Field Monitoring and Hygrothermal Modeling of Interior Basement Insulation Systems

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Abstract:

Interior insulation of basement walls has been linked to moisture accumulation, damage, and mold growth within the vulnerable portions of the assembly. Four basement interior insulation wall systems were installed and monitored in a house in a cold climate; these assemblies included those with and without polyethylene vapor control layers, as well as extruded polystyrene foam for comparison.

Measurements indicated that summertime inward vapor drive occurs in the above-grade portions of the walls, but that an interior vapor control layer reduces the amount of moisture transmitted from the interior in the winter. However, both framed walls showed wood moisture content levels within acceptable limits, with and without polyethylene.

The measured boundary conditions from field monitoring were then used in one-dimensional hygrothermal simulations. Validation simulations were performed, followed by extrapolations that varied interior conditions, assemblies, and climate location. The validity of this simulation tool for designing interior basement insulation assemblies is discussed.

Introduction

Due to a combination of demand to lower energy use, stricter building energy codes, and the desire for maximizing finished space in a house, an increasing number of basements are being finished and insulated (often on the interior). However, this practice has resulted in more moisture-related failures of their wall insulation systems (Lstiburek 2006), including condensation and/or moisture accumulation within the vulnerable portions of the assembly.

The research reported in this paper is aimed at increasing the understanding of the hygrothermal performance of interior basement insulation systems by a combination of field monitoring of four assemblies and one-dimensional computer modeling. The work described here is part of a Canada Mortgage and Housing Corporation (CMHC) sponsored research program to determine the significance or insignificance of potential moisture problems due to an impermeable polyethylene layer in above- and below-grade walls (Wilkinson et al. 2007).

Background

Heat and moisture flows in the basement environment have been addressed by many researchers, including Timusk & Pressnail (1997), Cheple and Huelman (2001), and Ueno and Townsend (2006). Some important points that inform this research include the following:

- The soil adjacent to the basement walls is for all effective purposes at 100% relative humidity (saturation) throughout the year, except for the very topmost surface interface. As a result, the dewpoint (absolute moisture content) of the soil surrounding the basement is equal to its temperature.
- The thermal mass and insulating value of the soil moderate temperatures seen by the below-grade portions of the basement wall. As a result, the temperatures seen at the below-grade portion of basement walls are warmer in the winter and cooler in the summer than the above-grade portion. This effect increases with depth in the soil. Furthermore, the thermal mass of the soil causes a time delay of the below-grade temperatures relative to air temperatures (also increasing with depth). One example of this phenomenon is that condensation can occur on the inner face of the lower portions of wall during the spring, if exterior dewpoints are rising but the deep soil is still cool from the winter.
- Based on the two previous points, the vapor pressure and temperature conditions on both sides of the wall can be plotted on a psychrometric chart (for example, see Timusk, 1997). This presentation, which compares the soil boundary conditions with exterior air conditions (summer and winter), shows that the relatively constant temperature/dewpoint of the lower wall and floor slab will dehumidify the interior air in summer, and humidify in winter. In addition, if typical interior temperature and humidity conditions are plotted, it demonstrates that in most cases the vapor drive is inward (i.e., the wall is drying to the interior). The exception would typically be the above-grade portion of the wall during the wintertime; this is the case where interior vapor control is needed to prevent moisture accumulation and condensation at the concrete-insulation interface.
- Moisture is the primary cause of failure in these assemblies: it occurs when wetting exceeds drying, resulting in net accumulation. The following moisture sources may be acting alone or in combination in these failures (Rose 2005). Understanding the relative magnitude of various moisture transport mechanisms is useful in setting priorities for the design of the assembly. The mechanisms, in rough order from highest transport rate to lowest, are:
    - Bulk liquid water transports water at the greatest rates, as seen in massive water events such as flooding due to exterior or interior sources. This fact stresses the importance of keeping liquid water away from the foundation, with such measures as directing runoff away with

    eavestroughs and downspouts, and proper grading. Adding a drainage system to the wall, for instance with a dimpled drainage mat, reduces bulk water exposure of the concrete significantly. In addition, control of rising groundwater with a footing drain system is vital.
  - Liquid capillarity is a significant moisture transport mechanism; it is the absorption and transport of liquid water through the pore spaces of a porous medium such as wood or concrete. It is commonly referred to as "wicking;" an example would be water movement from the concrete footing sitting on wet soil into the bottom of a basement wall.
  - Air transported water vapor can be an important transport mechanism; it can both act across layers of an assembly, as a leak (e.g., warm humid interior air leaking into a cavity and condensing on a cold surface in winter), or within a layer (e.g., convective looping of air from one side of an insulated cavity to another, transporting moisture).
  - Vapor diffusion is the slowest-acting mechanism, although it often receives the most attention in regulations and codes (i.e., requirements for a vapor barrier). In common building applications, air transport typically moves moisture at rates orders of magnitude faster than vapor diffusion; however, vapor diffusion can still cause failures if excess wetting or inadequate drying is available.
- There is a significant amount of construction moisture in block or site-cast concrete basement walls. This moisture can cause damage if it accumulates in a vulnerable part of the assembly; a design goal is to let concrete dry out without causing harm to the remainder of the wall, or to safely contain the moisture.
- The critical moisture level for assembly failure is tied to the onset of mold growth initiation and amplification. There are several threshold levels stated in literature; typically, surface relative humidity levels below 80% or 20% moisture content (by weight) in wood are considered safe. Recent research (Doll 2002, Black 2006) has indicated that strong mold growth is linked with the presence of liquid water, as opposed to high relative humidity levels.
- The lowest-risk approach to basement insulation is to apply the insulation to the exterior; this is in line with concepts long known in the field of building science (Hutcheon and Handegord, 1983). This approach eliminates the need for interior vapor control (as there is no cold condensing surface), and strongly reduces the chances of seasonal condensation on the lower portions of the wall. More importantly, exterior insulation protects against both bulk water and capillarity, by providing a robust drainage plane and capillary break from liquid ground water. (Kesik et al. 2001). However, the building industry has proven to be reluctant to adopt this practice, due to construction sequencing issues, insect control, and difficulty in protecting the above-grade portion of the insulation.
- The lowest risk approaches for interior insulation of basement walls use non-moisture sensitive semi-vapor permeable materials at the interface between the concrete and the insulation (Lstiburek 2006). Alternately, in foundations known to leak liquid water, insulation assemblies specifically designed to safely drain this water can be retrofitted to the interior.

Previous Research

A selection of field surveys, simulation, and experimental work focused on interior insulation of basements is presented here:

Robert W. Anderson and Associates (1989) performed a field survey of 42 houses in Minnesota, measuring moisture content of wood framing of interior insulated basement walls. They included walls both with and without a polyethylene vapor retarder; the installation of the polyethylene was classified as "excellent," "good," or "poor" (i.e., from "air sealed" to having "many tears and rips"). Measurements were taken in both spring and summer; higher moisture contents were seen in the summer, both above and below grade. Some condensation was noted on the exterior side of the polyethylene during the summer at the above-grade portion. There was no correlation between the quality and/or presence of a vapor retarder and framing moisture content;

walls without polyethylene did not show excessive moisture content levels. In addition, the authors noted that the polyethylene inhibited the drying of incidental wetting (such as leakage due to improper drainage), and suggested that it might be better to omit this layer.

Swinton and Karagiozis (1995) examined the phenomenon of condensation on the exterior side of the polyethylene vapor barrier during spring and summertime, at the above-grade portion of the wall. This problem is caused by inward vapor drives from the damp concrete; when there is an inward thermal gradient, the moisture moves inwards and condenses on the polyethylene. They replicated this problem using two-dimensional hygrothermal modeling in a Montreal climate and demonstrated that using semi-permeable materials (building paper) on both sides of a fiberglass batt cavity had the best overall performance. Although removing the interior polyethylene layer eliminated the summertime problem, it resulted in moisture accumulation at the concrete-insulation interface during the winter.

Goldberg has tested a variety of interior basement insulation configurations at a Minnesota test facility. After testing frame walls with fiberglass insulation (Goldberg and Huelman 2001), she recommended an assembly with polyethylene on both sides of the stud bay, as adopted by the Minnesota building code. However, a 2002 addendum provided warnings against using this assembly in "superficially dry" basements, which would accumulate moisture behind the exterior polyethylene. Tests were also run using a variable permeability vapor control layer made of polyamide-6 (PA-6) (Goldberg and Gatland 2006). The PA-6 wall experienced minimal condensation during the summertime, and was able to dry inwards, unlike similar polyethylene walls. The PA-6 had similar monitored performance to Kraft-faced batts. In addition, some walls were constructed with a latex elastomeric waterproofing on the concrete surface. These walls had noticeably higher wintertime condensation than the uncoated concrete walls (which largely showed only surface dampness), due to the elimination of the storage capacity of the hygroscopic material, by the hydrophobic dampproofing layer.

Zuluaga et al. (2004) examined seven interior basement wall insulation assemblies in a test installation in the Chicago area; they included two rigid insulation systems (foil-faced polyisocyanurate and expanded polystyrene), two fiberglass blanket systems (perforated and unperforated), and three types of framed walls with fiberglass insulation (encapsulated batts, unfaced batts, and Kraft-faced batts). They were run for two years; the summer conditions were changed between low relative humidity, and high RH between years. The moisture levels behind the rigid insulation systems were dominated by their vapor permeability; the impermeable foil-faced polyisocyanurate showed high sustained moisture levels. The roll blanket walls, at their above-grade portion, had moisture levels matching their permeability: the unperforated blanket accumulated moisture during the summer. The framed walls showed responses that did not correspond to their permeability; in contrast, they were dominated by airflow, bypassing the remainder of the assembly. This was demonstrated by noting that the absolute moisture content levels in the assembly closely tracked interior levels. In this experiment, this airflow caused drying of the assembly.

Ueno and Townsend (2006) examined eight interior insulation assemblies in a Chicago-area basement. These assemblies included rigid foam (foil-faced polyisocyanurate and extruded polystyrene/XPS), fiberglass batt frame and polyethylene walls (polyethylene on one or both sides), composite walls (XPS with a stud frame to the interior; two versions), a perforated roll blanket, and rigid fiberglass board with a PA-6 facer. The assemblies were periodically wetted to measure their drying response. In non-wetted operation, some of the walls showed signs of air leakage from the interior behind the assemblies, as indicated by identical dewpoints to inside (e.g., foil-faced polyisocyanurate). The perforated blanket also showed similar dewpoints to interior, but this could be due to the permeability of the facer (13 perms or 720 ng/Pa·m·s^2). The composite walls showed that the wood framing was completely protected from concrete-sourced moisture by the XPS insulation. In the wetting experiments, some walls very quickly (polyisocyanurate, due to air leakage, and perforated blanket). Others dried in a controlled manner, allowing drying through the vulnerable portions of the assembly without damage (composite walls). The XPS (2"/50 mm) wall, however, showed extended periods of high humidity after the wetting event, showing that drying occurred more slowly through the 0.5 perm or 29 ng/Pa ·m ·s² material; the PA-6 wall had a similar response. The double polyethylene showed minimal wetting, which was a surprise given its low drying potential. However, it is likely that during wetting, drainage out of the wall cavity occurred (due to the hydrophobic materials lining both sides), so a low initial dose of water was retained.

This review of the literature indicates that a consistent failure seen in a wall with a single layer of polyethylene on the interior is condensation due to spring or summertime inward vapor drives. Wintertime condensation on the above-grade portion was occasionally seen; this was worsened by removing the hygric buffer capacity of the concrete. Monitored data showed that interior insulation has drying potential to the interior in most cases, especially in the below-grade portions of the wall.

Experimental Program

Four interior basement wall insulation assemblies were monitored in a field installation; following the first year of operation, some of the walls were disassembled and inspected.

Wall Selection and Details

The tested assemblies are described in Table 1 below, which lists wall components from exterior (concrete side) to interior. Assemblies with an interior polyethylene layer were tested, both in a roll blanket form, and as a wood frame wall. A frame wall that omits the polyethylene was also built; latex paint on drywall functions as an interior vapor control layer. Finally, a 2"/50 mm extruded polystyrene wall was installed as a comparison, directly applied to the concrete, with gypsum board for fire protection. Permeability of the vapor control layer is also reported in the table below.

Table 1: Test wall assemblies

Layer	Below grade wall 1: 2" XPS	Below grade wall 2: polyethylene/ fiberglass roll blanket	Below grade wall 3: 2x4 with polyethylene	Below grade wall 4: 2x4 without polyethylene
Framing & insulation	2"/50 mm extruded polystyrene (XPS) R-10/RSI 1.8	R-12/RSI-2.1 fiberglass roll blanket	2x4 16" o.c. with R-12/ RSI-2.1 fiberglass	2x4 16" o.c. with R-12/ RSI-2.1 fiberglass
Other	19 mm / 3/4" airspace and furring strips	n/a	6 mil polyethylene	n/a
Interior finish	½"/12.7 mm gypsum wallboard with latex primer & paint	Polyethylene roll blanket facing material	½"/12.7 mm gypsum wallboard (GWB) with latex primer & paint	½"/12.7 mm gypsum wallboard (GWB) with latex primer & paint
Vapor control layer	XPS 0.55 perm 31 ng/(Pa·s·m^2)	Polyethylene 0.06 perm 3.4 ng/(Pa·s·m^2)	Polyethylene 0.06 perm 3.4 ng/(Pa·s·m^2)	Gypsum w. latex paint Dry cup: 2.6-3.5 perm 150-200 ng/(Pa·s·m^2) Wet cup: 18 perm 1000 ng/(Pa·s·m^2)

R-value in ft^2·°F·h/Btu; RSI value in K·m^2/W; perm in gr/h·ft^2·in. Hg

Experimental Site and Test Wall Installation

The test site was an occupied house located in Kitchener, Ontario; it is built on a full basement with 8" (203 mm) cast concrete walls. Exterior spray-applied dampproofing is covered by a polyethylene dimpled drainage mat to grade. The basement has a walkout at the rear; the test walls are located on the side of the house, which is the southeast orientation. The basement is unfinished; code-compliant roll blanket insulation is installed on the upper half of the wall. The house was built in winter 2004-2005 and occupied in late June 2005, so construction moisture loading was still significant.

Due to the walkout condition the grade level changes at the side of the house; the test sections were installed to minimize this effect, as shown in **Figure 1**. Thermal anomalies such as the foundation corner and basement window were avoided. There is a house adjacent to the test walls; it is located 9 feet (2.8 m) away from the test house, resulting in differential solar and rain exposure of the sets of test walls. A relatively large fraction of the basement wall is exposed above grade: approximately 16"/400 mm.

Figure 1

Indoor and outdoor temperature and relative humidity were recorded. Soil temperatures and moisture contents were measured at two lateral locations and three depths (6"/150 mm, 12"/300 mm, and 36"/900 mm), for a total of six sensor locations. Each wall was instrumented with electrical resistance pins (for wood moisture content measurement), temperature sensors (0.2ºC accuracy thermistors), and capacitance-based relative humidity sensors (2% RH NIST traceable) in multiple locations, as per the methodology described by Straube et al. (2002). Given the change in exterior conditions with depth, instrumentation was placed in groups at a "high" (near grade), "middle," or "lower" location (below grade).

The temperature at the exterior face of the drywall and interior of the concrete are variables of critical interest for moisture problems. As an RH sensor would change the localized thermal properties if placed between a batt and a surface, the sensor was instead located within the highly vapor permeable batt insulation. Using the vapor pressure measured at the RH sensor and the surface temperature measured from the small thermistors, one can calculate the surface RH with good accuracy by using the knowledge that the vapour permeance of the batt is almost constant across its thickness. Also, an RH sensor located in $95\%^+$ RH environment (i.e., next to the concrete) will neither be accurate nor durable. Hence, wood moisture content surrogate sensors (or "wafers")—essentially larger versions of Duff gauges (TenWolde and Carll 1996)—were used to measure patterns of long-term moisture accumulation at surfaces. Laboratory calibration of these sensors indicated a slow response time (time constant of 20-50 hours at a 50-100% RH step change), and an accuracy of ±3% at 100% RH. However, they are able to resolve the presence of liquid water (as opposed to 100% RH), making them quite useful as indicators of substantial condensation.

The test walls were separated by XPS "buffer" panels; vertical joints between walls and buffers were sealed with builder's tape (see **Figure 1**); the frame walls were air sealed to the concrete using canned urethane foam at sides and the top plate. Wall 1 has a greater above-grade exposure than the remaining walls; however, the polyethylene/non-polyethylene assemblies were of greater interest.

Field results

Test instrumentation was installed in August 2005; data was collected and analyzed for the first year, and data collection continues into a second year of operation. Some of these results were presented in Wilkinson et al. (2007); however, it is necessary to include this data for comparison to modeling results.

Boundary Conditions

Interior and exterior temperature and relative humidity conditions are shown in **Figure 3** (daily average values). Interior humidity varied from a low of 20-30% (wintertime) to 60% (summertime); this is equivalent to wintertime dewpoints of 25-40°F (–5 to 5°C), and summertime dewpoints of 50-60°F (10-15°C). This is representative of Canadian basements and matches data collected in a cross-Canada survey of 50 houses by Ruest (1993), which showed wintertime dewpoints in the same range (–5 to 5° C), except for British Columbia (a more humid and milder Pacific marine climate).

Soil temperatures showed very strong damping of exterior conditions. Diurnal variations were completely damped out at a depth of just 6"/150 mm in the wintertime. In the summer, daily amplitudes were 2-4°F (1-2°C) at that depth. In addition, even at this shallow depth, temperatures never dropped below freezing, despite sustained daily average temperatures in the 15-25°F (–5 to –10°C) range. The monitored data suggests that the latent heat of fusion presents a barrier to achieving freezing conditions in soil.

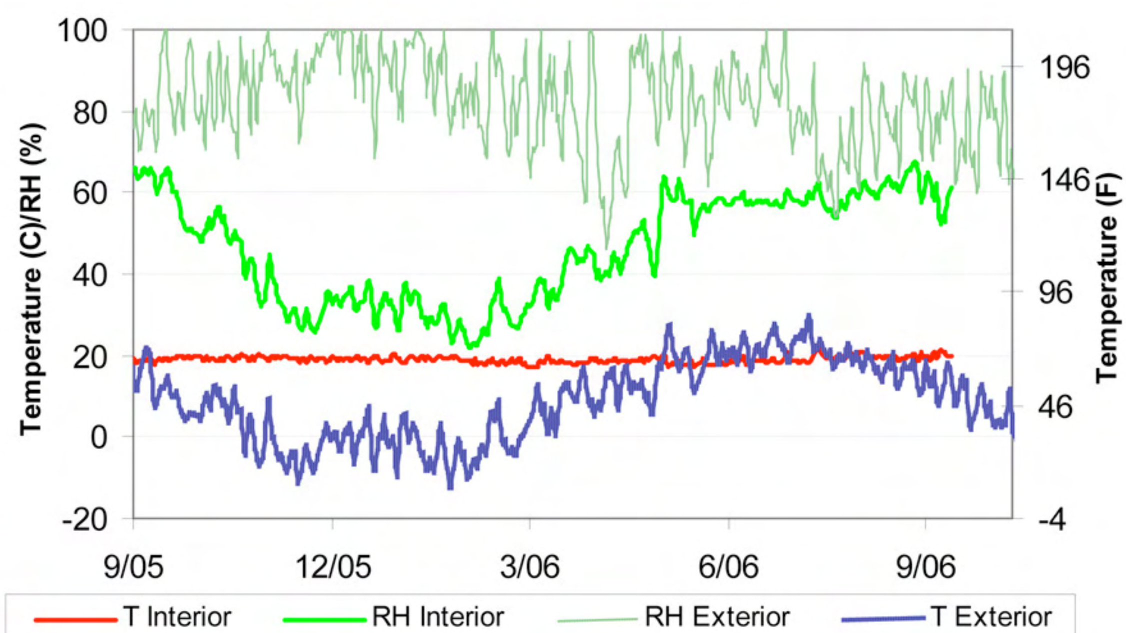

Figure 2

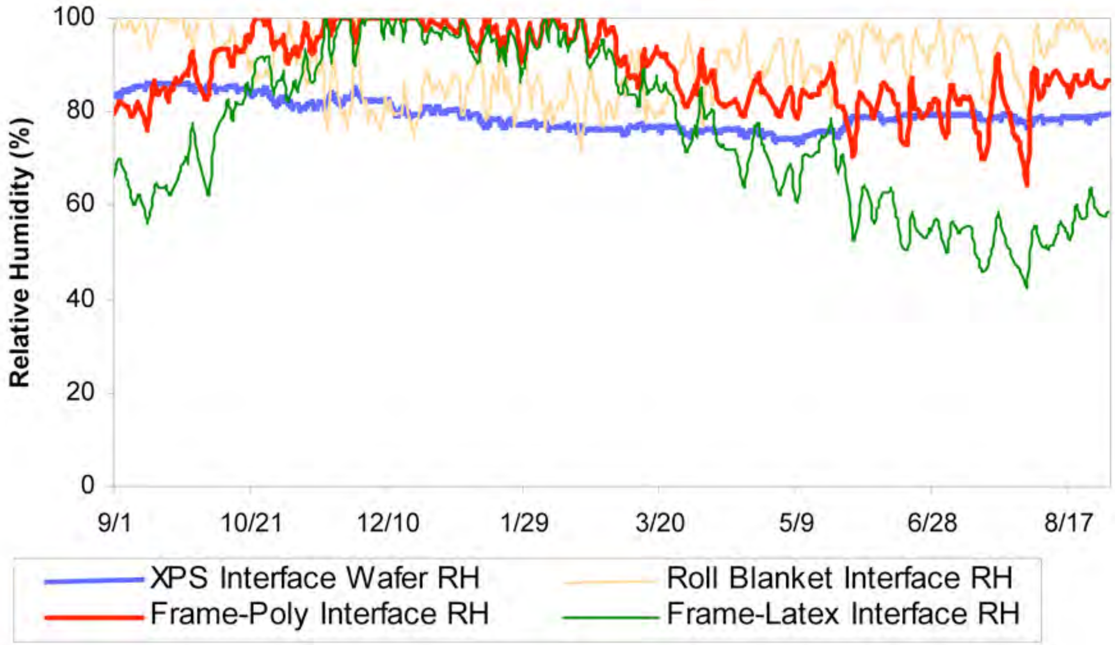

Figure 3

Analysis of Measured Data

In the wintertime, the main concern is with condensation or frost accumulation at the concrete-insulation interface at the upper portion of the wall. This problem is due to movement of moisture (via vapor diffusion, or air transport if there is an incomplete air barrier) from the interior to that interface. In the spring and summer, as noted in the literature, condensation can occur on the exterior side of a polyethylene vapor retarder at the upper part of the wall. A concern in all seasons is the accumulation of moisture within an interior insulated assembly, at the below grade portions of the wall. Finally, the wood moisture contents (MCs) are compared in the two frame walls.

Wintertime condensation: This issue is examined by plotting the relative humidity at the interface between the concrete and the insulation (see **Figure 3**). The sensor is located at the upper part of the wall, which is roughly at grade level. Note that the relative humidity sensor was placed mid-thickness in the batt insulation; the plotted relative humidity values are calculated based on the dewpoint at the sensor location, and the temperature of the concrete surface. However, the vapor resistance of batt insulation is very low, so this is a reasonable assumption for the purpose of this calculation. In the XPS wall, no RH sensor was available at that location; however, a moisture content wafer was placed at the concrete-insulation interface. Based on previous calibration data and a standard sorption isotherm for wood (Straube and Burnett 2005), a curve fit was used to provide estimated relative humidity values in the XPS wall.

The data show that two of the walls (frame/polyethylene and frame/latex paint) both experience high relative humidity during the winter at the concrete-insulation interface. In contrast, the roll blanket wall has lower wintertime humidities (80-90%), but shifts into the 90-100% RH range during the following summer. In contrast, during the spring and summer, the frame/latex paint wall drops to 50-60% RH, and the frame/polyethylene drops to roughly 80%. During the entire monitoring period, the XPS wall maintains a stable RH, close to 80%. These results indicate that in terms of wintertime condensation issues, both the frame/polyethylene and frame/latex paint wall seem to be at risk. In addition, the results show that inward drying is available in the more permeable frame/latex paint wall: during the summer, it is the driest wall. Also, it is notably drier during the first summer (start of monitoring), compared to the frame/polyethylene wall (which does not allow any inward drying).

Summertime condensation: This problem was examined by plotting the conditions at the insulation-polyethylene (or insulation-gypsum board) interface, where condensation would occur at the upper part of the wall. Although this could also be done in terms of calculated relative humidity (as per the wintertime plot), more informative results are produced by plotting the moisture content of the "wafer" sensor, which was actually placed at this interface (see **Figure 4**). Exterior temperature is also plotted in that graph.

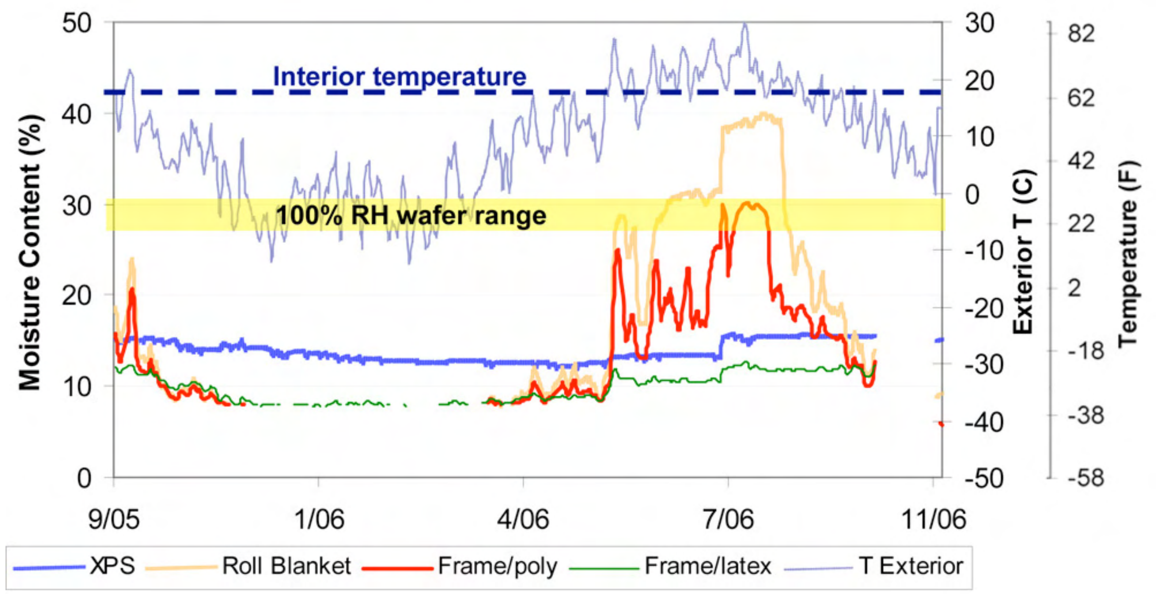

Figure 4

The graph clearly shows the inward vapor drive described earlier: during the late spring and summer, the moisture content of the wafer rises sharply. The roll blanket wall shows a greater rise in moisture content (peak at 40% MC) than the frame/polyethylene wall (peaks near 25%). Laboratory calibration of the wafers showed that 100% RH roughly corresponds to 25-30% MC; the roll blanket data indicates liquid water condensation.

The pattern of moisture accumulation at the wafer is tied to outdoor temperature, as indicated by the matching spikes; this is reasonable given that inward vapor drives are proportional to the temperature of the saturated layer (concrete). The interior temperature is roughly plotted on the graph; the wetting of the wafer is tied to an inward temperature gradient. When the exterior temperature cools below interior temperature (as in fall 2005, and mid-June 2006), the moisture content drops.

The roll blanket and frame/polyethylene walls do not behave identically, even though in a one-dimensional section through the insulation, they are identical. However, the presence of wood stud framing has a substantial effect. First, unlike the roll blanket, which has a continuous layer of polyethylene sealed to the concrete on all sides, the frame/polyethylene wall is made of discrete components that are air sealed to create an assembly. Although best efforts were made to create an air seal on all sides, it is still possible that small incidental air leakage exists. Second, the presence of wood framing results in a great increase in moisture storage capacity. The storage capacity of the wood studs was calculated for a shift of relative humidity from 50% to 97% RH, the difference was

32 to 116 kg/m³. This is a relatively conservative estimate, given the sharp rise in the sorption isotherm near 100%. This was compared in the storage available in air at 20°C, with the same humidity shift. Assuming a 16" stud spacing, a stud has over 1000 times the moisture storage capacity as the air in the adjacent stud bay. So even if only a portion of the stud stores moisture during seasonal flows, it still strongly changes the behavior of the assembly. Third, the framing was air sealed, but not vapor sealed at the sides and top of the frame/polyethylene wall. Although vapor diffusion through 1-½" (38 mm) of wood is low (0.26-3.6 perms/15-205 ng/Pa ·m ·s²; Straube and Burnett 2005), the permeability of polyethylene is so low that this vapor "flanking" could result in a noticeable change in the overall permeability of the assembly. Note that this effect is disproportionately large in this test installation, given the large exposed framing fraction (see **Figure 1**).

The frame/latex paint wall, in contrast, does not show this sharp rise in moisture content during the summer. Although there is a slight jump with the onset of warm weather, moisture content peaks at roughly 12%, which is well within the safe range for wood. This indicates that the inward vapor drive passes through the gypsum board and latex paint, and does not accumulate in the cavity.

The XPS wall shows a much more stable wafer moisture content, remaining close to 15% throughout the year, which is equivalent to the 80% RH level seen in **Figure 3**.

Below-Grade Behavior: Another concern is the accumulation of moisture behind or within the insulation assemblies, resulting in high humidity and favorable conditions for mold growth. A relative humidity sensor was located at the concrete-insulation, at mid-height (4'/1.2 m above finish floor and roughly 32"/0.8 m below grade), in all four walls; the results are plotted in **Figure 5**. However, the sensor in the frame/polyethylene wall failed due to prolonged exposure to high RH, so relative humidity was calculated from the moisture content wafer placed as a backup to the RH sensor. The wafer sensor was expected to be less responsive than RH sensors, and some caution should be exercised in comparisons.

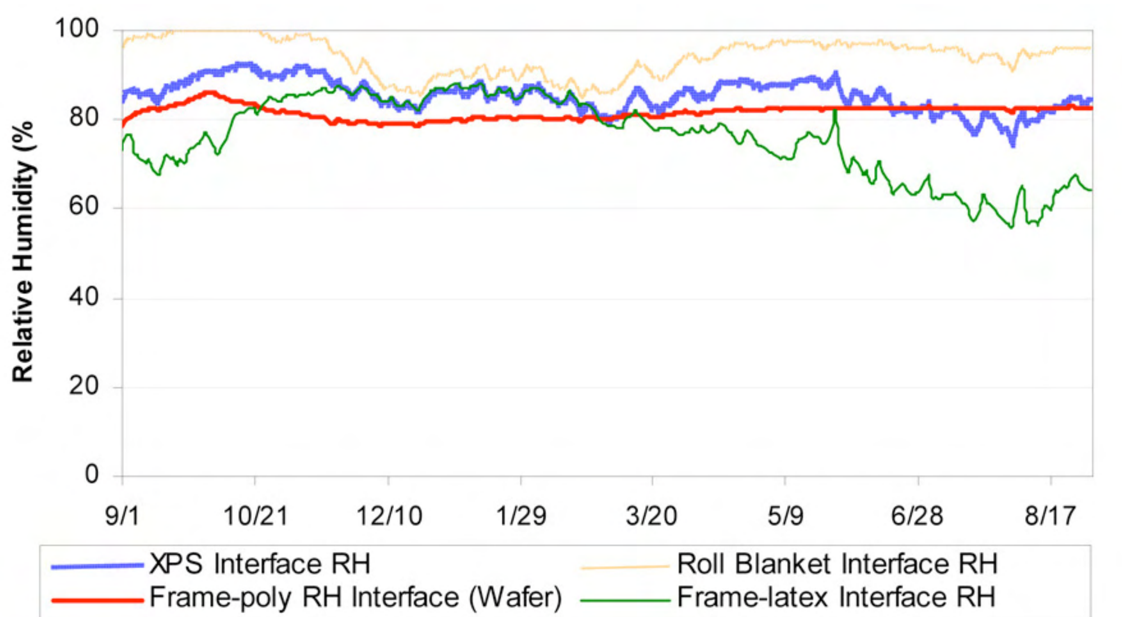

Figure 5

The plot shows that moisture accumulation roughly corresponds to the vapor resistance of the assembly. The polyethylene roll blanket shows the highest sustained RH levels: near saturation in fall, spring, and summer, dropping to ~90% RH in winter. The XPS wall has vapor permeability an order of magnitude higher, and shows RH levels in the 80-90% range. The frame/latex paint wall has permeability an order of magnitude higher than XPS, and shows the lowest humidity levels, indicating drying of the assembly. In this wall, RH values are at their peak during winter when the concrete wall is coldest. The frame/polyethylene wall shows relatively low calculated RH levels; after replacement of the damaged RH sensor, this relationship will be verified.

Framing Moisture Content: When assessing the risk of a wall assembly, the danger is not necessarily condensation *per se*, but mold growth and damage to moisture-sensitive portions of the wall, such as the framing. The moisture content of the framing at the upper portion of the wall is plotted for the monitored period in **Figure 6**. Moisture contents were measured at the inboard and outboard edges (3/8" or 9 mm from the faces) of the stud. The summertime increases in the frame/polyethylene wall are seen at the interior side, similar to the moisture content wafer; however, peaks are roughly 17% MC, which is still in the safe range. A similar rise in wintertime moisture content is seen at the outboard side of the frame/latex paint wall; again, the MC remains within the safe range (15% peak). Overall, moisture contents at all of these upper framing locations presented minimal concern for mold growth; based on over a year of data, these cycles appear to be stable.

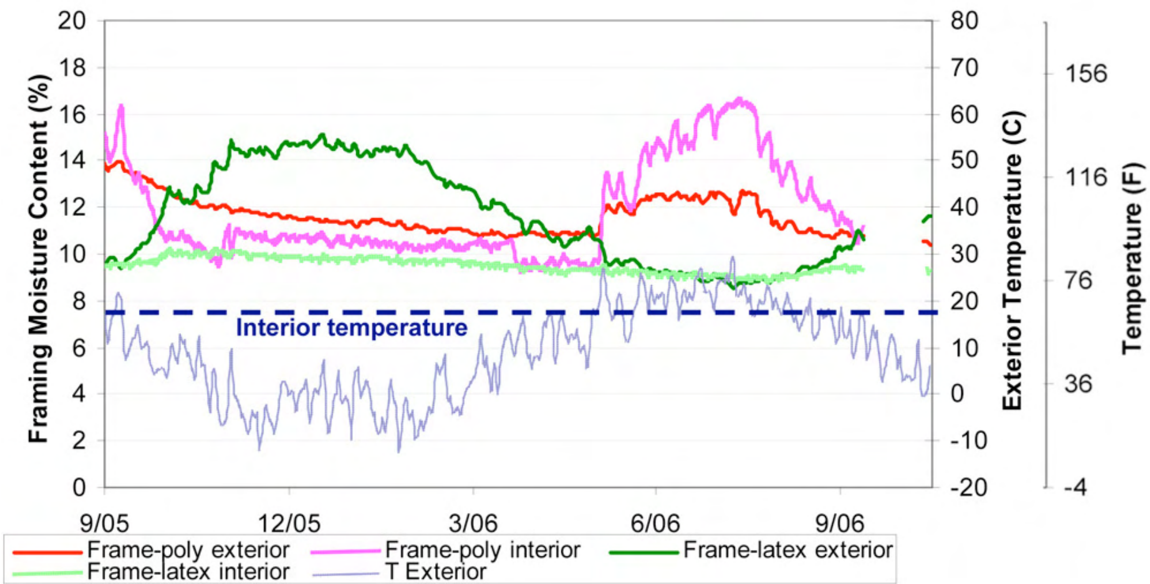

Figure 6

The moisture contents of the framing at the lower part of the walls were in the 8-15% range; again, these levels present little concern for mold growth. One pattern was that the frame/polyethylene moisture contents were consistently higher than the frame/latex paint wall. The frame/polyethylene MCs rise and fall seasonally, matching the temperature of the concrete at that height. The frame/latex paint wall has flatter moisture content behavior.

Disassembly Observations

In late September 2006 (after the first year of operation), some of the walls were disassembled and inspected for evidence of mold growth or other moisture-related damage. Spatial distribution of moisture content in the framing was measured with a handheld Delmhorst BD-10 electrical resistance-based meter.

The extruded polystyrene wall was not disassembled; this will be done at the conclusion of the experiment. The roll blanket wall data showed substantial condensation at the polyethylene during the summer monitoring; during the inspection the upper moisture content wafer had noticeable mold growth. In addition, there was some brown discoloration of the fiberglass insulation.

In the frame/fiberglass/polyethylene wall, data showed condensation at the upper portion of the wall (albeit less severe than the roll blanket); the moisture content wafer also showed mold growth. However, the framing did not show notable mold growth: there was a small amount of brown spotted discoloration of the stud at the interior edge. Handheld moisture content measurements were in the 12-14% range for most of the framing; the members at the exposed perimeter (top plate and edge studs) were at 9-10% MC.

In the frame/fiberglass/latex paint wall, there was no visible staining or mold growth on the insulation, framing, or wafers. Moisture contents were in the 9-11% range throughout the wall. One concern with omitting a polyethylene layer in assemblies is that inward vapor drives might cause mold growth on the back of the drywall, due to accumulation at that location. Monitored data showed that there was negligible accumulation; a visual inspection of the exterior side of the drywall showed no damage, discoloration, or mold growth.

Hygrothermal Simulations

Simulations of these basement walls were run in a one dimensional hygrothermal model (WUFI 4.0); several models were required for each wall, due to the change in boundary conditions along the height of the wall. The models were first validated against monitored data. Then, extrapolation simulations were run, changing the variables of interior relative humidity, geographic location, and wall assembly type.

Boundary Conditions

Simulations were run at three vertical locations in these walls, which corresponded with instrumentation placement ("upper," "middle", and "lower"). Different boundary conditions were required for each location. This approach was based on the assumption that vertical flow of heat and moisture would not dominate the performance (and hence makes a 1-D simulation valid).

At the upper (above-grade) portion of the wall, exterior conditions measured at the University of Waterloo exposure facility (BEGHut) were used; a comparison of temperature and relative humidity data showed close correspondence.

At the below-grade portions ("middle" and "lower" locations), the original plan was to use the measured soil temperatures to create boundary conditions. However, these sensors do not line up precisely with monitoring locations, so an alternate approach was used. Given the R-values of the wall components, we can calculate that 3-6% of the temperature drop occurs through the concrete; the remainder (94-97%) is through the insulation. Given the low ΔT across the below grade wall, 3-6% of that drop is smaller than variations seen between walls. Temperatures were measured at the concrete-insulation interface at high, middle, and lower locations; the R-value calculations indicate that it is reasonable to use those measurements as the exterior temperature conditions. Relative humidity was set at 100%; no liquid water capillarity was simulated (in the form of rain).

Interior conditions were as per measured interior temperature and relative humidity.

Setup and Initial Conditions

Painted Gypsum Board: Most of the materials used in the test walls are well characterized in the simulation database. However, the gypsum board with latex paint was simulated with a permeability that varies with relative humidity, as per published data (Kumaran 2002), summarized in Table 1 (dry cup and wet cup values).

Concrete Initial Moisture Profiles: The built-in construction moisture of a basement wall is significant; initial conditions were developed by running drying simulations. The default concrete material with a 0.5 water to cement (w/c) ratio was used; Swinton and Karagiozis (1995) reported that a residential basement wall would typically be closer to 0.7 w/c, and even higher values are not uncommon. Increasing the w/c ratio increases the porosity (and decreases the density) of concrete; this change would increase both the vapor permeance and water absorption (liquid uptake). However, testing these material properties is beyond the scope of this research.

The concrete was allowed to dry from its initial water content of 175 kg/m^3 for nine months, using boundary conditions described above; the concrete showed lower RH levels at the surfaces, but almost no drying was seen in the middle of the 200 mm wall. In a simulation of a full year of drying, the majority of the wall was still over 90% RH; further runs indicated that it will take 10 years for the concrete to fall below 90% RH through its entire thickness. Note that drying was reduced in the below-grade portion of the wall: only inward drying was available due to the impermeable asphalt dampproofing layer (0.14 perms or 8 $ng/(Pa \cdot s \cdot m^2)$) on the exterior.

Comparison of Transport Mechanisms: A supplemental simulation was run to estimate moisture transmission through an 8"/200 mm concrete wall by various transport mechanisms. No dampproofing was applied to the wall so as in order to demonstrate the highest fluxes. Under isothermal conditions (20°C), a comparison was run between a liquid capillarity case (10 mm/hour rain exposure, 100% RH) and a vapor diffusion only case (no rain, 100% RH); interior conditions were 50% RH. The simulations showed steady-state moisture transport rates of 11.1 $kg/m^2 \cdot year$ for capillarity, and an order of magnitude less, 1.4 $kg/m^2 \cdot year$, for vapor diffusion only.

These rates can be used to estimate the rate of moisture supply to a house by capillarity and diffusion through unfinished concrete basement walls. Assuming a 30 by 40 foot (9.1 m x 12.2 m) basement with 8-foot (2.4 m) high walls, and using the calculated rates for the entire height of the wall (an overestimate), gives 3.2 liters/day for the capillarity case, and 0.4 liters/day for vapor diffusion only case. These rates can be compared to moisture production rates of the activities of a family of four, at 10-15 liters/day, or of a person, at 0.75 to 1.2 liters/day (from sedentary to average) (Straube and Burnett 2005). These rates will vary with different concrete quality.

This suggests that if liquid transport can be eliminated (by a capillary break between the wall and the soil or footing) the moisture loading from a basement will have a small effect on interior moisture levels. Limiting capillarity should therefore be the highest priority to control basement-sourced humidity. However, water vapor transmission can still result in moisture accumulation within interior insulation assemblies, especially when impermeable interior finishes are used, limiting drying to the interior.

Validation Simulations

As noted earlier, two of the walls (polyethylene roll blanket and frame/polyethylene) are identical in their one-dimensional simplification; however, they had different monitored behavior. In most of the validation work, the fiberglass and polyethylene assembly was compared with the roll blanket, which is closest to the one-dimensional representation. However, the frame/polyethylene is sometimes presented for comparison as well.

Above Grade: Using the boundary conditions described above, three of the test assemblies were simulated: XPS, roll blanket (fiberglass & polyethylene), and frame/gypsum board with latex paint. Typically the first step for validation is to compare temperatures through the assembly for correspondence, and then to compare moisture levels. However, the model shows a lack of temperature correspondence, especially in the winter, as shown in the plot of the temperature (and dewpoint) at the concrete-insulation interface, **Figure 7**. The model predicts temperatures that drop to 19°F/–7°C, while measured data is substantially warmer, with minimums of 28°F/–2°C. Typical differences between measured and modeled are much smaller in summer; as shown in Figure 8; peak differences are roughly 5°F/3°C, and only occur during daytime peaks. Also, part of this difference might be explained by shading from the adjacent house (not included in the model).

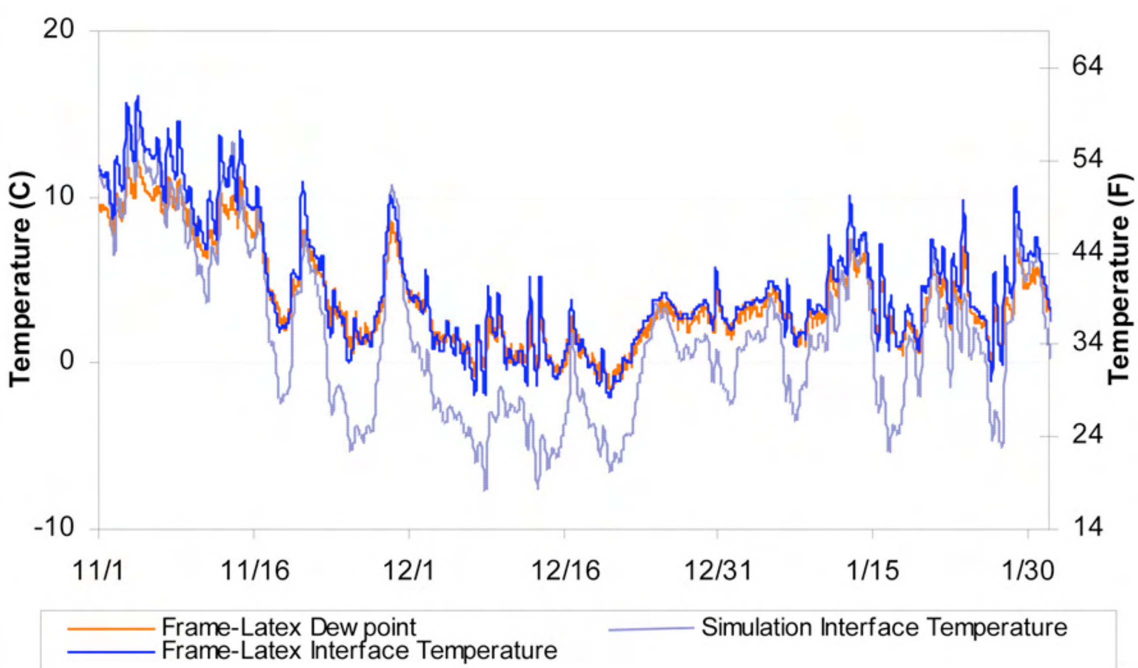

Figure 7

One initial theory to explain difference was that the R-values of the assembly components were not correct: for instance, that the insulation was wet or compacted (lower R-value), or the concrete was dryer than simulated (higher R-value). However, a plot of the concrete ΔT vs. the total ΔT showed a contribution of 20-30% for the concrete, compared to the calculated 3-6%. This is far too large to be explained by insulation value differences.

The soil temperature at 6"/150 mm was then plotted with the monitored interface temperature, which provided a closer match than exterior air temperature. It seems likely that two-dimensional effects, which cannot be captured in a one-dimensional simulation, such as heat flow to/from the soil, are dominating the above-grade portion of the wall. Since the temperature sensor is roughly at grade level, the above-grade and below-grade environments both have an effect, as shown in **Figure 9**. The details at the rim joist, such as the brick ledge and the transition to the insulated wooden framing, result in further thermal anomalies. Finally, the aspect ratio of the wall at this location does not favor a one-dimensional simplification: only a small portion of this wall is reflected by the one-dimensional simplification, so thermal flanking seems quite possible.

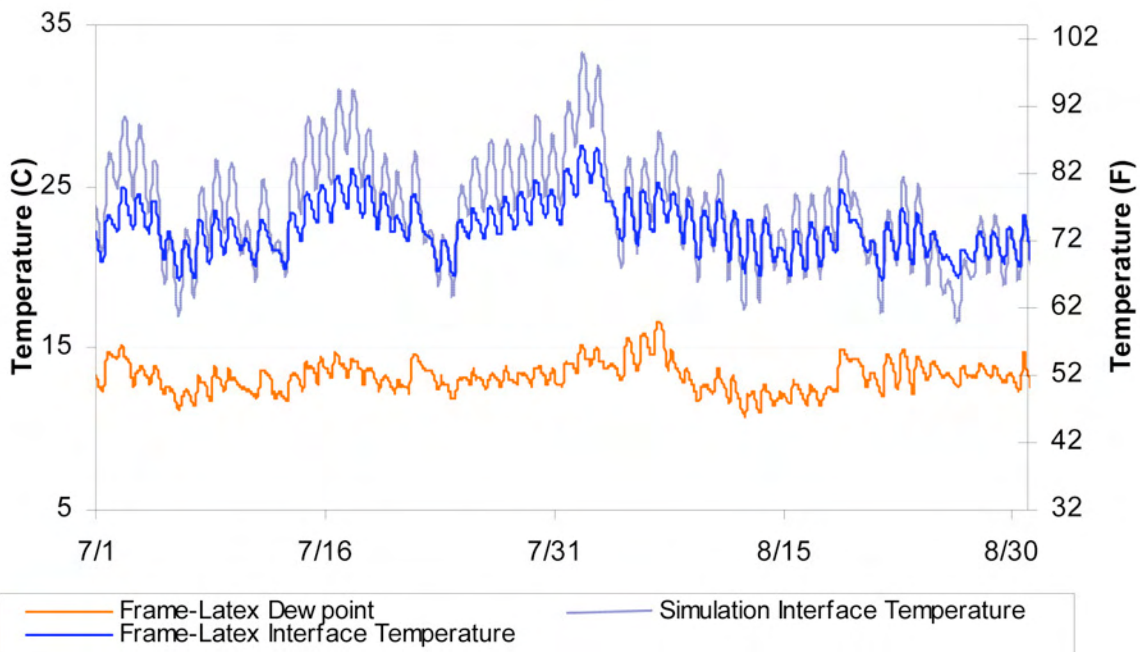

Figure 8

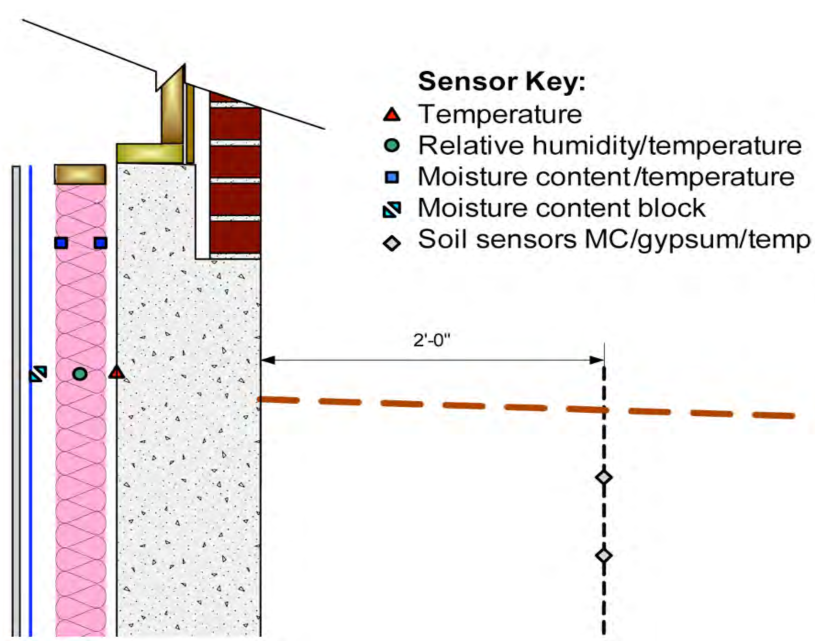

Figure 9

Another question is whether the specific placement of the temperature sensor (at grade level) causes this poor correspondence when using above-grade boundary conditions. For instance, it seems plausible that the upper portions of the above-grade concrete wall are closer to modeled behavior. However, this seems unlikely, given dewpoint behavior. The dewpoint in an assembly cavity with high vapor permeability (e.g., fiberglass batt) tends to be "pulled down" to the lowest temperature that the cavity is exposed to, when coupled to a hygrically massive material such as concrete. Therefore, if the upper parts of the wall are much colder, the dewpoint should reflect this effect. As shown in **Figure 7**, the dewpoint falls somewhat below the concrete surface temperature, but not by a large margin—nowhere near the 18°F/–8° C lows seen in the simulation.

Overall, the lack of temperature correlation in the above-grade simulations prevents full validation. However, it seems possible that this simulation can be used as a tool to look at the "worst case" wintertime situation, with colder temperatures at the concrete-insulation interface than the monitored data would imply. This might occur with a larger above-grade portion of the wall (i.e., taller than 16"), which would be closer to the one-dimensional simplification.

Below Grade: The below-grade simulations presented a smaller challenge for matching temperatures, due to the use of measured boundary conditions, the lack of any solar influence, and the slow temperature variation over time (e.g., all diurnal variations are damped out). Hence, agreement was good between measured and simulated temperatures. Relative humidity levels at the mid-height concrete-insulation interface were compared; the results are shown in Figure 10, which can be compared to the monitored results in **Figure 5**.

The behavior of the two low-permeance systems (roll blanket and XPS) is quite different than monitored data. In the simulation, relative humidity levels quickly rise to the 95-100% range for both of these walls, and remain at that level for the rest of the simulation. In contrast, the monitored data shows humidity levels of 85-100% for the roll blanket, and 80-90% for the XPS.

There are several possible reasons for the difference: perhaps, despite best efforts, there is some air leakage or communication from the interior space to the concrete-insulation interface. Given the relative humidity levels during the test year, this would result in drying of the assembly. Second, the possibility of vapor diffusion "flanking" through the edge framing of the panel was discussed above; this would also cause drying. Finally, it is possible that more drying of the concrete occurred before the installation of the insulation than simulations would indicate. The significant influence of the sorption isotherm in the high RH range also makes the simulations highly sensitive to the material property data input. Needless to say, all of these RH levels are high and cause for concern.

The lack of correlation for the roll blanket wall is understandable, given the work of TenWolde and Carll (1998). They note that a very low permeance material (such as polyethylene) can effectively be bypassed by a very small air leak. Creating an air barrier system that would prevent this bypass would require an "extraordinary level of airtightness," well beyond the levels achievable in construction. Since these simulations did not account for airflow, no air bypasses the polyethylene layer and therefore it is fully effective at limiting water vapor flow.

The latex paint wall shows slightly better correspondence: the test wall operates at a roughly similar humidity regime as that shown in the simulation. However, the peak values are not coincident; in the monitored data, the large rise occurs in early winter, while in the simulation, it occurs in mid-winter, and remains at high levels through the spring. A possible explanation may come from the permeance values of latex paint; preliminary material testing shows higher dry-cup permeance levels than the published literature. This difference would cause greater outwards vapor diffusion (and thus wetting of the assembly) during the winter, thus explaining the earlier rise seen in the monitored data.

Simulations of the "lower" location compared measurements at the concrete-insulation interface (XPS wall), and at mid-thickness of the insulation (frame walls). A comparison of monitored and modeled behavior showed a closer correspondence than at the "middle" location. The relative ranking of relative humidity levels was the same, with the frame/latex paint wall the driest, and the XPS interface the wettest (roll blanket wall was not available). However, the monitored data was drier than the simulation results in all cases: for instance, in the frame/latex paint wall, the simulation predicted RH levels between 70-80%, while monitored data was closer to 50-80%. Again, this might be ascribed to low-level air leakage drying or drier concrete than simulation predictions.

Extrapolation Simulations

In an effort to understand the sensitivities of interior basement insulation systems, extrapolation simulations were run varying the geographic location/climate, interior relative humidity, and assembly.

The selected geographic locations included a very cold climate (Edmonton, AB), a mild Pacific marine climate (Vancouver, BC), and an Eastern maritime climate (St. John's, NL). Relevant climate data is shown in Table 2 below; it also includes other climates discussed later. Toronto was used in some comparison simulations as a baseline; climate conditions are close to Kitchener/Waterloo.

"Low," "mid," and "high" relative humidity loadings were used (see Table 3), which varied sinusoidally over the year, with peaks in early August. Humidity data is reported both in terms of relative humidity and dewpoint temperature (absolute humidity). Dry bulb temperatures varied sinusoidally as well, with a peak coincident with humidity.

Not all humidity levels were run with all climates: for instance, Edmonton is a dry climate, and is unlikely to experience "high" humidity conditions; similar for Vancouver and "low" humidity levels. This is supported by the literature: in Ruest's cross-Canada survey (1993), most basement dewpoint levels matched the "low RH" condition or drier, except for Vancouver, which showed levels closer to the "mid" or "high" levels.

Table 2: Extrapolation simulation climate summary

Location	Heating degree days (Base 65°F/Base 18°C)	Cooling degree days (Base 65°F/Base 18°C)	Annual Average T (°F/°C)
Kitchener/Waterloo, ON	7719 / 4288	608 / 338	44.1 / 6.7
Edmonton, AB	10275 / 5708	92 / 51	36.3 / 2.4
Vancouver, BC	5268 / 2926	143 / 80	50.1 / 10.1
Saint John's, NL	8787 / 4881	104 / 58	40.4 / 4.7
Toronto, ON	6425 / 3570	646 / 359	48.5 / 9.2
Montreal, QC	8804 / 4891	285 / 158	41.0 / 5.0
Minneapolis, MN	7877 / 4376	698 / 388	45.4 / 7.5

Table 3: Interior temperature, humidity, and dewpoint conditions

	Temperature (°F/°C)	Low RH (%)	Mid RH (%)	High RH (%)	Low DP (°F/°C)	Mid DP (°F/°C)	High DP (°F/°C)
Average	70 / 21	45	50	58	46.3 /7.9	49.5 /9.7	53.4 /11.9
Maximum	72 / 22	60	60	65	56.4 /13.5	56.4 /13.5	58.6 /14.8
Minimum	68 / 20	30	40	50	34.9 /1.6	42.2 /5.7	48.1 /8.9

Finally, assemblies not tested at the Kitchener site were simulated. One was the "bounding" condition of "no interior vapor control." In this simulation, the assembly effectively has a perfect air barrier, so no air movement occurred through the insulation—only vapor flow. Other assemblies were materials currently used or specified for interior basement insulation: roll batt with a permeable perforated facer, and Kraft paper-faced batt; material properties are found in Table 4.

Condensation Layer: Given the effect of liquid water on mold growth (Doll 2002, Black 2006), estimates of the magnitude of condensation are useful to determine relative risks of assemblies. Although condensation may momentarily occur, it can be safely stored in the assembly and then released in more favorable conditions. To model this, a fictitious "condensation layer" material was created in the simulation, with a very steep moisture storage function (sorption isotherm); the storage at 100% RH was set to the condensation limit. It is intended to capture the moisture accumulation at interfaces that are likely to experience condensation. The remaining material properties were set to minimize the effect of this layer on the simulation, including low vapor resistance and low specific heat.

This condensation layer was run in the Kitchener above-grade simulations and compared with disassembly observations. The simulated wintertime condensation for all walls was well below rundown limits (500 g/m^2), even in this simulation that predicts colder temperatures than measurements at the concrete-insulation interface. This matches the lack of wafer response or observed visible mold damage. During the simulation summer, the frame/latex paint wall showed minimal accumulation, but the fiberglass/ polyethylene wall showed a sharp spike in moisture content, peaking at over 900 g/m^2. This matches the condensation noted at this surface in monitoring and disassembly observations. This condensation layer is not presented as a fully validated tool; however, it does provide a simple metric to compare the risk of various assemblies and conditions.

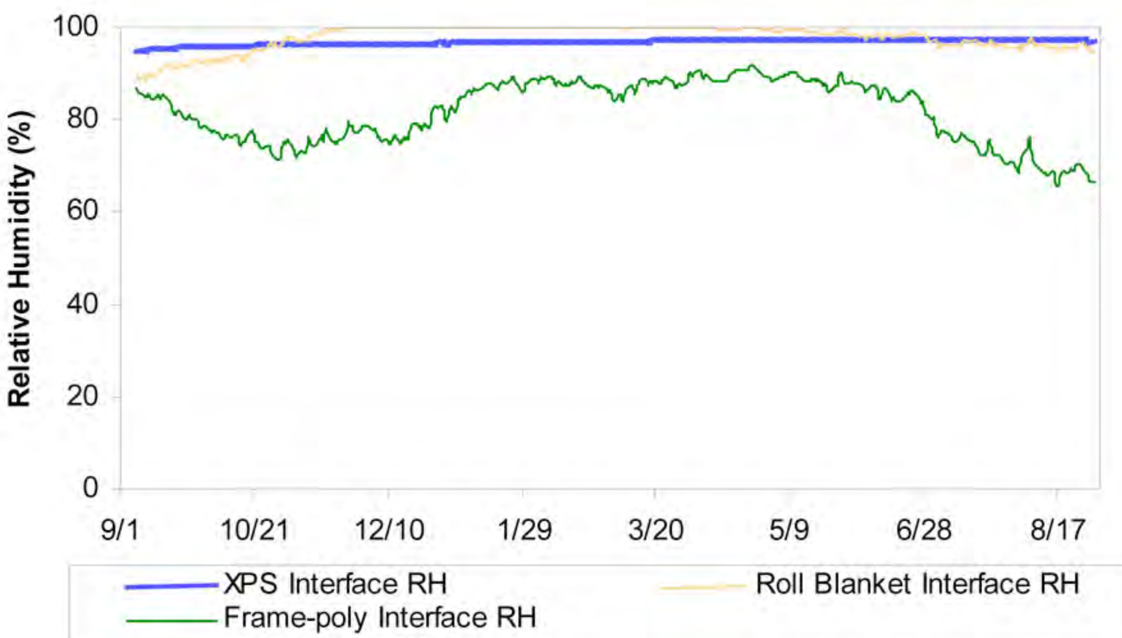

Figure 10

Wintertime Condensation Simulations: The first set of simulations examined wintertime condensation at the upper portion of the wall, at the concrete-insulation interface. The condensation layer was located at this point, and simulations were run using the worst-case conditions: a north-facing wall, with a "cold" climate year (when available). The XPS wall was not included in these simulations as preliminary runs demonstrated completely safe behavior.

It is important to remember that the results presented here are worse than would be expected in reality: warmer temperatures would likely be seen at the interface (due to two-dimensional effects) resulting in less condensation. This was true for a basement with 16" of above-grade exposure; many basements have smaller exposure, making this surface even warmer.

Sample results are shown in **Figure 11**, which plots accumulation in the condensation layer (in kg/m³, or g/m² for a 1 mm layer) for Toronto, at "low" RH conditions. The assemblies that would meet code requirements for a "vapor barrier" (polyethylene and Kraft paper) both show minimal accumulation. The latex paint assembly also shows minimal risk during the winter. However, the "perforated facer" and "no vapor control" walls both exceed 500 g/m² of storage—the latter for a significant portion of the year.

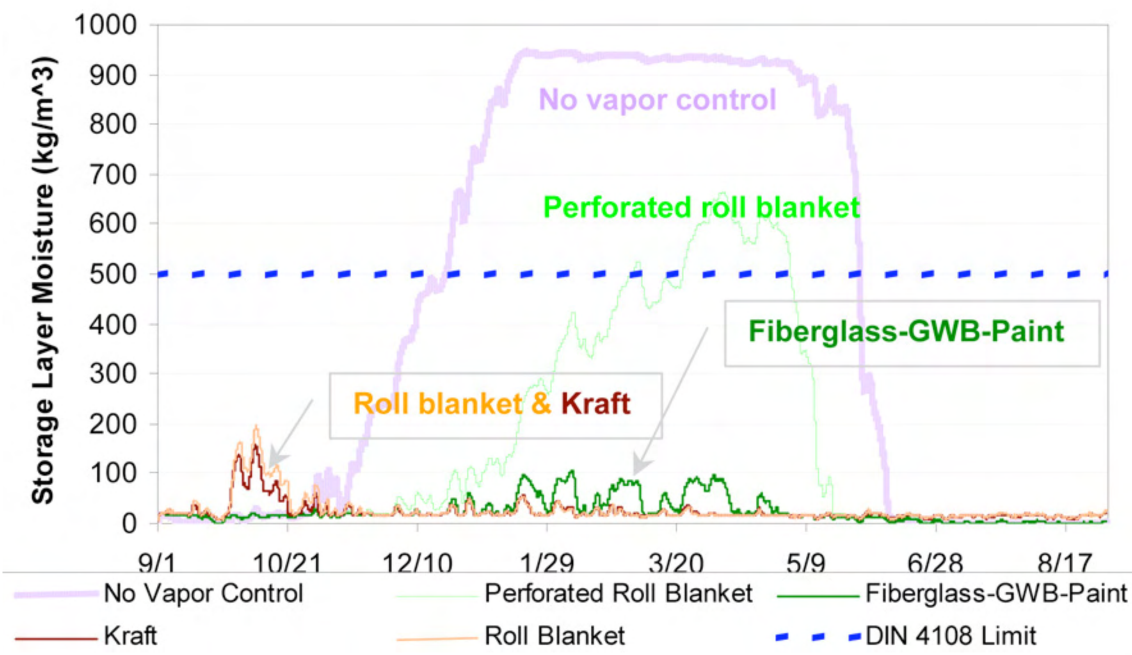

Figure 11

The simulation results are summarized in Table 4 below; the climates are listed by increasing heating load (HDD), and the assemblies are shown in order of increasing permeability.

Table 4: Wintertime simulation results: hours over 500 g/m² condensation

	RH Level	Roll blanket	Kraft paper batt	Fiberglass/ GWB/latex paint	Roll blanket w. perforated facer	No vapor control
Permeability (US perms)		0.06	0.3-0.6 dry/wet	2.6-18 dry/wet	13-14 dry/wet	∞
Vancouver, BC	Mid	0	0	0	0	3731
	High	0	0	2756	4437	7184
Toronto, ON	Lo	0	0	0	1102	3827
	Mid	0	0	776	3794	5709
	High	0	0	3994	5685	7360
St. John's, NL	Lo	0	0	0	4139	6722
	Mid	0	0	3249	6367	7187
	High	0	0	6430	7086	7557
Edmonton, AB	Lo	0	0	3024	5886	7602
	Mid	0	0	4937	7259	7757

These results show that wintertime condensation is exacerbated by colder climates (higher HDD), increasing interior humidity, and increasing permeability. Note, however, that there is a substantial gap between the permeability of the Kraft paper batt and the latex paint options: research on the performance of assemblies in this missing range may be worth pursuing. It is notable that in some of the cases with many hours of condensation, by the end of the year, the layer does not return to its original moisture content; it demonstrates ratcheting and increasing moisture content over time.

Summertime Condensation Simulations: The summertime condensation issue was examined in a similar manner; the condensation layer was placed at the intersection of the insulation and the interior vapor control layer. A south-facing wall was simulated, using a "warm" climate year if available. Note that only three assemblies were simulated here: the polyethylene roll blanket, the Kraft paper faced batt, and the latex paint-gypsum board. Assemblies with higher permeabilities do not demonstrate these problems. Furthermore, only one interior humidity condition was used ("mid"); the low-permeance materials used here isolate the cavity from the interior humidity, minimizing its effect on simulations.

Compared to the winter simulations, these results may have greater real-world applicability, as summertime monitored temperature data were a closer match to simulations. The results are similarly summarized in Table 5 below.

Table 5: Summertime simulation results: hours over 500 g/m^2 condensation

	Roll blanket	Kraft paper batt	Fiberglass/ GWB/latex paint
	0.06	0.3-0.6 dry/wet	2.6-18 dry/wet
Vancouver, BC	0	0	0
Toronto, ON	687	0	0
St. John's, NL	0	0	0
Edmonton, AB	0	0	0

These simulations show only one problem condition—Toronto with polyethylene: few problems were seen in the remaining locations. This fact is tied to the selection of Canadian climates for these simulations: Vancouver, St. John's, and Edmonton all have essentially no cooling loads (all were under 143 CDD 65°F/ 80 CDD 18°C). An inward thermal gradient is needed to create inward vapor drive problems; Toronto appears to have a large enough cooling load, at 646 CDD 65°F/ 359 CDD 18°C.

It is important to note, for instance, that summertime inward vapor drive issues may be a larger issue in the United States. For instance, Minneapolis, which is among the colder U.S. cities (DOE Zone 6; Briggs et al. 2002), showed 1159 hours above 500 g/m^2. Most U.S. climates have sufficient cooling loads that this issue may be a concern.

Below Grade Simulations: The below-grade extrapolations focused on the "lower" location: it would have the worst conditions for summertime condensation (due to thermal lag). Any wintertime condensation issues at the "mid" height would be worse in the above-grade portion. These simulations use the boundary conditions from monitored data, and vary interior RH and assemblies.

Geographic extrapolations are slightly more difficult: soil temperatures are a function of outdoor temperature and the soil's thermal diffusivity (ratio of thermal conductivity and volumetric heat capacity), and therefore soil composition and moisture content. Since there are too many unknowns to give definitive soil conditions, climate extrapolations are not included here.

The interior dewpoint was compared with the "lower" wall temperature over the course of the year: interior dewpoints are almost always below the wall surface temperature, so no condensation is expected. Incidentally, this fact also shows that drying is available to the interior, given the high relative humidity within the concrete. Hygrothermal simulations gave similar results: condensation accumulation never exceeded 500 g/m². However, the roll blanket wall showed a ratcheting increase in moisture content, peaking 300 g/m² after six years of simulation and still rising.

Although storage on the surfaces did not show significant problems, the below grade walls often showed extended periods of high RH. The proposed ASHRAE 160P Standard (2006) defines mold growth failure when the RH exceeds 80% RH for one month. All of these walls fail this metric; however, the vulnerability of the assembly components should be accounted for. For instance, the XPS wall has materials at the high humidity interface with minimal food value for mold growth, compared to wood studs in the frame walls. Therefore, the drying of the concrete over six years was plotted: if nothing else, faster-drying assemblies will be at lower risk levels sooner. The drying at "low" humidity conditions is shown in **Figure 12**; as would be expected, higher humidities reduce drying, but not by a large margin. The plot shows drying proportional to the permeability of the assembly: polyethylene has the slowest drying, while the "no vapor control" and "no insulation" approaches dry the fastest. Note that some of the more permeable assemblies, such as fiberglass/gypsum with latex paint and the perforated facer, have drying rates close to that of the completely vapor-open options.

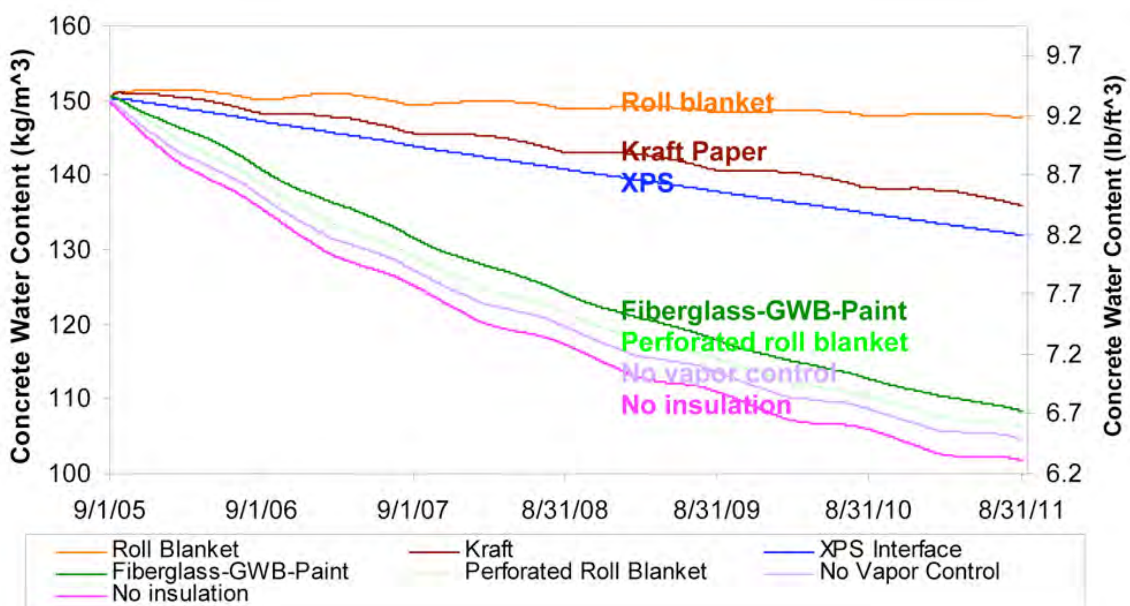

Figure 12

Double polyethylene assembly: One common assembly used in Ontario and Minnesota is a "double polyethylene" stud wall. There is a layer of polyethylene at the concrete-insulation interface, intended as a "moisture barrier," protecting the vulnerable components from concrete-sourced moisture. This moisture barrier typically runs from the slab level to grade. In addition, there is an interior polyethylene vapor barrier, which is full height. This assembly was not simulated here because the failures seen in the field are due to a lack of drying capacity of this assembly when imperfections or incidental wetting result in moisture entry into the stud bay (Ueno and Townsend, 2006). In contrast, simulations under "perfect" conditions (a dry start and no leaks) show dry and safe conditions in the stud bay.

Conclusions

Monitoring and disassembly results: Wintertime monitored performance showed no evidence of condensation on the above-grade portion of any wall, in both the polyethylene-based assemblies and the one using latex paint as a vapor control layer. Wood moisture contents at this location showed seasonal accumulations at the outboard side of the wood framing in the latex paint wall, but well within safe limits. Disassembly showed no evidence of moisture damage due to wintertime condensation.

Summertime behavior, however, showed condensation occurring in both assemblies with polyethylene vapor barriers; accumulation was correlated to inward thermal gradients. Condensation was substantially less in the framed poly wall; several possible reasons were air leakage, moisture storage in the framing, and vapor diffusion 'flanking.' The roll blanket wall had mold growth on the wood wafer sensor, as well as some discoloration of the fiberglass. In contrast, the stud frame/polyethylene wall showed few signs of damage; some mold on the wafer, but no damage to the framing. Framing moisture contents were higher than the latex paint wall, but in the safe range. The latex paint wall showed little moisture accumulation, and no damage to the exterior side of the gypsum board. The monitoring will be continued over the coming year: one point of interest is whether the drying of initial construction moisture will reduce the severity of inward vapor drives. Note that this system should not be replenished by ground-source moisture, due to the impermeable polyethylene dimple drainage mat on the exterior.

Our field results match Anderson's Minnesota field survey (1989), which showed wood framing moisture contents within safe levels, with and without interior polyethylene. It also matched the observation that the polyethylene wall accumulates slightly more moisture, due to the elimination of drying to the interior. The below grade portions showed no sign of impending moisture-related failure; humidity levels indicated that more permeable systems allow drying of the wall. The extruded polystyrene wall showed consistently safe behavior. While the interface was at a moderately high RH (over 80%), there was no sign of condensation; these observations match the performance of this assembly in the field.

Simulation results: Initial simulations showed that the two-dimensional effects of the soil-air-basement wall interface have a strong effect on wall temperatures. The wintertime temperatures seen at the concrete-insulation interface are much higher than those predicted by a model using exterior air temperature as a boundary condition. This means that simulations of the above-grade portion of the wall for wintertime condensation issues will generally be quite conservative. However, summertime temperatures showed closer correspondence between monitored data and the model.

In general, both above-grade and below-grade simulations showed wetter conditions than monitored results; this might be ascribed to drier than assumed concrete, mechanisms such as air leakage drying, moisture storage in wood framing, and possible flanking diffusion drying (in the polyethylene/frame wall).

Extrapolations to other assemblies and Canadian climate were ranked in terms of wintertime above-grade condensation risk; as mentioned earlier, these results are quite conservative. The polyethylene and Kraft paper assemblies both had acceptable performance, but the more permeable assemblies had varying degrees of risk, increasing with colder climates and higher interior relative humidity.

The only case with a substantial risk of condensation at the vapor control layer in the Canadian simulations was polyethylene in Toronto. These results suggest that climates lacking a significant cooling load do not have sufficient inward thermal gradients (and therefore vapor gradients) to cause this problem. However, many United States climates would be likely to have these issues.

Basic building physics demonstrate that the use of an impermeable material in the below-grade portion of a basement wall inhibits drying in the only available direction (Timusk 1997). Analysis supports this contention; a basic dewpoint analysis showed minimal chances of condensation, and hygrothermal modeling was in agreement. The modeling showed that drying of the below-grade portion of the wall was proportional to the permeability of the interior insulation system.

However, there was always a high relative humidity at the concrete-insulation interface, with both permeable and impermeable assemblies. This suggests that there is a consistent risk in placing moisture-sensitive materials in contact with concrete. On the other hand, monitoring data and disassembly suggest that this is a conservative prediction, due to factors such as air leaks and delayed closure-aiding drying.

A simulation comparing vapor diffusion and capillarity demonstrated that limiting capillarity (liquid transport) should be the highest priority to control basement-sourced humidity. If moisture entry can be reduced to only vapor diffusion through the concrete, the this source will be almost negligible. This can be achieved by capillary isolation between the wall and the soil (such as heavy asphalt coatings, dimpled drainage mats), and between the wall and the footing (adding a capillary break at that interface).

Synthesis: In synthesizing the results from monitoring and simulation, there are some apparent contradictions that should be addressed. The wintertime above-grade simulations imply that most options that have the vapor resistance of latex paint or higher would fail in many circumstances. Field experience indicates that a permeance between that of Kraft and latex can be sufficient even in relatively cold climates (HDD<4500ºC). For instance, the Anderson survey (1989) showed safe framing moisture contents, with and without vapor control, in Minnesota. Our measurements showed a slight rise in wood moisture content in the latex paint assembly, but within safe ranges. Builders in the Chicago area have been using the perforated roll blanket without widespread condensation failures—in fact, it is used to avoid condensation and accumulation issues resulting from non-perforated roll blankets.

Several aspects may be at play. The temperatures at the concrete-insulation interface are likely higher than those shown by simulation, reducing condensation risks. Relative humidity levels may actually be on the lower end of the spectrum, as suggested by Ruest's (1993) data. Finally, storage might be more generous than the limits used in the simulation: condensation rundown from concrete surfaces would travel to drier parts of the concrete wall, where it could be stored. In the more permeable systems, it would re-evaporate and leave the assembly under more favorable drying conditions.

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References

ASHRAE. 2006. *ASHRAE SPC 160P, Design Criteria for Moisture Control in Buildings.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Black, C.D. 2006. "Mould Resistance of Full Scale Wood Frame Wall Assemblies," MASc Thesis, Department of Civil Engineering, University of Waterloo, Waterloo, ON.

Briggs, R., Lucas, R., Taylor, Z. Todd. 2002. "Climate Classifications for Building Energy Codes and Standards." Technical Paper Final Review Draft. Pacific NW National Laboratory.

Carll, C. and TenWolde, A. 1996. "Accuracy of Wood Resistance Sensors for Measurement of Humidity," *Journal of Testing and Evaluation*, JTEVA, Vol. 24, No. 3, May 1996, pp. 154-160.

Doll, C. S., *Determination of Limiting Conditions for Fungal Growth in the Built Environment,* Sc.D. Thesis, Harvard School of Public Health, 2002

Goldberg, L., and Huelman, P. 2001. *Cloquet Research Facility: Rim Joist and Foundation Insulation Project Final Report,* Building Physics and Foundations Research Programs, University of Minnesota.

Goldberg, L., and Gatland, S. 2006. *Polyamide-6 Based Interior Foundation Insulation System: Experimental Evaluation,* Building Physics and Foundations Research Programs, University of Minnesota.

Huelman, P., and M. Cheple. 2001. Why we need to know more about basement moisture. *Thermal Performance of the Exterior Envelopes of Whole Buildings VIII.* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Hutcheon, N.B. and Handegord, G.O. 1983. *Building Science for a Cold Climate.* Ottawa, Ont.: National Research Council of Canada.

Kesik, T.J.; Swinton, M.C.; Bomberg, M.T.; Kumaran, M.K.; Maref, W.; Normandin, N. 2001. Cost effective basement wall drainage alternatives employing exterior insulation basement systems (EIBS). Eighth Conference on Building Science & Technology, Feb. 22-23, 2001, Toronto, Ontario.

Kumaran, M.K. et al. 2002. NRC-IRC (Institute for Research in Construction) "A Thermal and Moisture Transport Property Database for Common Building and Insulating Materials," Final Report from ASHRAE Research Project 1018-RP, Ottawa, Ont.: National Research Council of Canada.

Lstiburek, J. 2006. Understanding Basements. *ASHRAE Journal*, Jan. 2006, pp. 24-28.

Ruest, K., Fettes, P., Jezerinac, M., Gusdorf, J., Platts, B., Robinson, T., and Parekh, A. 1993. *Field Testing of House Characteristics.* Report to the Canada Mortgage and Housing Corporation. Ottawa, Ontario.

Robert W. Anderson and Associates. 1989. *A Survey of Moisture in Minnesota Home Interior Foundation Wall Insulation.* Final Report for Energy Division, MN Department of Public Service. St. Paul, MN.

Rose, W. 2005. *Water in Buildings: An Architect's Guide to Moisture and Mold.* New York: John Wiley & Sons.

Smegal, J.E. 2006. "Drainage and Drying of Small Gaps in Wall Systems," MASc Thesis, Department of Civil Engineering, University of Waterloo, Waterloo, ON.

Straube, J., D. Onysko, and C. Schumacher. 2002. Methodology and Design of Field Experiments for Monitoring the Hygrothermal Performance of Wood Frame Enclosures. *Journal of Thermal Env. & Bldg. Sci.*, Vol.26, No.2—October 2002.

Swinton, M.C., and A.N. Karagiozis. 1995. *Investigation of warm weather condensation in new and insulated basement walls.* Thermal Performance of the Exterior Envelopes of Buildings VI. American Society of Heating, Refrigeration, and Air-Conditioning Engineers, Inc.

TenWolde, A, Carll, C., and Malinauskas, V. 1998. Air Pressures in Wood Frame Walls. *Thermal Performance of the Exterior Envelopes of Buildings VII.* Atlanta, Geo.: American Society of Heating, Refrigeration, and Air-Conditioning Engineers, Inc.

Timusk, J., and K.D. Pressnail. 1997. *Another Look at Internally-Insulated Basement Wall.* Proceedings of the Seventh Conference on Building Science and Technology, Durability of Buildings – Design, Maintenance, Codes, and Practices, Toronto, Ont.: University of Toronto.

Ueno, K. and Townsend, A. 2006. *Field Monitoring of the Hygrothermal Performance of Interior Basement Insulation Systems*. Proceedings of the 2006 ACEEE Summer Study on Energy Efficiency in Buildings, American Council for an Energy-Efficiency Economy.

Wilkinson, J., K. Ueno, D. DeRose, J. Straube, and D. Fugler. 2007. *Understanding Vapour Permeance and Condensation in Wall Assemblies.* Proceedings of the 11th Canadian Building Science & Technology Conference, National Building Envelope Council.

Zuluaga, M., R. Aldrich, and D. Griffiths. 2004. *Field Performance of Different Interior Basement Insulation Systems*. Performance of the Exterior Envelopes of Whole Buildings IX. Atlanta, Geo.: American Society of Heating, Refrigeration, and Air-Conditioning Engineers, Inc.