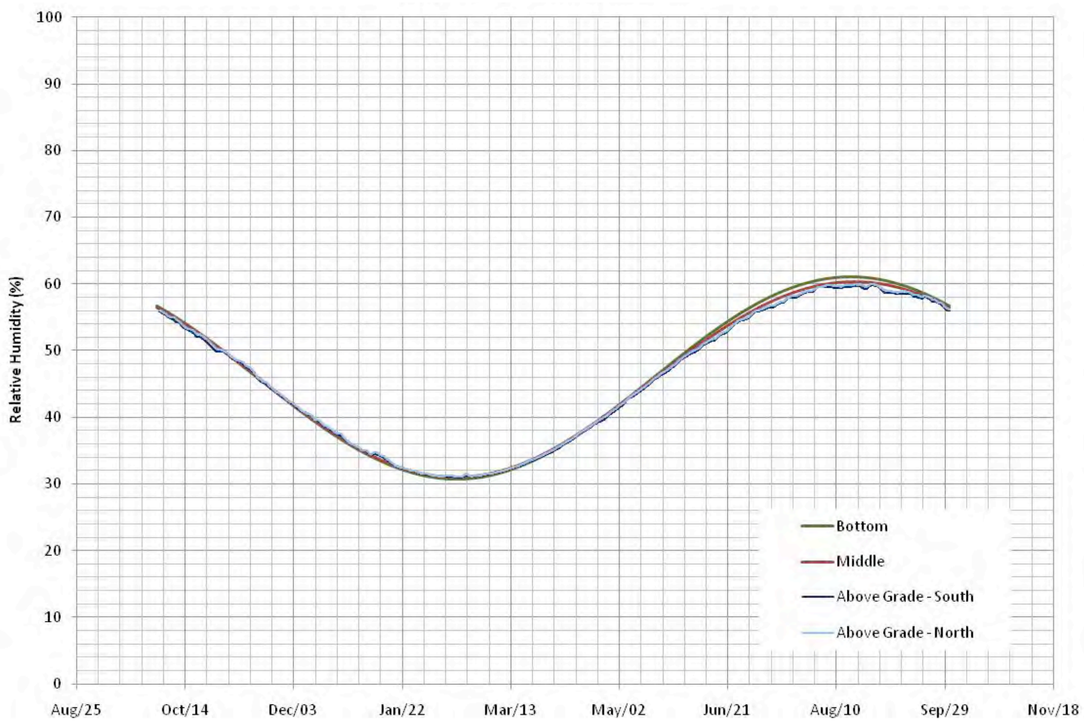

Figure 24 : Predicted Relative Humidity at the Interior Surface of Spray Foam of Open Cell Spray Foam Case 7

2.2.4. Case 8 - 2" XPS and 3.5" fibreglass batt

Case 8 is a good practical basement wall system. Figure 25 shows short periods of elevated RH at the interior surface of the XPS on the above grade portion (in the winter), and at the bottom of the wall (in the summer). Both the fiberglass batt insulation and the XPS are very moisture tolerant, and there is little risk of condensation under these simulated conditions.

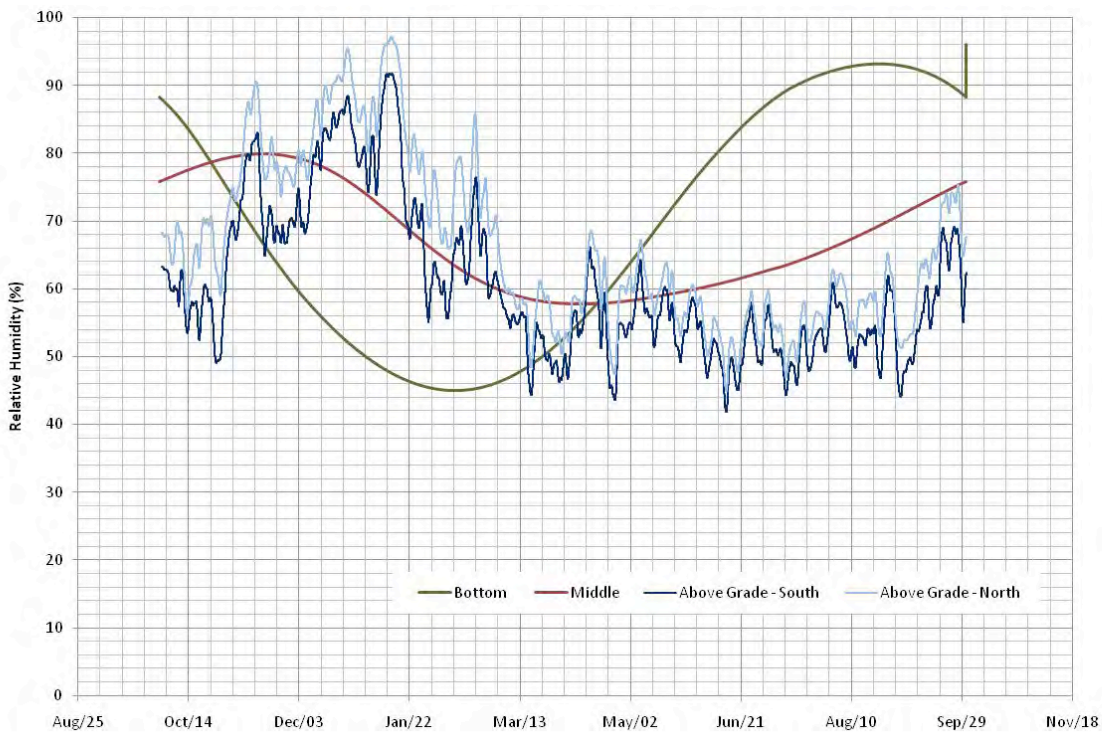

Figure 25 : Predicted Relative Humidity at the interior Surface of the XPS for Case 8

Figure 26 shows some periods during the year where there is a risk of air leakage condensation of interior basement air on the surface of the XPS insulation. It is important to ensure the XPS is well adhered and sealed to the foundation wall so there is no air leakage around the XPS. The risk of condensation only occurs on the above grade portion of the wall, and is worse on the north orientation than the south orientation where there are some solar gains.

The relative humidity between the drywall and fiberglass batt insulation is shown in Figure 27, and there are no risks of any moisture related durability issues.

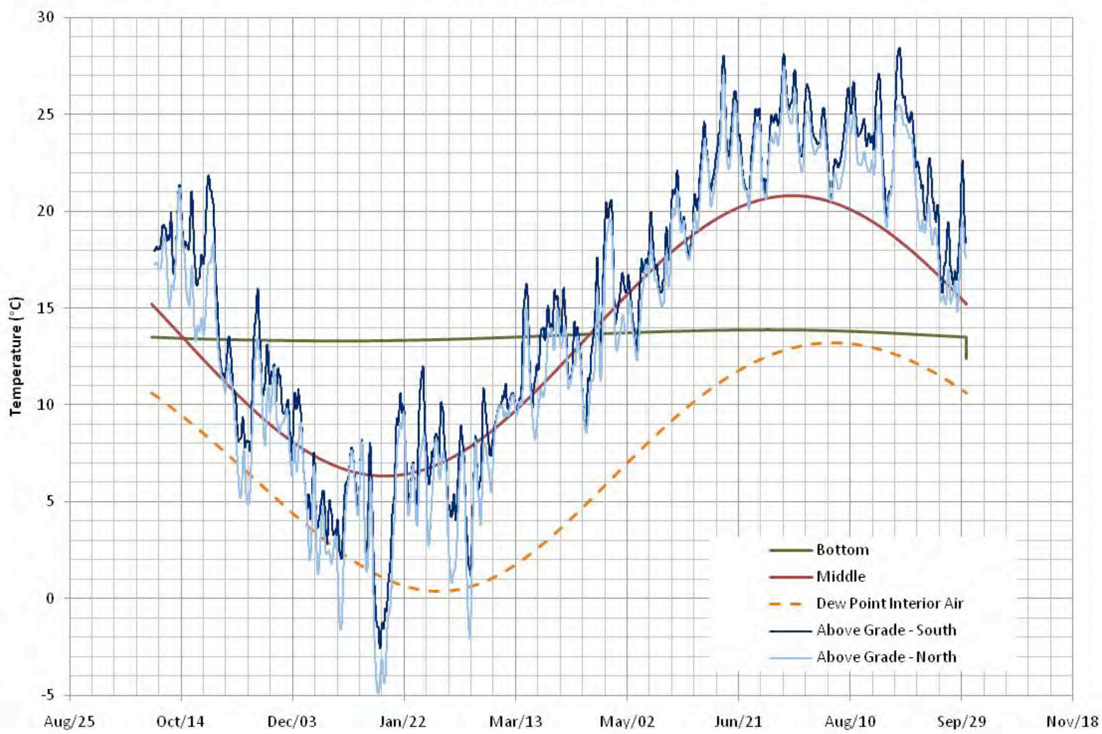

Figure 26 : Interior Air Leakage Condensation Potential for Case 8

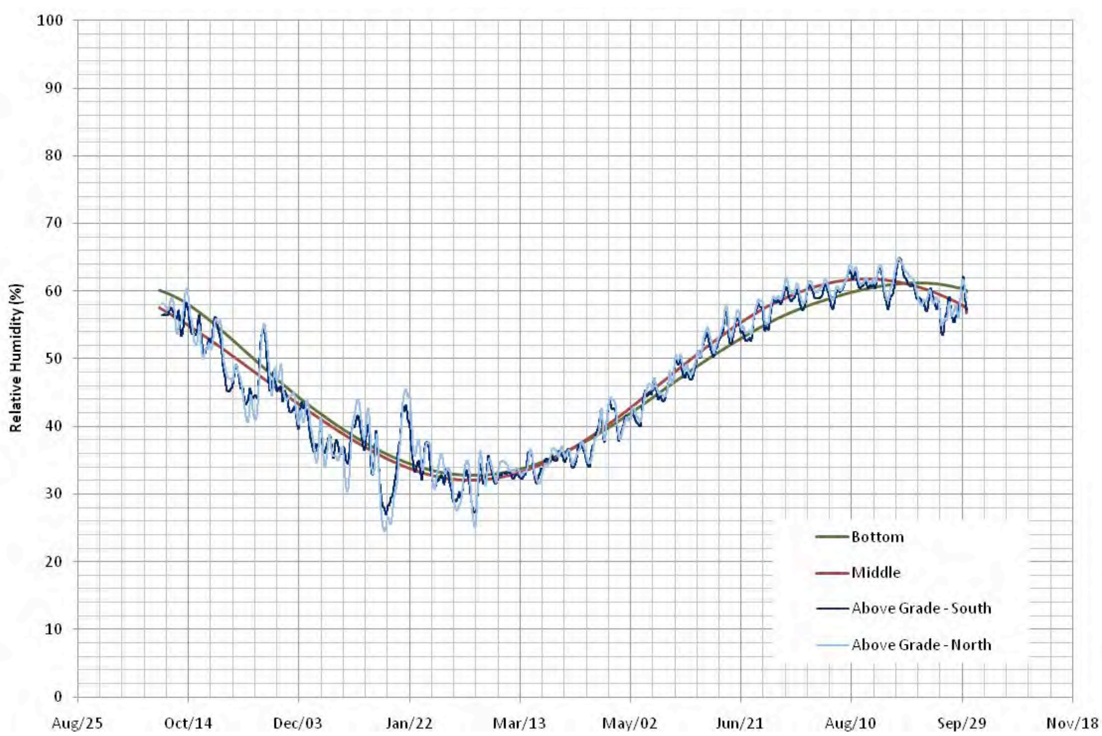

Figure 27 : Predicted Relative Humidity at the Exterior Surface of Gypsum Board for Case 8

2.2.5. 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.

2.2.6. 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. In Case 10, the inward moving moisture may increase the wood moisture content of the framing. Analysis showed that at the bottom of the basement wall the exterior of the framing will reach a predicted 85% and dry to 55% RH. At all other monitoring locations the predicted RH did not exceed 80%. This should be analyzed further, before being constructed, as it is a complicated three dimensional hygrothermal process with wood framing and spray foam. The wood is more thermally conductive than the foam, so the exterior surface of the stud will be warmer than the foam at the same depth. This will likely decrease the RH, but could, in some cases, increase the exterior temperature of the framing to more ideal conditions for mold growth.

2.2.7. 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 will 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.

2.2.8. 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.

2.2.9. Case 13 – ICF, 2” EPS on interior and exterior

Insulated Concrete Form foundations are a very durable and reliable construction strategy. The total of 4” of EPS 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 installed on the interior.

2.2.10. Case 14 - 2” XPS 5.5” Fibreglass Batt

Case 14 is the second 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. This wall is similar to Case 8, but with a higher R-value of air and vapor permeable fiberglass batt on the interior of the XPS. This wall performs similarly, but with slightly higher moisture related risks since the condensation plane temperature is kept lower at the top of the wall in the winter, and at the bottom of the wall in the summer.

Figure 28 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 28 : 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 29 : 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 30, 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.

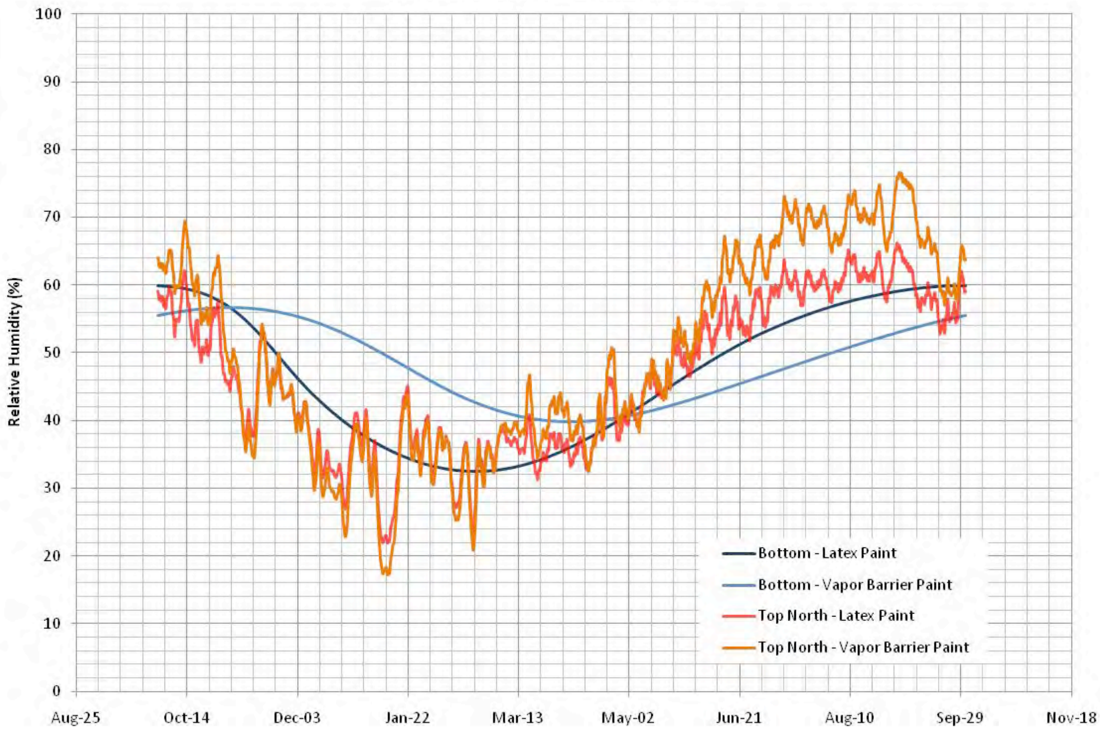

Figure 30 : Predicted Relative Humidity at the Exterior Surface of Gypsum Board for Case 14

2.2.11. Case 15 - 4" Foil-faced Polyisocyanurate 5.5" Fibreglass Batt

Case 15 is the highest R-value assembly in this study at an installed insulation R-value of R45 with 4" of polyisocyanurate (PIC) at R26 and an R19 fibreglass batt. This wall is similar to Case 14, but with a higher R-value of rigid foam board between the foundation wall and wood framing. This wall performs similarly, but with decreased moisture related risks since the condensation plane temperature is kept warmer by the higher R-value PIC.

Figure 31 shows there are elevated relative humidites (~90%) but no risk of condensation on the surface of the PIC throughout the year at any height on the wall.

Figure 31 : Predicted Relative Humidity at the interior Surface of the PIC for Case 15

There is practically no potential for air leakage condensation in the above grade portion of this wall system (Figure 32), and significantly less than Cases 8 and 14. Airtight drywall details can be used to minimize the potential for air leakage condensation.

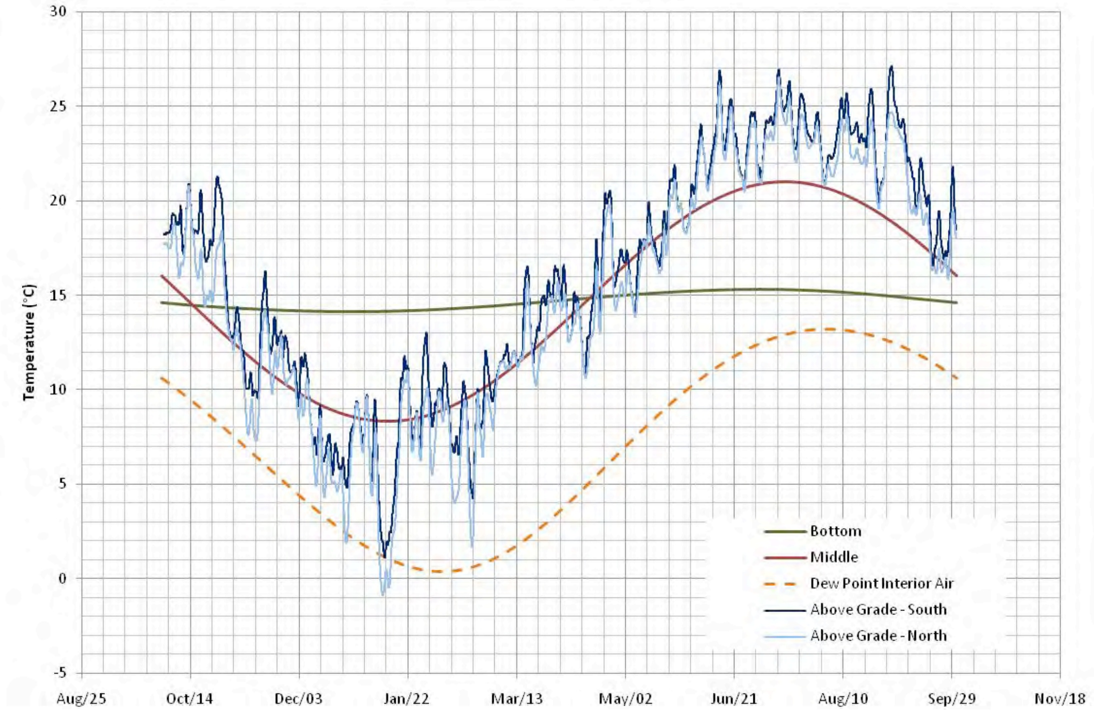

Figure 32 : Interior Air Leakage Condensation Potential for Case 15

The relative humidity was predicted at the exterior surface of the gypsum wall board in Figure 33, 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.

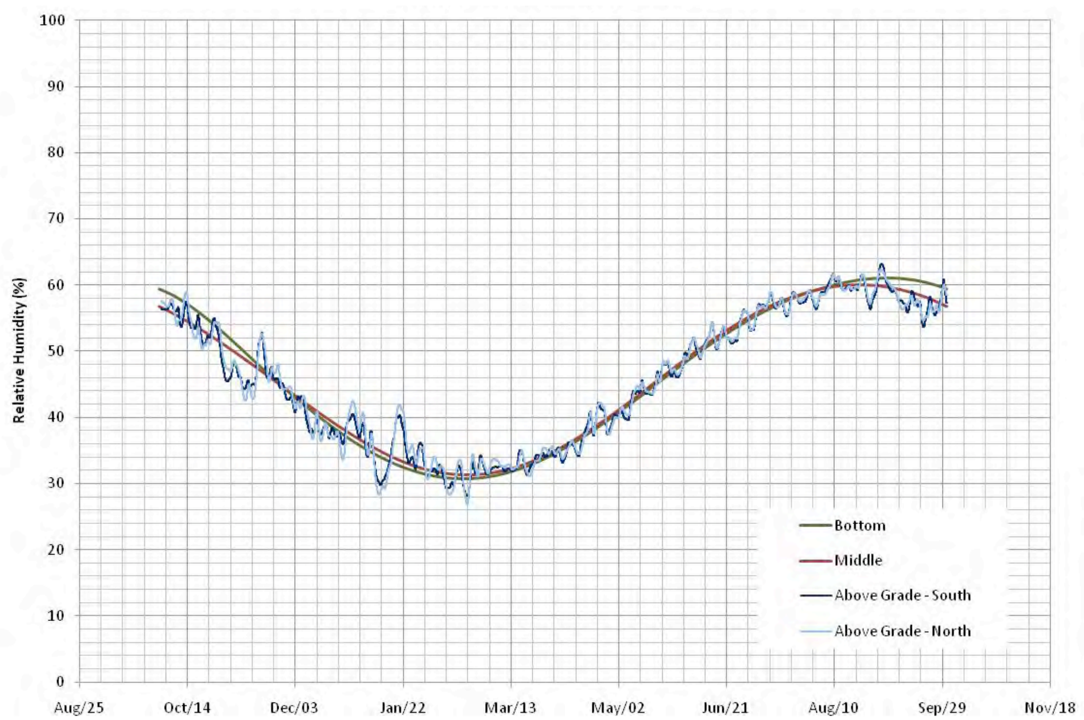

Figure 33 : Predicted Relative Humidity at the Exterior Surface of Gypsum Board for Case 15

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 because of 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.

At the time this report was written, some insulations, such as XPS and closed cell spray foams, have higher global warming potential than alternative insulations, 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 global warming than 1 kg of CO_2.

Research is being done to reduce the global warming potential in many cases, and changes are being made in the industry, so specific insulations should be reviewed on a case by case basis before being used to determine their global warming potential.

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 where the basement is conditioned. The uninsulated basement was included as a baseline for comparison purposes.

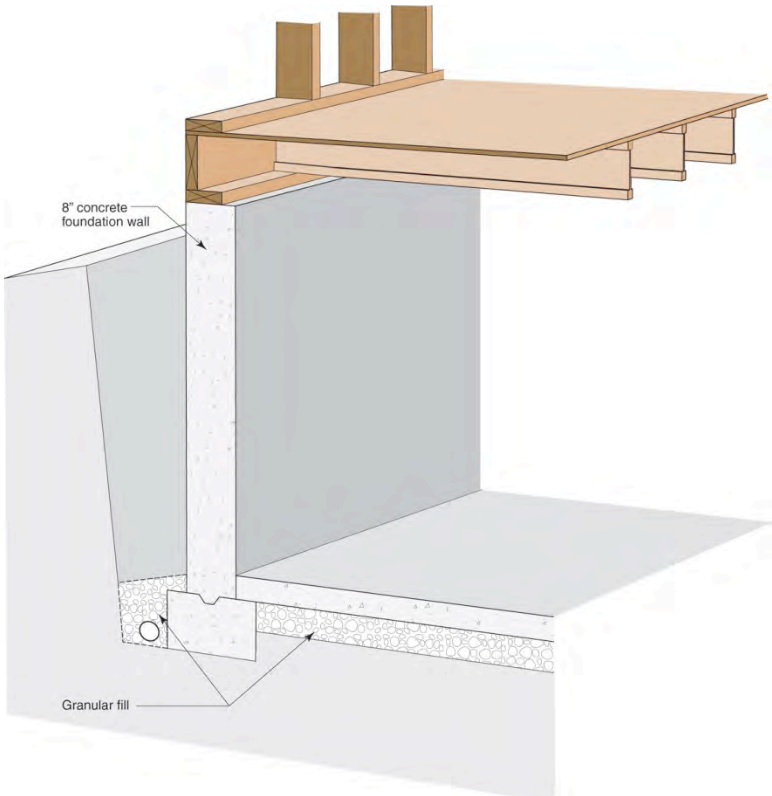

Figure 34 : Uninsulated Basement

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 13 and Figure 14), 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

According to the IECC, new residential construction of conditioned basements 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 recommend a 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.

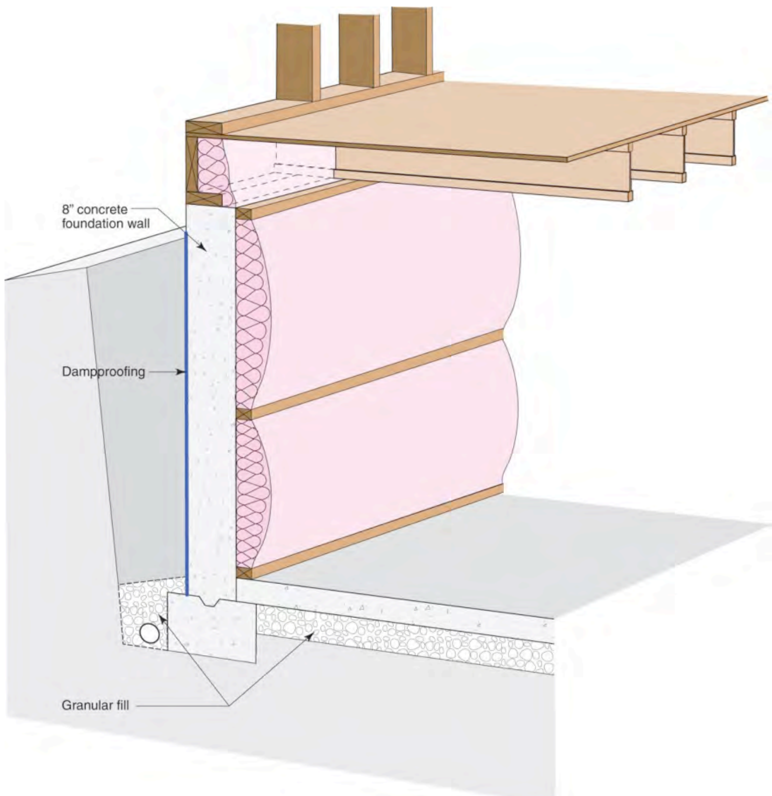

Figure 35 : Typical Basement Insulation Strategy

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 15, 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 16. 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.

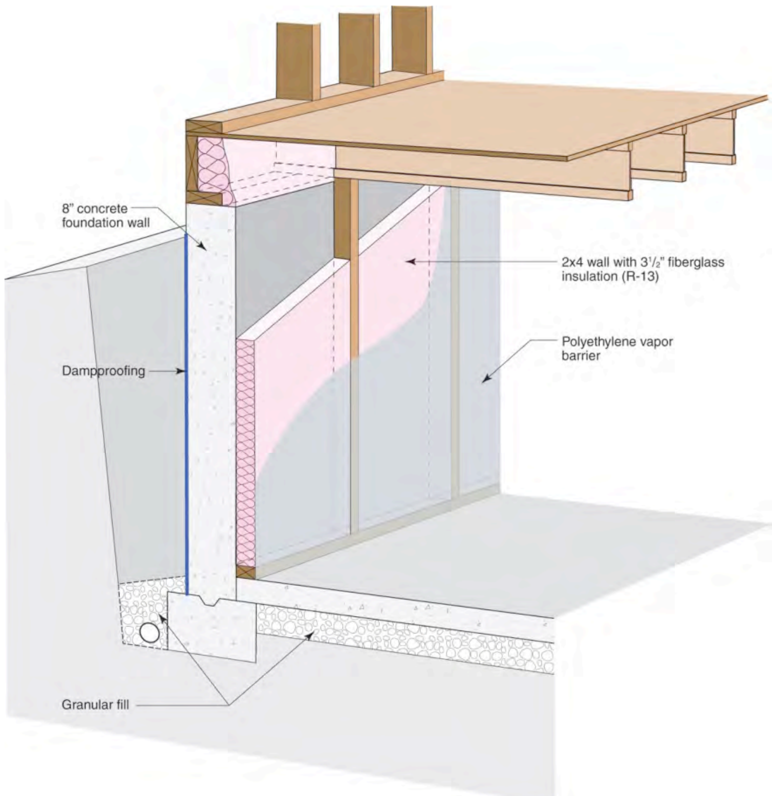

Figure 36 : Case 3 - 2x4 framed wall with fiberglass batt

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, a savings of 32.8 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 15). 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 16. 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 drywall easier.

3.4 Other Considerations

This wall construction technique is not recommended, because of the obvious moisture related durability issues observed in the field, and shown by simulations. The wood framing in this wall is at risk of 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.

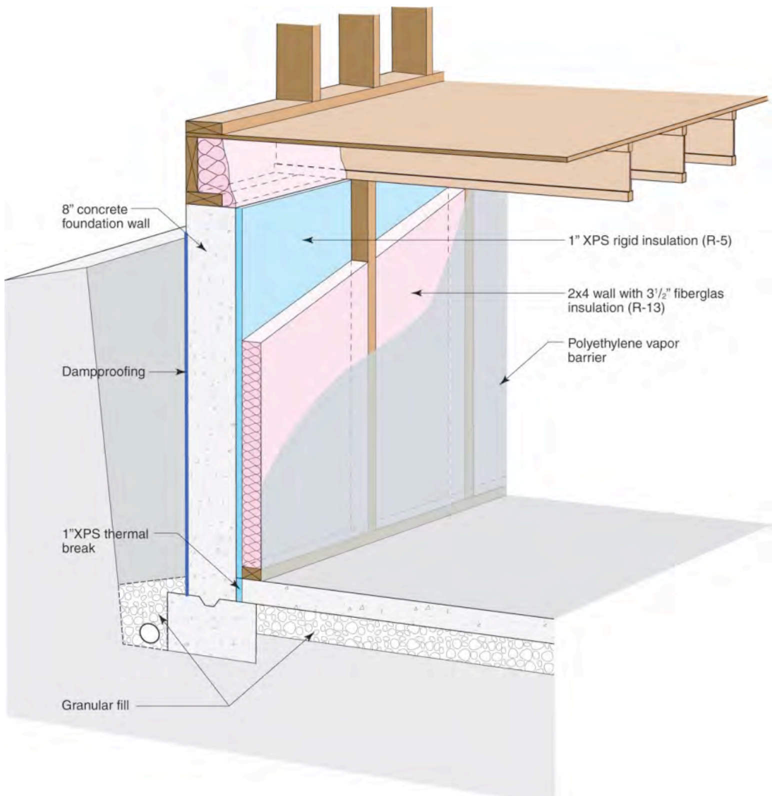

Figure 37 : Case 4 - 1"XPS and 2x4 framed wall with fiberglass batt

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.

The XPS insulation also increases the temperature of the condensation plane, minimizing condensation of elevated interior relative humidity. Figure 19 shows that there is still potential for moisture condensation but it is significantly less than Case 3.

Figure 18 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 an improvement over Cases 2 and 3, but there are even better options for thermal and moisture control 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 electrically wired to meet the electrical code, which drives up cost substantially.

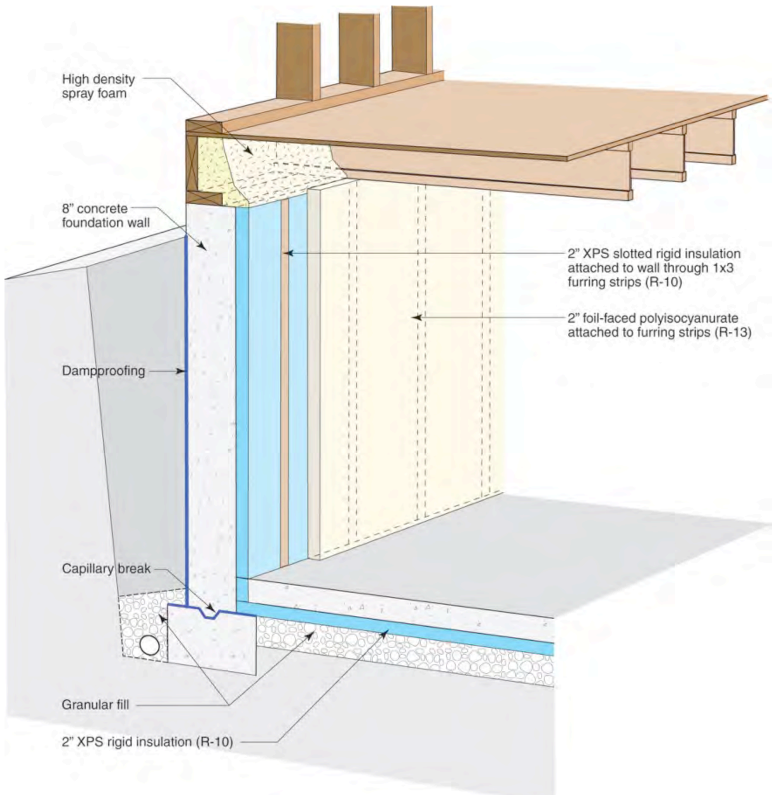

Figure 38 : Case 5 – 2” XPS, 2” foil faced polyisocyanurate (Recommended)

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 38, the predicted annual heating energy loss is 15.8 MBtus, an improvement of 40.8 MBtus over an uninsulated wall for the case study house.

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.

To finish the basement, drywall would be added, which obviates the need for fire control in the foam.

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.

Instead of using two different board foam insulations, it could be constructed with two layers of PIC, or two layers of XPS with drywall interior finish.

This basement insulation strategy is recommended as a durable, comfortable, and healthy basement system.

6. CASE 6 : 3.5" 2.0 PCF CLOSED CELL SPRAY POLYURETHANE FOAM

As shown in Figure 39, 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 as the thermal barrier.

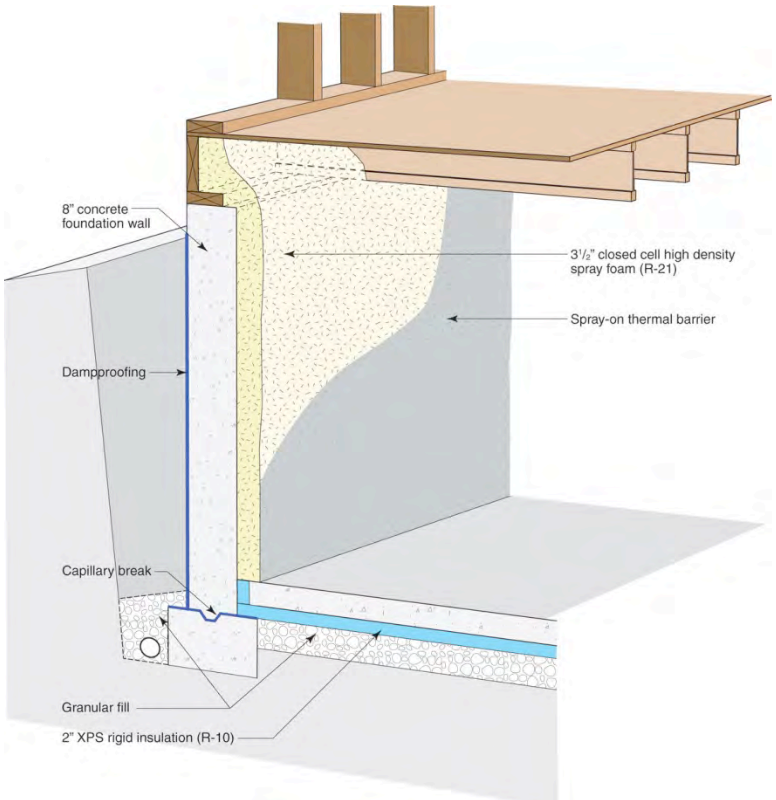

Figure 39 : Case 6 – Closed Cell spray foam

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 21 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 bridging, 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 have liquid water ingress issues.

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" 0.5 PCF OPEN CELL SPRAY FOAM

As shown in Figure 40, 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, or the basement can be finished with drywall.

Figure 40 shows XPS or foil-faced polyisocyanurate installed on the interior of the rimjoist and foundation wall. The WUFI simulations for the foundation wall were conducted without this layer of board foam in Minneapolis, and it was found that there were no moisture related issues, in part because the concrete is not as susceptible to moisture. Installing board foam on the foundation wall will further increase the factor of safety over the predicted results and may be required in colder climates. The rimjoist was not simulated in this study, since it was simulated previously, but because of the susceptibility of the wood to moisture related durability issues, and the vapor permeance of the foam, it is recommended to use the board foam at the rim joist to limit vapor diffusion and increase the temperature of the potential condensation surface.

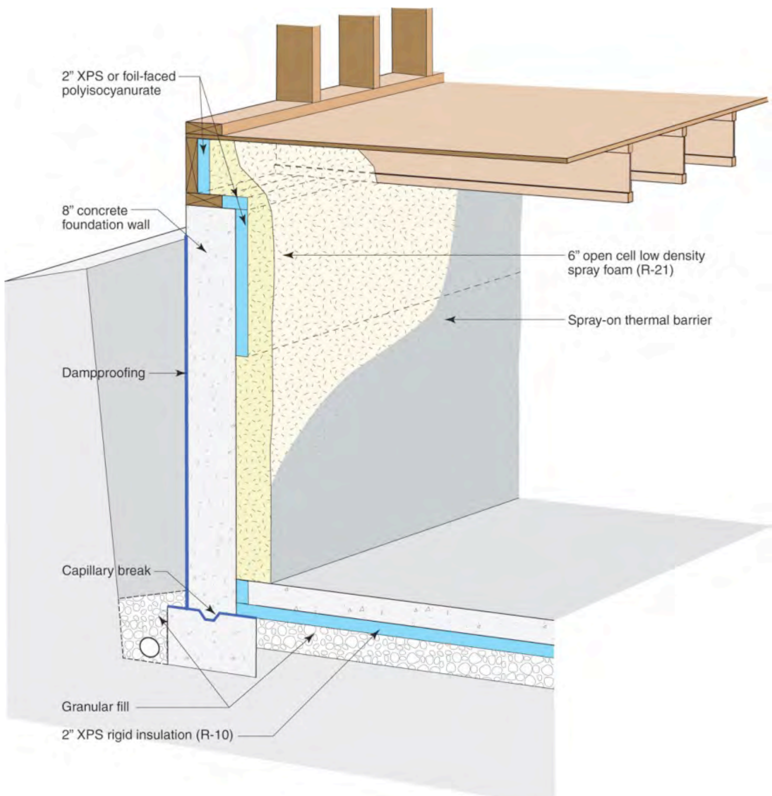

Figure 40 : Case 7 – Open Cell Spray Foam (Recommended)

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 40 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 24).

Low permeance interior wall finishes (< Class III) should be avoided with this construction strategy so the material characteristics of the spray on thermal barrier must be considered.

7.3 Constructability and Cost

Open cell spray foam is less expensive than closed cell spray foam but does decrease the interior useful space and vapor control should be considered for this system.

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 do not 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

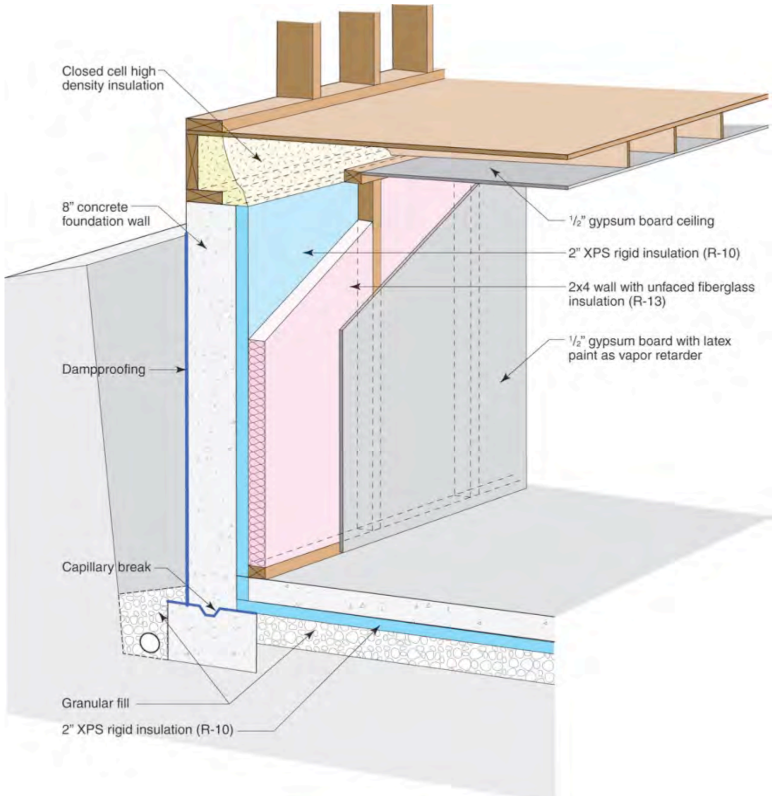

Figure 41 : Case 8 – 2"XPS, 2x4 framing with fiberglass batt

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 15.8 MBtu for the example house.

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 fiberglass 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

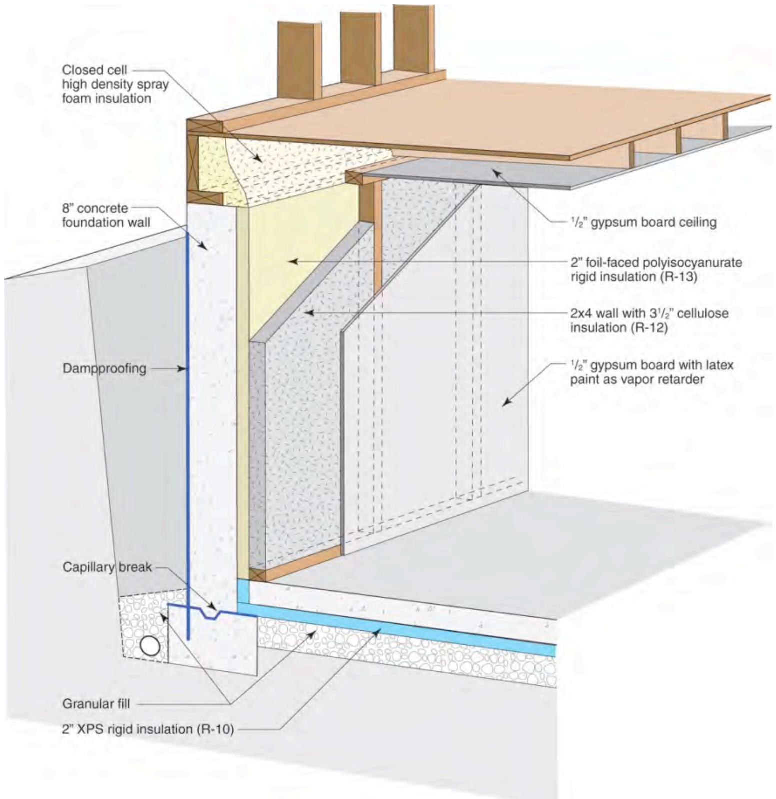

Figure 42 : Case 9 – 2" polyiso, 2x4 framing with cellulose

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 fiberglass batt or spray fiberglass.

10. CASE 10 : 6" 0.5 PCF SPRAY FOAM WITH 2X4 FRAMING OFFSET 2.5" FROM CONCRETE

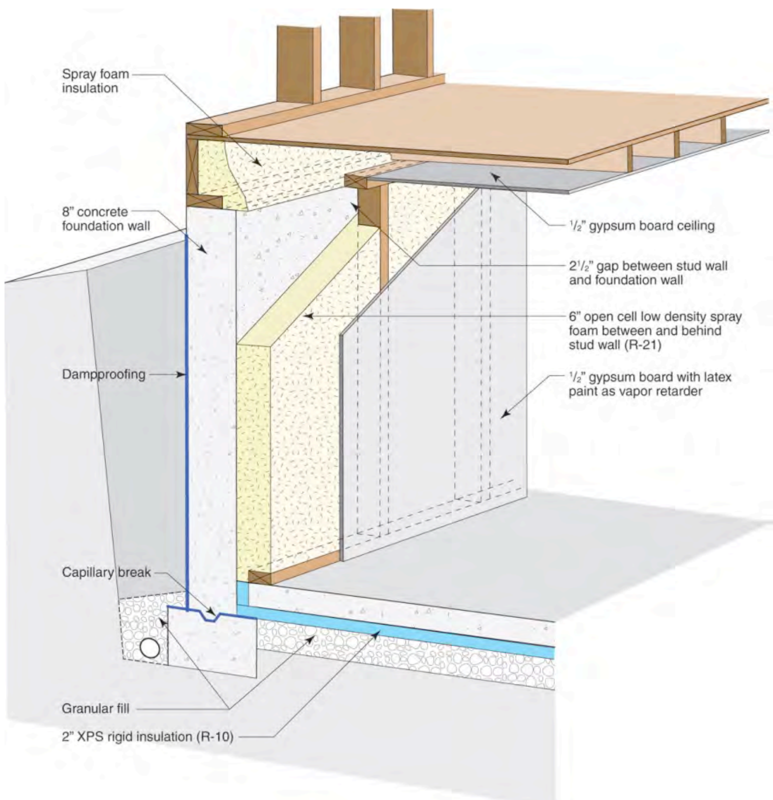

Figure 43 : Case 10 – 6" open cell foam

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 24).

Low permeance interior wall finishes should be avoided with this construction strategy.

10.3 Constructability and Cost

This solution is more practical 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

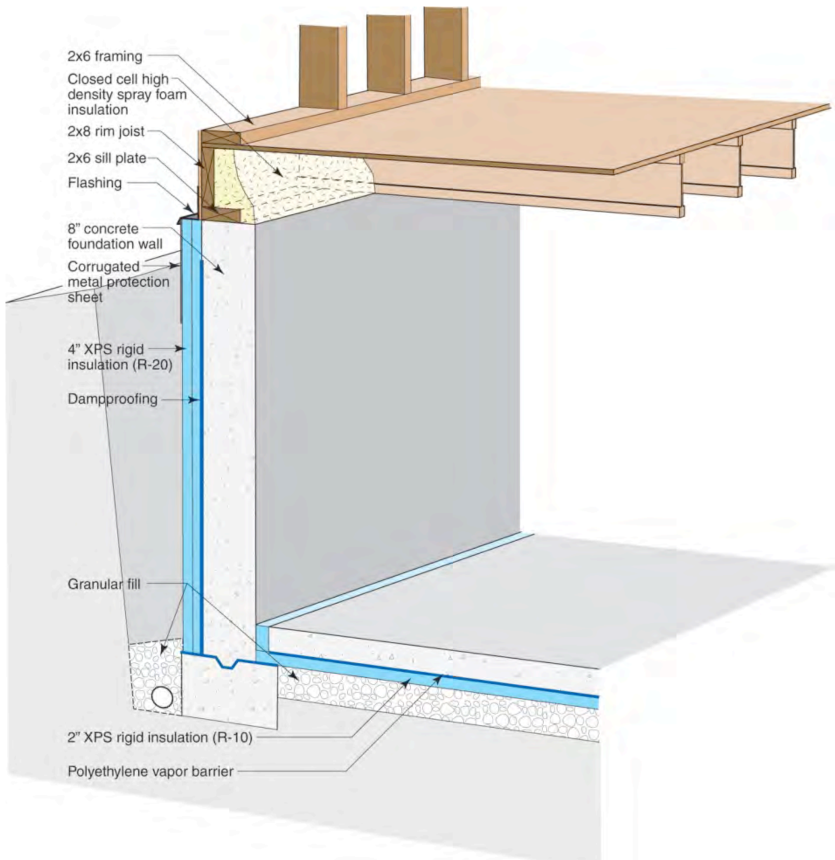

Figure 44 : Case 11 – Exterior XPS insulation

11.1 Thermal Control

This proposed wall system has an installed insulation R-value of R20 and results in heating energy loss 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 thermal disadvantage of this system is that there is a thermal bridge through the concrete wall, and footing into the ground.

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 grade 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

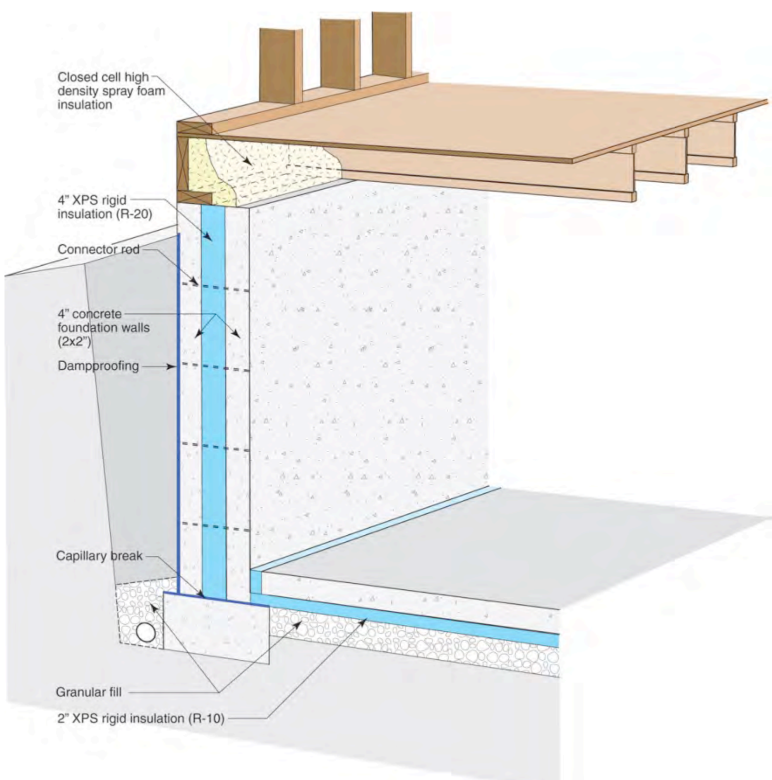

Figure 45 : Case 12 – Interstitial XPS Insulation

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 may be 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 45). 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

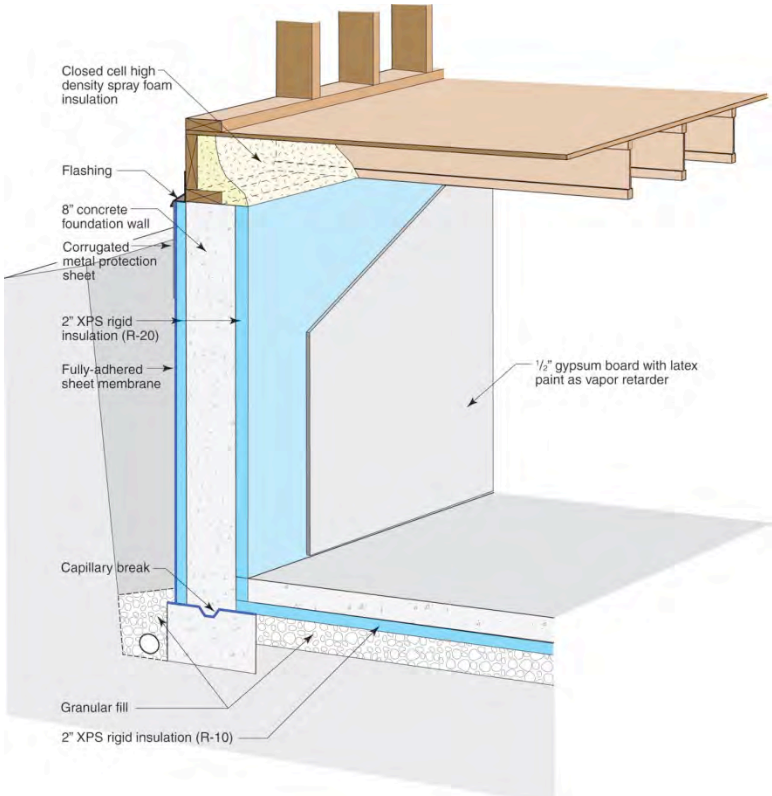

Figure 46 : Case 13 –Insulated Concrete Forms (ICF)

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. Since additional interior vapor control should be avoided, no more than latex paint should be used on the interior surface of the drywall.

14. CASE 14 : 2" XPS, 2X6 FRAMING WITH FIBREGLASS BATT

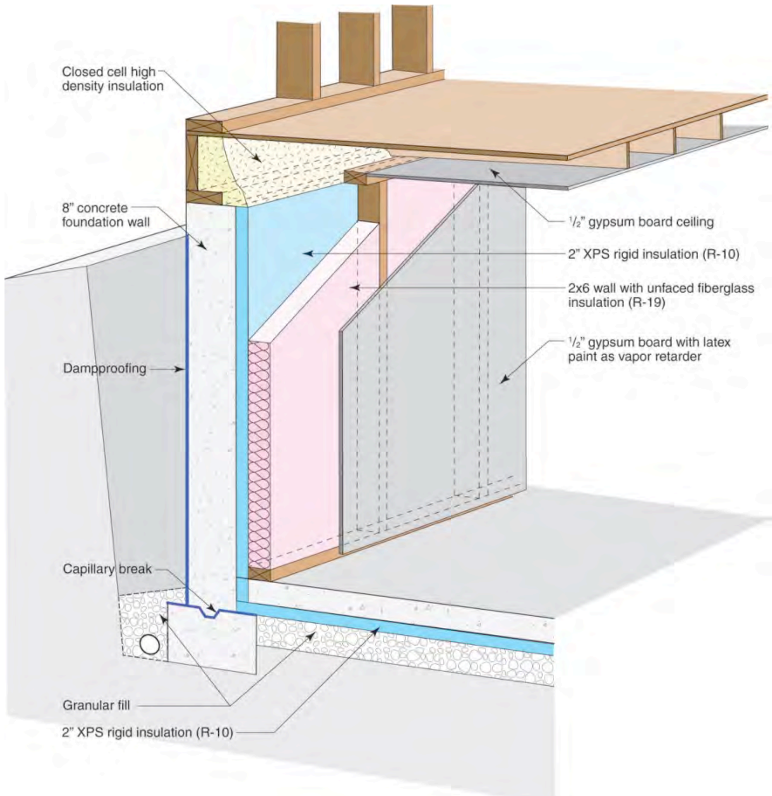

Figure 47 : Case 14 – 2"XPS, 2x6 framing with fiberglass batt

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. 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 28), and that there is some condensation potential alternating with periods of drying potential at the top of the foundation wall. (Figure 27). 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

15. CASE 15 : 4" PIC, 2X6 FRAMING WITH FIBREGLASS BATT

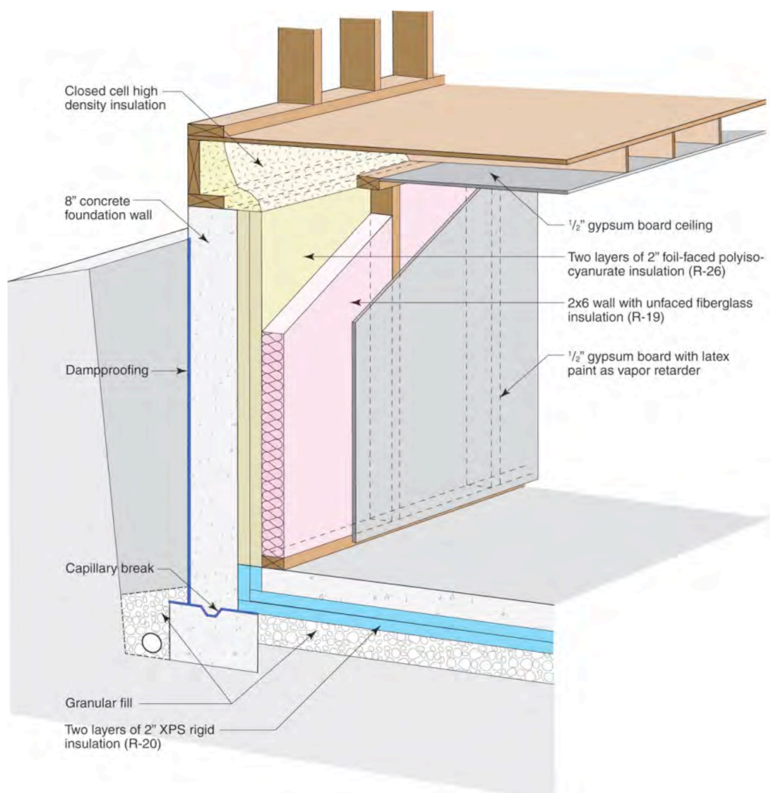

Figure 48 : Case 14 – 2"XPS, 2x6 framing with fiberglass batt

15.1 Thermal Control

This foundation wall system has a calculated parallel path R-value of R45.0, and a yearly heating energy consumption of 11.09 MBTus assuming R20 under the slab and in the thermal break.. This is the highest Rvalue foundation system in this study, and is likely not cost effective unless the rest of the house is super insulated and airtight.

15.2 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 slightly elevated in the winter months (Figure 31), but does not exceed 90%. There is almost no condensation potential (Figure 32) except on the upper wall of the north orientation for two very short periods. There is virtually no 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.

15.3 Constructability and Cost

This wall system is slightly more expensive than Cases 14 by changing the 2" of XPS to 4" of foil-faced polyisocyanurate. 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.

15.4 Other Considerations

Depending on site specific conditions, and local costs, this wall is likely not economical to build unless the house is very highly insulated and airtight.

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	Description	location	Installed Insualation R-value	Parallel Path Method	underslab and thermal break R10	MMBtus Annual Energy Losss
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 slab / Y t.break	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" EPS int. and ext.	int/ext (ICF)	15	na	Y	18.6
14	2" XPS, 2x6 wood framed, R19 fiberglass batt	interior	29	28.7	Y	14.8
15	4" PIC, 2x6 wood framed, R19 fiberglass batt	interior	45	45	Y (R20)	11.1

Analysis showed that even a small amount of insulation on the foundation wall decreased the heating energy losses significantly compared to an uninsulated basement, but 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 should be based 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 worst, 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 Case 6 with 3.5" of 2.0pcf closed cell spuf and Case 7 with 6" of 0.5 pcf oc spf. 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/drying)	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: 2.5" 0.5 oc spuf, 2x4 framing with same foam	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 wall	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**
Case 15: 4" PIC, 2x6 framing with fgb	5	5	3	2	2	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. Some work has been conducted already by Kohta Ueno of Building Science Corporation as part of a Building America Foundations Experts Group Meeting.

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.

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About this Report

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

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