RESEARCH REPORT

Understanding Vapour Permeance and Condensation in Wall Assemblies : Volume 1: Main Report

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FINAL REPORT

UNDERSTANDING VAPOUR PERMEANCE AND CONDENSATION IN WALL ASSEMBLIES

for
Canada Mortgage and Housing Corporation

Halsall Associates Ltd.
and
University of Waterloo

May, 2007

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0.0 ABSTRACT

This research investigated the significance/insignificance of potential moisture problems due to plastic sheeting as a vapour barrier in above-grade and basement wall assemblies. The research aimed to outline cases where performance can be improved, and changes that could reduce inappropriate use. Finally, the research looked at the benefits/risks with polyethylene sheeting with clearer delineation of the situations in which it is necessary, potentially damaging, or unimportant.

This report presents key findings from the research work and field tests within the following framework:

- A literature review;
- Field testing of four common basement wall assemblies (with and without polyethylene sheeting) in a southern Ontario home;
- Field testing of six common above-grade wall assemblies (with and without polyethylene sheeting) in the University of Waterloo test exposure facility (BEGHut);
- Comparison of the field testing data and computer models, to provide validation of the model against this installation.
- Extending the test results to broader practice across Canada through computer modeling.

1.0 EXECUTIVE SUMMARY

The use of polyethylene vapour barriers is well integrated into building codes and the Canadian construction industry, a result of substantial investment in research and training. Their use as an air barrier has also resulted in significant improvement in building envelope air tightness when properly detailed. Contractors and inspectors have developed a strong understanding of the details and practices required to achieve tight and reliable enclosures.

However, some groups have expressed concerns that polyethylene sheeting may reduce drying and entrap moisture due to its low vapour permeance. In particular, problems have been encountered with basement walls where inward drying of initial construction moisture within the concrete foundation walls is trapped by polyethylene sheets. Problems have also been identified in above-grade walls where absorptive and non-ventilated claddings are employed.

Field testing and simulation results show that low permeance layers make sense in some situations and not others. Moisture issues could arise in certain situations with low or high permeance interior vapour control layers. This research gives guidance on the situations where polyethylene sheeting is or is not a problem, and regarding appropriate vapour permeance levels for walls in different geographical areas.

2.0 INTRODUCTION / LITERATURE REVIEW

The intention of this research program was to determine the significance/ insignificance of potential moisture problems due to plastic sheeting in above-grade and basement wall assemblies. The research aimed to outline cases where performance can be improved, and to recommend changes that could reduce inappropriate use. Finally, the research addressed the benefits/risks with polyethylene sheeting to find a clearer delineation of the situations in which it is necessary, potentially damaging, or unimportant. The concern in this research is low permeance interior vapour retarders. Polyethylene sheeting is the most common but other materials such as vinyl wallpaper are of interest and are referenced.

This research program consisted of the following:

- A literature review;
- Field testing of four common basement wall assemblies (with and without polyethylene sheeting) in a southern Ontario home;
- Field testing of six common above-grade wall assemblies (with and without polyethylene sheeting) in the University of Waterloo test exposure facility (BEGHut);
- Comparison of the field testing data and computer models, to provide validation of the model against these installations.
- Extending the test results to broader practice across Canada through computer modeling.

2.1 Summary of Theory and Literature

The goals of the literature review were to (1) determine where and under what conditions the use of plastic sheeting could cause failure or has been shown to cause problems; and (2) summarize potential adverse consequences if impermeable vapour barrier layers are omitted. A full reference/summary of the literature reviewed is in Appendix A. Excerpts of our review are as follows:

- Inward vapour diffusion driven by solar heating of the exterior parts of walls has long (since the 1950's) been observed to cause damaging levels of condensation in Canadian walls (Hutcheon 1953).
- The incidence, severity, consequences, and hence significance of solar driven inward drives are not well understood.
- The factors that have been demonstrated or calculated to affect the quantity and significance of solar driven inward diffusion include the:
  - orientation to wind-driven rain and sun heating
  - absorptive and storage capacity of the cladding
  - presence of ventilation behind the cladding
  - vapour permeance of the sheathing layers behind the cladding
  - vapour permeance of the interior finish / vapour control layers
  - interior temperature

This research project focused on the fifth item above, as polyethylene sheeting has a very low vapour permeance. The research also had orientation and permeance of sheathing as experimental variables.

- An air barrier should be installed in all walls. If plastic sheeting (used as an air barrier) is removed, then other measures/systems/materials need to be employed to provide the air-tightness in a wall assembly.
- There is no consensus of the maximum vapour permeance allowable on the interior of Canadian walls to reduce cold weather diffusion problems. Recommended values in the literature vary with exterior climate, wall assembly, and interior humidity conditions, but range from 60 to over 1000 metric perms. However, there appears to be little doubt that a layer with the vapour permeance of polyethylene sheeting will control winter diffusion.
- Some speculation exists about the effects on drywall of high humidity levels in cavities and the benefits to the drywall and interior finish when protected by polyethylene (Lawton & Brown 2003).

2.2 Above-Grade Walls

2.2.1 Conditions Where Plastic Sheeting Could Cause Problems

Risks related to inward vapour drive during periods of warm weather have been identified by Christensen (1985), Straube & Burnett (1995), Pressnail et al. (2003), Derome & Huang (2005) and others. In some situations, high humidity and condensation has been in evidence at the interior surfaces of the building envelope. Moisture-sensitive organic materials are often present at these locations; warm-weather inward vapour drive can create temperature and moisture conditions favourable for mold growth and wood rot. Related literature is summarized as follows:

a) **Hutcheon (1953) -** (As referenced in 2005 by Derome & Huang): In summer, hot sun following a rain drives moisture as vapour to the inside of the wall, and condensation behind the vapour barrier can occur.

b) **Wilson (1965)**: Demonstrated from field measurement in residential masonry walls that summer condensation could occur in permeable insulation and on the vapour barrier.

c) **Sandin (1993)**: High cavity relative humidity (RH close to 100%) was measured and condensation was observed on the exterior side of the vapour barrier in a masonry wall in Sweden. This occurred during extreme summer conditions: heavy driving rain followed by sunshine. It was indicated that the condensation could be worse if the interior air were cooled.

d) **Straube & Burnett (1995)**: Field-testing was completed on brick-veneer clad wood-framed walls sheathed with rigid fiberglass. It was found that summer time solar driven inward vapour drives caused wood frame to become saturated, stained and exhibited mold growth over a period of several months. It was concluded that cladding type, orientation, and solar-induced vapour-drive are important parameters for wall moisture management. It was indicated that the condensation potential may be greater for air-conditioned buildings.

e) **Straube (1997)**: Field-testing was completed on masonry walls with a cavity filled with rockwool or fiberglass board, and vapour permeable weather barriers. The filled cavities limited ventilation. Wood frame moisture contents were measured to be in excess of 28% for over 7 months in the summer/fall. These were ideal conditions for mold growth and rot. Mold and incipient decay was noted.

f) **Straube & Burnett (1998)**: Field-testing was conducted on unventilated east-facing brick walls with vapour permeable sheathing. The wood frame and interior polyethylene vapour barrier were observed to become wet with condensation. It is speculated that building envelope problems will arise if ventilation is restricted and there is little vapour resistance between the cladding and an inner vapour retarder.

g) **Straube (2001)**: Surface temperatures of an east-facing red brick wall (above 40°C for 12% of the hours in summer) are compared with a light-grey vinyl siding (above 40°C for 3.1% of summer) to examine solar absorption characteristics required for solar heating. Parameters necessary for condensation from solar driven vapour drive are identified as: high outboard vapour permeance, wet materials (absorptive cladding, built-in moisture, or penetrating water), and low permeance inner vapour barriers.

h) **Pressnail et al. (2003)**: Extensive wood decay within a wall clad with wood siding was attributed to sun-driven moisture. Particulars regarding details or factors causing the problem are not provided.

i) **Straube, Van Straaten, Burnett (2004)**: Field tests were conducted on wood-framed ventilated and non-ventilated brick-clad east-facing walls with asphalt impregnated felt sheathing paper. It was discovered that a significant amount of moisture was redistributed from wet outer layers (sheathing or cladding) to the interior by short-term peak solar radiation. Inward solar-driven vapour diffusion was most significant in spring and early summer. Condensation at the inner vapour barrier, high moisture contents in the wood frame, and mold growth occurred in the unventilated walls but not the ventilated ones.

j) **Mukhopadhyaya, Kumaran & Van Reenen (2004)**: State (without evidence) that there is no evidence of problems as a result of compliance with prescriptive National Building Code (NBC) requirements for warm-side low vapour permeance barriers.

k) **Derome & Huang (2005)**: Laboratory testing found that solar driven condensation requires specific conditions to occur. As testing by others has shown, these conditions include: high wood-siding moisture content, non-ventilated cladding/assembly, sheathing with high vapour permeance, and long exposure to simulated solar radiation.

2.2.2 Potential Consequences of Omitting Interior Impermeable layers

By removing interior impermeable layers that have traditionally been relied upon as a vapour barrier, wall assembly moisture could escape to the interior when vapour drives are in this direction. However, this may also increase vapour flow into wall assemblies at other times; typically during cold weather, creating conditions which are favourable for mold growth and wood rot (Goldberg 2001).

Water penetration into a wall or solar heating of saturated absorptive cladding will increase the potential for mold growth on interior drywall finishes if the polyethylene is removed. Polyethylene has been found to protect interior drywall even where studs had rotted and corroded from water ingress (Lawton & Brown 2003).

Where low vapour permeability interior finishes (such as vinyl wall coverings) are employed in lieu of plastic sheeting or accidentally in walls without plastic sheeting, moisture may accumulate within the interior drywall (Building Research Establishment 1989).

Literature that discussed associated risks is summarized as follows:

a) **Building Research Establishment, UK (1989)** (As referenced in 2005 by Derome & Huang): It was stated that removing the vapour barrier should not be considered since summer condensation could occur behind low-permeability interior finishes.

b) **Energy Design Update (1989)**: Two series of lab tests (at the Manville Research Centre in Denver and the National Institute of Standards and Technology (NIST)) involved interior drywall with latex paint, no vapour barrier and an interior relative humidity close to 50% in a simulated cold climate. Results indicate that moisture would accumulate within the exterior sheathing in winter. Although the results were inconclusive, they suggest that moisture accumulation may be significant and that the importance of proper vapour retarders as well as air barriers should not be underestimated.

c) **Sandin (1993)**: Conditions required before the polyethylene vapour barrier is removed are identified as: no vapour tight layer on the outer side of the wall, and the vapour concentration of the interior air should be low.

d) **TenWolde, Carll & Malinauskas (1998)**: It is suggested that polyethylene vapour barriers have significantly reduced condensation within walls in cold climates due to the improved air tightness. It is suggested that omitting polyethylene vapour barriers may result in increased condensation problems due to air leakage. This may be true unless the industry can rely on contractors to make other layers airtight.

e) **Lawton & Brown (2001):** Computer modeling for wood-framed stucco walls in Vancouver predicts that unpainted interior gypsum board moisture content will be acceptable both with and without a polyethylene vapour barrier. There is limited drying potential to the interior in this climate where there is a painted interior finish and no interior mechanical dehumidification. When leakage problems develop, vapour drive towards the interior may cause mold growth on interior drywall finishes if the polyethylene is removed. Polyethylene has been found to protect interior drywall even where studs had rotted and corroded from water ingress. This is contrasted with a Seattle building where leakage led to widespread drywall mold growth on the drywall where it was not protected by polyethylene.

f) **Goldberg (2001):** A test house in Minnesota with various vapour barrier configurations was dismantled after 4 heating seasons. Significant moisture effects (mold growth and wet/bowed Oriented Strand Board (OSB) sheathing) were observed in walls without an interior polyethylene vapour barrier, particularly on north facing walls. (The interior humidity in the winter ranged predominantly from 40% to 60% at 20°C to 22°C.)

g) **Kakela & Vinha (2002):** Field-testing was conducted on walls in Finland with and without interior vapour barriers. In a wall without a vapour barrier, critical conditions for mold growth were identified (but none observed) on the interior of fiberboard sheathing in autumn. It is concluded that the internal wall must have sufficient vapour resistance to prevent condensation and reduce risks for mold growth.

h) **Pressnail et al. (2003):** It is pointed out that one must address cold weather vapour diffusion, condensation, and the need to economically humidify the interior air if a vapour barrier is excluded in cold climates. No calculations/testing were provided to illustrate these items.

i) **Mukhopadhyaya, Kumaran & Van Reenen (2004):** Computer modeling predicts that the removal of the vapour barrier can significantly increase the moisture content of the interior gypsum board facing. In the absence of the vapour barrier, the interior facing/finish becomes a critical factor. It is worthy to note that the vapour permeance for the painted gypsum was not varied with relative humidity (See Appendix A).

j) **Holm (2004):** This presents results from computer modelling for Seattle where a humidity-dependant smart vapour retarder is employed. It is predicted that the amount of moisture that can be dried to the interior in spring can be 2.5 times greater than interstitial winter condensation.

2.2.3 Recommendations to Address Inward Vapour Drive

Measures to control inward vapour drive are identified by Christensen (1985), Straube & Burnett (1995), Pressnail et al. (2003) and others; they include employing ventilated cavities within the walls, lower permeance external cladding or sheathing, and/or cladding with low or reduced water absorption.
Related literature is summarized as follows:

a) **Wilson (1965):** Recommended ventilation or non-absorptive claddings to address summer condensation.

b) **Christensen (1985)** (As referenced in 2005 by Derome & Huang): Proposed overhangs, siliconating masonry, non-absorptive claddings, ventilation, and external low permeance materials to prevent summer condensation.

c) **Sandin (1993)**: Field tests showed that condensation from inward vapour drive was avoided by employing a water repellant impregnated brick with a 20mm air space and no interior vapour barrier.

d) **Straube & Burnett (1995 & 1998):** It was demonstrated that ventilation and the use of vapour resistant exterior sheathings could control wetting from inward vapour transport.

e) **Straube (1997):** A maximum sheathing permeance of 50-100 ng/Pa.s.m^2 is recommended to control inward vapour drive and prevent significant moisture content in wood framing or condensation on interior polyethylene vapour barrier.

f) **Pressnail et al. (2003):** Laboratory experiments demonstrated that low permeance foam based exterior sheathing, or mechanically or naturally vented air spaces greatly reduce solar driven moisture ingress. It was speculated that overhangs, non-absorptive cladding, or water repellant treated cladding could also be considered.

g) **Straube, Van Straaten & Burnett (2004)**: Field testing showed that ventilation of brick veneer clad walls was effective in avoiding condensation and excessive stud moisture contents caused by solar-driven inward vapour diffusion. If water was introduced into the wall, faster drying occurred with higher permeance sheathing membranes.

h) **Derome/Huang (2005):** It was experimentally demonstrated in the lab that condensation from inward vapour drive was eliminated with a ventilated assembly.

2.2.4 Recommendations on the Permeability of Building Assemblies

Literature that provides guidelines or recommendations regarding vapour permeability is summarized as follows:

a) **National Building Code of Canada (1995):** Clause 9.25.1.2: states that layers in walls with vapour permeance less than 60 ng/Pa.s.m^2 (and air leakage characteristics less than 0.1 L/s.m^2 at 75 Pa) shall be placed:

- on the warm face of the insulation
- outboard of an air space that is vented/drained to the exterior
- at a location where the ratio of thermal resistance outboard of the impermeable layer to inboard of impermeable is not less than values given in table 9.25.1.2. The ratio of outboard to inboard thermal resistance required increases for colder climates (distinguished by heating degree days).

b) **Straube (2001):** In order to control inward vapour drive in cool to temperate climates, a component with moderate vapour permeance (100-200 metric perms) should be employed at the exterior combined with a moderate vapour retarder on the interior (150-300 metric perms)

c) **Mukhopadhyaya, Kumaran & Van Reenen (2004):** Computer modeling for wood-framed stucco clad walls in Vancouver predicts optimum moisture management in walls with total interior vapour permeance of 55-370 ng/Pa.s.m^2 (or 60-1000 ng/Pa.s.m^2 for the vapour barrier only). Lower or higher interior vapour permeance results in higher sheathing relative humidity throughout the year.

d) **Lstiburek (2004):** U.S. Building Code requirements for vapour retarders are proposed based on climate and properties of other materials in the wall assembly. Identified hygrothermal regions include those applicable to Canada. Most assemblies do not use polyethylene and incorporate latex paint or vapour semi-permeable interior finishes. The following main principles are recommended:

- Avoid vapour barriers where vapour retarders will work, avoid vapour retarders where vapour permeable materials will work.
- Avoid the installation of a vapour barrier on both sides of the wall assembly.
- Avoid using poly, foil faced batts, reflective barrier foils, and vinyl wall coverings on the interior of air-conditioned assemblies.
- Ventilate enclosures

e) **Simonson, Ojanen & Salonvaara (2005):** Analysis for a cold climate (Finland) suggests moisture should be acceptably controlled for an air-tight assembly with an interior-to-exterior vapour diffusion resistance ratio from

3:1 to 5:1 (or as much as 500:1 for walls with polyethylene). However, solar effects were not included in this modeling. Limited field-testing in Finland demonstrated that small amounts of winter moisture accumulation dried rapidly in the spring, but the indoor relative humidity (21 ± 3%RH at 20 to 23°C) was lower than that typically expected in modern Canadian homes.

2.3 Basement Walls

The challenges of the interior insulation assemblies in the basement environment have been addressed by Timusk (1997), Huelman and Cheple (2001) and others. One issue is the contrasting requirements for the above-grade and below grade portions of the wall: the former has an outwards wintertime vapour gradient, suggesting the need for an interior vapour control layer, while the latter in Southern Ontario, British Columbia and the Maritimes has a year-round inwards vapour gradient (colder regions may vary), suggesting that drying to the interior is often necessary. Furthermore, similar to above-grade wall assemblies, inwards vapour drives can result in issues, as found in the literature below

2.3.1 Conditions Where Plastic Sheeting Could Cause Problems

a) **Swinton & Karagiozis (1995):** Case studies and hygothermal modeling of basement walls, looked at fresh concrete foundation walls with interior fibreglass insulation and polyethylene sheeting. With this construction, extensive condensation on polyethylene was seen, even with partial height insulation and finishes installed 3 months after foundations were poured. Modeling suggested that vapour diffusion driven by inward and downward temperature gradients is a probable contributing factor to condensation and pooling water.

b) **Goldberg & Aloi (2001):** Field-testing in Minnesota involved concrete block basement walls insulated from the interior with glass fibre insulation, and polyethylene inboard of the insulation. The wall had condensation form within the insulation from March to September, primarily at the upper section of the wall. The insulation was not likely to dry out before condensation/moisture absorption was likely to recur. This wall was not deemed to be appropriate for long-term use with fibreglass insulation.

c) **Lstiburek & Yost (2002):** Numerous basements with concrete foundation walls, interior batt insulation and interior polyethylene, vinyl or foil interior have been found with serious problems with mold, decay, and odours.

d) **Goldberg (2004):** Field-testing in Minnesota involved a low-density open cell spray foam insulation. Polyethylene between insulation and block led to condensation on the polyethylene interior in the winter and condensation on the polyethylene exterior in summer. Condensate rundown was noted but there was no visible mold growth. Interior polyethylene led to condensation on the wall side of the poly during the summer with an upwards-trending wetting and drying cycle (i.e. net moisture accumulation from year to year). Condensate rundown was noted and there was visible mold growth on the spray foam surface and wood studs.

2.3.2 Potential Consequences of Omitting Interior Impermeable Layers

Onysko, Gates & Van Rijn (2003): Field Testing in Ottawa found that preserved wood foundations with exterior plywood sheathing with interior glass fibre insulation, polyethylene and unpainted drywall showed little condensation on the interior of the exterior plywood sheathing. When the polyethylene was removed there was an accumulation of moisture in the above grade portions of the plywood sheathing. And the rate of drying was slower then when polyethylene was used.

2.3.3 Recommendations to Reduce Inward Vapour Drive Risks

Field testing in Minnesota by Goldberg & Aloi (2001) and Goldberg (2004) found that concrete block basement walls insulated from the interior with glass fibre or low-density open cell spray foam and with no polyethylene provided a stable wetting and drying cycle that did not lead to moisture accumulation. This did not lead to gross wetting or condensate running down the wall surface.

Lstiburek & Yost (2002) report that moisture from initial construction, air leakage, capillary rise, diffusion, and/or ground water leakage must be allowed to dry to the interior since it is unable to dry to the exterior below grade. They describe analysis by Jeong (2001) at the University of Waterloo on several basement wall configurations with insulation and with and without polyethylene . Extruded polystyrene insulation (XPS) on the interior (25mm to 89mm thick) performed well. Thin XPS (38mm) can be used outboard of a fibre-glass insulated cavity providing the interior relative humidity does not exceed 50%. Further recommendations include vapour-permeable and moisture-tolerant interior finishes.

3.0 METHOD

3.1 Field Testing Experimental Set-up

The literature review provided focus for the scheduled field testing. Typical assemblies with and without polyethylene sheeting were tested side by side to allow direct comparisons.

3.1.1 Above-Grade Walls

Three above-grade assembly types (north and south duplicates; six walls total) were installed in the University of Waterloo's BEGHut exposure facility; Table 3.1 details these assemblies. The interior of the hut was maintained at a 50% relative humidity and 20° to 21° C year round. This is a very high interior relative humidity for winter conditions, and was expected to cause wintertime diffusion wetting. The temperature is lower than most residential applications in summer, and hence is expected to increase the risk of summer condensation problems.

Wall sensors measure temperature, relative humidity, and wood moisture content, using methodology described in Straube et.al. (2002). Wood resistance sensors, similar to those examined by Carll and TenWolde (1996) are also installed; they provide surrogate moisture content measurements. These sensors (referred to as 'wafer sensors' here) include moisture accumulation in their response to changing humidity conditions. Interior and exterior test hut conditions are also measured, including temperatures, relative humidity, wind speed & direction, horizontal solar radiation, and rainfall. The same sensor layout was used in all walls, in order to allow direct comparisons between the walls. All sensors were installed at the vertical centerline of the wall, as shown in Figure 3.1 and Figure 3.2. Wall assembly 2 is essentially the same as wall 1 but without the polyethylene sheeting.

Table 3.1: Above grade wall assemblies

Layer	**Above grade wall 1: 2x6 with Polyethylene**	**Above grade wall 2: 2x6 without Polyethylene**	**Above grade wall 3: 2x4 with XPS**
Interior finish	½"/12.7 mm gypsum wallboard w. latex paint	½"/12.7 mm gypsum wallboard w. latex paint	½"/12.7 mm gypsum wallboard w. latex paint
Vapour control layer	6 mil polyethylene	None	None
Framing/insulation	2x6 16" o.c. with R-20/RSI-3.5 fibreglass batt	2x6 16" o.c. with R-20/RSI-3.5 fibreglass batt	2x4 16" o.c. with R-12/RSI-2.1 fibreglass batt
Sheathing	½"/12.7 mm OSB	½"/12.7 mm OSB	1"/25 mm XPS R-5/RSI 0.9
Water resistive barrier	Spun-bonded polyolefin (SBPO) housewrap	Spun-bonded polyolefin (SBPO) housewrap	Spun-bonded polyolefin (SBPO) housewrap
Drainage cavity	1"/25 mm space; bottom vents only	1"/25 mm space; bottom vents only	1"/25 mm space; bottom vents only
Cladding	Single wythe brick veneer	Single wythe brick veneer	Single wythe brick veneer

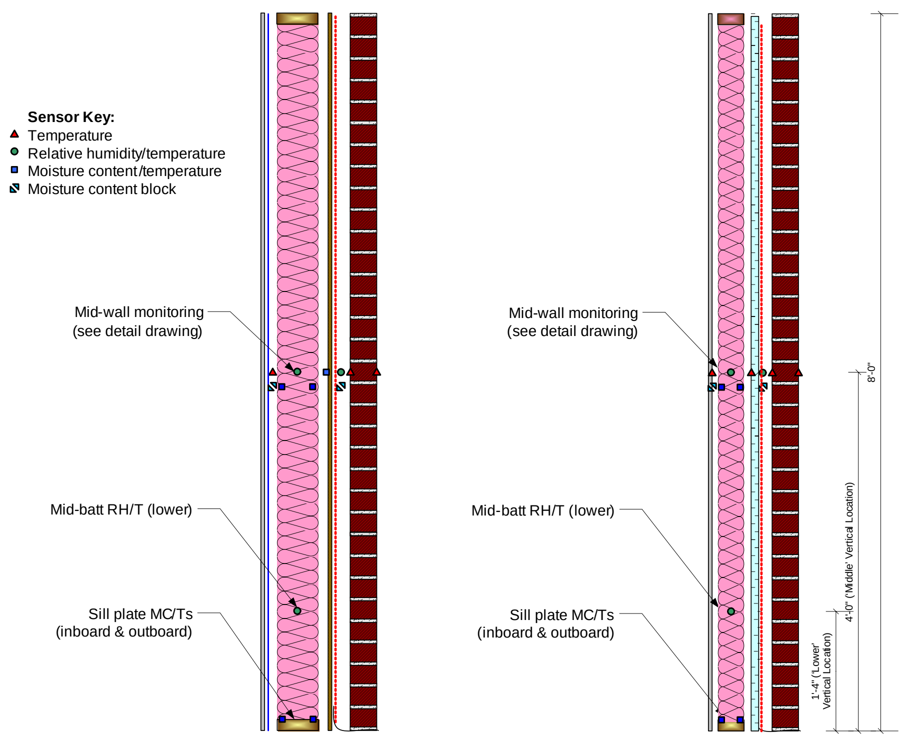

Figure 3.1: Section and monitoring layout for above grade walls 1 and 2 (left) and 3 (right)

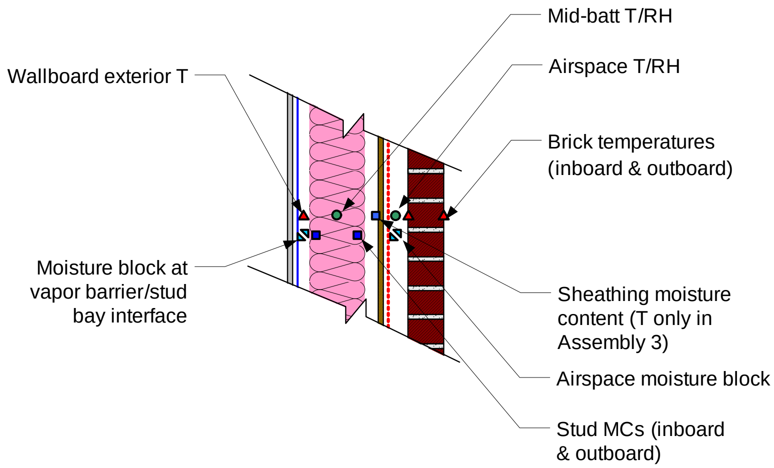

Figure 3.2: Detail of mid-height monitoring locations

3.1.2 Basement Walls

Four interior wall insulation assemblies were constructed and monitored in a house in Kitchener, Ontario. Installation and instrumentation was completed in the first year of service; the test walls are roughly south facing. The basement wall assemblies are detailed in Table 3.2; schematics and sensor layouts are shown in Figure 3.3. Basement wall 2 has fibreglass insulation with plastic sheeting on the interior side only, wall 4 is the same as wall 3 without the polyethylene sheeting.

The house was built in the winter, occupied in June of that same year, with the monitoring beginning in August, a few months later. A roll blanket similar to the one monitored was installed during construction, and replaced at the time of monitoring with the assemblies noted in Table 3.2.

The exterior conditions were reviewed at the time of the monitoring installation (sensor placement). A drainage layer ("dimple sheet") was in place against the foundation. From the top, the exterior fill was noted to be sod, 1' – 1½' dense soil, and relatively free draining soil below this.

Table 3.2: Basement wall assemblies

Layer	Basement wall 1: 2" XPS	Basement wall 2: vinyl fibreglass roll blanket	Basement wall 3: 2x4 with polyethylene	Basement wall 4: 2x4 without polyethylene
Interior finish	½"/12.7 mm gypsum wallboard w. latex paint	Polyethylene roll blanket facing material	½"/12.7 mm gypsum wallboard w. latex paint	½"/12.7 mm gypsum wallboard w. latex paint
Other	19 mm / 3/4" airspace and furring strips	None	6 mil polyethylene	None
Framing/ insulation	2"/50 mm extruded polystyrene (XPS) R-10/RSI 1.8	R-12/RSI-2.1 fibreglass roll blanket	2x4 16" o.c. with R-12/RSI-2.1 fibreglass	2x4 16" o.c. with R-12/RSI-2.1 fibreglass

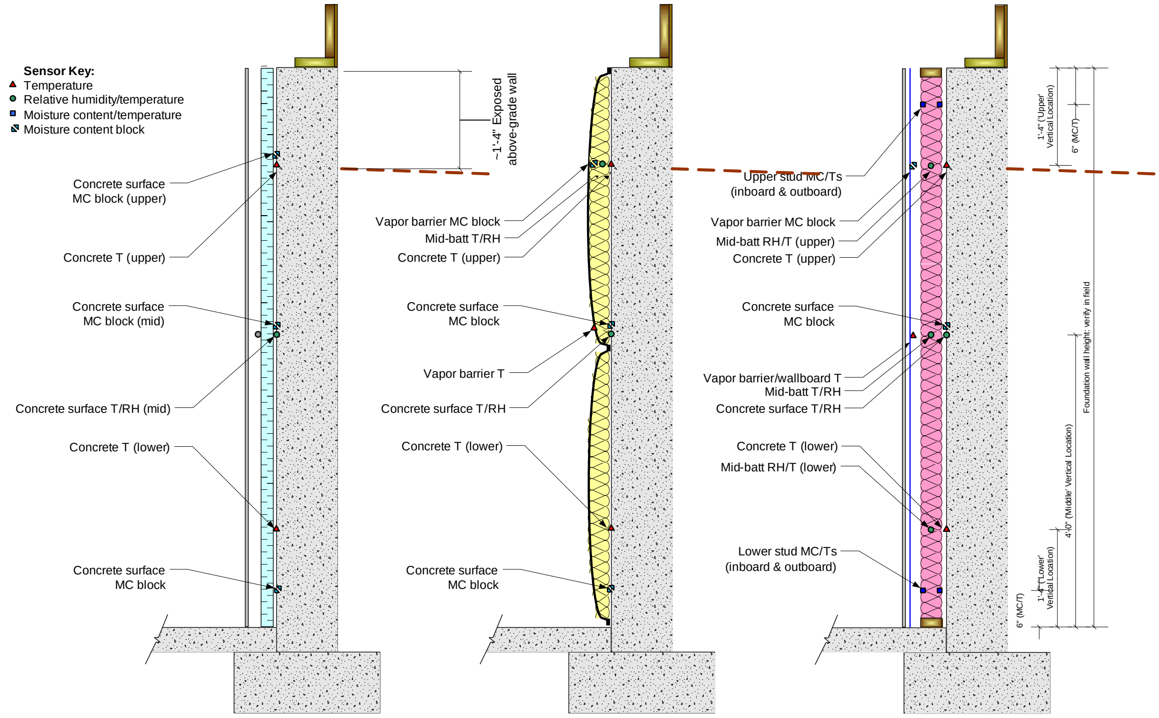

Figure 3.3: Basement wall assemblies 1, 2, and 3

In addition to the wall sensors, interior and exterior temperature and relative humidity were recorded. Soil temperatures and moisture content were recorded at multiple depths as shown in Figure 3.4 as well as lateral locations to provide foundation wall boundary conditions.

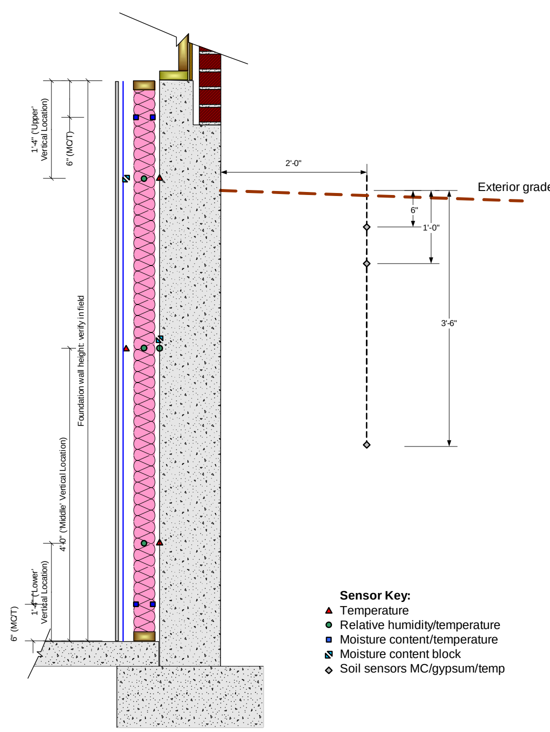

Figure 3.4: Basement exterior monitoring locations

3.2 Computer Modeling Set-up

3.2.1 Above Grade Walls

The above grade wall assemblies in the experimental set-up above were modeled to review the dynamic thermal and moisture transport performance of the wall assemblies. This was done using a computer based analytical program (WUFI® Pro 4.1, Fraunhofer Institute for Building Physics 2006). The three walls modelled are outlined below, each one was reviewed for a North and South orientation:

- Wall 1: Brick, Air Cavity, SBPO, OSB, 150mm Fibreglass Batt, 4 ng/(Pa.s.m^2) Poly, Painted Gypsum
- Wall 2: Brick, Air Cavity, SBPO, OSB, 150mm Fibreglass Batt, Painted Gypsum
- Wall 3: Brick, Air Cavity, 25mm XPS, 102mm Fibreglass Batt, Painted Gypsum

Modelling assumptions are outlined in Appendix C1. All runs performed are shown in Figure 3.5 below.

3.2.1.1 Validation

The model was checked/refined against the filed monitoring data to match the results from the test facility as closely as possible. The moisture content of the OSB, the relative humidity of the air space and fiberglass batt, and the dew point of the fiberglass batt were all compared against field-monitored data to verify the model. These graphs can be seen in Appendix D1. There is generally good agreement between the simulated and monitored data.

The major variables adjusted to match the experimental data were: material properties, rain exposure and absorption, and monitoring positions.

The moisture content of the OSB was reviewed at different slices to simulate the moisture content pins used in the experimental set-up. The results are presented in Appendix D1.

3.2.1.2 Baseline (Waterloo)

Once validated, the model was then adjusted to a Waterloo baseline with less severe interior conditions. We also reviewed the 2nd year of all computed data to reduce the impact of initial conditions on the results.

The interior condition was chosen after careful review of available options in WUFI and a CMHC study "Field Testing of House Characteristics" by (Ruest, 1993). The moisture loads in WUFI were selected to represent a normal (medium) or high (heavy) interior moisture load.

3.2.1.3 Geographic Extrapolation

The base line Waterloo model was then extrapolated to several other geographic areas. The major adjustments for the extrapolation were exterior and interior climates and orientation.

The interior moisture loads in WUFI were selected to represent a normal (medium) or high (heavy) interior moisture load in the given geographic region (with respect to the CMHC study referenced in 3.2.1.2).

Wall orientation was chosen to represent worst-case scenarios. Accordingly the North elevation was chosen for all cities as well as the South for Waterloo and St.Johns, the West for Edmonton, and the East for Vancouver.

3.2.1.4 Variations

Variations were then performed for each geographic location to explore the impact of higher interior moisture loads, and a low perm interior paint under normal moisture loads on the North walls with no poly.

3.2.1.5 Thresholds

Threshold limits were set to provide benchmarks by which to compare the data for the given runs.

Although the risk threshold for the onset of mold growth is typically stated as 80% RH or higher, more recent research has shown that mold growth take a very long time to begin at this RH, and is greatly intensified by the introduction of liquid water (Doll 2002, Black 2006). Therefore, measuring the occurrence of condensation is useful to determine relative risks between assemblies.

The proposed ASHRAE 160P Standard (2006) defines mold growth failure when the RH exceeds 80% RH for one month. However, the vulnerability of the assembly components is not accounted for.

Sedlbauer (2004) proposed a system of Lowest Isopleth for Mold (LIMs) curves for various building material substrates, indicating risk conditions for mold growth. They included the LIM_{Bau} I level (biodegradable materials such as wallpaper, plasterboard) and the LIM_{Bau} II level (porous substrates such as mineral building materials and some woods). These limits are known to be generally conservative.

Based on the above, we selected the following thresholds to compare data at monitoring positions:

1. Time above 85%RH and 5°C
2. Time above 95%RH and 10°C
3. Time above 99.9%RH (to represent condensation conditions)

We also tracked time where sheathing surface moisture content was above 20% and 30% moisture content (known as Thresholds 4 and 5).

Run	Assembly	Orientation	Materials	Int. Conditions	Ext. Conditions		Data Analy-sed
Run 1.1	Poly	South	Base model	BEGHut values	BEGHut Values		1st yr
Run 1.2	Poly	North	Base model				
Run 1.3	No poly	South	Base model				
Run 1.4	No poly	North	Base model				
Run 1.5	XPS	South	Base model				
Run 1.6	XPS	North	Base model				
Run 2.1	Poly	South	Base model	prEN - regular load	BEGHut Values		2nd yr
Run 2.2	Poly	North					
Run 2.3	No poly	South					
Run 2.4	No poly	North					
Run 2.5	XPS	South					
Run 2.6	XPS	North					
Run 2.7	No poly	North	Base model	prEN - high load	BEGHut Values		2nd yr
Run 2.8	XPS	North	Base model	prEN - high load			
Run 2.9	No poly	North	low perm int. paint	prEN - regular load			
Run 2.10	XPS	North	low perm int. paint	prEN - regular load			
Run 3.1	Poly	South	Base model	prEN - regular load	St. Johns	warm yr	2nd yr
Run 3.2	Poly	North					
Run 3.3	No poly	South				cold yr	
Run 3.4	No poly	North					
Run 3.5	XPS	South					
Run 3.6	XPS	North					
Run 3.7	No poly	North	Base model	prEN - high load	St. Johns	cold yr	2nd yr
Run 3.8	XPS	North	Base model	prEN - high load			
Run 3.9	No poly	North	low perm int. paint	prEN - regular load			
Run 3.10	XPS	North	low perm int. paint	prEN - regular load			
Run 4.1b	Poly	West	Base model	prEN - regular load	Edmonton, standard yr		2nd yr
Run 4.2	Poly	North					
Run 4.3b	No poly	West					
Run 4.4	No poly	North					
Run 4.5b	XPS	West					
Run 4.6	XPS	North					
Run 4.7	No poly	North	Base model	prEN - high load	Edmonton, standard yr		2nd yr
Run 4.8	XPS	North	Base model	prEN - high load			
Run 4.9	No poly	North	low perm int. paint	prEN - regular load			
Run 4.10	XPS	North	low perm int. paint	prEN - regular load			
Run 5.1b	Poly	East	Base model	prEN - heavy load	Vancouver	warm yr	2nd yr
Run 5.2	Poly	North					
Run 5.3b	No poly	East				cold yr	
Run 5.4	No poly	North					
Run 5.5b	XPS	East					
Run 5.6	XPS	North					
Run 5.7	No poly	North	Base model	EN - class 3, 21oC	Vancouver	cold yr	2nd yr
Run 5.8	XPS	North	Base model	EN - class 3, 21oC			
Run 5.9	No poly	North	low perm int. paint	prEN - high load			
Run 5.10	XPS	North	low perm int. paint	prEN - high load			

Table 3.5: Record of Runs Performed for Above-Grade Computer Modeling

3.2.2 Basement Walls

One-dimensional hygrothermal modeling of the basement wall assemblies was undertaken using WUFI® Pro 4.1 (Fraunhofer Institute for Building Physics 2006).

The assemblies installed in the test basement were as follows:

1. 2"/50 mm extruded polystyrene foam, furring strips, and gypsum drywall with latex paint (referred to as "XPS")
2. Full-height fiberglass roll blanket with polyethylene facer (referred to as "roll blanket")
3. 2x4 stud frame with fiberglass batt, polyethylene, and gypsum drywall with latex paint (referred to as "stud frame polyethylene")
4. 2x4 stud frame with fiberglass batt and gypsum drywall with latex paint (no polyethylene) (referred to as "stud frame no polyethylene" or "stud frame latex paint")

Modelling assumptions are outlined in Appendix D2.

3.2.2.1 Validation

The assemblies from the test basement were modeled and compared to monitored data; simulation parameters were tuned to provide closer correspondence. To run these simulations, it was necessary to generate boundary conditions for several heights in the assembly, since exterior wall conditions vary above and below grade. The "low", "middle," and "high" (i.e., above-grade) monitoring locations were simulated, to match instrumentation data. Comparisons of temperature, relative humidity, dewpoint, and condensation potentials were used to calibrate the model. These comparisons are outlined in Appendix D2.

Correspondence between monitored data and simulations was marginal. Simulations of the above grade portion of the basement wall show wintertime concrete-insulation temperatures being warmer than monitored conditions. Inspection of the details of the wall assembly at this location indicate that two-dimensional effects are likely significant. Since the temperature sensor is roughly at grade level, the above-grade and below-grade environments both have an effect. Furthermore, 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; a taller above-grade portion would be a better candidate. Only a small portion of this wall is reflected by the one-dimensional simplification, so two-dimensional effects seem quite likely.

This lack of temperature correspondence at the above-grade portion makes the goal of validation and calibration of the simulation difficult. However, these simulations can still serve some use. A taller exposed above-grade section is more likely to have temperatures closer to the simulation, and a lower concrete-insulation interface temperature would be more challenging for wintertime condensation at this location. Therefore, the simulation may be able to provide some insight for these worst-case extremes, even if they were not experienced at the experimental site. Modeling of these assemblies (using the Kitchener site data) is thus presented under the extrapolation modeling section.

Simulations of the below-grade portion of the basement wall show the two low-permeance systems (roll blanket and XPS) behave very differently than the monitored data. In the simulation, relative humidity levels quickly rise to the 95-100% range for both of these walls, and stay at that level for most of the year. In contrast, the monitored data shows humidity levels of 85-100% for the roll blanket, and 80-90% for the XPS. The fact that the monitored data is drier than simulation has several possible explanations: perhaps, despite best efforts, there is some air leakage or communication from the interior space to the concrete-insulation interface (very low permeance material such as polyethylene can effectively be bypassed by a very small air leak, TenWolde and Carll (1998)). Given the relative humidity levels during the test year, this would result in drying of the assembly. Second, the possibility of vapour diffusion "flanking" through the edge framing 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.

Despite the marginal overall correspondence between monitored data and simulations, in all cases, the simulation shows higher humidity levels than in reality. Therefore, the simulation shows more challenging conditions in the assembly than experienced in reality, which means the simulation could be judged as a conservative representation of the situation. Where simulations vary radically, as noted above, the results are dismissed and/or viewed strongly in light of the limitations.

3.2.2.2 Geographic Extrapolation

After gaining this understanding of the relationship between measured data and the simulation results, extrapolations with different exterior and interior climates were run and analyzed. Extrapolations are divided into the above-grade and below-grade simulations; exterior weather locations used included Toronto, ON, Vancouver, BC; St. John's, NL; and Edmonton, AB. Various interior relative humidities were simulated, including "low," "mid," and "high" loadings.
Finally, assemblies not tested at the Kitchener site were simulated. They included "bounding" conditions (i.e., no interior vapour control), and some materials currently used for interior basement insulation (perforated facer roll batt, Kraft paper-faced batt).

3.2.2.3 Thresholds

Although condensation may momentarily occur, it can be safely stored in the assembly and then released in more favorable conditions. This type of storage has been quantified by the German DIN 4108 Standard (Deutsches Institut für Normung 1999), which specifies maximum condensation levels in the design of wall assemblies, based on the limits of storage at the interface before rundown of liquid water occurs. The standard allows maximums of 500 g/m^2 for non-absorptive materials, or 1000 g/m^2 for absorptive materials (e.g., wood sheathed walls). Based on recent research these limits may be quite generous, especially when compared with measurements of liquid water stored by surface tension on non-absorptive surfaces such as polyethylene film and acrylic plastic (Smegal 2006). These measurements showed storage levels of 35-65 g/m^2. It is likely that the DIN standard includes other forms of storage, such as surface tension within fiberglass batt insulation, or adsorption or absorption in the wall materials. Further to Section 3.2.1.5, areas with expected condensation were distinguished between that which could be safely stored and condensation that could cause run-down.

4.0 RESULTS

4.1 Field Testing Experimental Results

4.1.1 Above Grade Walls Monitoring Results

Full monitoring data is presented in Appendix B1.

Data presented here is for the period of September 7, 2005 through September 19, 2006. Temperature and humidity boundary conditions for the interior and exterior are shown in Figure 4.1.

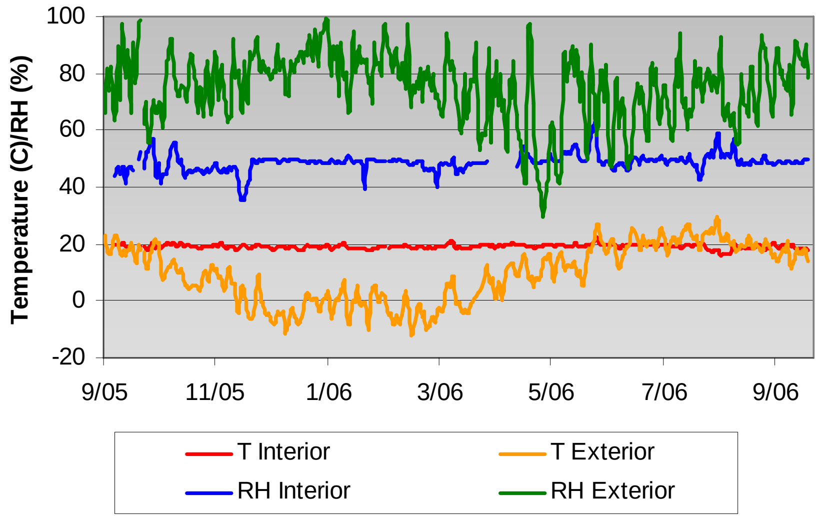

Figure 4.1: Interior and exterior temperature and humidity conditions (daily avg. values)

The following points summarize the key findings:

- Over the winter, the walls with polyethylene showed the lowest moisture levels, in terms of relative humidity, dewpoint, or wood moisture content. In comparison, the walls with an interior latex paint layer as vapour control (XPS wall and no polyethylene/2x6) had higher moisture levels in the winter. Wood moisture content measurements in the XPS and "no poly" walls showed levels above the generally accepted safe limits (20-25% MC). It must be emphasized that these walls have exceptionally high interior moisture loading (50% RH in a cold climate, approximately 4200 HDD18° C / 7600 HDD65° F). Dewpoints are considered high when compared to those measured in a CMHC cross Canada study by Ruest et al. (1993). This study conducted on 52 houses, with 10 in Ontario, found average wintertime first floor dewpoints to be 2.0°C across Canada, and -2.3°C in Ontario, which compares to an average winter time dewpoint of 9.3 °C in the field testing. The interior moisture loading in this study is higher than approximately 93% of the first floors in the cross Canada study (100% in Ontario).

- During the summer, the polyethylene walls showed elevated moisture levels, especially towards the interior surface (i.e., accumulating at the vapour barrier). This was seen in framing moisture content measurements, MC wafer measurements, and humidity/dewpoint measurements. The MC wafer measurements and framing measurements show evidence of condensation and rundown on the south poly wall. It must be emphasized that the interior temperatures are maintained slightly below most residential applications (20-21° C).

- Condensation risks during the winter and summer seasons were examined by plotting stud bay dewpoints with temperatures of potential condensing surfaces, for the respective worst cases. During the winter, the polyethylene functions as designed, reducing the stud bay dewpoint below the sheathing temperature for most of the winter hours. However, this is also true of the XPS wall, which only uses latex paint as a vapour control layer. In the "no poly" wall, stud bay dewpoints go above sheathing temperatures for considerable parts of the winter.

- During the summer, the increase in stud bay dewpoint due to the polyethylene is evident, and there is significant condensation risk. In comparison, the XPS and "no poly" walls have minimal to no risk of condensation.

The following graphs present the collected data in greater detail.

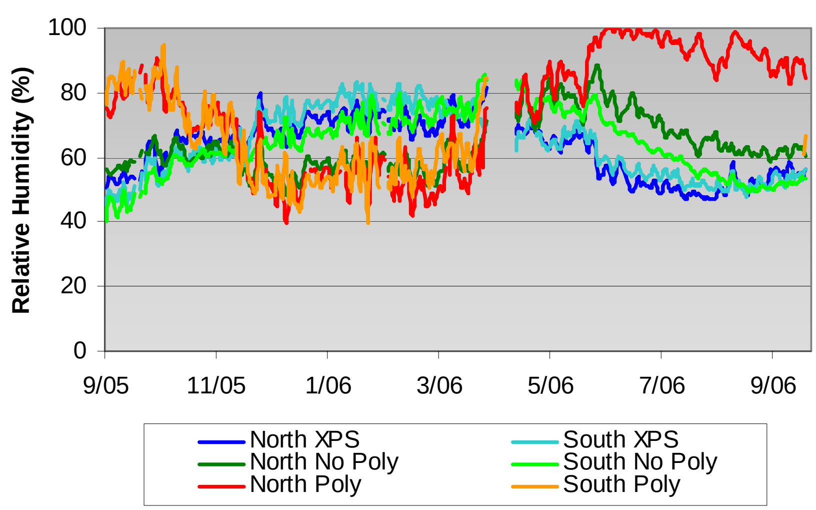

Figure 4.2: Stud bay mid-batt mid-height humidity levels (daily avg. values)

The poly walls have elevated humidity during the summer of 2005, and the lowest in the winter. The walls with latex paint as interior vapour control (XPS and "no poly") have the lowest humidity levels in summer, which then rise to the 70-80% range in winter.

In the summer of 2006, the poly walls have RH levels near 100%. The XPS walls have the lowest humidity levels; they are dryer than the "no poly" walls; this could be a combination of less wintertime moisture accumulation (due to the insulating sheathing), and/or the lower vapour permeance of the XPS sheathing, compared to OSB and housewrap. The south poly humidity sensor failed in April, but a similarly placed sensor shows continued elevated humidity levels, similar to the north side.

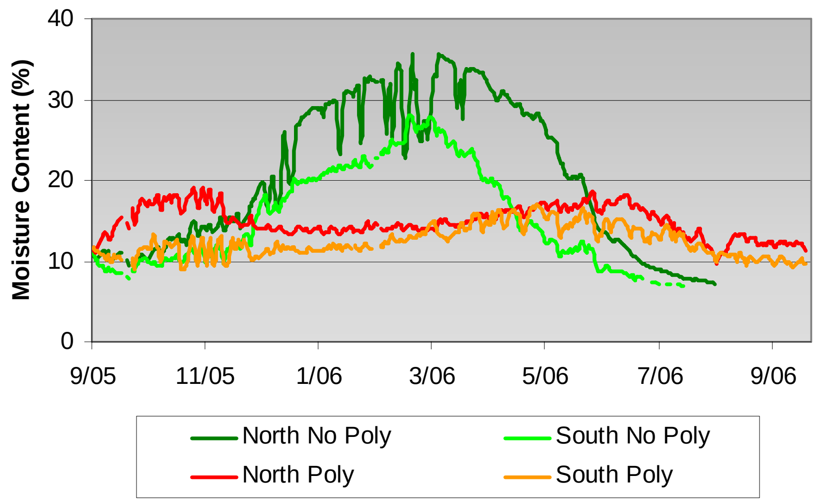

Figure 4.3: Sheathing moisture content (Walls 1 & 2), north & south (daily avg. values)

Moisture content readings of the OSB sheathing are compared in Figure 4.3 ("poly" and "no poly" walls). Note that the OSB moisture readings are uncorrected for species, but the framing MC is expected to be accurate within 2%. In the winter, the "no poly" walls show substantial rises in MC (peaking at approximately 35% and 28%, north and south, respectively), while the poly walls remain in the 10-15% range. As the high moisture contents of the No Poly walls continue during warm exterior temperatures there is a risk for mold growth during this period. The poly walls show some rise in moisture content, relative to the winter, but generally stay in the safe range (under 20%).

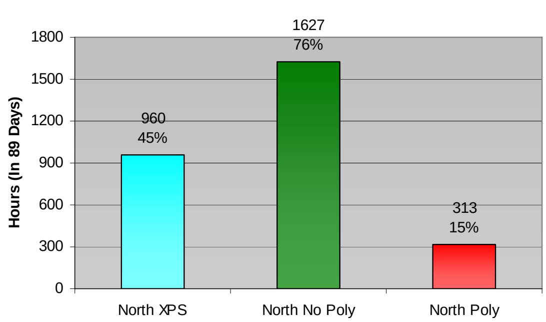

Figure 4.4: Number of hours with wintertime condensation risk

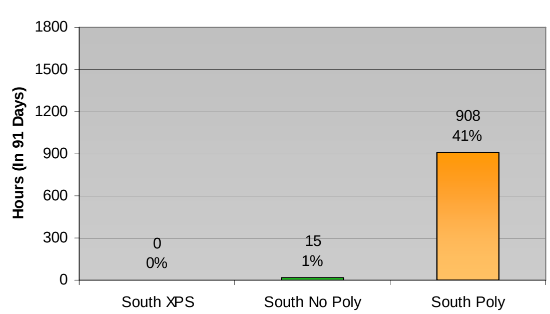

Figure 4.5: Number of hours with summertime condensation risk

The risk of wintertime condensation is examined further by plotting the number of hours when stud bay dewpoint was above sheathing surface temperature. Figure 4.4 plots these values for the north walls, for the three months of winter (December through February, 89 days).

It shows that the 2x6 wall with no polyethylene has a considerable condensation risk for a majority of those hours (76%). The XPS wall has approximately two-thirds the number of hours at risk (45%), and the polyethylene wall has the safest wintertime performance.

Summertime moisture risks due to polyethylene sheeting are of particular interest. The number of hours when stud bay dewpoint was above drywall surface temperature is plotted in Figure 4.5, for the south walls, for the three months of summer (June through August, 91 days).

It shows that the XPS wall has no risk of condensation: this is likely due to the low vapour permeance of the sheathing. In comparison, the "no poly" wall has a minimal (1% of hours) condensation risk. However, the poly wall has a considerable risk of 41% of hours at condensing conditions, due to the low permeance interior vapour control layer.

4.1.2 Above Grade Walls Disassembly Photos/Observations

Photo 4.1: XPS South wall. Possible mold at outboard side of sill plate.

The XPS south wall exhibited no evidence of mold or damage on the back (exterior) face of the drywall. There was no evidence of moisture accumulation or damage in the fiberglass batt and no evidence of moisture damage on the back of the sheathing (See Photo 4.1).

Photo 4.2: XPS Wall North - Mold growth at outboard side of sill plate

There was mold and significant evidence of condensation on the outboard side of the wood framing (See Photo 4.2) in the XPS North wall. Some water damage was seen on the back of the drywall, at the bottom plate. There was also evidence of moisture accumulation or staining in the fiberglass batts.

Photo 4.3: No Poly Wall South. No discernable damage or staining visible.

There was no damage or evidence of mold on the back (exterior) face of the drywall in the No Poly South Wall. There was also no evidence of moisture accumulation or damage in the fiberglass batts or framing (see Photo 4.3).

Photo 4.4: No Poly Wall North. Close-up of sheathing showing mold growth.

There was mold and significant evidence of condensation on the outboard side of the wood framing and on the sheathing in the No Poly North wall (See Photo 4.4). There was also noticeable grain/flake raising or thickness swelling of the OSB; a straightedge held against the sheathing revealed daylight. There was also evidence of moisture accumulation or damage in the fiberglass batts. No water damage was observed on the back of the drywall.

Photo 4.5: Poly Wall South. Mold visible at inboard side of bottom plate, also some visible condensation on the polyethylene

There was significant evidence of condensation and very high moisture contents on the inboard side of the wood framing on the South Poly Wall. Mold damage was visible on the inboard side of much of the framing, especially at the bottom plate, with some visible condensation on the polyethylene (See Photo 4.5). There was no damage or evidence of mold on the back (exterior) face of the drywall.

Photo 4.6: Poly Wall North. No evidence of condensation or mold growth

Sheathing and framing showed no mold or moisture damage evidence in the North Poly Wall (See Photo 4.6). There was minimal evidence of moisture accumulation or damage in the fiberglass batts and no water damage was seen on the back of the drywall.

4.1.3 Basement Walls Monitoring Results

Data shown below is for the period of August 30, 2005 through July 25, 2006; interior and exterior temperature and humidity conditions are shown in Figure 4.6. More data is provided in Appendix B2 and Appendix D2.

The basement conditions are relatively stable and presumed to be typical of new residential construction. The interior relative humidity is considered moderate when compared to those measured in a CMHC cross Canada study by Ruest et al. (1993). This study conducted on 52 houses, with 10 in Ontario, found average wintertime basement dewpoints to be 0.6°C across Canada, and -2.75°C in Ontario, which compares to an average winter time dewpoint of 1.9 °C in the field testing. The interior moisture loading in this study is higher than approximately 60% of the basements in the cross Canada study. Interior dewpoints could be higher, but this is not recommended.

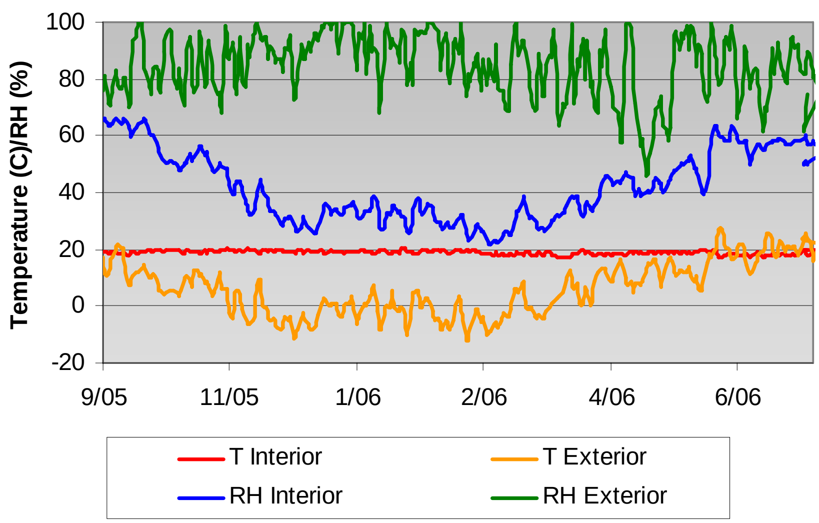

Figure 4.6: Interior and exterior temperature and humidity conditions for basement walls (daily avg. values)

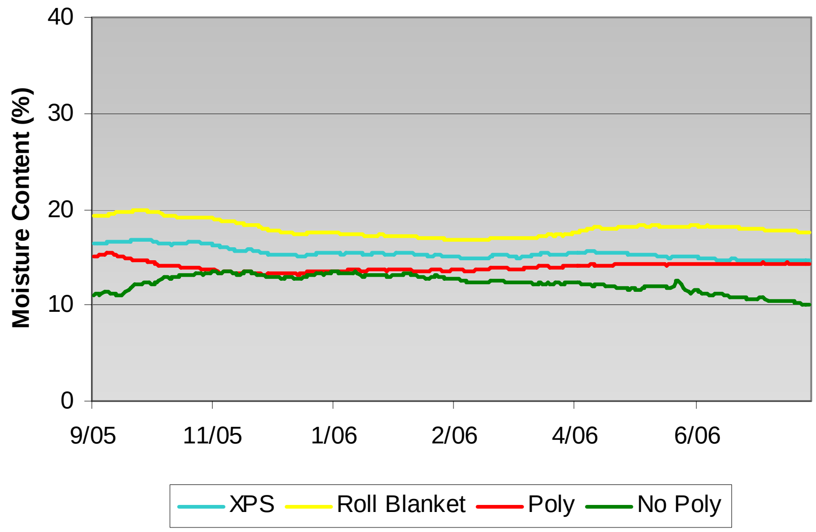

Figure 4.7: Moisture content wafer response, concrete-insulation interface, mid-height (daily avg. values)

The response of the MC wafers (moisture content blocks) at the interface between the concrete wall and the insulation system at mid-height is plotted in Figure 4.7. The response shows the accumulation of moisture at the concrete behind the insulation system; it demonstrates that the below grade environment (approximately 1 meter below grade) is relatively static, compared to the dynamic response of the above-grade potion of the basement wall. However, several points can still be discerned. The "no poly" wall gains some moisture into the winter, but moving into the summer, it is able to dry to the interior. In contrast, the poly wall has a relatively stable but higher moisture content. However, both walls are at safe moisture levels (~10-15% MC). The moisture content in the roll blanket is consistently ~3% to 6% higher than the “poly” wall, and shows a slight rise in moisture during the warmer seasons.

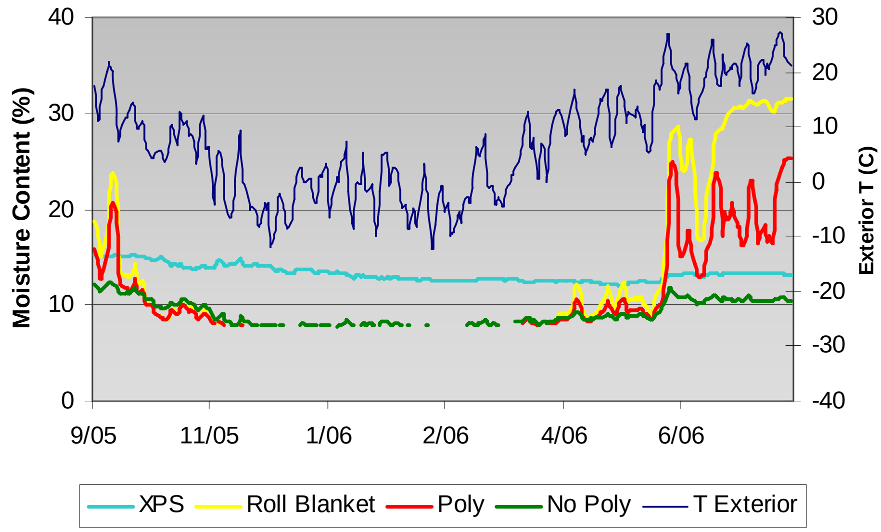

Figure 4.8: Moisture content wafer response, interior side, upper height with exterior temperature (daily avg. values)

In contrast, the MC wafers at the upper location (roughly at grade) show a much more dynamic response, due to the effects of above-grade weather. Wafer response and exterior temperature are plotted in Figure 4.8. This wafer sensor is located between the insulation and the polyethylene for walls 2 and 3, between the insulation and drywall for wall 4, and between the XPS and concrete in wall 1. Looking at the roll blanket and poly walls, we see that there is a strong rise in moisture content that coincides with the thermal gradient changing from outwards to inwards in late May. Moisture content levels rise to 25% in the poly wall and over 30% in the roll blanket wall. In contrast, the "no poly" wall shows a slight rise in moisture content, but well within safe levels, and the XPS wall remains at safe levels throughout. The moisture behaviour of the roll blanket and poly walls is correlated strongly with the outdoor temperature (i.e., thermal gradient across the wall).

The difference in performance between the roll blanket wall and the “poly” wall is worth examining further. Firstly, although strong efforts were made to air seal the stud frame-polyethylene wall, leakage is more likely in an assembly composed of discrete parts, compared to the “monolithic” roll blanket. Second, the frame-polyethylene wall has wood framing within the cavity (unlike the roll blanket), which provides some hygric storage mass. Finally, vapour diffusion laterally through the framing members might play some role. The diffusion through the framing is low, given both material properties of wood and its area relative to the face of the wall. However, the permeance through polyethylene is low enough that the wood can provide a noticeable contribution. This lateral flanking could result in an increase between double and fifteen times the vapour transmission through the polyethylene. Note that the test wall is assembled with an unusually high ratio of exposed framing (32” wide wall, side studs exposed): this effect would be much lower in field-installed walls.

The behaviour of the stud frame wall systems during the winter was compared by looking at framing moisture content at the upper portion of the wall. The polyethylene wall remained very dry through the winter (~8% MC), while the framing in the no polyethylene wall showed a rise in moisture content. However, the moisture content peaked only at 12-13%, which is well within safe ranges. Furthermore, by early summer, the no polyethylene walls dried to approximately 8%. At the same time, the polyethylene walls began to gain moisture (but still within the safe range), rising to 14% by late summer.

4.1.4 Basement Wall Disassembly Photos/Observations

Photo 4.7: Poly Wall. Brown staining at inboard side of stud.

There was some staining at the inboard side of the Poly Wall (See Photo 4.7). There was no evidence of moisture damage to the fiberglass insulation. There was no visible condensation on the polyethylene vapour barrier and no moisture damage on the drywall.

Photo 4.8: No Poly Wall - No evidence of moisture damage.

There was no evidence of moisture damage on the drywall, framing, or in the fiberglass insulation in the No Poly Wall (See Photo 4.8).

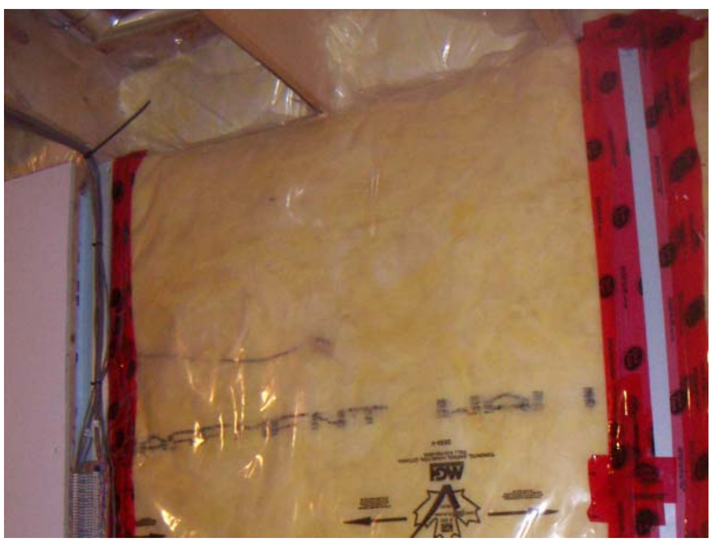

Photo 4.9: Roll Blanket Wall - Discoloration of upper batt (evidence of moisture).

Evidence of moisture accumulation (discolouration) was seen in the upper batt in the Roll Blanket Wall (See Photo 4.9). This wall was not disassembled, due to the disturbance that would result to the wall, and the lack of framing members to measure with a moisture meter.

The 2″ XPS wall was not disassembled, due to the difficulty of the procedure (detaching and re-attaching Tapcon screws), the disturbance that would result to the wall, and the lack of framing members to measure with a moisture meter.

4.2 Computer Modeling Results

4.2.1 Above-Grade Walls

Above-grade modeling results are presented in the following formats:

- Figure 4.17 below shows the number of hours that conditions at the monitoring positions are above the set threshold limits. These tables are also included in Appendix E1 (sorted by city and by wall type).
- Appendix E1 contains plots showing the time that a given threshold is exceeded for the various wall assemblies. Some key plots are included below.
- Appendix E1 also contains plots with Relative Humidity or Moisture Content versus time at critical locations.

The following highlights the key findings from the modeling.

4.2.1.1 Poly Walls, South/West/East

Mold/condensation was visible on the BEGHut Poly South wall upon field disassembly. Run 1.1 from Figure 4.17 clearly shows several hours with condensation and high humidity conditions outboard of the polyethylene sheeting. Modeling suggests that condensation on the outboard face of the poly is not expected to occur (Runs 2.1, 3.1, 4.1b, 5.1b in Figure 4.17) under normal summer interior temperature conditions in Waterloo, St. John’s, Edmonton, and Vancouver. The time above the 85%/5˚C and 95%/10˚C thresholds are also reduced outboard of the poly as shown in Figures 4.9 and 4.10 for these walls under normal summer interior temperature conditions. The above clearly shows that cooler interior summer temperatures, similar to those in the BEGhut, are key for condensation and/or visible deterioration.

It is interesting to note that the modeling suggests substantial amounts of time above the 85%/5˚C threshold on the inboard face of the exterior sheathing in Waterloo, St. John’s, Edmonton, and Vancouver (See Figure 4.9). However, Figure 4.10 shows no time above the 95%/10˚C threshold. Fig 4.12 also shows few hours above the 30% moisture content threshold at the interior face of the sheathing in these walls with poly.

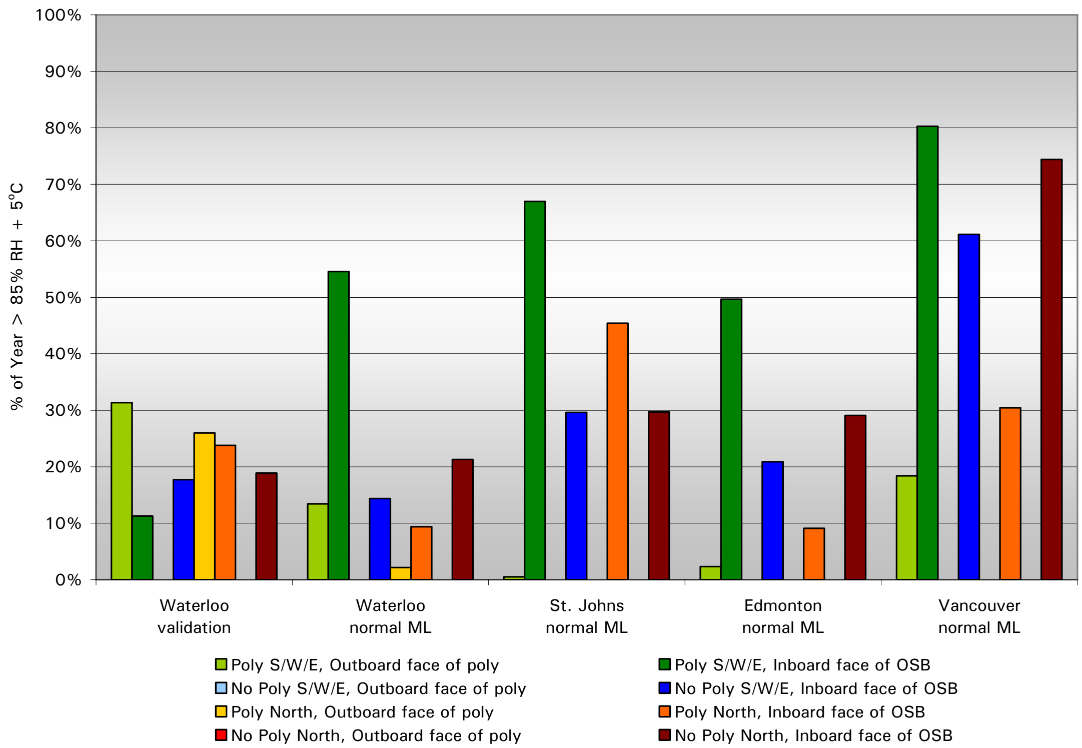

Fig 4.9: Poly/No Poly Walls, % of Year above 85% RH/5°C Threshold

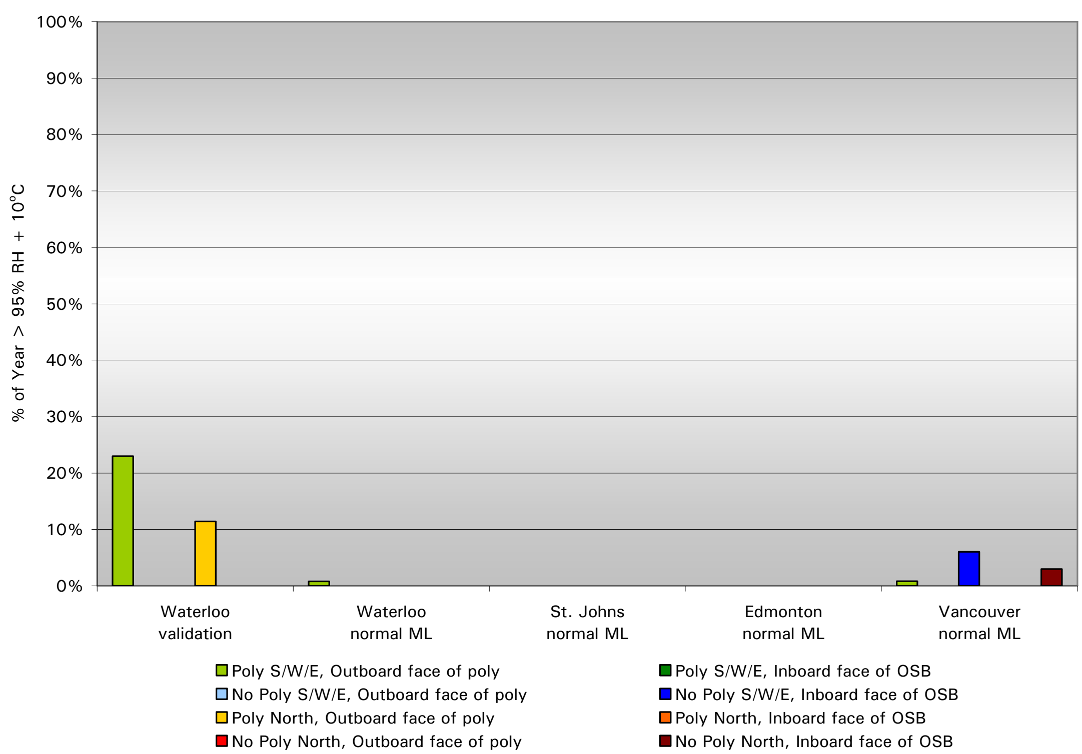

Fig 4.10: Poly/No Poly Walls, % of Year above 95% RH/10°C Threshold

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4.2.1.2 Poly Walls, North

There was no evidence of condensation run-down on the BEGhut Poly North wall upon field disassembly. Run 1.2 (simulated Waterloo BEGHut) from Figure 4.17 shows some condensation risk outboard of the polyethylene sheeting but much lower than the South Poly wall (Run 1.1). Modeling suggests that condensation on the outboard face of the poly is not expected to occur (Runs 2.2, 3.2, 4.2, 5.2 in Figure 4.17) under normal summer interior temperature conditions in Waterloo, St. John's, Edmonton, and Vancouver.

It is interesting to note that Run 1.2 (simulated Waterloo BEGHut) from Figure 4.17 shows similar time above the 85%/5˚C threshold and roughly half as much time above the 95%/10˚C threshold outboard of the poly but this is not expected to lead to any deterioration given the observations during North Poly wall disassembly.

4.2.1.3 No Poly Walls, South/West/East

There was no discernible damage or water staining observed from run-down when the BEGHut South No Poly wall was disassembled; neither was any predicted for this wall through modeling (See Run 1.3 from Figure 4.17). In climates such as Southern Ontario, issues are not expected in walls without a poly vapour control layer on elevations that get the majority of solar heating even with heavy interior loads such as those in the BEGHut.

The same cannot be said for other climates. Figures 4.11 and 4.12 show the increase in time where the inner face of the exterior sheathing is above 20% and 30% moisture content in colder climates such as St. John's and Edmonton (under normal interior moisture loads), and climates where higher interior moisture loads are expected such as Vancouver.

A vapour control layer is expected to be required in colder climates with normal moisture loads or warmer climates with higher or heavy interior moisture loads.

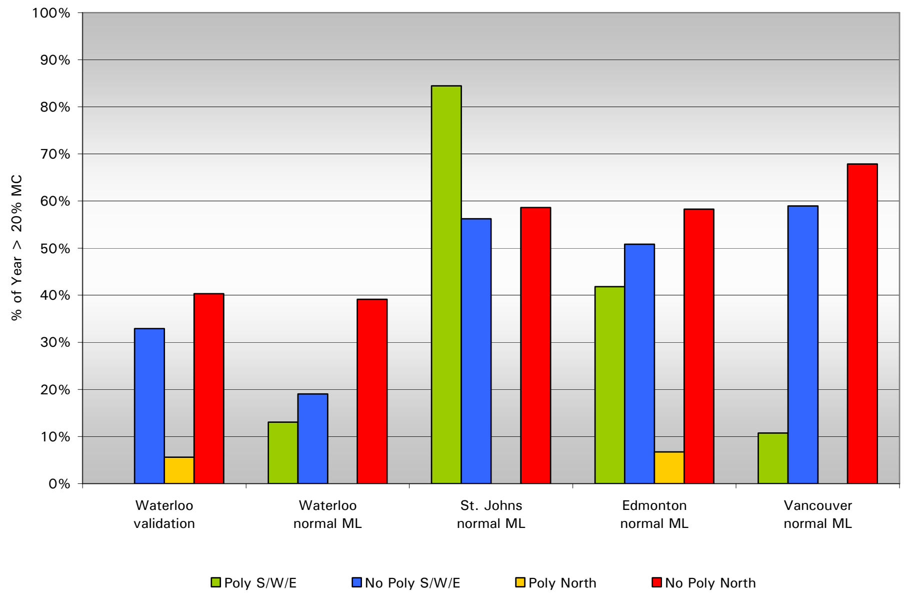

Fig 4.11: Poly/No Poly Walls, Inboard Face of OSB, % of Year above 20% MC Threshold

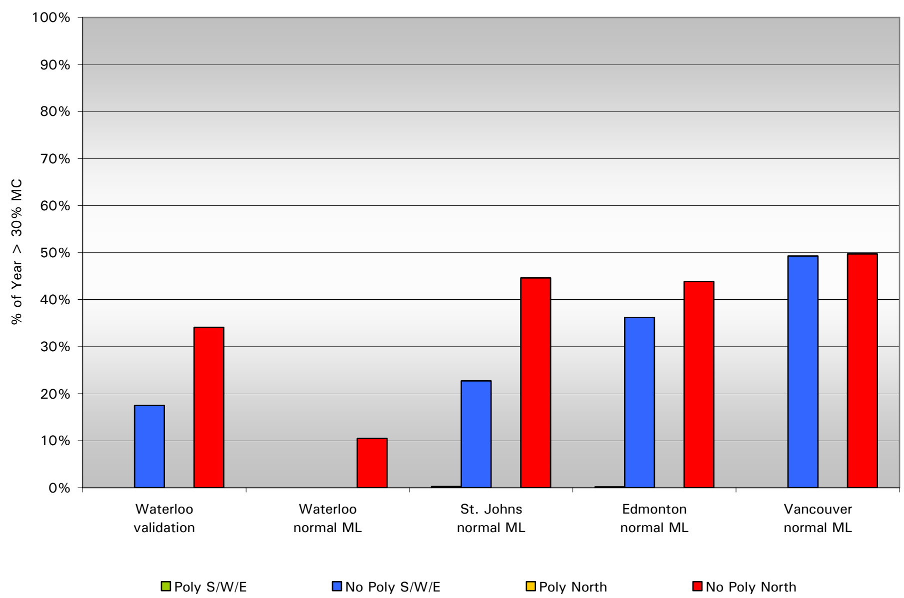

Fig 4.12: Poly/No Poly Walls, Inboard face of OSB, % of Year above 30% MC Threshold

4.2.1.4 No Poly Walls, North

Mold covered the inside of the OSB sheathing and the OSB showed signs of swelling/flaking when the BEGHut North Wall without poly was disassembled.

Figures 4.11 and 4.12 show significant time where the inner face of the OSB sheathing is above 20% and 30% moisture content in Waterloo and the other geographic locations. Modeling suggests that these deterioration risks may be controlled with a low permeance paint and a normal interior moisture load as shown in Figs 4.13 and 4.14.

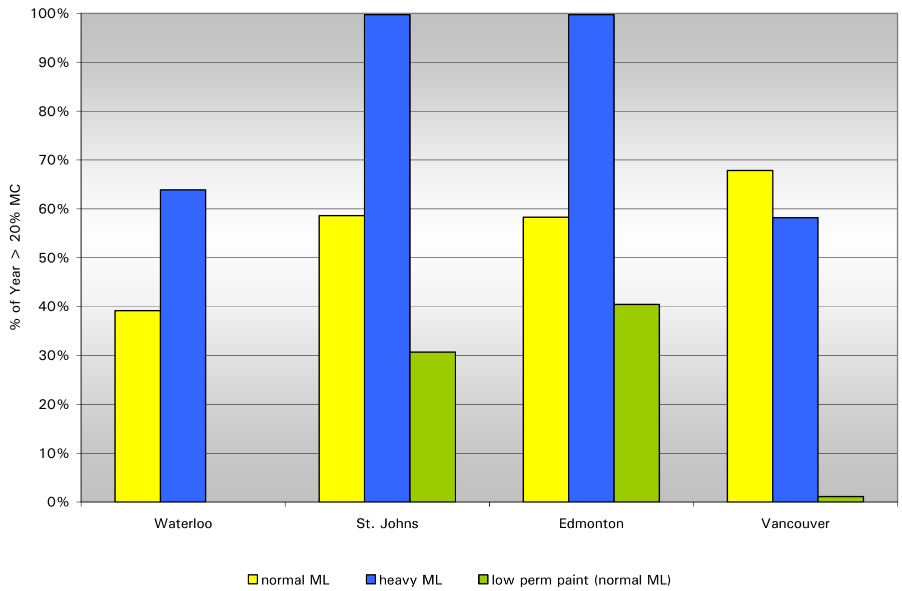

Fig 4.13: No Poly North Walls, Inboard face of OSB, % of Year above 20% MC Threshold

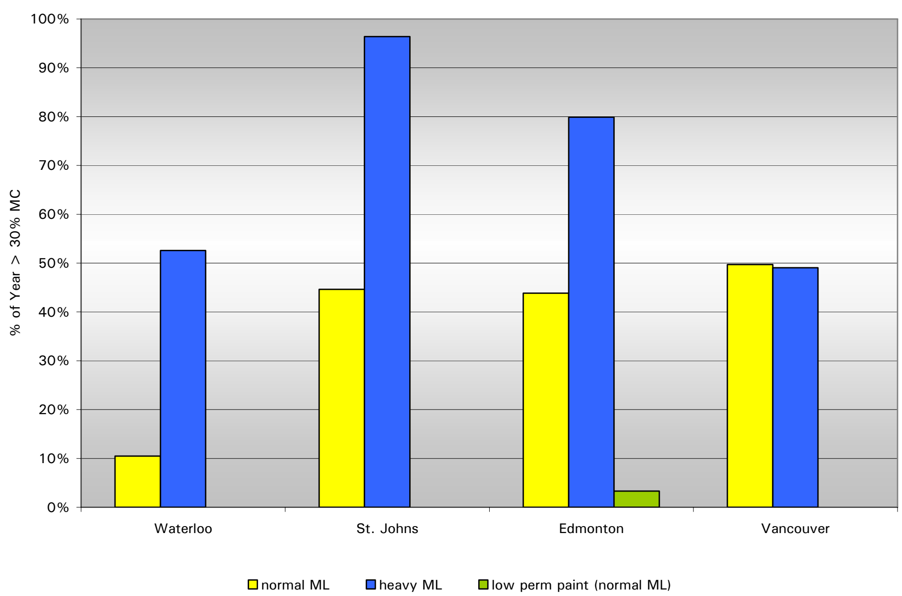

Fig 4.14: No Poly North Walls, Inboard face of OSB, % of Year above 30% MC Threshold

4.2.1.5 XPS Walls, All Elevations

Mold and evidence of condensation rundown was observed on the North XPS wall when the BEGHut walls were disassembled. Condensation is predicted in the exterior of the stud cavity (or on the interior face of the XPS) with the high interior moisture conditions in the BEGHut (See Run 1.6 from Figure 4.17). Condensation is also expected in St. John's with high interior moisture conditions. Condensation is expected in Edmonton and Vancouver under normal and high interior moisture loads. (See Runs 3.8, 4.6, 4.8, 5.6, and 5.8 from Figure 4.17.)

The same deterioration is not likely in Waterloo or St. John's under normal interior moisture loads.

Modeling suggests that these deterioration risks may be controlled with a low permeance paint and a normal interior moisture load as shown in Figs 4.15 and 4.16.

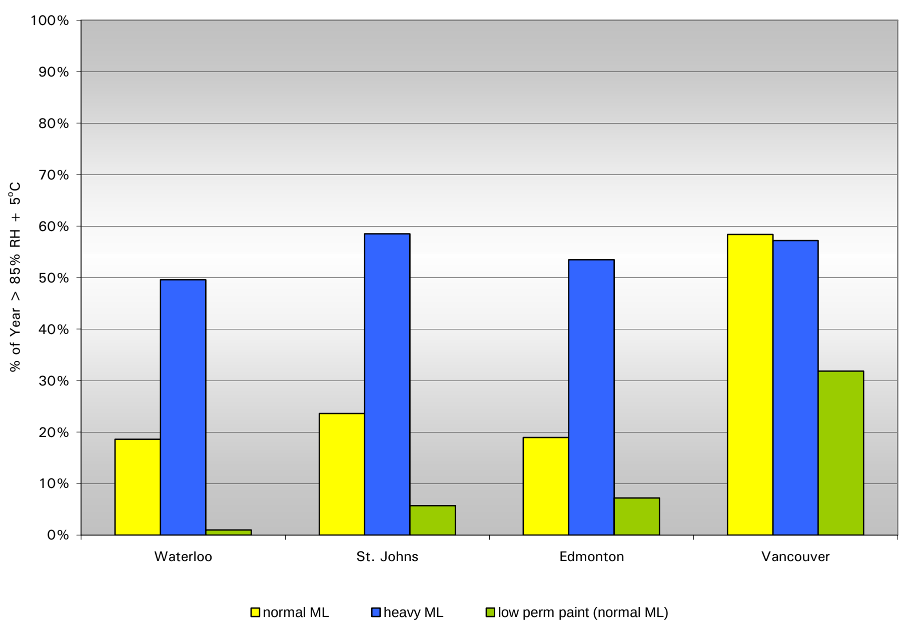

Fig 4.15: XPS North Walls, Inboard face of XPS, % of Year above 85% RH, 5°C Threshold

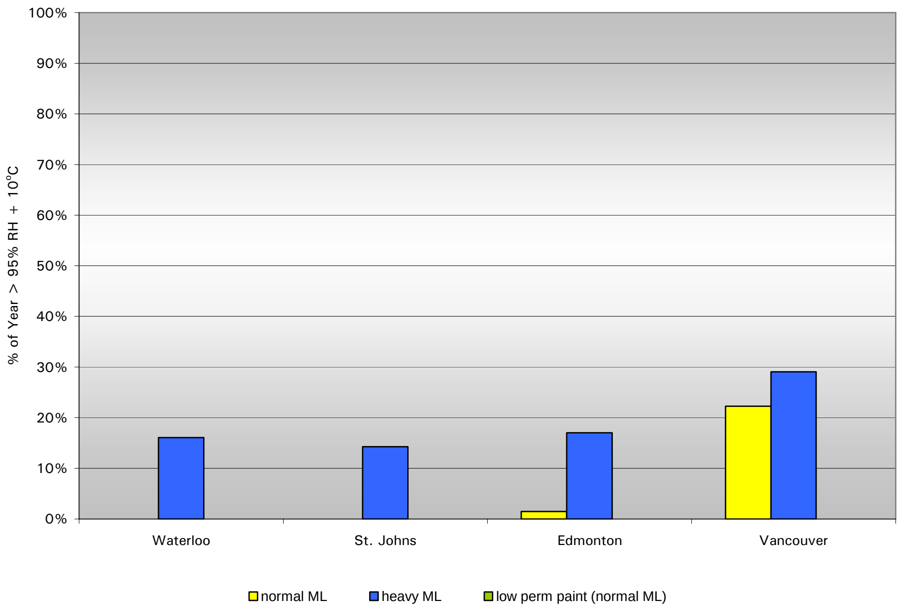

Fig 4.16: XPS North Walls, Inboard face of XPS, % of Year above 95% RH, 10ºC Threshold

Run	Assembly	Orientation	Materials	Int. Conditions	Ext. Conditions		Data Analy-sed	OSB (EXTERIOR FACE) thres 4	OSB (EXTERIOR FACE) thres 5	OSB (INTERIOR FACE) thres 4	OSB (INTERIOR FACE) thres 5	STUD CAVITY (EXTERIOR) thres 1	STUD CAVITY (EXTERIOR) thres 2	STUD CAVITY (EXTERIOR) thres 3	STUD CAVITY (INTERIOR) thres 1	STUD CAVITY (INTERIOR) thres 2	STUD CAVITY (INTERIOR) thres 3
Run 1.1	Poly	South	Base model	BEGHut values	BEGHut Values		1st yr	2455	0	0	0	986	0	0	2747	2013	646
Run 1.2	Poly	North	Base model					624	0	493	0	2083	0	0	2277	999	89
Run 1.3	No poly	South	Base model					2875	0	2883	1530	1551	0	0	0	0	0
Run 1.4	No poly	North	Base model					905	0	3532	2988	1653	0	0	0	0	0
Run 1.5	XPS	South	Base model									2127	396	0	0	0	0
Run 1.6	XPS	North	Base model									2207	537	2095	0	0	0
Run 2.1	Poly	South	Base model	prEN - regular load	BEGHut Values		2nd yr	3719	0	1143	0	4779	0	0	1177	68	0
Run 2.2	Poly	North						483	0	0	0	822	0	0	188	0	0
Run 2.3	No poly	South						2530	0	1670	0	1259	0	0	0	0	0
Run 2.4	No poly	North						714	0	3430	917	1862	0	0	0	0	0
Run 2.5	XPS	South										901	0	0	0	0	0
Run 2.6	XPS	North										1629	0	0	0	0	0
Run 2.7	No poly	North	Base model	prEN - high load	BEGHut Values		2nd yr	1377	0	5596	4606	4129	442	0	11	0	0
Run 2.8	XPS	North	Base model	prEN - high load								4342	1410	3511	0	0	0
Run 2.9	No poly	North	low perm int. paint	prEN - regular load				617	0	0	0	964	0	0	47	0	0
Run 2.10	XPS	North	low perm int. paint	prEN - regular load								86	0	0	0	0	0
Run 3.1	Poly	South	Base model	prEN - regular load	St. Johns	warm yr	2nd yr	8737	8284	7399	21	5866	0	0	43	0	0
Run 3.2	Poly	North						5472	0	0	0	3979	0	0	0	0	0
Run 3.3	No poly	South				cold yr		8475	1827	4925	1989	2592	0	0	0	0	0
Run 3.4	No poly	North						4287	0	5134	3910	2602	0	0	0	0	0
Run 3.5	XPS	South										1388	0	0	0	0	0
Run 3.6	XPS	North										2068	0	0	0	0	0
Run 3.7	No poly	North	Base model	prEN - high load	St. Johns	cold yr	2nd yr	7909	2156	8737	8444	4795	869	1642	0	0	0
Run 3.8	XPS	North	Base model	prEN - high load								5123	1248	4641	0	0	0
Run 3.9	No poly	North	low perm int. paint	prEN - regular load				4371	0	2689	0	2796	0	0	0	0	0
Run 3.10	XPS	North	low perm int. paint	prEN - regular load								502	0	0	0	0	0
Run 4.1b	Poly	West	Base model	prEN - regular load	Edmonton, standard yr		2nd yr	3952	835	3665	16	4351	0	0	204	0	0
Run 4.2	Poly	North						1371	0	589	0	794	0	0	0	0	0
Run 4.3b	No poly	West						3100	117	4454	3173	1830	0	0	0	0	0
Run 4.4	No poly	North						1907	0	5105	3841	2546	0	0	0	0	0
Run 4.5b	XPS	West										1082	55	957	0	0	0
Run 4.6	XPS	North										1660	129	1554	0	0	0
Run 4.7	No poly	North	Base model	prEN - high load	Edmonton, standard yr		2nd yr	3323	1138	8737	6999	4751	1007	2793	0	0	0
Run 4.8	XPS	North	Base model	prEN - high load								4684	1491	4733	0	0	0
Run 4.9	No poly	North	low perm int. paint	prEN - regular load				1854	0	3542	291	2066	0	0	0	0	0
Run 4.10	XPS	North	low perm int. paint	prEN - regular load								630	0	0	0	0	0
Run 5.1b	Poly	East	Base model	prEN - heavy load	Vancouver	warm yr	2nd yr	6454	3605	943	0	7031	0	0	1610	72	0
Run 5.2	Poly	North						3248	0	0	0	2666	0	0	0	0	0
Run 5.3b	No poly	East				cold yr		6306	2117	5166	4317	5355	528	0	0	0	0
Run 5.4	No poly	North						784	0	5944	4354	6518	260	0	0	0	0
Run 5.5b	XPS	East										4617	1933	1589	0	0	0
Run 5.6	XPS	North										5112	1952	970	0	0	0
Run 5.7	No poly	North	Base model	EN - class 3, 21oC	Vancouver	cold yr	2nd yr	507	0	5094	4296	5324	602	0	0	0	0
Run 5.8	XPS	North	Base model	EN - class 3, 21oC								5010	2545	2971	0	0	0
Run 5.9	No poly	North	low perm int. paint	prEN - high load				0	0	98	0	2286	0	0	0	0	0
Run 5.10	XPS	North	low perm int. paint	prEN - high load								2789	0	0	0	0	0

THRESHOLDS

No.	>= MC %	>= Temp oC	>= RH %
1	-	5	85
2	-	10	95
3	-	-	99.9
4	20	-	-
5	30	-	-

Table 4.17: Above-Grade Modelling. Time (Hrs) above indicated thresholds.

4.2.2 Basement Walls

4.2.2.1 Simulations for Above-Grade Portion

All of the wintertime condensation simulations were run using a north facing orientation and a “cold” year for a given climate (when available).

All summertime simulations were the south-facing orientation, with a “warm” year for a given climate. The simulations were run using concrete that had dried for six months prior to the installation of insulation. In contrast to the winter simulation, temperatures at the concrete-insulation interface had a reasonable match between monitored data and simulation in the summer.

a) Toronto

The first set of simulations examined the risk of wintertime condensation at the above-grade portion of the wall. Five materials were compared: the roll blanket (polyethylene), the fiberglass batt with gypsum board and latex paint, fiberglass with Kraft paper, fiberglass with the perforated facer, and no interior vapour control. The XPS wall was not included in the Results Graphs plotted in Appendix E2: early simulations indicated superior performance compared to the cavity walls even at the worst conditions; success of this assembly in the field is evidence that the simulation captures the behavior correctly.

The results for Toronto show consistent patterns: the walls with polyethylene or Kraft paper, which are classified as vapour barriers (less than 57 ng/(Pa·s·m^2)/1 perm), have consistently safe behavior, with minimal condensation. The more permeable walls show behavior that becomes worse in the order of their permeability (from least to most): latex paint, perforated facer, and no vapour control. Also, increasing interior humidity causes increasing failures, starting with the most permeable. For instance, at low humidity conditions, the latex paint wall shows minimal accumulation, while the perforated facer and no vapour control walls show accumulation over the safe storage limit. At higher humidity conditions, the performance of these permeable walls grows worse; at high humidity conditions, even the latex paint wall has significant time over the safe storage limit (500 g/m^2) during the winter. Note that under high humidity conditions, the “no vapour control” wall is unable to dry the accumulated moisture in the following spring/summer, indicating a seasonal increase in moisture content (i.e., “ratcheting”). These results are summarized in Appendix E2, showing the increase in hours over the condensation limit with increasing permeability, and with increasing interior humidity.

Another phenomenon simulated was the inward vapour drives causing condensation on the exterior side of the polyethylene, in the roll blanket wall. The simulations compared the performance of the roll blanket, a Kraft-faced batt, and fiberglass/gypsum board/latex paint. The modeling clearly shows the condensation that would occur in late summer at this location in the polyethylene wall; the Kraft paper wall shows some accumulation, but below the rundown threshold. The more permeable latex paint-fiberglass assembly shows no accumulation. Inward vapour drive condensation may be worse than the wintertime accumulation due to assembly geometry: the condensation would run down the impermeable polyethylene surface and accumulate. In contrast, in the winter situation, moisture accumulation would be absorbed into the concrete as it ran down the wall—specifically, at the below-grade portions that did not accrue condensation.

b) Vancouver

Vancouver has mild winters (3.3° C average January temperature, vs. –4.2° C for Toronto); therefore, wintertime condensation was expected to be a smaller problem. This proved to be the case, as shown for "mid" and "high" interior humidity levels in Appendix E2. The latex paint-fiberglass wall gives reasonable performance at "mid" humidity, but exceeds the rundown limit at "high" humidity. The other two permeable options (perforated facer and no vapour control) both exceed the safe storage limit at the "high" level.

The magnitude of inward vapour drive was examined in the simulation. It appears that the lack of a cooling load results in minimal accumulation at the polyethylene (i.e. below the safe-storage limit).

c) St. John's

The wintertime condensation simulations for St. John's were similar to the Toronto results: the assemblies with a vapour barrier (polyethylene or Kraft) showed little accumulation, while the more vapour permeable options showed moisture accumulation within the wall, increasing with interior humidity and with permeability (See Appendix E2). The latex paint wall remained below the accumulation threshold only at "low" humidity conditions; all other combinations exceeded the safe-storage limit.

In the summertime simulations, the results showed insignificant summertime inward vapour drive. Peak accumulation at the interior-side condensation layer in the roll blanket assembly was 16 g/m^2, compared to over 700 g/m^2 in Toronto (safe storage limit being 500 g/m^2). This can be explained by comparing the cooling loads of these two climates: 58 CDD 18° C in St. John's, compared to 360 CDD 18° C in Toronto.

d) Edmonton

Edmonton is a substantially colder climate (5708 HDD 18° C) than St. John's (4881 HDD 18° C). Therefore, it is not surprising that the wintertime condensation performance of the permeable assemblies is even worse (see Appendix E2), even the fiberglass-latex paint assembly under "low" humidity conditions has significant hours over the safe-storage threshold (500 g/m^2). Many of the walls demonstrate an unstable wetting cycle over the first year; they do not dry down to their original moisture content over the course of the summer. The walls with a vapour barrier (polyethylene and Kraft paper) both show acceptable performance.
In addition, Edmonton has a minimal cooling load, so the inward vapour drive was negligible, as in St. John's. Peak accumulation at the polyethylene condensation layer was 25 g/m^2.

4.2.2.2 Simulations for Below-Grade Portion

A simple analysis of the boundary conditions used in the Kitchener basement simulations showed that there is only an inward drying potential for the construction moisture of the concrete wall. In addition, the dewpoint relationships showed that there was a minimal chance of condensation of interior moisture on the concrete. The hygrothermal modeling provided the same conclusions: the only situation heading towards condensation was the polyethylene roll blanket. That wall had a ratcheting increase in moisture content at the concrete-insulation interface due to the impermeable layer eliminating drying to the inside. Levels approached (but did not exceed) the condensation accumulation limit after six years. However, all walls had sustained periods over the LIM_{Bau} II level considered conducive for mold growth. Drying of the concrete through the interior insulation is proportional to the permeability of the finishing system, and inversely proportional to the interior relative humidity (although this is a weaker effect).

However, these simulations must be taken with a degree of caution: the results are for assemblies that have a “perfect” air seal, with no airflow between the assembly layers and the interior. This type of a bypass can increase the drying and/or reduce accumulation in the less permeable systems; small construction defects can easily cause air leakage that will effectively negate extremely low permeance materials such as polyethylene (TenWolde 1998). Further evidence is the comparison between the monitored and simulated data in below grade locations (see Appendix D2). The monitored data was consistently drier than the simulation results, possibly because of incidental air leakage.

Simulations using a “synthesized” Edmonton exterior condition (“lower” measured wall conditions shifted by the average annual temperature difference between Kitchener and Edmonton) showed strongly different results. The simple dewpoint temperature comparison showed that interior conditions would have a tendency to cause condensation at the wall over the course of the year. This was supported by the hygrothermal modeling: condensation over the 500 g/m^2 limit was seen for the more permeable options (no vapour control, perforated facer, and latex paint). Also, the less permeable options (polyethylene, Kraft) showed increasing moisture accumulation headed towards this limit. The only option that showed consistently acceptable performance was the uninsulated bare concrete wall option.

Again, the simulations should be viewed with some skepticism. Widespread failures of the below-grade portions of walls in extremely cold climates such as Edmonton are not known to be an issue. There are several explanations that might be acting alone or in combination.

First, the below grade boundary conditions were synthesized from a best estimate; it is quite possible that actual below grade conditions have a different temperature regime. Second, it is possible that relatively high relative humidity levels are being experienced in these assemblies, but levels are not high enough to cause widespread problems. Finally, Edmonton has an extremely dry climate; a modified version of the dewpoint-temperature is shown with average Edmonton weather exterior dewpoints (Figure 4.18).

It shows that the summertime exterior dewpoint is well below the "low" and "mid" humidity levels used in simulations. During the winter, interior dewpoints are expected to be higher than exterior due to moisture generation by occupancy, humidification, and an air sealed building enclosure. However, during the summer, operation of windows for ventilation and cooling are more likely, resulting in similar inside and outside dewpoints. If anything, monitored data in cold climates show lower interior dewpoints than exterior during the summer, due to dehumidification from running a cooling system.

In the graph below, it is notable that these exterior dewpoints are below the wall surface temperatures; as a result, a drying potential would exist, like the Kitchener simulations. Therefore, it seems unreasonable to assume that no drying potential for the wall to the interior would exist for the entire year.

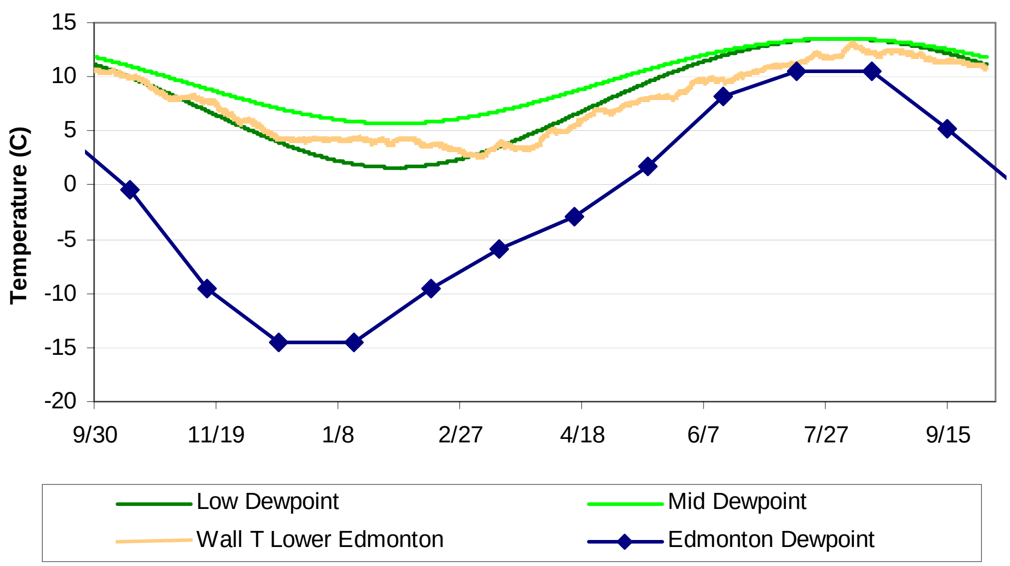

Figure 4.18: Interior dewpoint, lower wall temperature, and Edmonton exterior dewpoint

5.0 DISCUSSIONS

5.1 Above-Grade Walls

5.1.1 General

The field monitoring of above grade walls demonstrates several points: first, it showed that the presence of a polyethylene vapour barrier reduces the potential for wintertime condensation and moisture damage of the wall cavity at high interior relative humidity (50%) conditions. However, the presence of the polyethylene significantly increased the occurrence of summertime condensation in the stud bay cavity when using an absorptive cladding. In one case, the wall with extruded polystyrene foam sheathing had good performance; it showed the greatest resistance to summertime condensation from inward diffusion.

It should be noted that summertime condensation is of particular concern for moisture damage of walls, because it occurs during a temperature regime favourable to microbial growth. In comparison, wintertime sheathing condensation occurs at temperatures that are less conducive to mold growth; damage then becomes a function of how quickly drying occurs relative to the onset of warmer temperatures.

The operating conditions of the test hut are extreme; 20 to 21° C during the summer is lower than a typical residential interior setpoint, and increases the condensation risks on the interior surfaces. Winter operation at constant 50% relative humidity requires substantial humidification of the interior space, and is a stringent winter condition. These conditions resulted in condensation events in both the "poly" and "no poly" walls, at different times of year. Under normal operating conditions, problems will be reduced.

One goal of this inspection was to address Lawton and Brown's (2003) concern with drying to the interior: the danger of moisture accumulation and damage of gypsum board when not protected by polyethylene. Only the North XPS wall showed water damage on the back of the drywall. The exterior face of the drywall was in good condition after 1 year of monitoring in the other 3 walls without polyethylene sheeting.

Finally, this study compares the vapour control strategies of latex paint and polyethylene, which have permeance values that are two orders of magnitude apart. The second year of this study will provide field monitoring of a vapour control material that is between these extremes, but still meets code requirements for a vapour barrier.

5.1.2 Walls With Poly

Mold/condensation was visible on the BEGHut Poly South wall upon field disassembly. There was no evidence of condensation run-down on the BEGhut Poly North wall upon field disassembly. Modeling suggests that condensation on the outboard face of the poly is not expected to occur under normal summer interior temperature conditions in Waterloo, St. John's, Edmonton, or Vancouver irrespective of the orientation/elevation. Cooler interior summer temperatures, similar to those in the BEGhut, are key for condensation and/or visible deterioration.

Our findings show that the following factors led to moisture issues at the outboard face of the poly:

- a specific orientation to wind-driven rain and sun heating
- a rain absorptive cladding (brick)
- a non-ventilated cladding
- a relatively higher vapour permeance of the sheathing layer behind the cladding (OSB as opposed to XPS)
- a low permeance interior vapour control layer (poly)
- a lower than typical interior temperature (similar to conditions in the BEGHut)

Interior temperature conditions and cladding ventilation are the two factors that can be easily altered to improve performance. The expected impact by changing the interior temperature conditions was investigated through modeling and improvements have been reported above where interior temperature conditions were raised. A non-absorptive cladding or a relatively lower sheathing permeance (such as that associated with 25 mm of XPS) are variables that can also be altered during design to improve performance. The wall assemblies have been modified on site and will be monitored for another year to demonstrate the expected impacts from either: ventilating the brick cladding on walls with poly, or by painting the interior drywall with a low vapour permeance paint on the framed walls without poly.

5.1.3 Walls Without Poly

Mold covered the inside of the OSB sheathing and the OSB showed signs of swelling/ flaking when the BEGHut North Wall without poly was disassembled.

Although damage or water staining from run-down was not visible when the BEGHut South No Poly wall (with high interior moisture loads) was disassembled, high sheathing moisture contents are expected in colder climates such as St. John's and Edmonton (with normal interior moisture loads), and climates where higher interior moisture loads are expected such as Vancouver.

The modeling shows that a vapour control layer with a vapour permeance as low as polyethylene sheeting can control outward winter diffusion in all climates reviewed.

Modeling also suggests that deterioration risks may be controlled with an interior low permeance paint for all geographic locations reviewed with a normal interior moisture load. The additional year of monitoring will show whether the low permeance paint can effectively control outward winter diffusion in Waterloo with a heavy interior moisture load.

The above conclusions are also applicable where open-cell sprayed foam with vapour resistance similar to fiberglass batt is used. The above vapour control strategies are recommended even though they may rarely be used in practice.

5.1.4 Walls with exterior XPS and No Poly

Mold and evidence of condensation rundown was observed on the North XPS wall when the BEGHut walls were disassembled. Condensation/deterioration is also expected in St. John's with heavy interior moisture conditions. The same deterioration is not likely in Waterloo or St. John's under normal interior moisture loads.

Condensation/deterioration is expected in Edmonton and Vancouver under both normal and heavy interior moisture loads.

Modeling suggests that these deterioration risks may be controlled by an interior low permeance paint in all geographic locations reviewed with a normal interior moisture load.

The additional year of monitoring will show whether the low permeance paint can effectively control outward winter diffusion in Waterloo with a heavy interior moisture load.

It goes without saying that additional exterior insulation outboard of the sheathing can also be an effective strategy to reduce condensation/deterioration risks.

5.2 Basement Walls

5.2.1 General - Experimental Wall Design Decisions

a) Insulation

The basement walls tested have full height insulation. This is in contrast to the building code requirements at the time that the samples were constructed (which only required insulation for the above-grade portion of basement walls and for parts of the below grade portion of the basement wall). This decision was made since full height insulation is standard in basements where people decide to occupy/finish the basement, and occupied basements are those where moisture problems can become an issue. At the time the research was initiated, we were informed that Code changes were likely to include full height insulation as a requirement, which provided further reason to perform the experiment in this manner. Moisture problems where the batt is poorly roughed-in by the builder in unfinished basements are easily remedied.

b) Interior Dampproofing (NBC, Item 9.14.3.3)

The basement wall samples built/tested do not have dampproofing on the interior of the foundation wall below-grade. The studs were also placed in contact with the foundation wall (some gaps were likely since the wall was out-of-plumb at isolated locations). Below-grade interior dampproofing is generally required by the National Building Code where basement walls are finished.

In some areas, the use of plastic sheeting on the interior of foundation walls below-grade is common practice. This may lead to condensation issues in some instances/climates.

In other areas, off-setting studs from the wall so that they are not in direct contact with the foundation wall is seen as sufficient in place of interior damp-proofing. This approach may also lead to condensation if interior air bypasses the interior finishes and is allowed to flow freely within this space.

Further still, some argue that walls require neither by code, provided that the foundation wall is separated from soil by an exterior treatment (waterproofing or drainage board) and a rising damp break. All these options present a unique set of conditions with their own performance characteristics.

The walls in this study were constructed without interior damproofing, and with studs flush to the foundation wall for the following purposes:

- This is an experiment designed to investigate certain wall assemblies under certain conditions. The experimental interest, was to examine the hygrothermal behaviour of these walls without dampproofing.
- This is not a study on the effectiveness of dampproofing.

- It is our experience that common building practice in Ontario is not to use dampproofing on the interior of the foundation walls. Accordingly these walls represent a cross section of walls currently being built in Ontario.

5.2.2 Above-Grade Portion

5.2.2.1 Winter-Time Condensation Issues

The initial interpretation of the above-grade extrapolation simulations would suggest the necessity of an interior vapour control layer to prevent wintertime condensation at the concrete-insulation interface, at most boundary conditions. Creating a pass/fail criterion will always be somewhat subjective; estimating mold risk by examining hours over given humidity or humidity/temperature thresholds seemed to show strong risk for all examined walls. However, use of a "condensation accumulation/rundown" limit of 500 g/m^2 at the interface did a reasonable job of differentiating the options.

Using this metric, assemblies with polyethylene or Kraft paper showed wintertime accumulation peaks well below this level. The extruded polystyrene (XPS) wall showed excellent performance, due to its combination of vapour resistance and insulating value. More permeable assemblies, such as latex paint/gypsum wallboard, a perforated facer, or no vapour control, showed increasingly worse performance with colder climates, higher interior humidity levels, and increasing permeability. For instance, the latex paint/gypsum board assembly showed accumulation below the limit in some climates (Toronto, St. John's) at "low" relative humidity levels, or even "mid" humidity levels with a sufficiently mild winter (Vancouver). In all cases, using no interior vapour control resulted in accumulation over the 500 g/m^2 limit.

There was a stark difference in behavior between materials considered to be vapour barriers (i.e., below 57 ng/(s·m^2·Pa)/1 perm) and more permeable options. As would be expected, the walls with low permeance interior layers were minimally affected by changes in interior RH, as they are effectively decoupled from the interior. Recent BEG work suggests that modern latex paints may have a higher dry cup permeability in practice, reducing the wintertime safety margin of this assembly.

However, some important caveats must be noted when interpreting these simulations. First, the concrete-insulation interface remains much warmer than one-dimensional above-grade simulations predict. This was attributed to the effects of the two-dimensional geometry, specifically the tempering effect of the moderate soil temperatures. The difference was much more pronounced during the winter; summertime interface temperatures matched more closely.

In addition, field data suggests that assemblies with higher permeability interior layers can work under conditions that are shown to fail in these simulations. For instance, a field survey of 42 houses in Minnesota with and without interior vapour control (Robert W. Anderson and Associates 1989) showed framing wood moisture content levels well within safe ranges for both types of walls. Simulations of vapour open assemblies in Minneapolis show moisture accumulation well above the limit, as shown in Figure 5.1. Similarly, anecdotal reports and monitored data from the Chicago area indicate that roll blankets with perforated facers give acceptable performance.

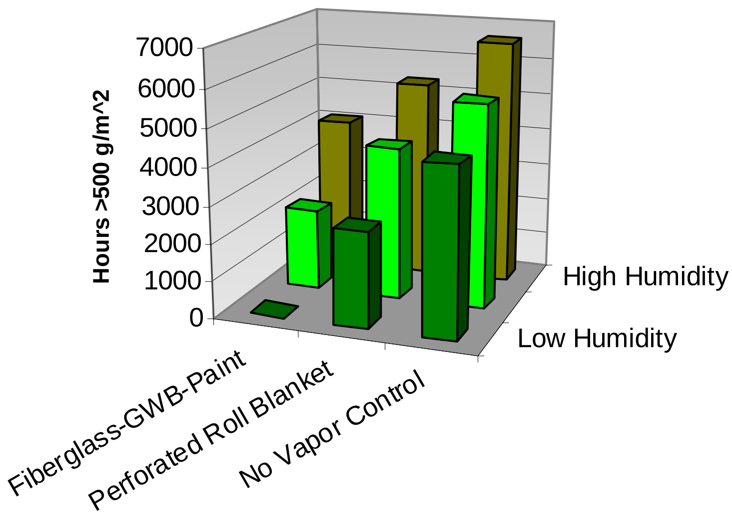

Figure 5.1: Minneapolis AG condensation layer hours over 500 g/m^2

This information suggests that one-dimensional simulations of the above-grade portion are not the best method to determine interior vapour control requirements. The acceptable performance of these more permeable systems might be caused by a combination of several factors, including low interior relative humidity levels, the tempering effect of soil/two-dimensional thermal effects, and possibly the ability of the assemblies to dry between wintertime accumulation seasons (as demonstrated in simulations).

5.2.2.2 Summer-Time Condensation Issues

In comparing results for four geographic locations, simulations indicated that summertime condensation at the interior vapour control layer due to inward vapour drive is only a problem in climates with significant cooling loads. In order for this problem to occur, a notable portion of the year must have an inward thermal gradient. Climates with negligible cooling loads, such as Vancouver, St. John's, or Edmonton showed minimal accumulation in simulations. Note that the risk factor is an inward thermal gradient; it does not mean the climate must be cooling dominated: problems were noted in heating-dominated climates such as Toronto, ON, Waterloo, ON, or Minneapolis, MN (as shown below in Figure 5.2).

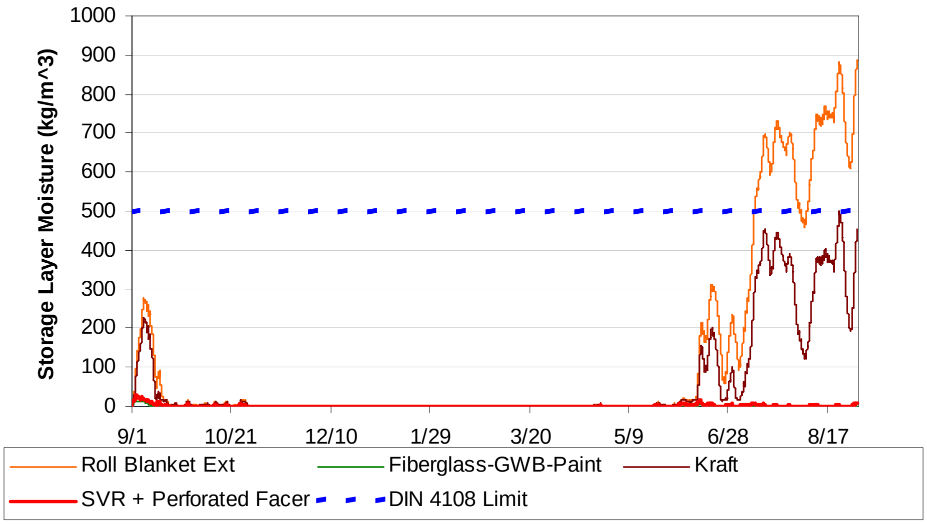

Figure 5.2: Vapour barrier condensation layer MC, Minneapolis above grade, mid RH

In all of these climates, significant problems were only seen with polyethylene. In contrast, Kraft paper, which has an order of magnitude higher permeability (3.4 vs. 17-34 ng/(s·m^2·Pa)), demonstrated accumulation, but below the rundown limit stated above. An additional simulation was run using a variable-permeability polyamide-6 (PA-6) membrane (colloquially known as a "smart vapour retarder"/SVR). This material has permeability that can change between 43-700 ng/(s·m^2·Pa) or 0.8-12 perms, dry/wet cup. Simulations had excellent summertime performance, with negligible accumulation at the exterior side of the membrane, showing the "flow-through" properties of this material at high relative humidity.

Some sources have raised concern that eliminating the impermeable layer (such as polyethylene) would allow moisture accumulation and damage to the gypsum wallboard interior finish during this summertime inward vapour drive. Although the gypsum board shows a seasonal rise in moisture content over the summer, it is a stable cycle, becoming drier every year (due to the drying of the concrete moisture source). The maximum relative humidity experienced by the gypsum layer is approximately 90%: it does not experience condensation conditions, as found in the polyethylene assembly. This behavior is matched by observations made during disassembly of the Kitchener field site: no indication of mold growth was seen on the exterior side of the gypsum board after the first year of operation. The situation could be considered analogous to a dammed or undammed river: moisture only begins to accumulate at that location when it can no longer travel through the system; otherwise, it flows through without causing damage. The moisture damage only occurs because of the presence of the dam, or impermeable layer.

5.2.3 Below-Grade Portion

A simple analysis of the boundary conditions used in the Kitchener below grade simulations showed that there is only an inward drying potential for the construction moisture of the concrete wall. In addition, the dewpoint relationships showed that there was a minimal chance of condensation of interior moisture on the concrete. The hygrothermal modeling provided the same conclusions: the only situation heading towards condensation was the polyethylene roll blanket. That wall had a ratcheting increase in moisture content at the concrete-insulation interface due to the impermeable layer eliminating drying to the inside. Levels were approaching (but did not exceed) the condensation accumulation limit after six years. However, all walls had sustained periods over 80% RH and the LIM$_{Bau}$ II isopleths: conditions considered favourable for mold growth. Drying of the concrete through the interior insulation is proportional to the permeability of the finishing system, and inversely proportional to the interior relative humidity (although this is a weaker effect).

However, these simulations must be viewed with some skepticism: the results are for assemblies that have a “perfect” air seal, with no airflow between the interstitial spaces and the interior. In reality, this type of air leakage can increase the drying and/or reduce accumulation in the less permeable systems; small construction defects can easily cause air leakage that will effectively negate extremely low permeance materials such as polyethylene (TenWolde 1998). Further evidence is the comparison between the monitored and simulated data in below grade locations (Appendix E2, Sections 8.1.2.4 and 8.1.2.5). The monitored data was consistently drier than the simulation results, possibly because of incidental air leakage.

Simulations using a “synthesized” Edmonton exterior condition (“lower” measured wall conditions shifted by the average annual temperature difference between Kitchener and Edmonton) showed strongly different results. The simple dewpoint temperature comparison showed that interior conditions would have a tendency to cause condensation at the wall over the course of the year. This was supported by the hygrothermal modeling: condensation over the 500 g/m^2 limit was seen for the more permeable options (no vapour control, perforated facer, and latex paint). Also, the less permeable options (polyethylene, Kraft, XPS) showed increasing moisture accumulation headed towards this limit. The only option that showed consistently acceptable performance was the uninsulated bare concrete wall option.

However, there is some disagreement between the simulation results and in-situ walls. Widespread failures of the below-grade portions of walls in extremely cold climates such as Edmonton are not known to be an issue. Reasons proposed for these differences included the lack of realism of below grade boundary conditions, and the dry climate of Edmonton, resulting in drier interior conditions than used in the model.

Further simulations were run using the Kitchener below-grade boundary conditions and interior air with a dewpoint equal to exterior conditions. This dewpoint only exceeded lower wall temperatures during brief summertime spikes; as a result, minimal moisture accumulation was seen in assemblies. Some simulations were run at very high interior summertime relative humidity levels; the insulation assemblies demonstrated condensation, but these boundary conditions were found to be quite unrealistic. Instead, the climate has a self-limiting or self-protecting nature: high summertime dewpoints are usually seen in climates that have moderate winters, and therefore, warmer temperatures at the lower wall.

5.2.4 Other Concerns and Observations for Basement Walls

Simulations were used to estimate initial moisture content of the concrete wall; they indicated that concrete remains very wet for long periods of time. For instance, even after a year of drying with no insulation or vapour barrier, the majority of the thickness of the wall is still over 90% relative humidity, at which the concrete stores roughly 100 kg/m^3 of water. An important comparison point is the storage capacity of air, which is much smaller: 17 g/m^3 (0.017 kg/m^3) at 100% RH at 20° C. Therefore, this stored moisture can easily cause high relative humidity conditions in assembly cavities. This behavior may explain why summertime condensation issues at polyethylene can be seen even with walls that have been allowed to dry for several years, as mentioned anecdotally by Swinton and Karagiozis (1995). Note that these results are contingent on the material properties used in the simulations. Concrete with a water/cement ratio of 0.5 was used in simulations; a w/c of 0.7 is more typical for residential basements. A higher w/c ratio yields concrete with higher vapour permeability (as well as faster liquid water uptake); these properties would likely change drying simulations.

In addition, conditions at the concrete-insulation interface remained at sustained high relative humidity levels (typically above the LIM$_{Bau}$ II level) for the simulations in both the above-grade portion and below-grade portions of the basement walls. This behavior was noted by Timusk (1997) in discussing internal basement insulation:

> … the outer layers of the insulation are, at all times, close to the one hundred percent relative humidity line. The region between the one hundred percent and the eighty percent relative humidity lines represents a region where many organic materials and metals are prone to decay. This “danger zone” must be recognized since it can lead to serious deterioration and indoor air quality problems if it is not considered in the design process.

To some degree, this points out the risk of using moisture-sensitive materials such as wood framing or batt insulation in contact with the concrete surface. However, in reality, extensive mold and rot does not always occur at this interface. Several mechanisms are likely at work. First, wood framing has a considerable safe storage volume. Second, imperfections in the assembly will likely results in air leakage, which in most cases will tend to dry the assembly. Finally, the thresholds for mold growth set by the isopleth might be too stringent; work by Doll (2002) and Black (2006) show that the presence of liquid water causes much more rapid mold amplification than sustained high relative humidity levels.

As mentioned in Appendix E2, one concern with eliminating a vapour control layer in the basement environment is that moisture sourced from the concrete will increase interior relative humidity. Calculations indicated that drying of concrete construction moisture in a typical house would release roughly 0.5 liters/day, which can be compared with typical interior generation rates for a family of four of 10-15 liters/day. This is not a significant loading in terms of increasing relative humidity, but is important when that moisture is localized and "trapped" behind impermeable finishes. Simulations were performed to gauge the relative effects of the moisture transport mechanisms of vapour diffusion and liquid capillarity through a concrete wall. They showed that capillarity is far more important, transporting water at a rate an order of magnitude higher than vapour diffusion (from a 100% RH environment); this demonstrates the vital importance of liquid water drainage and capillary isolation of the basement walls from the soil.

One common assembly used in Ontario 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 full height polyethylene vapour barrier; however, this assembly was not simulated. The reason for the failures seen in the field is a lack of drying capacity of this assembly when imperfections or incidental wetting result in moisture entry into the stud bay. In simulations, given the "perfect" conditions, this assembly would likely show dry and safe conditions in the stud bay. In practice, it has been shown to be a relatively risky assembly.

A cursory simulation was performed to examine the moisture accumulation behind the outer "moisture barrier" layer. The behavior at the concrete-polyethylene (or concrete-insulation) interface is shown in Figure 5.3, in terms of the condensation layer moisture content and relative humidity. Results are shown both for the double polyethylene wall, as well as the single polyethylene (roll blanket) wall, as a comparison point.

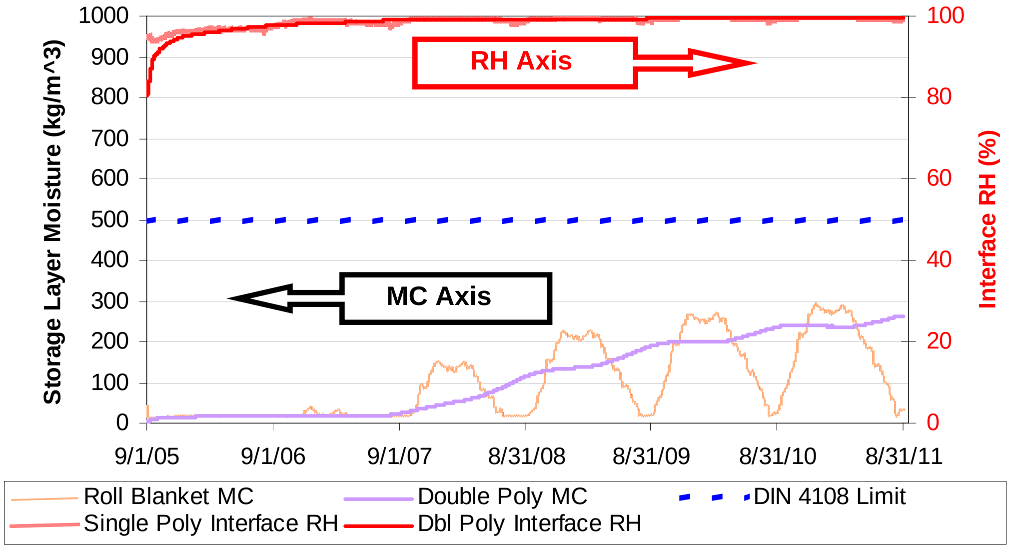

Figure 5.3: Roll blanket and double polyethylene interface condensation layer MC and RH

The results show that as would be expected, moisture accumulates behind the polyethylene at the double polyethylene wall. Although the condensation layer does not show accumulation above the safe storage limit (500 g/sq.m.), the relative humidity at that location rises to a consistent 99.5% after six years. In comparison, in the roll blanket wall, the relative humidity is close to this level, but shows more variation. The moisture content of the condensing layer increases continuously though the simulation; although it might reach the 500 g/m^2 limit, it also seems likely that incidental air leakage might cause some drying in reality. However, it is important to remember that these simulations only include the drying of construction moisture, as opposed to capillary or vapour state moisture coming from the soil or the interior.

6.0 CONCLUSIONS

6.1 Above-Grade Walls

a) The first year of monitoring at the Waterloo BEGhut show that all four wall assemblies with and without polyethylene (and without XPS insulation) demonstrate high humidity conditions in the wall cavities, and mold growth can result. All monitored conditions used quite severe summer and winter indoor conditions. It is unlikely that most Canadian houses would experience the wall moisture accumulation found in this research.

b) The wall assemblies with polyethylene had higher summer moisture contents and lower winter/spring moisture contents than those wall assemblies without polyethylene.

c) In walls with polyethylene sheeting, special conditions have been demonstrated to be necessary to lead to condensation on the outboard face of the polyethylene sheeting in the summer. Some conditions can be altered during design to reduce summer condensation risks. Modeling suggests that condensation on the outboard face of the polyethylene is not expected to occur under normal summer interior temperatures irrespective of the orientation/elevation for the cities reviewed.

d) There was no damage observed on the exterior side of the drywall in the above-grade walls including those without polyethylene sheeting, with the exception of a minor water stain at the North XPS wall.

e) The computer models were calibrated against the measured data in Kitchener Waterloo, and good agreement was generally observed. The wall assemblies in this study were then modeled for three other Canadian cities. All had more moderate (i.e. cooler) summer conditions than Waterloo and 2 cities had more severe heating season conditions. For these cities, under the modeled conditions, the walls with polyethylene were drier than those with only interior latex paint. Modeling suggests that deterioration risks may be controlled in these walls with an interior low-permeance paint (in lieu of latex paint) for all geographic locations reviewed under normal interior moisture loads.

f) Although XPS sheathing can control summertime inward vapour diffusion, it must be designed to have enough thickness to reduce wintertime condensation when no interior polyethylene or low permeance paint is used. Modeling suggests that deterioration risks may be controlled with an interior low permeance paint in all geographic locations reviewed with a normal interior moisture load.

6.2 Basement Walls

(note: basement walls have above-grade and below-grade conditions)

a) While there was evidence of dynamic moisture conditions in several of the walls, actual evidence of mold was limited during wall disassembly. (Only south walls that received sunlight or that were partially shaded were monitored.) Walls with and without polyethylene had moisture levels within acceptable limits. The non-polyethylene wall had higher wood framing moisture contents at the above-grade section in winter, but within safe limits. The polyethylene wall showed generally wetter behavior, demonstrating the effect of eliminating moisture drying to the interior.

b) Wintertime condensation was not found to be a problem in the monitored walls, with or without an interior vapour control layer. The temperatures of the above-grade portion of the wall were much warmer than would be predicted by analysis of a one-dimensional wall section, demonstrating the two-dimensional thermal effects of coupling to the ground. This results in a much lower risk for wintertime condensation. Simulations suggest that vapour control is necessary at the above-grade location, but these simulations did not capture this important temperature phenomenon, and therefore give overly conservative results. Modeling of the above-grade portion of basement walls suggest increasingly worse performance with colder climates, higher interior humidity levels, and increasing vapour permeance.

c) Measurements demonstrated summertime inward vapour drives at the above-grade portions of the walls; condensation was seen in walls with an interior polyethylene vapour barrier, and correlated to an inward thermal gradient. Simulations showed that this issue is likely in climates with a significant cooling load (i.e., inward thermal gradient); therefore, locations with negligible cooling loads, such as Edmonton, Vancouver, or St. John’s, are unlikely to have these problems.

d) The below-grade sections of all four wall assemblies had moderate and stable humidity conditions.

e) This research suggests that interior vapour control at the lower portion of the basement wall is unnecessary or inhibits drying. These locations experience temperatures that are similar to geographic locations that require no vapour control layer. The monitored data shows that an interior impermeable layer at this location reduces drying and results in longer periods of elevated humidity at the concrete-insulation interface. Simulations showed that performance at the lower portion of the wall improves with increasing vapour permeability. Furthermore, simulations of ventilating the basement with exterior dewpoint air showed negligible accumulation, which could dry in the winter. Instead of a vapour barrier, these results suggest that an air barrier might be all that is required to control condensation in the below-grade portion of the basement wall.

f) The drywall was is in good condition in all walls after 1 year of monitoring.

g) The wall with extruded polystyrene (XPS) showed excellent performance, due to its combination of vapour resistance and insulating value. However, high humidity was measured on the exterior side of the XPS, and the wall was never taken apart to confirm the actual condition. The presence of high humidity in this location should not present any risks if it is not connected to the interior environment.

6.3 Further Work

a) There remains a significant amount of uncertainty surrounding the performance of above-grade portions of internally insulated basement assemblies. One-dimensional modeling was found to be inadequate to capture the temperature and moisture variations in this part of the building enclosure.

b) Wall assembly moisture storage capability and this effect on mold growth is still largely unknown.

c) This report considers unventilated brick and vapour control layers that are orders of magnitude apart (3 metric perms to 600 metric perms). A further study is currently underway for the above-grade walls that will review the effect of a vapour control layer in the middle of this range, as well as the impact of ventilated brick.

d) This research suggests that interior vapour control at the lower portion of the basement wall is unnecessary or inhibits drying. Code officials should be informed about the results. Changes to codes and construction practice are likely. Permeability in the below-grade portion of the basement wall can be advantageous and should be explored further.

7.0 REFERENCES

ASHRAE, 2005, ASHRAE Handbook-Fundamentals, Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

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

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

Building Research Establishment. 1989. Solid External Walls: Internal Dry-Lining-Preventing Summer Condensation. BRE Defect Action Sheet (Design) DAS 133, Garston, Watford, UK

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

Christensen, G. 1985. Summer Condensation in Post-Insulated Exterior Walls – Some Results from Measurement in a Test House. CIB/W61, Building Physics Division, Danish Building Research Institute, Horsholm, Denmark, pp. 1-7.

Deutsches Institut für Normung. 1999. Wärmeschutz und Energie Einsparung in Gebäuden, Teil x: Vermeidung von Schimmelpilzen (Heat Protection and Energy Saving in Buildings, Part X: Prevention of Mold Growth), Beuth Verlag.

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

Goldberg, L., and Aloi, T. 2001. "Space Humidity/Interior Basement Wall Insulation Moisture Content Relationships With and Without Vapour Retarders." Indoor Air Quality 2001. American Society of Heating, Refrigeration, and Air-Conditioning Engineers Conference.

Goldberg, L. 2004. Icynene Foundation Insulation Project, Building Physics and Foundations Research Programs, University of Minnesota.

Huang, S., and Derome, D. 2005. Moisture Performance of Walls with Wet Cladding Under Summer Solar Radiation. Building Envelope Performance Laboratory, Department of Building, Civil and Environmental Engineering of Concordia University.

Huelman, P., and Cheple, M. 2001. "Why We Need to Know More About Basement Moisture". Proc. of Thermal Performance of the Exterior Envelopes of Whole Buildings VIII. Atlanta, Geo.: 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.

Hutcheon, N. 1953. Fundamental Consideration in the Design of Exterior Walls for Building. NRC Paper No. 3087, DBR No.37. Ottawa: Division of Building Research.

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.

Künzel, Hartwig M. 2002. WUFI® PC-Program for calculating the coupled heat and moisture transfer in buildings. Fraunhofer Institute for Building Physics. Holzkirchen, Germany.

Lawton, M., and Brown, W. 2003. "Considering the Use of Polyethylene Vapour Barriers in Temperate Climates." Proc. of the Ninth Building Science and Technology Conference, Vancouver, Canada.

Lstiburek, J., and Nathan, Y. 2002. Basement Insulation Systems. Report to the U.S. Department of Energy. Westford, Mass: Building Science Corporation.

Pressnail, K., Timusk, J., Kan, L., Doug, B., and Kan, V. 2003. "In Search of a Wall for all Seasons: Controlling Sun-Driven Moisture." Proc. of the Ninth Conference on Building Science and Technology. Vancouver, Canada, pp. 157-170.

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.

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.

Sedlbauer, K. 2004. Prediction of mould fungus formation on the surface of and inside building components, PhD Thesis, Fraunhofer Institute for Building Physics.

Straube, J.F., and Burnett, E.F.P., Building Science for Building Enclosure Design, Building Science Press, 2005.

Straube, J., and Burnett, E. 1995. “Moisture Movement in Building Enclosure Wall Systems.” Proc. of Thermal Performance of the Exterior Envelopes of Buildings VI. Atlanta, Geo.: American Society of Heating, Refrigeration, and Air-Conditioning Engineers, Inc.

Straube, J., Onysko, D., and Schumacher, C. 2002. "Methodology and Design of Field Experiments for Monitoring the Hygrothermal Performance of Wood Frame Enclosures," J. of Thermal Env. & Bldg. Sci., Vol.26, No.2. Thousand Oaks, Calif.: Sage Publications.

Swinton, M., and Karagiozis, A. 1995. "Investigation of Warm Weather Condensation in New and Insulated Basement Walls." Proc. of Thermal Performance of the Exterior Envelopes of Buildings VI. Atlanta, Geo.: 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 Pressnail, K. 1997. “Another Look at Internally-Insulated Basement Wall.” Proc. of the Seventh Building Science and Technology Conference, Toronto, Canada.

See Appendix A for more References