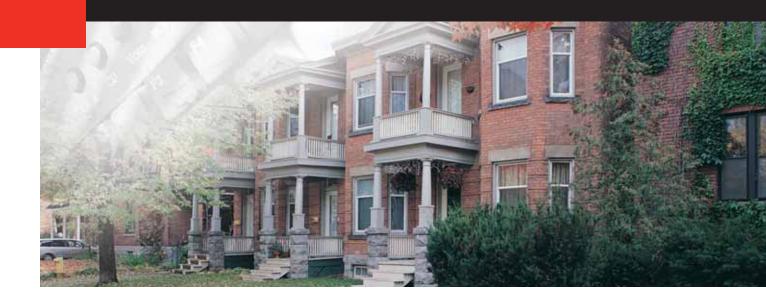
# RESEARCH REPORT



Understanding Vapour Permeance and Condensation in Wall Assemblies : Volume 2: Appendices





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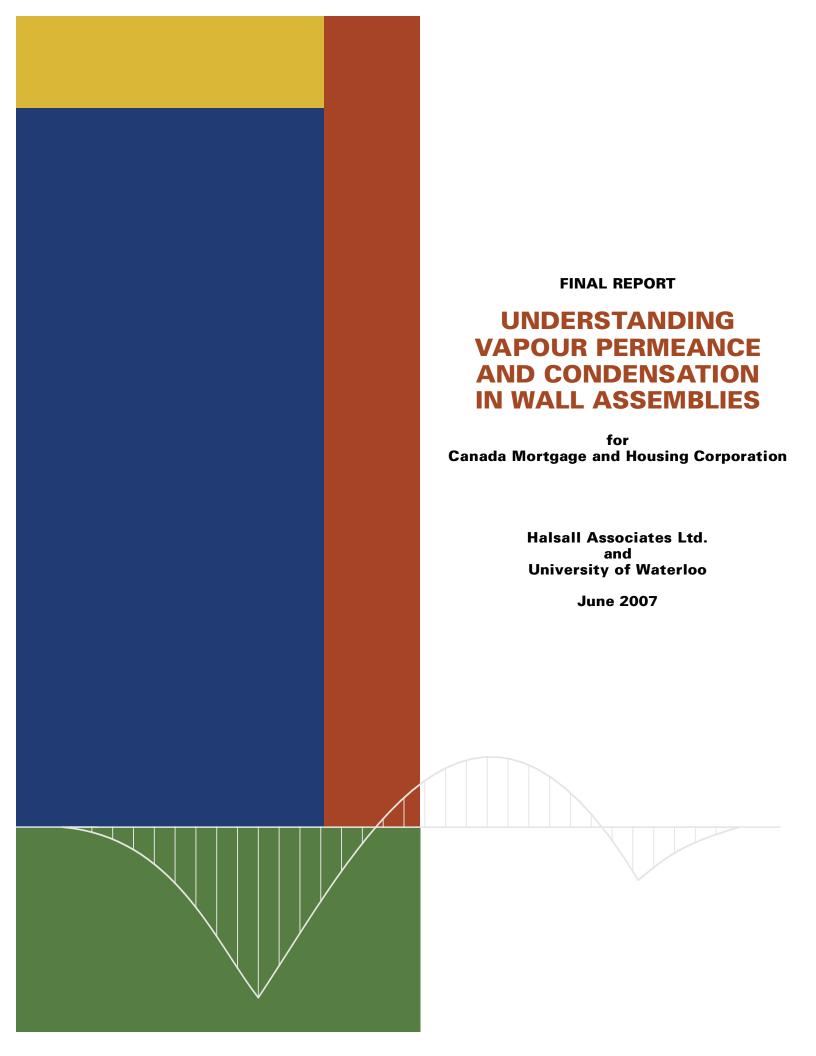
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# APPENDIX A - REFERENCE LIST/SUMMARY



Key
A - Evaluation Type
B - Wall Assembly
C - Climate
D - Key findings

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No.	No. Publications/Journals	Author	Source	Date	Findings
-	Moisture Performance of Walls with Wet Cladding Under Summer Solar Badiation	Shan Huang; Dominique Derome	Concordia	2005 (not published yet)	A - Literature Review  B - Various walls assemblies with and without poly  C - Locacions across N. America and Europe  C - Locacions across N. America and Europe  D - Suggestions across N. America and Europe  D - Suggestions to reduce solar driven moisture (from Canadian and Danish Studies); the use of low absorption cladding, ventilation between masonry and inner components where absorptive masonry is used, overhangs, asphalt felts between bricks and insulation, foam based insulations in lieu of batt insulation, siliconating masonry products to minimize water absorption. The U.K. Building Research Establishment (1989); removing the vapour barrier should not be considered since condensation could also occur behind low-permeability interior finishes. Other findings from literature review summarized in this table under the appropriate authours.  A - La D Testing, Concordia  B - Wet red cedar, 19mm air space (vented/unvented), Spun Bonded Polyolefin membrane, 11mm fibre sheathing board, 89 mm wood studs with batt insulation, 6 mil poly, D.W. C - High intensity infared lights to simulate solar heating of the wall exterior. Ext. 24 + /- 2C + heat lamps, 35 to 45%RH; Int: 21 +/-1.5C, 30 to 40%RH  D - Results indicated that solar driven condensation requries very specific conditions to occur: high permeance of sheathing, absence of ventilation, high moisture content of wood s
7	Field Performance of Different Basement Insulation Systems		Building Conference IX	2005	see below
м	Moisture Performance of an Airtight, Sapour-permeable Building Envelope in 8 a Cold Climate	Sinonson; Ojanen; Salonvaara	& Bidg. Sci	2006	A - Field testing, and numerical results using TCCC2D  B - 22mm wood siding, 50mm air space, 25mm wood fiber board, 250mm wood fiber insulation, building paper, and interior DW (no Poly). The ratio of the internal to external vapour resistance study 30 et al. depending on RH.  C - Tests were performed on N and S walls in a house in Helsinki, Finland.  Int winter: 20 to 23C, 21 + /- 3%RH. Int summer: 22 to 25C, 30 + /- 7%RH.  - Conditions used for numerical results: Int: 21C when outside < 18C, 3C > outdoor when outdoor temp > 18C. Interior RH is set at 2g/m <sup>3</sup> above exterior humidity (approx. 70%RH in summer), and a minimum of 35%RH in winter.  70%RH is summer), and a minimum of 35%RH in winter.  70%RH is summer, and a minimum of 35%RH in winter.  70%RH is set at 2g/m <sup>3</sup> above exterior humidity (approx. 70%RH in winter).  70%RH is set at 2g/m <sup>3</sup> above exterior humidity (approx. 70%RH in winter).  70%RH is set at 2g/m <sup>3</sup> above exterior humidity (approx. 70%RH in winter).  70%RH is set at 2g/m <sup>3</sup> above exterior humidity (approx. 70%RH in winter).  70%RH is set at 2g/m <sup>3</sup> above exterior humidity (approx. 70%RH in winter).  70%RH is set at 2g/m <sup>3</sup> above exterior humidity (approx. 70%RH in winter).  70%RH in winter.  70%RH is set at 2g/m <sup>3</sup> above exterior humidity (approx. 70%RH in winter).  70%RH is set at 2g/m <sup>3</sup> above exterior humidity (approx. 70%RH in winter).  70%RH is set at 2g/m <sup>3</sup> above exterior humidity (approx. 70%RH in winter).  70%RH is set at 2g/m <sup>3</sup> above exterior humidity (approx. 70%RH in winter).  70%RH in winter.  70%RH is set at 2g/m <sup>3</sup> above exterior humidity (approx. 70%RH in winter).  70%RH in winter.  70%RH in winter on the exterior portion of the framed cavity was rapidly dried in the station of the framed results.
4	Field Studies of Ventilation Drying (We John Straube; Rank will review aspects pertaining to inward Van Straaten; Eric vapour drives)  Burnett	John Straube; Randy Van Straaten; Eric Burnett	Thermal IX, Clearwater	2004	A - Field testing (10 Walls)  B - Case 1: Brick, 50mm Air Space, SBPO or #15 Asphalt Impregnated Felt (AIF), 12mm low-den fiberboard, 140mm Fiberglass (FG batt), 12mm Melamine coated MDF permaence valous barrier)  Case 2: Vinyl, 10mm Air, SBPO or #15 AIF, 12mm low-den fiberboard, 140mm FG batt, 12mm Melamine coated MDF  Case 3: Brick, 20mm Air, SBPO or #15 AIF, 12mm low-den fiberboard, 140mm FG batt, 12mm Melamine coated MDF  Case 3: Brick, 20mm Air, SBPO or #15 AIF, 12mm low-den fiberboard, 140mm FG batt, 12mm Melamine coated MDF  Case 3: Brick, 20mm Air, SBPO or #15 AIF, 12mm low-den fiberboard, 140mm FG batt, 12mm Melamine coated MDF  Case 3: Brick, 20mm Air, SBPO or #15 AIF, 12mm low-den fiberboard, 140mm FG batt, 12mm Melamine coated MDF  Case 3: Brick, 20mm Air, SBPO or #15 AIF, 12mm low-den fiberboard, 140mm FG batt, 12mm Melamine coated MDF  Case 3: Brick, 20mm Air, SBPO or #15 AIF, 12mm low-den fiberboard, 140mm FG batt, 12mm Melamine coated MDF  Case 3: Brick, 20mm Air, SBPO or #15 AIF, 12mm low-den fiberboard, 140mm FG batt, 12mm Melamine coated MDF  Case 3: Brick, 20mm Air, SBPO or #15 AIF, 12mm low-den fiberboard, 140mm FG batt, 12mm Melamine coated MDF  Case 3: Brick, 20mm Air, SBPO or #15 AIF, 12mm low-den fiberboard, 140mm FG batt, 12mm Melamine coated MDF  Case 3: Brick, 20mm Air, 20mm Air, 21C  Intentional sheathing membrane sheathing membrane after induced wetting (i.e. faster drying over years and be unaffected.  Faster drying noted with higher permaence sheathing membrane after induced wetting (i.e. faster drying over years and be unaffected.



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A - Field Observations/ Hygothermal Modelling/ and Experience B - Suggests 14 wall as semblies ranging from MVSS, MV Block backup, Stucco with block or SS backup, EIFS with SS backup, and Precast. Most assemblies on to use poly.  Most assemblies incorporate letex paint or vapour semi-permeable interior finishes.  C - Various hygotroate letex paint or vapour semi-permeable interior finishes.  D - Indicates are across N.America where the listed wall assemblies can be used Author suggests the following principles:  1 - Avoid vapour barries where vapour retarders will work, avoid vapour retarders will work, avoid vapour retarders will work, avoid vapour retarders will work was sembly.  3 - Avoid using poly, foil faced batts, reflective barrier foils, and vinyl wall coverings on the interior of air-conditioned assembles.  4 - Ventilate enclosures  Proposes Building Code requirements for vapour retarders across the U.S. based on climate and properties of other materials in the wall assembly.	A - Hygrothermal Modeling (hygIRC-2D) B - 19mm Stucco, 0.23mm Sheathing Brd, 89mm lns. Space, Vapour Barrier, 12mm Gypsum Board - Total interior vapour permeance reviewed: 15, 55, 86, 272, 373, 591, and 2753 ng/Pa.s.m2 (vapour bar. and painted/unpainted gypsum board) C - Ext = Vancouver, lower mainland, avg yr Int = 3 sets of data for each set of vapour permeance (proved to have little effect on results) Int = 3 sets of data for each set of vapour permeance (proved to have little effect on results) Int = 3 sets of data for each set of vapour permeance (proved to have little effect on results) Constant: 22C/40% RH 3. Weathersmart weather analysis tool: 45-70% RH (avg approx 60%RH)/21C Constant: 22C/40% RH 3. Weathersmart weather analysis tool: 45-70% RH (avg approx 60%RH)/21C Low/Pigh interior vapour permeance of 55-370 Ng/Pa.s.m2 (translates to 60-000 Ng/Pa.s.m2 for vapour barrier only) Low/Pigh interior vapour permeance results in relatively higher sheathing RHT index throughout year Removal of the vapour barrier significantly increased the moisture content of the impact of inadvertent interior finishes such as vinyl wallpaper or low permeance paint.	A - Hygrothermal Modelling (WUFI).  B - Vinyl siding, Bituminous building paper, moist OSB sheathing, 6" insulated wood stud cavity, gypsum board, moderate vapour retarder (1 perm).  C North walls, 3 cities across N.America with interior winter temp set to 21C.  Minneapolis interior RH of 50%  - Seatle interior RH of 55%  - In Summer 24C/60%RH  D - Compare results using vapour diffusion balance (wetting potential versus drying potential)  - Winter moisture that permeates retarder does not dry out completely by the end of July. Thus, 1 perm vapour retarder cannot be recommended for unvented constructions like this one in these critics.  - Winter moisture that permeates retarder does not dry out completely by the end of July. Thus, 1 perm vapour retarder cannot be recommended for unvented constructions like this one in these critics.  - Winter moisture that permeates retarder allowed spring inward drying 2.5 times (Seatlle, Minn) to 4 times higher (Boston) than interstitial winter condensation (more drying allowed since sheathing started weet).	A - HygIRC modelling  B - Stucco, EIFS, Masonry, Wood, Vinyl, with Interior Poly.  C - Seven areas reviewed: Presno, Fresno, San Diego, Winnipeg, Ottawa, Seattle, and Wilmington. Summer and winter interior temperature and humidity was simulated in consorted property. Fresno, San Diego, Winnipeg, Ottawa, Seattle, and Wilmington. Summer and winter interior temperature and humidity was simulated in C - Seven areas reviewed: Process, Fresno, San Diego, Winnipeg, Ottawa, Seattle, and Wilmington. Summer and winterior deficiency was added, all wall assemblies show by the high received into cavity exceeding evaporative drying potential. The masonry wall had the lowest moisture load with deficiency present, followed by vinyl, stucco, and EIFS yielding the highest moisture load with deficiency present.  Increasing vapour barrier permeance generally allowed drying to the inside. Further analysis for various indoor conditions was recommended.
2004	2004	2004	2003
ASHRAE	CIB 2004	E.Sim	Building Science and Technology 9th
Joseph Lstiburek	Mukhopadhyaya; Kumaran; Van Reenen	Holm	Kumaran; Mukhopadhyaya; Cornick; Lacasse; Rousseau; Maret; Nofal; Quirt; Dalgliesh
Understanding Vapor Barriers	Vapor Barrier and Moisture Response of Mukhopadhyaya; Wood-frame Strucco Wall - Results from Kumaran; Van Hygrothermal Simulation Reenen	Vapor Control in Cold and Coastal	An Integrated Methodology to Develop Moisture Management Strategies for Exterior Wall Systems



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A - Field testing  B - Case 1: vertical paneling (type unknown), 20mm air space, 25mm porous fiberboard, 150mm Cellulose, vapour permeable bitumen paper, 13mm drywall  B - Case 1: vertical paneling (type unknown), 20mm air space, 25mm porous fiberboard, 150mm mineral wool, 0.2 mm poly, 13mm drywall  C - Finland Turku) 28 km from Baitic sea, South wall, occupied house 2 adults one child.  Ext: 51 to 92%HH, avg 55%HH summer, avg 80%HH winter; -5 to 20C  - In: 35 to 55%HH, avg 45%KHH summer, avg 80%HH winter; -5 to 20C  - In: 55 to 55%HH, avg 45%KHH summer, avg 80%HH winter; -9 to 26C  - In: 55 to 55%HH, avg 45%KHH summer, avg 80%HH winter; -9 to 26C  - In: 55 to 55%HH, avg 45%KHH summer, avg 80% flow the measured.  - Interior of fiberboard is critical area noted due to high RH measured.  - Uniterior of fiberboard is critical area noted due to high RH measured.  - Winter/springffall: Case 1 higher RH than Case 2. Case 1 avg RH > 80% for 4 months, Case 2 avg RH > 80% for 1 month.  - Critical conditions for mould growth existed for Case 1 in autumn (fiberboard interior).  - Case 2 performed better than Case 1.  - Case 2 performed better than Case 1.	A - Modelling using WUFI  B - Wall A - Brick, 25mm airspace, tyvek, 13mm dens-glass, 152mm SS with R-19 batt insulation, with either vapour barrier or drywall with vapour retarding paint (28.5 ng/Pa.s.m.2) relax paint.  B - Wall A - Brick, 25mm airspace, 38mm XPS, tyvek, 13mm dens-glass, 152mm SS with R-11 batt insulation, Drywall with vapour retarding paint (28.5 ng/Pa.s.m.2).  Wall C - Brick, 25mm airspace, 38mm XPS, peel and stick membrane, 13mm densglass, 152mm SS with no batt insulation, Drywall with latex paint and primer.  C - Pacific northwest, Int: winter 20C/40% R.H., summer 24C/60% R.H.  D - Wall C performed well: Wall B could be deemed safe with some minor changes such as ventilation.  Wall A (latex paint) dried quicker in the spring and allowed inward vapour drives to the interior, resulting in lower RH at the drywall location.  Wall A (all 3 assemblies): RH in the dens-glass reaches dangerously high levels during the rainy and cool periods. Wall A (Latex paint) had a higher winter RH in the dens-glass reaches small.	A - Literature review B - Various wall assemblies C - Pacific coastal B.C., and N.W. United States. D - Pacific coastal B.C., and N.W. United States. D - Pacific coastal B.C., and N.W. United States. D - Inmited drying potential to the interior in this climate if one assumes a painted interior finishes are used. Vapour drive from the cavity to the interior may cause mould growth on interior implies a reliance on mechanical dehumidification and control over what interior finishes are used. Vapour drive from the cavity to the interior may cause mould growth on interior finishes such as drywall if poly is removed. Examples have shown that where poly protected drywall in walls with rain penetration, framing members were less degraded but there was wide spread mould growth on the drywall since it was not protected by the poly.  A - Hygrothermal modelling (HygRC) B - 19mm acrylic stucco, sheathing paper, 11mm OSB, 89mm wood stud with batt insulated cavity, modelled with and without poly, and modelled latex, oil, and no finish on the D-SE are in onintentional moisture source. Case 2: infitial moisture source (sheathing wetted). Case 3: continual rain penetration through defects.  C - Exterior East, Vancouver (1969 weather data); interior 21°C, 30 to 70%RH.  D - Lower permeance on the interior of the wall yielded lower moisture levels in the OSB board (with no cladding defects present). With exterior cladding defect allow wind driven reconent of the OSB with little change during winter conditions. Solar driven wapour drive was not considered.	A - Field Testing (Basement Walls with no w/p or dampproofing)  B - Wall 1 - concrete block, 64mm rigid fibre glass (interior polyolefin covering), Wall 2 - concrete block, poly, 64mm rigid fibre glass (interior polyolefin covering), Doly.  concrete block, 64mm rigid fibre glassifuration polyolefin covering), poly.  concrete block, 64mm rigid fibre glassifuration polyolefin covering), Doly.  C Ext: Foundation field Fall.  Test performed using assemblies and the NW, Sand E elevations of the basement interior.  Test performed using assemblies on the NW, Sand E elevations of the basement interior.  Test performed using assemblies on the NW, Sand E elevations of the basement interior.  Das To make anter vapour load: Previous research by Goldberg 2001 showed that hollow masonry block (uninsulated or unwaterproofed from the exterior) demonstrated worst- case moisture test conditions for interior insulation systems (vs. pourd concrete). Well drained (sandy soil) drained to a water table at least 20 feet below grade required to  By the primary condensation while allowing a significant water vapour source throughout the year.  Wall 1: provided a stable wetting/drying cycle without annual moisture accumulation. No evidence of gross wetting or condensate running down the wall surface.  Wall 3: collected condensation on the insulation side of the poly during the winter and on block side of the poly in the summer. During the winter, condensate are and own the face of t Wall 3: absorbed condensate within the insulation from March to September. The insulation would not dry out before condensation must get virtual this insulation system.
2002	2002	2001	2001
Symposium	E.Sia	Building Science and Technology 9th	IAQ 2001
P. Kakela, J. Vinha. 8y	Schumacher E.:	Brown Science Technol 9th	Louise Goldberg; Traci Aloi
13 Outdoor Field Test of Timber-Framed External Wall Element Structure	14 The Role of Hygrothermal Modeling in Practical Building Design: Case Studies	Considering the Use of Polyethylene Vapor Barriers in Temperate Climates	16 Space Humidity/Interior Basement Wall Insulation Moisture Content Relationships with and without Vapor Retarders



71	The Influence of Design on Drying of Wood-Framed Walls Under Controlled Conditions	Donald Hazledon; Paul Morris	Buildings VIII 2001		A - Lab testing (12 panels)  B - 7 x Case 1: Tax Case 2: Red Cadear Siding. O mm to 19mm air space, 30 min Asphalt Impregnated Felts (AIF) or SBPO, 11.5mm OSB  - 2 x Case 2: Red Cadear Siding. O mm to 19mm air space, 30 min AIF, 11.5mm DSB  - 2 x Case 3: 2.1mm Stucco, 0 mm to 19mm air space, 30 min AIF, 11.5mm plywood  - 3 x Case 3: 2.1mm Stucco, 0 mm to 19mm air space, 30 min AIF, 11.5mm plywood  - 4 Ion: Fiber Glass Insulated Wood Frame, 5min Johy, Panited Plywood  - 4 Ion: Fiber Glass Insulated Wood Frame, 5min Johy, Panited Plywood  - 4 Ion: Fiber Glass Insulated Wood Frame, 5min Johy, Panited Plywood  - 4 Ion: Fiber Glass Insulated Wood Frame, 5min Johy, Panited Plywood  - 4 Ion: Fiber Glass Insulated Wood Frame, 5min Johy, Panited Plywood  - 4 Ion: Fiber Glass Insulated Wood Frame, 5min Johy, Panited Plywood  - 5 X Fiber Glass Insulated Wood Frame, 5min Johy, Panited Plywood  - 5 X Fiber Glass Insulated Wood Frame, 5min Johy, Panited Plywood  - 5 X Fiber Glass Insulated Wood Frame, 5min Johy, Panited Fiber Glass Fibe
60	The Influence of Low-Permeance Vapor JaBarriers on Roof and Wall Performance	John Straube	Buildings VIII	2001	A - Literature Review, Calculations, Modelling, Field Testing Experience B - Various wall assemblies were discussed, however no clear description of components was given. C - Various coations (makes reference to Manyere no clear description of components was given. C - Various coations (makes reference to Many Nebraska, and Winnipeg). D - Karagiozis and Kumaran (1993; showed through modelling that a 400 metric perm finish on the interior of the drywall was sufficient to avoid winter diffusion problems in Winnipeg with interior R.H. of 38%. Similarly in Omaha Nebraska a 60 metric perm Vapour retarder is shown to be sufficient under similar conditions, and suggests that 6 mill poly, would provide little additional protection. Shall payer is sufficient to control condensation within the stud space in Omaha when installing a EPS insulated sheathing on the exterior and maintaing a 40% interior R.H. One cannot make rules or statements regarding vapour barriers and their permeance without considering: Int environment, outdoor temp, solar absorptance, rainwater absorption, and vapour/thermal resistance of other materials in the wall.
0	Why We Need to Know More About Nasement Moisture	Marilou Cheple; Patrick Huelman	Buildings VIII	2001	A - Literature review  B - 6 conceptual solutions are presented for basement walls using concrete or block 1 - Exterior insulation, waterproofing on concrete 2 - No waterproofing, concrete and permeable interior wall finish. 3 - No w/p, concrete, interior drainage cavity, low vapour permeable interior wall finish. 3 - No w/p, concrete, interior drainage cavity, low vapour permeable interior wall finish. 3 - draining insulation, partial dampproofing (upper portion), concrete, interior insulation (lower portion) air right vapour retractor insulation, block wall, optional interior moisture barrier/insulation/air, vapour barrier.  C - Cold Climates.  The portion of the wall below the neutral vapour pressure plane and above the floor slab will experience an inward diffusion flux throughout the year.  Types 1 and 3 possess lowest comparative risk. Types 2 and 5 show moderate comparative risk, and type 4 and 6 show moderate to high comparative risk.
50	Drying of walls with ventilated Stucco J cladding parametric analysis	Jacques Rousseau	CMHC - SCHL	1999	A - Hygrothermal Modeling (WallDry)  B - Stucco, 0 to 38mm air cavity with and without venting modelled, OSB or plywood, 89mm wood stud and batt insulation, with or without poly, and drywall. C - Winter organizations in Vancouver (interior R.H. not given) without exteror wetting by rain. D - 12mm or greater vented air space aids in drying within the stud cavity Plywood sheathed walls appear to dry faster than walls with OSB No poly vapour barrier showed quicker drying of wall assemblies - Walls with permeable stucco dried quicker than walls with impermeable stucco.
21	Drainage, Ventilation Drying, and Unicolosure Performance	John Straube; Eric Burnett	Thermal Envelopes VII	1998	A - Field testing B - Wald A - Brick (vented/unvented), 30nm air space, 50nm fibre board insulation, exterior gypsum sheathing, 89nm steel framing with batt, poly and interior D.W. Wall B - B - Wald A - Brick (vented/unvented), 30nm air space, 32nm extruded polystyrene, 89mm wood framing, poly and interior D.W. C - University of Waterloo BEGhut, Wall A (east), Wall B (N, E, S, W) C - University of Waterloo BEGhut, Wall A (east), Wall B (N, E, S, W) D - Unvented Wall A showed summertime wetting (15 - 20% framing moisture content from mid June to November) and condensation on the poly. Vented wall A framing moisture content thoughout the year due to the relatively vapour resistant exterior sheathing. Problems can arise if ventilation is restricted and if there is little vapour resistance between the cladding and an inner vapour-retarding layer.



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22	Field Testing of Filled-Cavity Wall Systems	John Straube; Eric Burnett	108651 97	1997	A - Field testing B - Case 1: 85mm Brick, 30mm Air Space, 3600 Ng/Pa.s.m2 Weather barrier, 38 mm low dens. fiberglass board, - Case 2: 85mm Brick, 38mm untreated med den. fiberglass board, 3600 Ng/Pa.s.m2 Weather barrier - Case 3: 85mm Brick, 50mm Air Space, 300-700 Ng/Pa.s.m2 Weather barrier - Case 4: 85mm Brick, 50mm Air Space, 300-700 Ng/Pa.s.m2 Weather barrier - Case 4: 85mm Brick, 50mm hydrophobically-treated low dens. rockwool board, 700 Ng/Pa.s.m2 Weather barrier - All over Wood frame with glasse fiber insulation, 0.15 mm poly, drwvall, paint - All over Wood frame with glasse fiber insulation, 0.15 mm poly, drwvall, paint - Extr. U of Wasterloo Tast Hut, Ontario. Case 1, 2 each facing E.W., Case 3,4 each facing N,5.E.W - Int: 21C/50%RH constant. D - Filled cavity walls demonstrated MC > 28% in stud space for over 7 months in summer/fall (ideal conditions for mould growth and rot, though none noted). Moisture condensed on the exterior side of the poly Intimaterial limited ventilation on poly resulted from inward drives after rain/solar heating of masonry Fill material stored water which was driven inward with solar radiation. Hydrophobically-treated material is it sufficient to eliminate this problem Fill material stored water which was driven inward wething due to increased ventilation (and low permeance sheathing where used) - High vapour permeable weather barriers allow for winter drying, but also allow warm weather inward vapour diffusion Maximum sheathing permeance recommendations set at 50-100 Ng/Pa.s.m2. to prevent significant MC in framing and condensation on poly due to inward vapour
23	In-Service Performance of Enclosure Walls	John Straube; Eric Burnett	7	1997	A - Field testing, lab testing, modelling.  B - Variances on 14 main well types including filled cavity walls and walls with insulated sheathing.  B - Variances on 14 main well types including filled cavity walls and walls with insulated sheathing.  B - Int 210 (SoS 48 Hzt. U of Waterloo Test Hut.  D - 6 mil Poly in exterior insulated walls (such as EIFS) not needed to prevent vapour diffusion. RH was 10% in stud space in winter in such walls without poly.  B - Filled-Cavity walls: Brick, Filled Cavity, Weather Barrier, Sheathing, Wood Frame, Poly, Drywall  D - Summertime wetting due to solar driven inward vapour drives. Wetting is related to sun exposure, driving rain, vapour resistance of outer wall layers, air conditioning (the cooler the worse).  B - Insulating Sheathing: such as XPS applied over framing  D - Resulted in drier stud spaces as condensation was reduced.
24	Ontario Building Code, Part 5, Wind, Water and Vapour Protection	Ministry of Municipal O Affairs and Housing F	Queen's Printer for Ontario	1997	Same as NBC Part 5.
25	Ontario Building Code, Part 9, Housing and Small Buildings	Ministry of Municipal (Affairs and Housing F	Queen's Printer for Ontario	1997	Same as NBC Part 9.
26	Moisture Movement in Building Enclosure Wall Systems	John Straube; Eric T	Thermal Envelopes VI	1995	A - Field Testing B - Birk or Vinyl, vapour permeable fiberglass sheathing or vapour resistant XPS sheathing, wood framing with insulation, poly, drywall B - Birk or Vinyl, vapour permeable fiberglass sheathing or vapour resistant XPS sheathing, wood framing saturation for the period of several months.  D - Birk-veneer-clad wood-frame walls sheathed with rigid fiberglass: summer solar driven inward vapour drives) caused wood framing saturation/staining/mould over the period of several months. Condensation potential may be greater for air conditioned buildings.  The presence of a relatively vapour-impermeable layer near the outside of the assembly (e.g. XPS) can be effective in reducing the potential for damage due to inward vapour or prives.  Drying of framing to exterior reduced by low permeance exterior sheathing.  Brying of framing 103 M.C., with fiberglass sheathing, gained moisture in framing over summer  - Built in moisture in framing (30% M.C.), with fiberglass sheathing, gained moisture in framing over summer  - Built and storage and material tolerance considerations must be balanced.  - Cladding type/orientation, and solar-induced vapour drive are important parameters for wall moisture management.
27	National Building Code of Canada, Part 5, Environmental Separation	National Research Council of Canada	Federal Publications Inc.	1995	D - 5.5 - A building component subject to a temperature, and water vapour pressure difference shall have a vapour barrier.  - Vapour barrier shall be designed to minimize condensation to a rate that will not compromise building use or operations, effect occupants health or cause deterioration.  - A vapour barrier is not required where it can be shown that uncontrolled vapour diffusion does not compromise building use or operations, effect occupants health or cause deterioration.

<ol> <li>9.25 - Measures to control air leakage and condensation</li> <li>9.25.1.2 - States that layers in wall with air leakage &lt; 0.1 L/s.m² at 75 Pa or vapour permeance &lt; 60 Ng/Pa.s.m² shall be placed:</li> <li>1. inboard of insulation</li> <li>2. outboard of cavity vented to exterior</li> <li>3. or that ratio of thermal resistance outboard of impermeable layer to inboard of impermeable is not less than values given in table provided. The ratio of thermal resistance outboard increases for colder climates (distinguished by heating degree days).</li> <li>9.25.4 - Thermally insulated walls, calings, and floors shall be constructed with a vapour barrier limiting vapour movement into walls, floors, attic or roofs.</li> <li>vapour barrier permeance shall be &lt; 45 Ng/Pa.s.m².</li> <li>e.g. where high resistance to vapour movement req'd permeance shall be &lt; 15 Ng/Pa.s.m² (e.g. where outer layers have low permeance).</li> </ol>		A - Modelling (assuming air tight assemblies) B - 12.5mm wood siding with oil based finish, 12.5mm fiber board sheathing, R11 glass batts, poly / no poly, 12.5mm Drywall with latex finish C - Madison Wi, Boston MA, Atlanta Ga C - Madison Wi, Boston MA, Atlanta Ga C - Sheathing mosture content will never reach saturation in walls without poly (for these US cities) if indoor R.H. is less than 35%, Saturated sheathing will result in walls without poly in both Madison and Boston with interior at 50% R.H (Atlanta would remain below 20% moisture content). Sheathing moisture contents much lower in walls with poly. Paper suggests that poly is cheap insurance to provide air leakage control.	A - Literature Review C - Cold climates C - Cold climates D - Main Corolusions: Poly is overkill even in "very cold regions". Ordinary latex paint on drywall should provide adequate resistance to vapour diffusion through walls and ceilings provide that there is a continuous air barrier. A systematic approach defining when, where, and what type of vapour retarders are necessary for various situations is needed.  Karagiozis/Kumaran (NRC): Study in '94, in 8 Canadian cities, in walls with no accumulation.  Karagiozis/Kumaran (NRC): Study in '94, in 16 lowing summer with no accumulation.  CMHC: Field test, calgary, walls with 150mm wet cellulose, no poly and poly. Walls with and without poly had same MC 5 months after construction.  - Isongas: 2 field tests (1889, 1891, no relationship between vapour retarder presence and moisture content (see Tsongas, Northwest Wall Moisture Study, 1990). Subsequent study (1993) found correlation between air leakage and moisture problems.	A - Field observations B - brick, air space, shearthing, mineral wool insulation in stud cavity, with and without vapour barrier, plaster board. C - Sweden summer conditions with actural interior temp, no mention of RH D - Inway apour diffusion caused high cavity RH (close to 100%) and condensation on the exterior side of the vapour barrier in extreme summer conditions: heavy driving rain, sushine; could be worse with cooling indoor air Recommends reducing inward drives with: ventilation, sheathing with some vapour resistance, remove interior vapour barrier. Testing showed that optimal conditions occurred when a water repellant impregnated brick was used with a 20mm air space and no interior vapour concentration of the interior air should not be high He describes 2 conditions for poly removal: no vapour right layer on the outer side of the wall, and the vapour concentration of the interior air should not be high.	Lab testing Absorbent roofing materials: Callulose-fiber-reinforced cement shingles (various ages), Concrete tiles, clay tiles, wooden shingles. Absorbent roofing materials used New Zealand summer, Ext. 13 mm rain over 16 hrs followed by 4 hrs of 750W/m2 solar radiation. Int: 20C, 65%RH Shingles absorb a substantial amount of moisture when exposed to rain. Moisture passes through saturated shingles only when exposed to solar radiation. Vapour diffusion driving force across the shingles measured as high as 15,000 Par. The amount of vapour diffusion through the shingles is reduced by 33% when an impermeable (poly) underlayment is interwoven between the shingles. Vapour diffusion through the shingles is only reduced by 37-50% with: building paper underlayment, creating gaps between shingles or painting/sealing shingle exterior ace. There may be rotting of wooden shingles when a poly underlayment is used without a gap between the shingles and the shething.	Field Study 124 energy efficient homes built after 1980, according to Model Conservation Standards (MCS). Northwestern United was built after 1980, according to Model Conservation Standards (MCS). Northwestern United by Standards and Standards (MCS) according to the Standards (MCS) according to t
D - 9.25 - Measures to control air leakage and condensation - 9.25.1.2 - States that layers in well with air leakage < 0.1 L/s.m² at 75 Pa or vapour permeance < 60 Ng/Pa.s.m² shall be placed: 1. inboard of insulation 2. outboard of insulation 3. so that ratio of thermal resistance outboard of impermeable layer to inboard of impermeable is not less that of outboard thermal resistance required, increases for colder climates (distinguished by heating degree days) 9.25.4 - Thermally insulated walls, ceilings, and floors shall be constructed with a vapour barrier limiting vapour movement into walls, vapour barrier permeance shall be < 45 Ng/Pa.s.m² where high resistance to vapour movement red'd permeance shall be < 15 Ng/Pa.s.m² (e.g. where layers have low permeance).	We cannot source complete report.	A - Modelling (assuming air tight assemblies)  B - 12.5mm wood siding with oil based finish, 12.5mm fiber board sheathing, R11 glass batts, poly / no poly, 12.5mm Drywall with E - Madison Wi, Boston MA, Atlanta Ga  C - Madison Wi, Boston MA, Atlanta Ga  D - Sheathing moisture content will never reach saturation in walls without poly (for these US cities) if indoor R.H. is less than 35% Saturated sheathing will result in walls without poly in both Madison and Boston with interior at 50% R.H (Atlanta would remain be moisture contents much lower in walls with poly. Paper suggests that poly is cheap insurance to provide air leakage control.	A - Literature Review C - Cold climates D - Main Conclusions: Poly is overkill even in "very cold regions". Ordinary latex paint on dry provide that there is a continuous air barrier. A systematic approach defining when, where, a reagiozis/kumaran (INRC): Study in '94, in 8 Canadian cities, in walls with wood-chip shea winter. Some condensation forms, but it will dry in following summer with no accumulation Listiburek: recommended paint as alternative to poly since '84, with rigid components as air - CMHC: Field test, Calgary, walls with 150mm wet cellulose, no poly and poly. Walls with a - Tsongas: 2 field test, Calgary, walls with in relationship between vapour retarder presence and study (1993) found correlation between air leakage and moisture problems.	A - Field observations  B - brick, air space, sheathing, mineral wool insulation in stud cavity, with and without vapour barrier, plaster board C - Sweden summer conditions with natural interior temp, no mention of RH D - Inward vapour diffusion caused high cavity RH (close to 100%) and condensation on the exterior side of the var sunshine; could be worse with cooling midoor air Recommends reducing inward drives with: ventilation, sheathing with some vapour resistance, remove interior vap when a water repellant impregnated brick was used with a 20mm air space and no interior vapour barrier He describes 2 conditions for poly removal: no vapour right layer on the outer side of the wall, and the vapour con	A - Lab testing B - Absorbent roofing materials: Cellulose-fiber-reinforced cement shingles (various ages), Concrete tiles, clay tiles, wooden shingles various underlay materials used C - New Zealand summer. Ext: 13 mm rain over 16 hrs followed by 4 hrs of 750W/m2 solar radiation. Int: 20C, 65%RH D - Shingles absorb a substantial amount of moisture when exposed to rain Moisture passes through saturated shingles only when exposed to solar radiation Vapour diffusion driving force across the shingles measured as high as 15,000 Pa The amount of vapour diffusion through the shingles is only reduced by 37-50% with: building paper underlayment, creating gaps between shingle sufface There may be rotting of wooden shingles when a poly underlayment is used without a gap between the shingles and the shething.	A - Field Study B - 124 energy efficient homes built after 1980, according to Model Conservation Standards (MCS). C - Nortwestern United States D - 124 homes studied in 1986, 28 of these homes with very wet walls studied in summer 1988, 16 of the 28 that still had we - MC > 20% found in framing and sheathing. High MC attributed to: ligh indoor RH, high outdoor RH and leaks due to poor construction. No statistical significance between moisture in walls and the interior vapour barriers such as polyethylene or foam sheathing.
1995	In 1994	1994	1994	1993	1990	1990
Federal Publications Inc.	Energy Design 1994 Update	Energy Design Update	Update	Building Research and Information	ASHRAE	Study for Bonnewille Power Administratio n Perpective
National Research Council of Canada	Cutter Information Corp.	Curter Information	Cutter Information	Kenneth Sandin	M.J. Cunningham, G.A. Tsongas, D. McQuade	G.A. Tsongas
28 National Building Code of Canada, Part National Research 9, Housing and Small Buildings Council of Canada	29 42 Houses, two seasons, no problems - with or without vapor retarders	30 Moisture Accumulation in Walls (Without Vapor Retarders (	31 Ordinary Paint as Replacement for Poly (Vapor Retarder	32 Moisture Conditions in Cavity Walls with Wooden Framework	33 Solar-Driven Moisture Transfer Through I	34 The Northwest Wall Moisture Study: A field Study of Excess Moisture in Walls and Moisture Problems and Damage in New Northwest Homes



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Material reviewed. Specific subject matter to this study not found.	A - Lab testing B - D.W. with values finishes D - Oil based paints/sealers and vapour retarding paints yielded similar results (12 to 46 metric perms) Latex paint with latex sealer yielded resutis from 145 to 255 metric perms (compares with: unpainted gypsum board - 2875 metric perms, 25mm of XPS - 70 metric perms, and 6 mil poly - 3 to 4 metric perms)	A - Lab testing  B - Tested plywood sheathing vs foil faced isocyanurate sheathing, with cellulose batts vs fiber glass batts (no interior vapour barrier)  C - Interior 20C @ 45%RH, exterior 5C at 90%RH.  D - 80% lower moisture content in insulation when foil faced foam sheathing used in lieu of plywood. Fiber glass insulation shower moisture gain than cellulose insulation.	A - Experience/ Literature Review D - Vapour barriers can be placed on the exterior/cold side of the insulation or eliminated in moderately cold climates without problems. No moisture problems have been noted in some walls constructed with low permeance sheathing and siding outboard of the insulation (Author doesn't note if interior vapour barriers were also used, amount of insulation outboard of exterior vapour barrier, and if siding is vented. Walls without vapour barrier have had no severe moisture problems as per Tsongas study of homes in Northwest US. (See Tsongas 1990) - No moisture problems have been noted in walls with sprayed cellulose or fibreglass insulation on exterior metal skins and no internal air/vapour barrier.	Literature Review  A - Lab testing (Marville Research Centre in Denver)  B - Cill Paint, pilvwood, 3.5" fibreglass bat between framing, drywall and latex paint (as vapour retarder)  C - Winter conditions: Int: 21° 50 6WH, Ext 6 to 4 <sup>C</sup> cycled daily, and -6C constant (both run for 62 days).  D - moisture accumulation in both tests was 0.7 lbs/1100sqt/day. With cycled temp: 97% of moisture accumulated in sheathing, With constant temp: 69% of moisture accumulated in sheathing, 31% in insulation.  - Moisture will accumulate in exterior sheathing in winter if only latex paint used as vapour retarder.	A - Field testing B - 110 mm Brick, Mineral Wool filled wood stud, PE foil Vapour barrier, Drywall C - Dutch climate, south facing, unheated D - Condensation formed on exterior side of foil in autumn and spring MC > 20% in wood framing for 3 months in autumn, and 2 months in spring (water ran out of wall onto floor in spring). Unheated case is in serious danger of fungus attack Less problems with moisture existed when heated. Max MC of 20% at wood framing only for short periods, and drying was faster.	Material reviewed. Paper not significant to our study.	A - Test hut assembled for testing  B - Hardboard wood siding, wood fiber board or aluminum faced EPS, 89mm insulated stud cavity. One assembly had poly between the siding and sheathing, one had an air cavity between the siding and sheathing, and two had jursailed.  C - Beaumont Texas, 20-36C and 60-80%RH on the exterior, and 20-23C and 50-60%RH on the interior.  D - Little difference observed with and without air space on cavity moisture level. Exterior vapour barrier or no exterior vapour barrier showed dry interior cavity. Condensation occured on the exterior side of the poly (when it was used on the interior). Condensation typically occured during the day with drying at night. Warm/humid climate: interior vapour retarder in installed as well.	Material reviewed and not significant to our study.	Material reviewed and not significant to our study.
1989	n 1989	n 1989	1989	1989	1987	1985	1985	1979	1976
Construction Technology Centre Atlantic Inc.	Energy Design 1989 Update	Energy Design 1 Update	Energy Design 1989 Update	Energy Design 1989 Update	Nordic Symposium	National Research Council Canada	ASHRAE/DOE 1985 /BTECC Buildings III	National Research Council	Canadian Building
Neil Hutcheon, Gustav Handegord	Curter Information Corp.	Cutter Information Corp.	Cutter Information Corp.	Curter Information Corp.	Nils Erik Anderson	R.L. Quirouette		J.K. Latta	J.K. Latta
Building Science For a Cold Climate	Latex and Oil Paints as Vapor Retarders Cutter Information Corp.	The Effect of Folied-faced Foam Sheathing on Wall Moisture	38 The Vapor Barrier Goes on the Outside	39 Vapor Retarder Performance in Walls	40 Summer Condensation in an Unheated Building	Building Practice Guide Note No. 54, The Difference Between a Vapour Barrier and an Air Barrier	Moisture Movement in Walls in a Warm A. TenWolde, H.T. Humid Climate  Mei  Mei	Walls, Windows and Roofs for the Canadian Climate - A Summary of Current Design Basis for Selection and	Vapour Barriers: What Are They? Are They Effective



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45	Moisture and Thermal Considerations in C.R. Crocker Basement Walls		Canadian Building Digests	1974	A - Experience D - If basement insulated on exterior, then interior of foundation wall may be simply painted or finished (above and below grade). D - If basement insulated on interior (from ceiling down to 500 mm below grade), vapour/moisture barrier should be installed directly on the foundation wall below grade. A vapour barrier should be installed on the interior of the insulation Interior insulation should also be placed tight to the wall to minimize intersittial air movement (minimize condensation) Interior finishes will become damp and deteriorate if no interior moisture barrier is installed below grade.
94	Condensation in Insulated Masonry Walls in the Summer	A.G. Wilson	CIB Symposium	1965	A - Field Measurements D - Summer condensation could occur in the insulation and on the vapour barrier of walls incorporating permeable insulation Recommended use of non-absorbent claddings or ventilation between cladding and inner components where absorptive cladding is used.
47	Vapour Diffusion and Condensation	J.K. Latta, R.K. Beach	Canadian Building Digests	1964	Material reviewed. Paper not significant to our study.
48	House Basements	C.R. Crocker	_	1961	Relevant material noted in summary of article on "Moisture and Thermal Considerations in Basement Walls" in 1974.
49	Vapour Barriers in Home Construction	G.O. Handegord	<u> </u>	1960	A - Experience D - Excessive condensation and deterioration is likely in wood frame walls without vapour barriers during the winter. The use of a vapour barrier reduced such moisture from entering the wall from the building interior Tast show that high permeance vapour barrier (that still meet code) will perform fine under severe conditions Repeatedly highlighted vapour barrier continuity importance; discontinuous barrier is useless due to air flow carrying moisture into wall.
20	Basement Insulation Systems	Nathan Yost, Joseph bldg sci corp.		2002	A - Literature Review and Field Observations.  B - Various Basements C - Various Parious Pario
12	Building Envelope Performance Monitoring	Brian Hubbs, Matthew Hircock			A - Field Review B - Vinyl and stucco cladding (Various retrofits and new construction) C - Vancouver B.C. D - No signs of condensation on poly from inward drive but data presented is without precipitation. Claims vapour drives do occur with hot days following several days of driving rain as plywood sheathing mositure content increased. Suggests less inward vapour drive with vinyl cladding vs stucco.
52	Vapor Control Strategy Favoring the Drying Potential of Building Enclosures	H.M. Kunzel	ASHRAE		Very similar to "Vapour control in cold and costal climates"
23	Owens Corning Basement Finishing System	obtained from Dr. Goldberg	University of Minnesota	2002	Similar to paper # 16
54	lcyene Insulation in basement applications	Dr. Goldberg	Univ of Minnesota	2004	A - Field Testing (Basement Walls with no w/p or dampproofing)  B - 300mm concrete block, poly/no poly, 89mm framing (25mm off block wall) filled with icynene, poly/no poly, drywall. Similar to Goldberg 2001.  C - Ext: Foundation Test Facility (Basemount, Minnesoria)  D - Icynene only provides stable annual westing and drying cycles with no condensate rundown or mould.  Full height poly between insulation and block caused condensation on poly interior in the winter and condensation on poly exterior in summer.  Condensate rundown noted. No visible mould growth.  Interior poly caused condensation on the wall side of the poly during the summer with unstable wetting/drying cycle. Condensate rundown. Visible mould growth on the Icynene surface and wood studs.



# Appendix A1 - Reference List/Summary

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A - Dismantling a test house after 4 heating seasons B - Vinyl cladding, housewing, OSB Sheating, instalation (batt, cellulose, blown-in-blanket system(BIBS), wood and steel stud framing, drywall. Assemblies with either: no poly, varietior poly only (between housewing and OSB), interior and exterior ( between housewing and OSB) poly. C - Ext.Northern Minnesota climate, north and south facing walls. Int: conditions not analyzed/published yet. Goldberg gave us data for a 160 day period starting Dec 22, 2003; 40%RH for first 70 days, 85% for the next 3d days, 100 kG or the next 30 days. Interior temp ranged from 20 to 22C during this period. Int: conditions not analyzed/published yet. Goldberg gave us data for a 160 day period starting Dec 22, 2003; 40%RH for first 70 days, 85% for the next 3d days, 100 kG or the next 30 days. Interior temp ranged from 20 to 22C during this period. Interior to 160%, at 50% for the next 30 days, 100 kG or the next 30 days, 100 kG or the next 30 days. Interior temp removed to be effective (not totally effective in every case as some minor mould was noted particularly on north every case as some minor mould was noted particularly on north walls (mould and OSB bowing).  Exterior poly with BIBS and wood studs: North side had wet OSB, mould throughout cavity, bowed OSB, interior poly yardings and wood studs: North side had some mould along bottom 300mm of avoir your south side.  No poly, BIBS and wood studs: north side had moild north side sould side had light mould on north or south side and bowed OSB bowing. South side had sight mould at bottom of cavity.  Interior poly/kraft, R-19 fibre glass and steel studs: North side had light mould on SB bowing. South side had sight mould at bottom of cavity.  Interior poly/kraft, R-19 fibre glass and steel studs: North side had light mould on SB bowing. South side bowing only.  Interior poly, BIBS, and steel stud: north side had some mould and OSB bowing. South side bowing only.  Interior poly, BIBS, and steel stud: north side had mould and OSB	A - Field Measurements D - Walls without a carefully applied air barrier may render vapour retarders ineffective. It has been reported that Intro of poly has significantly lowered the incidence of condensation in walls in cold climates. Testing from this program suggests that this has more to do with improved air tightness than with its very low vapour permeance. Specifying low perm vapour retarders (0.1 perm or 5 metric perms) requires specifying an extraordianry level of air tightness.	A- Hygrothermal modelling, with consideration taken for soil temperture and moisture  B- Modelled in Toronto, Canada internor maintained at 20C <sub>2</sub> Agr8RH in winter, 50%RH in spring and fall, and 60% RH in summer, exterior conditions taken from  Woww.wastherbase.com. Concrete RH was calculated for 70, 90, 100%  C- wall extends 2100mm below grade with 200mm portion above grade. Wall type 1 damp-proofing - 200mm concrete wall - 89mm wood stud with batt insulation - pohy - gypsum board - paint. Wall Type 2 damp-proofing - 200mm concrete wall - 89mm wood stud with batt insulation - with and without poly - gypsum board - gypsum board - paint. Well Type 2 damp-proofing - 200mm concrete wall - 89mm EXPS airspace - gypsum board - paint. BYPS is type 3, damproofing has vapour permeance of .004 ng/s.m.Pa.  D- Critera for failure if interstial RH is above 80% and 5C as there is a potential for mould growth. Wall type 1 RH within batt insulation will remain below 80% only if RH of concrete is 70% or less. Exterior temp of 80 or less results in inward vapour drive, 80 cxterior temp > 20C condensation will occur. System 2 with 19mm EXPS and no VB, exterior temp > 12C and < 40% interior RH system will fail, less than 4C exterior temp condensation will occur. System 2 shame EXPS and no VB, exterior temp less than 9C box system fails, below 4C Exterior temp condensation occurs. System 3 best performance regardless of interior RH and exterior temp with interistial RH approximatley 10-15% above interior RH reg
2001	8 6 6	
Minnesota	envelopes VII	Waterloo Univ 2002
Dr. Goldberg	TenWolde, Carll, Malinauskas	Jeongsik Jeong
Cloquet Residential Research Facility: Wall Section Dismanting	Air Pressure in Wood Frame Walls	Simplified hygrothermal Analysis for Building Enclosure Design
<u>ه</u> ۵	20	57



# Pg A-11 Appendix A1 - Reference List/Summary

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Lit review - Swinton and Karagiozis (1995) 2-D transient numerical study of hygrothermal performance of newly insulated basement walls in response to moisture accumulation at the bottom of interior insulation systems during the first summer after construction. Found that summer inner appoints is a likely contributing factor to the observed moisture problem.  Goldberg and Aloi (2001) developed basic conceptual models for moisture diffusion through poured concerted foundations. In winter moisture diffuses from moist soil to interior along most of the height of the wall. In winter above grade portions or slightly below diffuse from the interior to the exterior. Suggests a neutral plane were portions above diffuse in a different direction then portions below. A decrease in exterior humidity shifts the neutral plane down, and a decrease in interior humidity shifts the plane up. In summer conditions below and above grade tend to diffuse inwards.  A - Feild Testing	B - 8 wall types minimum of 8' wide sections on 8" poured concrete foundations with 1' above grade, rim joist and top of concrete wall was insulated with fibre glass batts. Wall type 1- 38mm of Polyisocyanutate with foil facing on both sides adhered with 25mmx100mm wood strapping and 12.5mm of dryw wood strapping nailed through insulation. Insulation was cut 150mm above floor slab. Wall type 2- 50mm of EPS fastened between the 25mm of the 4- Same as 3 except different insulation manufacturer. Wall type 6- 50mmx100mm stud wall with fibre glass insulation between concrete and stud wall. Wall type 6- 50mmx100mm wood studs with unfaced fibre glass batts, stud wall is maintained 25mm from concrete wall. Wall type 7- Fibre glass insulation was cut 150mm above floor slab. Wall type 8- Fibre glass insulation with perforated poly facing stapled between 50mmx100mm wood studs on 400mm centres. insulation was cut 150mm above floor slab.  C - Chicago	D- Neither system 1 or 2 resulted in moisture accumulation over a full annual cycle. Type 1 showed that drying through the insulation was not possible resulting in a high vapour pressure at the foundation wall during the first summer (author suggest that type 1 can only diffuse vertically behind the insulation, and type 2 horizontally through the insulation. Fibre glass insulation systems 3-6 showed similar moisture performance with interior air m is due to air flow and not vapour diffusion in types 3-6, suggests a convective loop in the 25mm air space between the studs and concerte adding in drying. Wall type 3 was air seale of condensation increased as a result. Type 7 yielded similar results to Type 1 with vertical diffusion as the only option to dry. Type 8 yielded similar results at type 2 with perforations allowing for horizontal diffusion. Type 1, 2, 7 or 8 did not result in any moisture accumulation over a full annual cycle.
		, , , , , , , , , , , , , , , , , , ,
Robb Build		
Marc Zuluaga, I Aldrich, Dianne Griffiths		
it Interior		
Field Performance of Different Interior Marc Zuluaga, Robb Buildings 9 Basement Insulation Systems Griffiths Griffiths		

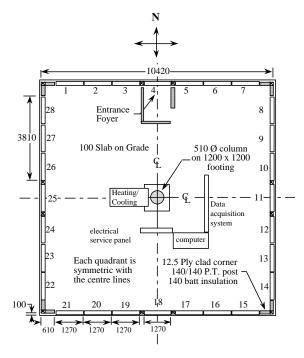


# APPENDIX B1 - ABOVE GRADE FIELD TESTING PHOTOGRAPHS AND MONITORING DATA



### Above Grade Field Testing Photographs and Monitoring Data

### 1. **PHOTOGRAPHS**



The Beghut contains 28 wall panels. One panel is reserved for the entrance door (#4)

All panels are nominally 1270 wide and 2465 high.

Note: All dimensions in mm

Figure 1.1: Plan view of BEGHut, showing orientation and removal panel locations



Figure 1.2: Opening details for removable panels



Figure 1.3: South Elevation of BEGHut. Exterior view, SBPO installed. Walls from left to right are Poly, No Poly and XPS





Figure 1.4: South Elevation of BEGHut. Exterior view, bricks being laid.



Figure 1.5: South Walls of BEGHut. Interior view, gypsum board installed.



### 2.0 MONITORING DATA

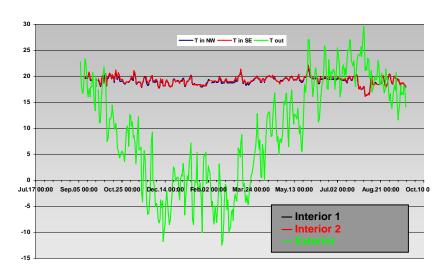
A summary of the six walls is shown below, with panel identifier number. Given the matching walls on the north and south sides of the test hut, several plots are comparisons of the same sensor in all six walls. The numbering system for the walls and matching color codes are as follows:

N1	1" XPS and 2x4 studs, R-12 insulation, North	Black
N2	OSB and 2x6 studs, R-19 insulation, no poly, North	Red
N3	OSB and 2x6 studs, R-19 insulation, polyethylene,	Green
	North	Green
<b>S</b> 1	1" XPS and 2x4 studs, R-12 insulation, South	Blue
<b>S</b> 3	OSB and 2x6 studs, R-19 insulation, polyethylene, South	Pink

Of course, in plots that do not compare all six walls, these color codes do not apply.



### **Interior and Exterior Boundary Conditions**



Interior temperatures (T in) at the northwest and southeast corners, and exterior temperature (T out).

Figure 2.1: Outdoor and indoor temperatures

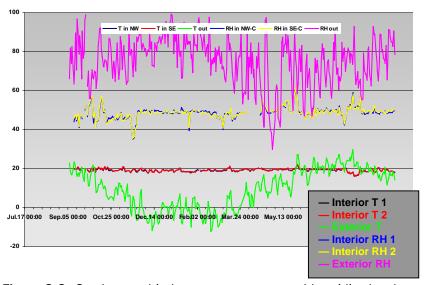
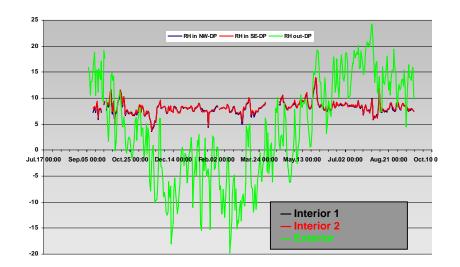


Figure 2.2: Outdoor and indoor temperatures and humidity levels

This shows the previous temperatures, along with the corresponding relative humidity levels.

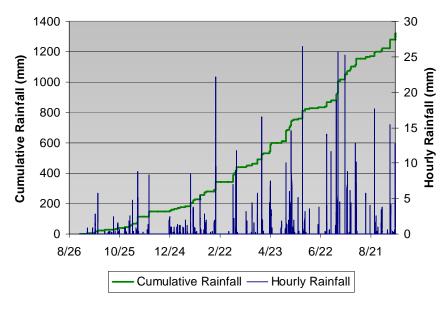
Interior humidity levels varied in a band mostly between 45-55%, except for controller failures in mid-November and late May.





Comparison of interior and exterior dewpoint temperatures; interior dewpoint remains relatively constant due to space conditioning system (20° C/50% RH); outdoor dewpoint drops in a manner similar to outdoor dry bulb temperature.

Figure 2.3: Interior and Exterior Dewpoint Temperatures



Rainfall for the monitoring period, shown both as hourly data (mm rain per hour), and cumulative rainfall (total mm).

Figure 2.4: Rainfall and cumulative rainfall at BEGHut



### **Brick Space Cavity Measurements**

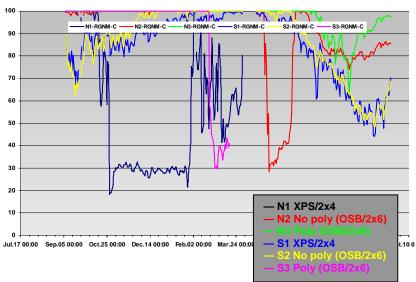


Figure 2.5: Brick Cavity Humidity Levels

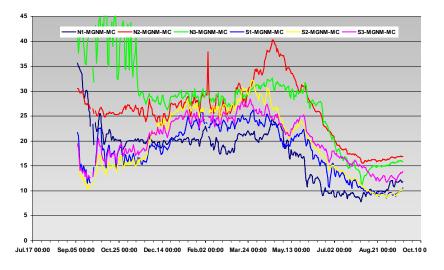


Figure 2.6: Brick Cavity Moisture Wafer MCs

Relative humidity levels in the brick drainage space cavity.

Out of the six sensors, two are now non responsive. N1, N2, and S3 show excursions from expected behavior (i.e., drop to 30% RH); this seems to precede sensor failure (N1, S3).

As a general pattern, it appears that the cavity is saturated through the winter, then starts to dry out in the spring/summer, as seen in the four reliable channels.

The drainage space RH sensors are backed up by moisture wafer sensors in the space; they provide greater resolution of the cavity conditions. They show the same spring/summer drying trend as seen in RH measurements, and have the same relative order as the RH sensors. The wafers are dropping into the 10-17% MC range (55-85% RH range, assuming a typical sorption isotherm).



### **Relative Humidity Stud Bay Measurements**

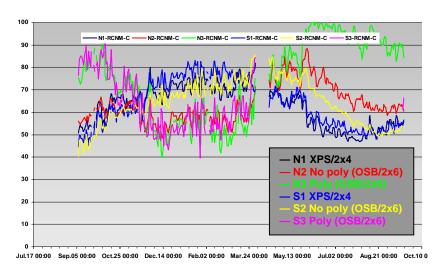


Figure 2.7: Stud bay mid-batt mid-height humidity levels

Note: the relative humidity sensor in the south poly wall (S3-RCNM)
failed in late March and was replaced in September.

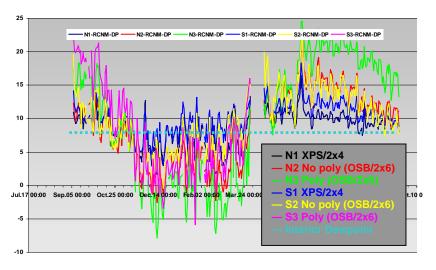


Figure 2.8: Stud bay mid-batt mid-height dewpoints, with interior DP

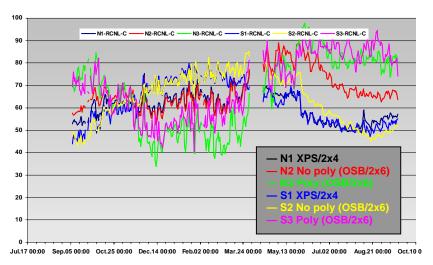
The poly walls have elevated humidity in the summers, and the lowest in the winter. The walls with paint as interior vapour control (XPS and no poly) have the lowest RHs in summer, which then rise to the 70-80% range in winter.

In summer 2006, the poly walls have RHs near 100% (also see Figure 2.9). The XPS walls are both dryer than the no poly walls; this is likely due to the lower vapour permeance of the XPS sheathing, compared to OSB and housewrap.

The dewpoint temperature at this location (mid insulation/mid height) was calculated from the relative humidity and temperature measurements. All six walls are plotted, plus a rough indication of interior dewpoint.

Similar temperature regimes were experienced in these walls, so the relative order is similar to Figure 2.7.

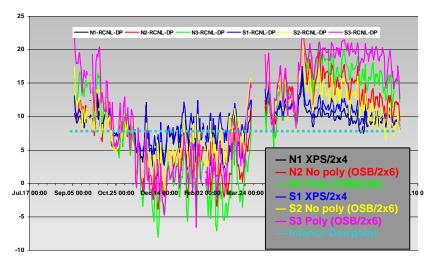




Relative humidity levels in the stud bay cavity, midinsulation and lower height (~16" off bottom plate).

Similar patterns to Figure 2.7 are seen: polyethylene wall RH levels are highest in the summer, and are lowest in the winter. The polyethylene summer RHs are lower than those seen in the mid-height location.

Figure 2.9: Stud bay mid-batt lower height humidity levels



**Figure 2.10:**Stud bay mid-batt lower-height dewpoints, with interior DP

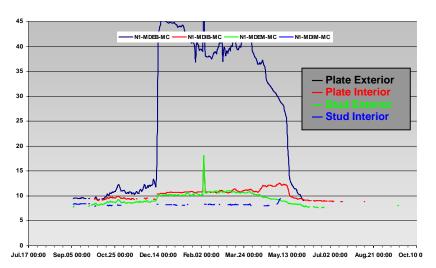
Dewpoint temperatures for at the lower stud bay location; similar patterns to Figure 2.8 are seen.

In the winter, the XPS walls have the highest dewpoint temperatures.

During the summer, in the XPS and poly walls, the dewpoint of the south wall of a pair is higher than the corresponding north wall. This makes sense, given greater solar driven moisture. However, in the no poly walls, the north wall has the higher dewpoint. This could be due to greater stored moisture from the winter in the north facing wall (see Figure 2.17).



### Moisture Content Measurements: Sill plate/stud/sheathing



Wall N1 (XPS) moisture content measurements of the bottom plate, interior and exterior (MDIB & MDEB), and wall stud at mid height, interior & exterior (MDIM & MDEM).

Figure 2.11: Wall N1 (XPS) Stud and plate moisture contents

In December, there is a large spike in outboard sill plate (MDEB) moisture content; based on disassembly of the wall, it appears there was a substantial condensation event, followed by rundown to the sill plate.

The moisture content spike in early February (seen here and in several plots below) appears to be a measurement anomaly. First, moisture content is identical before and after this short spike. Second, this spike occurs simultaneously across several channels. Third, an examination of hourly data shows a change in data consistency (fraction of successful measurements) coincident with this spike.



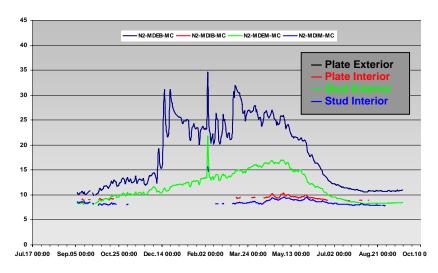


Figure 2.12: Wall N2 (No poly) Stud and plate moisture contents

Wall N2 (no poly) moisture content measurements of the bottom plate, interior and exterior (MDIB & MDEB), and wall stud at mid height, interior & exterior (MDIM & MDEM).

Both outboard framing measurements (plate and stud) have elevated moisture content through the winter, which dries down to 8-12% by the summer. Peak moisture contents are mostly in the 25-30% range.



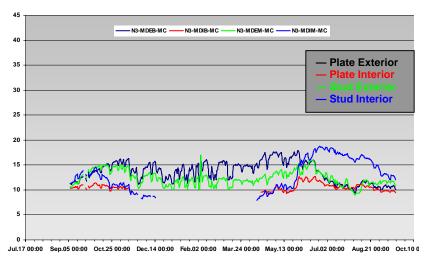
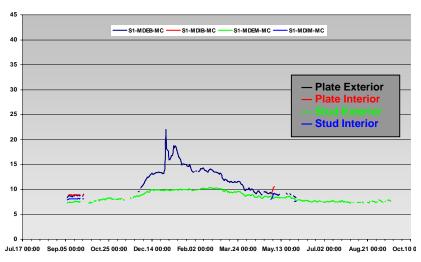


Figure 2.13: Wall N3 (Poly) Stud and plate moisture contents

Wall N3 (poly) moisture content measurements of the bottom plate, interior and exterior (MDIB & MDEB), and wall stud at mid height, interior & exterior (MDIM & MDEM).

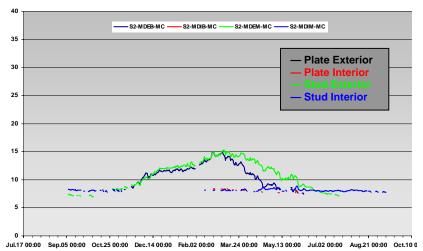
The framing moisture contents in the poly wall show no noticeable rise over the winter, indicating that the vapour retarder is functioning as intended. However, in early summer, the interior side stud moisture content appears to be rising, but still within safe limits (under 20%).



Wall S1 (XPS) shows a rise in the two sill plate moisture content measurements, with spikes on the outboard side. However, it is nowhere as large as the one seen on the north side. This could be due to higher sheathing temperatures (i.e., warming from solar exposure).

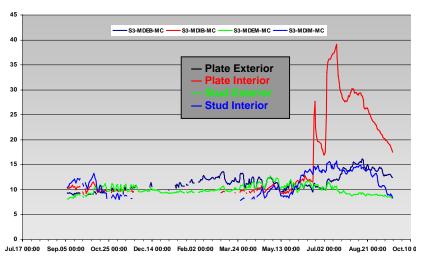
Figure 2.14: Wall S1 (XPS) Stud and plate moisture contents





Wall S2 (no poly) shows a slow rise in the sill plate and stud exterior moisture contents, with no sudden spikes, as seen in the XPS wall. Similar to the north side, it dries to original moisture content levels by early summer.

Figure 2.15: Wall S2 (No poly) Stud and plate moisture contents



Wall S3 (poly) shows the driest of the moisture content measurements of the three walls in winter. However, in the summer, there is a spike in the plate interior moisture content, up to dangerous levels (30-40% MC). This is likely condensation on the vapour barrier, followed by rundown to the plate. The stud shows a smaller rise in moisture content.

Figure 2.16: Wall S3 (Poly) Stud and plate moisture contents



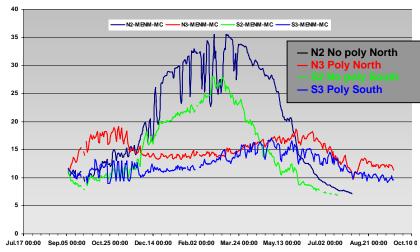


Figure 2.17: Sheathing moisture content (Walls 2 & 3), north & south

Moisture content readings of the OSB sheathing (Walls N2, N3, S2, S3). In the winter, the no poly walls show substantial rises in MC ( $\sim 35\%$  and ~28%, north and south, respectively), while the poly walls remain in the 10-15% range. However, by early summer, the no poly walls have dried to very safe levels. The poly walls show some rise in moisture content, relative to the winter, but still in the safe range (under 20%).



### MC Measurements: MC wafers at vapour retarder

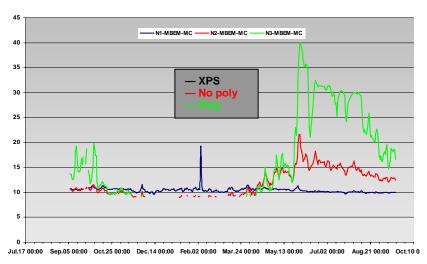


Figure 3: North Walls Moisture Wafer MCs at Vapour Retarder

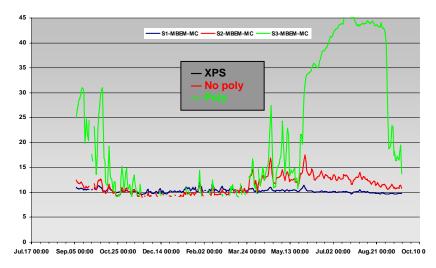
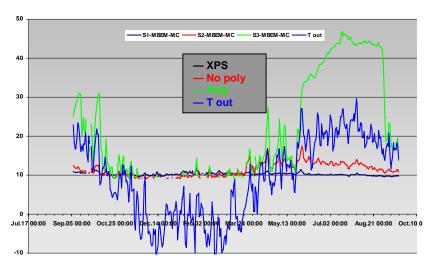


Figure 4: South Walls Moisture Wafer MCs at Vapour Retarder

Moisture wafer sensors at the exterior side of the vapour retarder layer (polyethylene or drywall), at mid-height; the measurements for the north walls are shown here. All wafers have low MCs through the winter, as would be expected given the thermal gradient. Moving into the summer, the polyethylene wall shows spikes in moisture content to the 35-40% range. In comparison, the no poly wall shows a slight rise to safe levels (15-22%), and the XPS wall shows no rise at all.

The south walls a similar trend, but the polyethylene wall is showing an even stronger rise in moisture content, peaking at 45%. The high moisture content would suggest the presence of condensation on the polyethylene, causing liquid water wetting of the wafer, as opposed to only hygroscopic adsorption at high humidity levels.





Outdoor temperature (T Out) was added to the previous plot; the sharp rise in moisture content coincides with the rise in temperature above interior setpoint (20° C). The drop in MC at the end of the summer coincides with the cooler weather, and a reversal of the thermal gradient.

Figure 5: South Walls Moisture Wafer MCs at Vapour Retarder w. Exterior T



# APPENDIX B2 – BASEMENT FIELD TESTING PHOTOGRAPHS AND MONITORING DATA



### 1.0 PHOTOGRAPHS



Figure 1.1: Basement walls under construction. Concrete foundation wall visible. Blue line indicates exterior grade level.



Figure 1.2: Basement walls under construction. Prior to gypsum board installation. From Left to right, XPS, Roll Batt, Stud w/ Poly, Stud w/o Poly.



## Appendix B2 Basement Field Testing Photographs and Monitoring Data



Figure 1.3: Basement walls Completed. Painted gypsum board in place.



Figure 1.4: Exterior view of basement test walls.



### Basement Field Testing Photographs and Monitoring Data

### MONITORING DATA 2.0

The observations of the wall conditions were compared to the monitored data, in order to correlate degrees of damage with measurements.

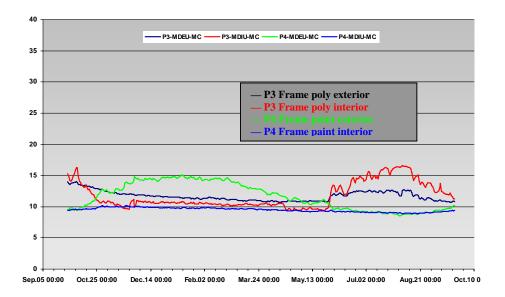
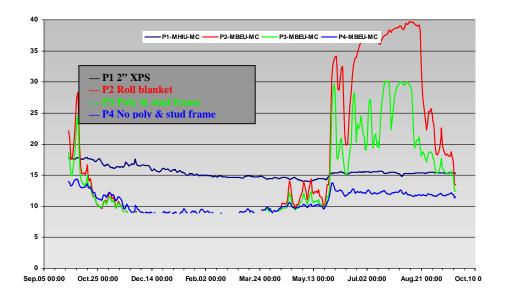


Figure 2.1: Upper framing moisture contents, exterior and interior sides

The framing in upper portions both walls showed little damage; the framing in the polyethylene wall on the inboard side shows some brown spotted marking that is likely microbial growth. The maximum moisture content seen at that location was approximately 17%. Although this is the highest moisture content in the plot above, it is considered well within the safe range. It is quite possible that the wetted area did not overlap the pin location to adequately reflect the degree of wetting.

The sill plate framing in both walls appeared completely intact in both walls; this matches the monitored data of moisture contents of less than 14% for the entire logging period.





**Figure 2.2:** Upper moisture content wafers at concrete-insulation interface (XPS wall) or at insulation-vapour barrier/drywall interface (remainder)

The upper MC wafers in the four walls are compared in the plot above; field observations showed that the "no poly" wafer was intact, and the "poly" and roll blanket walls had mold growth. This clearly matches the data plotted above: the two wafers with mold growth had moisture content peaks at 30 to 40%, while the intact wafers had moisture contents in the 10-15% range.

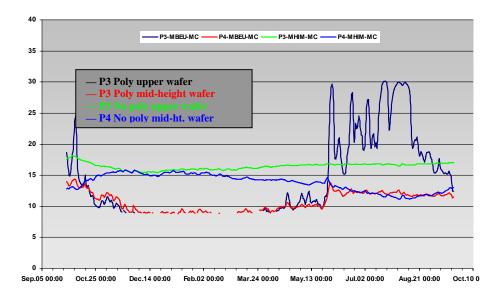


Figure 2.3: Upper and mid-height moisture content wafers in framed walls (P3 poly and P4 no poly)



## Appendix B2 Basement Field Testing Photographs and Monitoring Data

Finally, we compared the upper moisture content wafers with the mid-height wafers that were between the concrete and the batt insulation. The mid-height wafers showed some minimal exterior-side growth that might have been mold. However, those wafers do not show high moisture contents, especially when compared with the upper poly wafer. This could be due to localized wetting/moisture adsorption at the exterior face only, as shown by the growth on only one face.



# APPENDIX B3 - ABOVE GRADE FIELD TESTING DISASSEMBLY REPORT



This appendix covers the inspection and maintenance work on the BEGHut polyethylene/no polyethylene walls after running them for a full year. It included the following items:

- Disassembly and examination of the test walls. The framing and sheathing were examined for evidence of wintertime condensation and rundown, and/or microbial growth. A handheld Delmhorst was used to examine the spatial variation in moisture content measurements in the wall system.
- The XPS wall currently has no measurement of the sheathing moisture content.
   An MC wafer was installed as a surrogate measurement at the insulation-sheathing interface.
- The south poly RH sensor has failed, and was replaced.
- Samples of painted gypsum wallboard were taken for permeability testing.

The disassembly work was done on September  $18^{th}$ , from roughly 3 PM to 6 PM. Weather at that time was  $15\text{-}17^{\circ}$  C at 96% RH; interior conditions were  $18.5^{\circ}$  C at 50% RH.

The key findings included:

- South XPS wall: little to no damage or evidence of moisture damage
- South no poly wall: little to no damage or evidence of moisture damage
- South poly wall: mold and high framing moisture contents on inboard side of wall; some condensation visible.
- North XPS wall: mold on outboard side, showing evidence of condensation rundown. Moisture content measurements currently low.
- North paint wall: mold covering inside of sheathing; OSB thickness swelling/flake raising evident. Little damage to framing. Moisture content measurements currently low.
- North poly wall: mold seen on moisture content wafer, but framing and sheathing both dry and undamaged.

All of the observed damage was surface mold growth; there was no evidence of wood decay.

The damage found in these walls is a strong function of the interior conditions. The constant interior setpoint of 20° C and 50% RH is an exceptionally high wintertime humidity loading, and a lower than average summertime temperature.



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#### South Side Walls

#### South 1 XPS and 2x4 Frame

Findings for this wall:

- No mold damage or evidence was seen on the back (exterior) face of the drywall
- No evidence of moisture accumulation or damage was seen in the fiberglass batts
- No evidence of moisture damage was seen on the back of the sheathing



Left-hand stud bay bottom plate: possible mold





Center stud bay bottom plate

Some black "fuzzy" marking was visible on the outboard side of the sill plate in one stud bay (left hand side); it might have been mold, or construction dirt. In comparison, the center and right hand bays showed no such black marking.

Framing moisture content measurements were consistently in the 8-10% range throughout the wall.



#### South 2 2x6 Frame Without Polyethylene

Findings for this wall:

- No mold damage or evidence was seen on the back (exterior) face of the drywall
- No evidence of moisture accumulation or damage was seen in the fiberglass batts



Mid-height monitoring area; no discernable damage to sheathing or framing



Close-up of the moisture content pins in the sheathing, showing surface corrosion at one of the pins.



Center stud bay bottom plate; no discernable damage or water staining from rundown.

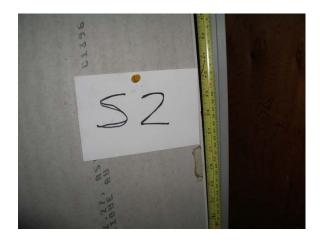


Stud on RH of center bay; no discernable damage to sheathing or framing

Although there was visible corrosion on the moisture content pin in the sheathing, and monitored data showed relatively high moisture content at the sheathing (see section "Correlation Between Monitored Data and Observed Damage"), there was no clear sign of mold growth on the back of the sheathing. The black marks visible in the photos are parts of the factory grade stamping. The framing was also in good condition, with nothing resembling moisture damage or mold growth.

Framing and sheathing moisture content measurements were consistently in the 10-11% range throughout the wall.







A pair of stains on the back of the drywall caused questions at first; they were both located approximately 36" off of the bottom of the wall. Measurement s showed that they matched up exactly with the cedar shims used to hold the walls in place. These stains are likely extractives from the end grain of the shim spacers.

#### South 3 2x6 Frame With Polyethylene

Findings for this wall:

- No mold damage or evidence was seen on the back (exterior) face of the drywall
- No clear evidence of moisture accumulation or damage was seen in the fiberglass batts
- Significant evidence of condensation and very high moisture contents on the inboard side of the wood framing



The moisture content wafer on the outboard side of the polyethylene shows mold growth; Delmhorst measurements of the wafer were at 19%.



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.





Moisture content measurements taken through the polyethylene ranged from "off scale high" (bottom plate) to 25% (1" up from bottom of stud) to 15% (corner of bottom plate): see complete list below.



A gradient of moisture content measurements were taken across the width of the sill plates; measurements shown below.

Delmhorst measurements of the framing taken of inboard face of framing through the polyethylene as follows:

Sill plate: consistently off scale high

• Sill plate at corner of wall: 16% (perhaps drainage at corners)

Stud 1" up from bottom of wall: 26%

• Stud mid-height: 16-18%

Stud high: 23%Top plate: 15%

Delmhorst measurements taken across the width of the sill plate as follows:

Outboard side: 16%

Mid-far side (outboard of centerline): 20%

• Mid-near side (inboard of centerline): 25%

Inboard side: Off scale high

Sheathing moisture contents were in the 8-10% range; no mold growth of evidence of moisture damage was seen on the back of the OSB.



#### **North Side Walls**

#### North 1 XPS and 2x4 Frame

Findings for this wall:

- Some water damage was seen on the back of the drywall, at the bottom plate
- Some evidence of moisture accumulation or damage in the fiberglass batts

 Mold and significant evidence of condensation on the outboard side of the wood framing



The back of the drywall showed some water staining, matching the locations where the studs butt into the sill plate.



Notable mold damage seen at the outboard side of the sill plate, consistently across the width of the wall.



Greatest mold growth at center bay sill plate. Black mold evident on sheathing.



Mold at the right-hand bay sill plate; water wicked under stud at the joint between stud and sill plate. Fiberglass was adhered to sill plate by the mold growth.

In addition, "wispy" blackish mold was evident on the back of the XPS sheathing, concentrated the worst at the bottom of the wall. The sill plate mold appeared slightly different in morphology than the sill plate mold in the south poly wall. This mold showed a more fine filamentary growth, compared to the "black dotting" seen in the south poly wall.

Surprisingly, Delmhorst readings of the wall showed consistent 9-10% MC in all of the framing, even at the locations showing clear mold growth (sill plate outboard). This is consistent with monitored data at that location, which shows a peak moisture content of 45% in December, and drying by May to 9% MC.

#### North 2 2x6 Frame Without Polyethylene

Findings for this wall:

- No water damage was seen on the back of the drywall
- Some evidence of moisture accumulation or damage in the fiberglass batts

Mold and significant evidence of condensation on the outboard side of the wood
 framing and an abathing.



The sheathing showed well-distributed mold; the moisture content pin showed corrosion sufficiently advanced to warrant replacement.



Mold on sheathing, and evidence of water rundown on the outboard side of sill plate. However, framing showed only traces of visible mold, only on sill plate.



Distribution of mold on the back of the sheathing; growth appeared to be distributed evenly across height and width of the panel.



Close up of sheathing showing mold growth, as well as fiberglass adhered to OSB sheathing. There was noticeable grain/flake raising or thickness swelling of the OSB; a straightedge held against the sheathing reveals daylight

#### Delmhorst measurements as follows:

Inner stud mid-height: 13%Outer stud mid-height: 12%Sheathing mid-height: 14%

Bottom plate outboard side: 12-14%

Bottom plate inboard side: 12%

Top plate inboard & outboard sides: 12%



#### North 3 2x6 Frame With Polyethylene

Findings for this wall:

- No water damage was seen on the back of the drywall
- Minimal evidence of moisture accumulation or damage in the fiberglass batts
- Sheathing and framing show no mold or evidence of moisture damage



The moisture content wafer at the polyethylene showed mold growth.



Sill plate showed no evidence of condensation rundown or mold growth.



Stud showed no evidence of mold growth; sheathing showed no moisture damage.

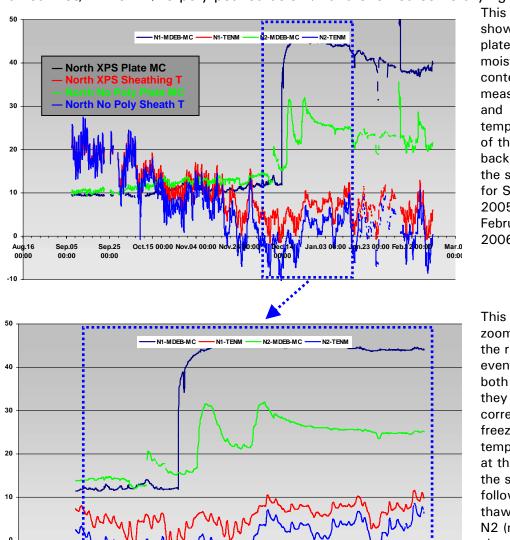
It appears that the Delmhorst measurements were not recorded the inspection; the best recollection is that moisture contents were generally in the low and safe range (e.g., 12-14% MC).



#### Correlation Between Monitored Data and Observed Damage

#### Condensation and Rundown Events in Walls N1 (XPS) and N2 (no poly)

The north side XPS and no poly walls both had evidence of condensation on the interior side of the sheathing followed by rundown. However, the observed damage was substantially different: the XPS wall showed mold growth all along the bottom plate, while the no poly wall only showed some staining. This is correlated by the response of the outboard sill plate moisture content measurements: N1/XPS peaked at 45% and remained wet, while N2/no poly peaked at 32% and showed some drying.



This plot shows sill plate outboard moisture content measurements and temperature of the backside of the sheathing for September 2005 through February 2006.

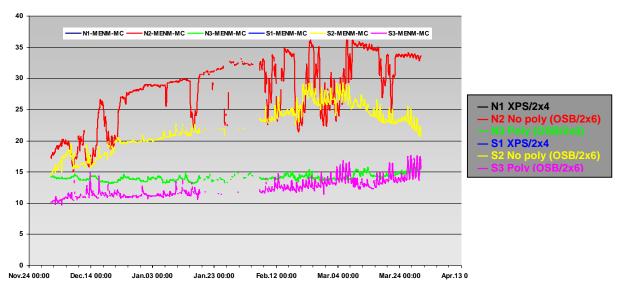
This plot zooms in on the rundown events: in both cases, they appear to correlate with freezing temperatures at the back of the sheathing, followed by a thaw. In fact, N2 (no poly) shows two spikes, each of which matches a freeze-thaw event.

The mold damage in the XPS sill plate is probably due to the lack of storage of the sheathing. In comparison, the "no poly" wall showed mold and thickness swelling on the back of the OSB sheathing, which stored the accumulated condensation by absorption and/or surface tension, resulting in less rundown or sill plate mold.

00:00

#### **Sheathing Moisture Content Winter Response**

The north side no poly wall had consistent mold growth on the OSB, while the identical south wall had little if any evidence of growth. Both of the polyethylene walls showed completely intact OSB sheathing. The moisture content measurements of those four walls are compared: it shows the north side no poly wall peaked around 37%, while the south side peaked only around 28%. In comparison, the poly walls stayed below 18% MC through the winter.

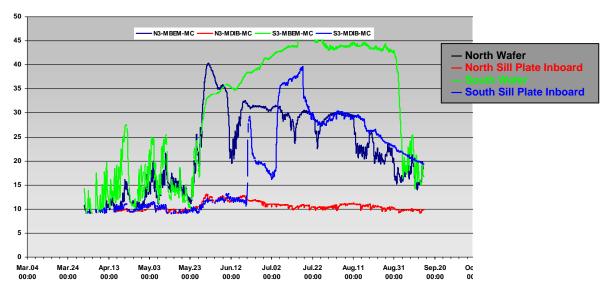


Note that the peak uncorrected moisture content of the south no poly OSB was around 28%: this is just at the boundary of condensation (100% RH), assuming a typical sorption isotherm. In comparison, the moisture content of the north side sheathing (37% maximum) suggests substantial condensation. This is in line with Susan Doll's work (2002), which demonstrated that fast mold growth occurs in the presence of liquid water, while it is much slower at non-condensing high humidity levels.



#### **Polyethylene Wall Moisture Wafers**

It was interesting to note that in the polyethylene walls, both wafers showed mold, while the framing was moldy only on the south-side wall, on the inboard face. The plot below includes moisture content wafer and inboard sill plate measurements for both walls. The plot shows data for April through September.



Results are consistent with observed behavior: the north framing remains dry throughout this period, but the north wafer shows wetting followed by slow drying over the summer. In comparison, on the south side, the wafer and sill plate both show substantial rises in moisture content. These results suggest that the wafer accurately reflects humidity conditions and condensation risk at an interface, but they do not necessarily indicate moisture damage suffered by the wood frame members at similar locations. This is likely a function of storage and thermal mass, as well as rundown of condensation.

For instance, although the stud-to-polyethylene interface may be at the same dewpoint as the fiberglass-polyethylene interface, the wood stud can store moisture under condensing conditions. This is shown by the slight rise in framing moisture content coincident with the sharp rise in wafer MC. Apparently, on the north side, condensation did not exceed the safe storage limits of the framing.

Furthermore, rundown of condensation at the polyethylene will tend to concentrate moisture at a wafer, while storage at a stud would prevent the rundown accumulation phenomenon. The difference in results show that the condensation was stored on the polyethylene (by surface tension) and re-released, as discussed in the DIN 4108.3 Standard:



The condensation water that is created during the dew period must be able to escape into the surrounding air again during the evaporation period. ...

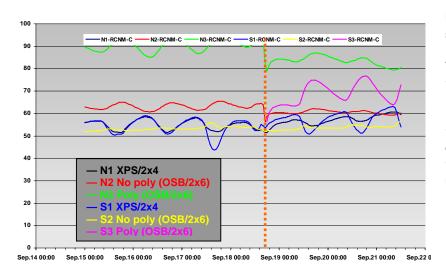
In order to prevent water running down or dripping condensation arising on contact surfaces of layers, that cannot absorb water, the amount of condensation water must not exceed 0.5 kg/m² (e.g. contact surfaces of fibre insulation, or air layers on the one hand with damp-proof or concrete surfaces on the other).

Finally, under summer conditions, the stud would be slightly warmer than mid-stud bay, due to thermal bridging, further reducing condensation risk.



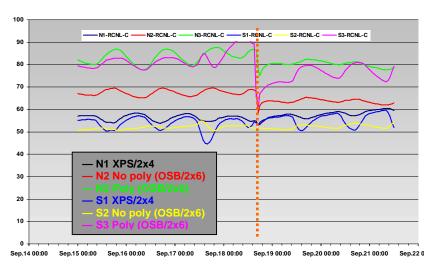
#### **Continuity of Data**

One concern with this intrusive inspection of the wall cavities was that it would disturb the experiment, allowing substantial interior air into the stud bay cavities, causing drying in the wetter walls. Various channels were graphed before and after the inspection, to judge the magnitude of the disturbance.



## Relative humidity sensors, mid-height

The polyethylene wall shows a drop in RH of approximately 10%. The no poly walls show a smaller drop, and the XPS walls appear to be mostly undisturbed.



## Relative humidity sensors, low height

The lower height sensors follow similar behavior patterns as the midheight sensors.

Moisture content measurements appeared to be entirely undisturbed by this inspection; this is a logical result, given the greater storage of wood compared to air.



#### **Summary of Moisture Content Measurements**

The table below compares the typical readings measured with the handheld Delmhorst meter with the concurrent readings taken by the datalogger system, at various monitoring locations. Moisture contents noted with a dash are showing resistance too high to read (i.e., dry wood).

Wall	N1 XPS	N2 No poly	N3 Poly	S1 XPS	S2 No poly	S3 Poly
Delmhorst meter measurements	9-10% (1)	12-14%	(2)	8-10%	10-11%	16% to off-scale high (3)
Logger sheathing (MENM)	n/a	-	11%	n/a	-	9.4%
Logger plate interior (MDIB)	-	-	9.5%	-	-	18%
Logger plate exterior (MDEB)	-	11%	10%	-	-	13%
Logger stud interior (MDIM)	-	-	12%	-	-	8.4%
Logger stud Exterior (MDEM)	-	8.4%	10.9%	-	-	8.2%

<sup>(1)</sup> Even at areas that showed obvious mold growth, the moisture content was still in the 9-10% range



<sup>(2)</sup> It appears that Delmhorst measurements were not recorded during the inspection; the best recollection is that moisture contents were generally in the low and safe range (e.g., 12-14% MC).

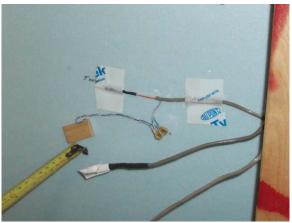
<sup>(3)</sup> See details in corresponding section "South 3 2x6 Frame With Polyethylene"

#### Sensor Replacement and Installation

#### Moisture Wafers in XPS Walls

Unlike the poly and no poly walls, the XPS wall does not have a sheathing moisture content measurement. Since there is a channel open for this, a moisture content wafer (similar to those placed at the vapour barrier or insulation/drywall interface) was installed in both XPS walls.



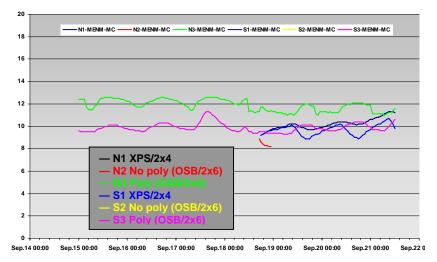


Wafer installation, south XPS wall

Close-up of wafer installation

Note that this wafer will provide analogous but not directly comparable information to sheathing moisture content. This is due to both the difference in resistance-moisture content response of the sheathing OSB and the wafer material, as well as hygric mass effects/rundown issues, as seen in "Polyethylene Wall Moisture Wafers."

Data is being returned from these sensors, as shown in the graph below.





#### **RH Sensor in South Poly Wall**



The relative humidity sensor in the south poly wall at mid-height (S3-RCNM) failed at the beginning of April, 2005. A replacement sensor was spliced in during the wall inspection.

A graph showing resumption of data collection is in the section "Continuity of Data"



#### **Drywall Permeability Samples**

For permeability testing of the drywall, 6"x6" samples were removed from a guard bay in each wall (one sample per wall). They were then repaired with blowout patches and mudded; latex primer and paint will be applied, to render it the same permeance as the remainder of the wall.



6"x6" drywall samples from north side



Sample location on south walls (north similar)



Blowout patch, pre-installation



Blowout patch, installed



## **APPENDIX B4 – BASEMENT FIELD TESTING DISASSEMBLY REPORT**



This Appendix covers the inspection and maintenance work on the basement polyethylene/no polyethylene walls, after a full year of service. Note that this field visit was not an exhaustive inspection and disassembly of all walls: the priority was sensor repair and wall inspection emphasizing the stud frame walls.

This visit was conducted on September 22, 2006, between 9 AM and 11:30 AM. Indoor conditions were 19° C and 59% RH; exterior conditions were 12-14° C and 73-82% RH (temperature rising and humidity dropping over the course of observations).

The completed tasks included the following:

- Failed relative humidity sensor in polyethylene wall, mid-height, concrete side replaced
- Spatial distribution of framing moisture contents were measured using a handheld Delmhorst meter
- The condition of the stud frames was visually inspected
- The vertical temperature gradient at the concrete to insulation interface was measured at the two stud frame walls.
- The stud frame to concrete air seal was inspected for durability

In contrast with the above-grade walls, very little damage or evidence of moisture accumulation was seen in the framed assemblies.



#### Poly Wall Disassembly and Inspection

The initial inspection after removing the drywall showed:

- No moisture damage on the drywall
- No evidence of moisture damage to the fiberglass insulation
- No visible condensation on the polyethylene vapour barrier



The only notable observation during initial opening was the mold growth on the upper moisture content wafer, located at the grade/below grade intersection, on the interior side.



Upper moisture content wafer



Close up; some mold growth was seen on both sides



After removing the polyethylene, a small amount of brown spotted staining was found on the upper, above-grade portions of the studs, on the inboard side. This staining or growth was superficial/surface in nature.



Brown staining at inboard side of upper portion of left-hand test bay stud

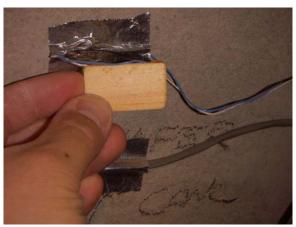


Brown staining at inboard side of upper portion of right-hand test bay stud

The mid-height wafer showed no mold growth or moisture damage on the inboard face, but a slight amount of brown spotted staining on the exterior face.



Interior face of mid-height wafer



Exterior face of mid-height wafer



The quality of the air seal between the stud frame and concrete was inspected; it appears to be completely intact on all sides.



Air seal at top of test stud bay



Air seal at bottom of test stud bay



Air seal at top of left-hand guard bay



Air seal at top of right-hand guard bay

Handheld Delmhorst moisture content measurements are addressed for both walls together in the section "Moisture Content Measurements."



#### No Poly Wall Disassembly and Inspection

The initial inspection after removing the drywall showed:

- No moisture damage on the drywall
- No evidence of moisture damage to the fiberglass insulation



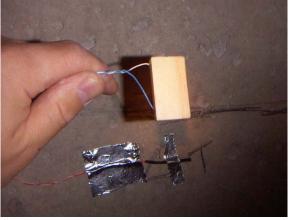
No damage evident on initial wall opening



Exterior side of gypsum drywall; no damage or evidence of moisture accumulation. Circles visible in image are dust/flash photographic artifacts.



Close-up of upper portion of the exterior face of gypsum drywall; no moisture damage seen.



No evidence of mold growth was seen on either face of the upper wafer sensor





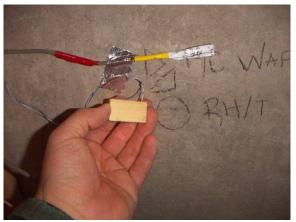
The upper portions of the stud were examined for mold or moisture accumulation evidence; none was seen (left hand test bay stud)



Right hand test bay stud; no moisture evidence seen. The remainder of the frame also showed no evidence of moisture damage.



The middle-height concrete-side moisture wafer showed no mold evidence on the interior side.



There was a slight amount of brown spotted staining on the exterior face of the mid-height moisture wafer.

The air seal on the perimeter of the frame was inspected; as per the polyethylene wall, it was intact and continuous.



#### **Moisture Content Measurements**

A handheld Delmhorst meter was used to examine the spatial variation of the moisture content measurements of the wood frames; results are shown in the table below.



Delmhorst moisture meter measurements of the test bay stud, parallel to moisture content pins



Delmhorst measurement of bottom plate



#### MCs at P3 Poly Wall 2006-09-22 ~9:30 AM

#### MCs at P4 No Poly Wall 2006-09-22 10:30 AM

Location	Reading	Location	Reading
Stud 60" AFF		Stud 60" AFF	
@ foundation	14%	@ foundation	9%
@ mid	12%	@ mid	9%
@ interior	12%	@ interior	9%
Bottom plate		Bottom plate	
@ foundation	14%	@ foundation	11%
@ mid	13%	@ mid	10%
@ interior	13%	@ interior	9%
Wafer @ concrete		Wafer @ concrete	
Interior side	13%	Interior side	9%
Exterior side	14%	Exterior side	10%
Wafer @ poly		Wafer @ GWB	
Interior side	9%	Interior side	9%
Exterior side	9%	Exterior side	9%
Top plate		Top plate	
@ foundation	10%	@ foundation	9%
@ mid	10%	@ mid	9%
@ interior	9%	@ interior	9%
Outer stud, upper location		Outer stud, upper location	
@ foundation	10%	@ foundation	10%
@ interior	10%	@ interior	9%
		Outer stud, lower location	
		@ foundation	11%
		@ interior	9%



Note that these are all small variations in moisture content, and they are all within the safe storage limits of wood. This presentation is meant more to show differences in behavior between the two walls, demonstrated in the spatial pattern of moisture levels in the framing. Some notable points were as follows:

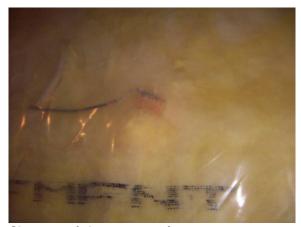
- The polyethylene wall shows consistently higher moisture contents than the no polyethylene wall, typically on the order of 13-14% MC vs. 9-11% MC.
- There is typically a small but measurable moisture gradient through the thickness of the framing members; the highest moisture contents are found at the exterior (concrete) side.
- In the polyethylene wall, the outer perimeter framing members (top plate, outer perimeter studs) show markedly lower moisture content than the test bay studs or bottom plate. These frame members are exposed to interior conditions on one side: as a result, they have moisture levels similar to the no polyethylene wall (9-10% MC).

#### **Roll Blanket Inspection**

The roll blanket 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. Evidence of moisture accumulation in upper batt was seen in the form of some discoloration of insulation, visible through the polyethylene. The upper moisture content wafer had visible mold on the exterior surface.







Close-up of the upper wafer

The moisture content of the wafer was measured through the polyethylene and resealed with builder's tape; the measurement was 9% MC.

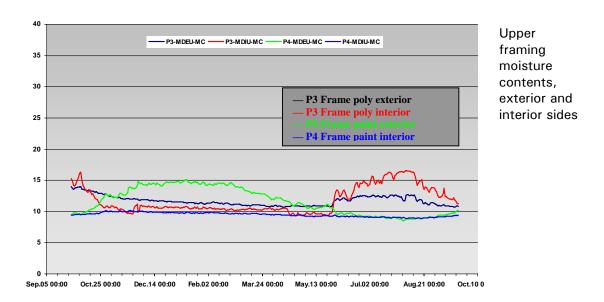


#### **XPS Wall Inspection**

The 2" XPS wall was not disassembled, due to the difficulty of the procedure (detaching and reattaching Tapcon screws), the disturbance that would result to the wall, and the lack of framing members to measure with a moisture meter. A full disassembly and inspection will occur at the final decommissioning at the conclusion of data collection.

#### **Comparison with Monitored Data**

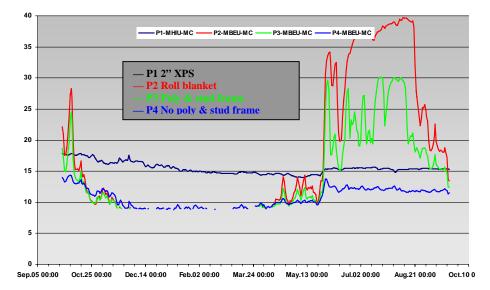
The observations of the wall conditions were compared to the monitored data, in order to correlate degrees of damage with measurements.



The framing in upper portions both walls showed little damage; the framing in the polyethylene wall on the inboard side shows some brown spotted marking that is likely microbial growth. The maximum moisture content seen at that location was approximately 17%. Although this is the highest moisture content in the plot above, it is considered well within the safe range. It is quite possible that the wetted area did not overlap the pin location to adequately reflect the degree of wetting.

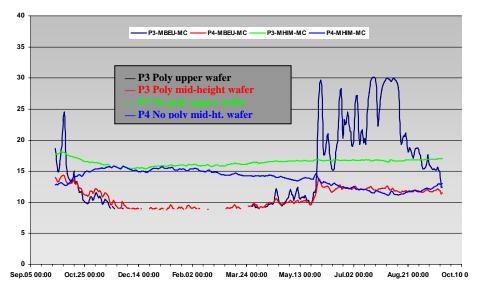
The sill plate framing in both walls appeared completely intact in both walls; this matches the monitored data of moisture contents of less than 14% for the entire logging period.





Upper moisture content wafers at concreteinsulation interface (XPS wall) or at insulationvapour barrier/drywall interface (remainder)

The upper MC wafers in the four walls are compared in the plot above; field observations showed that the "no poly" wafer was intact, and the "poly" and roll blanket walls had mold growth. This clearly matches the data plotted above: the two wafers with mold growth had moisture content peaks at 30 to 40%, while the intact wafers had moisture contents in the 10-15% range.



Upper and mid-height moisture content wafers in framed walls (P3 poly and P4 no poly)

Finally, we compared the upper moisture content wafers with the mid-height wafers that were between the concrete and the batt insulation. The mid-height wafers showed some minimal exterior-side growth that might have been mold. However, those wafers do not show high moisture contents, especially when compared with the upper poly wafer. This could be due to localized wetting/moisture adsorption at the exterior face only, as shown by the growth on only one face.

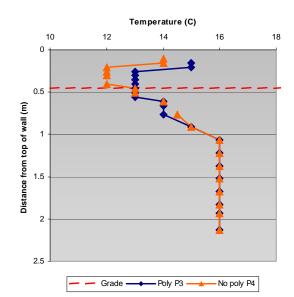


#### **Temperature Gradient**

The temperature of the interface of the concrete and the interior insulation interface was measured with an infrared laser thermometer immediately after the removal of the insulation batt, in order to take a vertical temperature gradient at that location.



Measurement of concrete-insulation interface temperature with infrared laser thermometer



Vertical temperature gradient seen in two test walls; red line indicates grade level

The measurements follow a consistent pattern: the above grade portion is close to exterior temperature (slightly cooler, due to thermal mass), and then increases over the space of 0.5 m to a mostly constant ground temperature of  $16^{\circ}$  C.

There is a consistent 1° C difference between the above-grade portions of the two walls. This can be explained by several factors. First, these measurements were taken approximately an hour apart; given the warming temperatures outside, it would be logical that the surface temperatures would be changing over that time. Second, the resolution of the infrared thermometer is 1° C, so (for instance) 12.4 and 12.6° C would be measured as 12 and 13° C, respectively.

The sharp 2° C difference between the very top of the wall and the remainder of the above-grade portion initially caused some confusion. This was explained by looking at the assembly geometry: on this orientation, the house has a brick veneer with a cast-in brick shelf. The higher temperatures seen at the top of the wall therefore reflect the thinner concrete wall at the air space and brickwork, which responds differently than the thicker full wall below.





Exterior view of basement window, for vertical reference



Interior view of basement window, for vertical reference, compared to test panels



## APPENDIX C - MODELLING ASSUMPTIONS, ABOVE GRADE



#### 1.0 ABOVE GRADE MODELLING ASSUMPTIONS

The dynamic thermal and moisture transport performance of the wall assemblies was evaluated using a computer based analytical program (WUFI).

#### 1.1 Assembly

The following cases were modelled:

- Wall 1 (Poly South, Poly North):
   Brick, Air Cavity, SBPO, OSB, 150mm Fibreglass Batt, 4ng/(Pa.s.m²) Poly, Painted Gypsum
- Wall 2 (No Poly South, No Poly North):
   Brick, Air Cavity, SBPO, OSB, 150mm Fibreglass Batt, Painted Gypsum
- Wall 3 (XPS South, XPS North):
   Brick, Air Cavity, 25mm XPS, 102mm Fibreglass Batt, Painted Gypsum
- SBPO, Spun bonded polyolefin.
- OSB, Oriented strand board sheathing.
- XPS, Extruded polystyrene insulation

#### 1.2 Modelling – Verification

The model was verified against the field test experimental set-up. The model was set-up to simulate the experimental set-up and adjusted to match the results from the test facility as closely as possible. The parameters which resulted in the best fit are as follows:

- Interior Conditions: Hourly data taken from field test facility (see Appendix B1).
- Exterior Conditions: Hourly data taken from field test facility (see Appendix B1).
- Orientation: The walls were set to South or North.
- Duration: The model was run for 1 year, starting on October 1<sup>st</sup>, to match the timing of the field test.
- Initial Conditions: Moisture content was set to match starting conditions of the field test monitored data. This starting condition was approximately 73% relative humidity and 19.2°C.
- Surface Conditions: These conditions were varied within ranges established from modelling experience until the model matched the field-monitored data. The surface conditions determined to be a best fit to measured data are as follows:

Short wave radiation absorptivity for brick set to 0.8 Long wave radiation absorptivity for brick set to 0.9



Rain water absorption factor for brick set to 0.5 Rain absorption coefficient set to 0.07

• Materials: Generally taken from WUFI database. Brick was selected to be 'Brick (old)', which is a fairly moisture absorptive brick. OSB chosen is of medium density. SBPO vapour permeance set equivalent to Canadian Tyvek at 1500 ng/Pa.s.m². IRC data for gypsum including primer and 2 coats of high permeance latex paint (modelled as single component) was used as follows (except when 1 perm interior paint used):

Relative	Permeance
Humidity (%)	(ng/ Pa.s.m²)
10	109
20	149
30	206
40	291
50	406
60	566
70	794
80	1137
90	1646
100	2457

- Monitoring positions:
  - Wall 1 Brick air space, Inboard face of OSB, Middle of Fiberglass batt
  - Wall 2 Brick air space, Inboard face of OSB, Middle of Fiberglass batt
  - Wall 3 Brick air space, Inboard face of XPS, Middle of Fiberglass batt

The moisture content of the OSB, relative humidity of the air space/fiberglass batt, and the dew point of the fiberglass batt were all compared to the field monitoring data to verify the model.

When comparing these results with WUFI models, several caveats must be noted. First, the OSB moisture content measurements have not been corrected with a & b wood species coefficients. Second, since it is an element with thickness in the wall, and the moisture content pins are fixed at a given depth. Therefore, differences between the total moisture content of the OSB layer in the simulation with the resistance pin results should be expected, even with accurate simulation parameters.

Finally, there were condensation events in several of the walls through the course of the year; this will result in deviations between the simulated data and the monitored data, unless source/sink factors are accounted for.

Some of the comparison graphs can be seen in Appendix D1 – Modelling Validation. The model results generally compared well with the monitored data.



The moisture content of the OSB was reviewed at different cross sections to match the moisture content measured by the pins in the experimental set-up. Measured from the interior the following sections were reviewed: The first 1mm, the first 3 mm's and the  $2^{nd}$  to  $3^{rd}$  mm's.

# 1.3 Modelling - Baseline (Waterloo)

Once validated, the model was then adjusted to a Waterloo baseline. The major adjustments from the validation were a change of the interior conditions and the length of time the model was run for. Baseline parameters which varied from the validation outlined above include:

#### Interior Conditions:

The 'Normal Moisture Load' conditions were selected for Waterloo

This is the prEN 15026 "Regular" Moisture Load in WUFI.

This load varies sinusoidally (with daily variation based on exterior climate), with maximum summer conditions (first week of August - *Temperature:* 25°C; *Relative Humidity:* 60%) and minimum winter conditions (*Temperature:* 20°C; *Relative Humidity:* 30%).

The interior condition was chosen with reference to a CMHC study "Field Testing of House Characteristics" by K.Russet et. al performed in 1993 (see Figure 1.1).

- Duration: Models were run for a 2-year period initiating on October 1<sup>st</sup>.
   However only the 2<sup>nd</sup> year from each run was analysed to reduce the impact of initial conditions on the results.
- Monitoring positions:
  - Wall 1 Outboard and inboard of OSB, outboard of poly
  - Wall 2 Outboard and inboard of OSB, outboard of gypsum
  - Wall 3 Inboard of XPS, outboard of gypsum

# 1.4 Modelling – Geographic Extrapolation

The base line waterloo model was then extrapolated to several other geographic areas. The major adjustments for the validation were exterior/interior climate and orientation. Parameters which varied from the baseline Waterloo run are outlined below:

#### Interior Conditions:

The 'Normal Moisture Load' conditions were selected as follows:



- prEN 15026 "Regular" Moisture Load selected for St.John's and Edmonton.
- prEN 15026 "High" Moisture Load selected for Vancouver.

The heavy load varies sinusoidally (with daily variation based on exterior climate), with maximum summer conditions (first week of August - *Temperature:* 25°C; *Relative Humidity:* 70%) and minimum winter conditions (*Temperature:* 20°C; *Relative Humidity:* 40%).

These interior conditions were chosen with reference to a CMHC study "Field Testing of House Characteristics" by K.Russet et. al performed in 1993 (see Figure 1.1).

- Exterior Conditions: Hourly weather data for a vertical surface in St. Johns,
   Edmonton and Vancouver. Warm year was used to evaluate walls with poly and cold year to evaluate all other walls, as these are the critical situations.
- Orientation: The wall orientation was set to North in all cities. It was also set to South in St.Johns, West in Edmonton and East in Vancouver. Through modelling experiment and review of data, these orientations were found to be the critical elevations in the given cities.

# 1.5 Modelling – Variations

Variations were then made for each geographic location to explore the impact of higher interior moisture loads and a low perm interior paint on the North walls with no poly. Parameters which varied are outlined below:

Interior Conditions:

The following 'Heavy Moisture Load' conditions were selected for the given geographical regions:

- prEN 15026 "High" Moisture Load was selected for Waterloo, St.Johns and Edmonton.
- EN 13788 Humidity Class 3 was selected for Vancouver This EN load varies sinusoidally (with variation based on exterior climate), with maximum summer conditions (first week of August *Temperature:* 21°C; *Relative Humidity:* 70%) and minimum winter conditions (*Temperature:* 21°C; *Relative Humidity:* 50%).

These interior conditions were chosen with reference to a CMHC study "Field Testing of House Characteristics" by K.Russet et. al performed in 1993 (see Figure 1.1).



Materials: The gypsum with a low perm interior paint was modelled as single component with the permeance as follows:

Relative	Permeance							
Humidity (%)	(ng/ Pa.s.m²)							
10	39							
20	43							
30	46							
40	50							
50	52							
60	54							
70	56							
80	57							
90	58							
100	59							



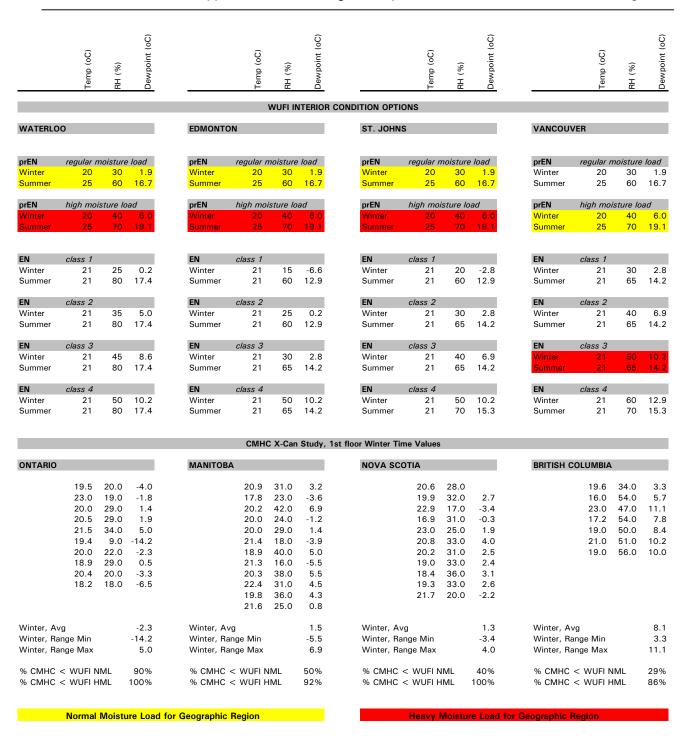


Figure 1.1: Comparison of Dewpoints for WUFI interior load options and measured regional interior loads from CMHC study "Field Testing of House Characteristics" by K.Russet et. al performed in 1993.



# APPENDIX D1 - MODELLING VALIDATION, ABOVE GRADE



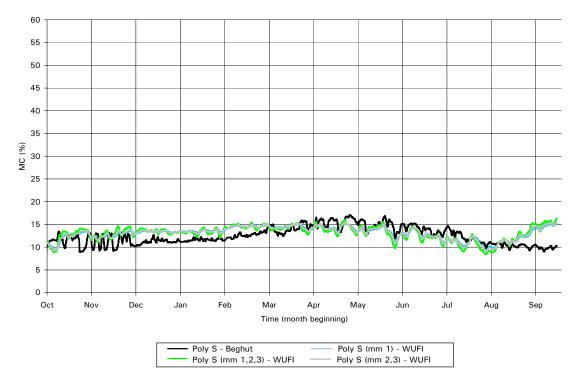


Figure 1.1: Poly South, OSB Moisture Content

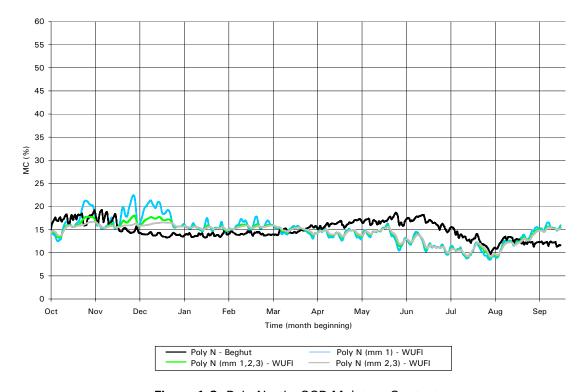


Figure 1.2: Poly North, OSB Moisture Content



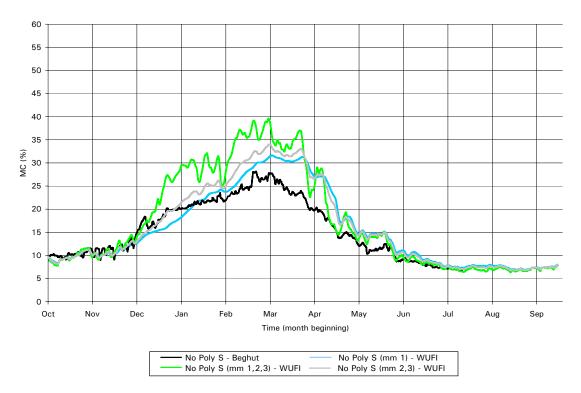


Figure 1.3: No Poly South, OSB Moisture Content

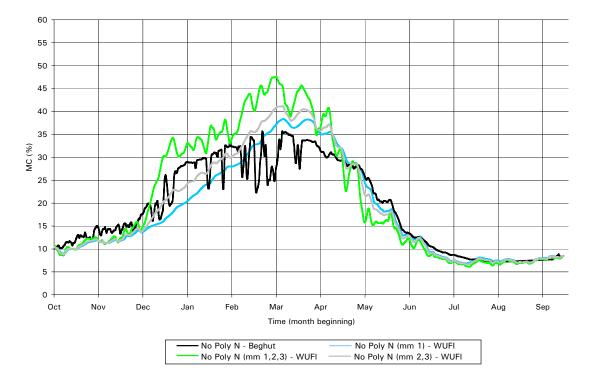


Figure 1.4: No Poly North, OSB Moisture Content



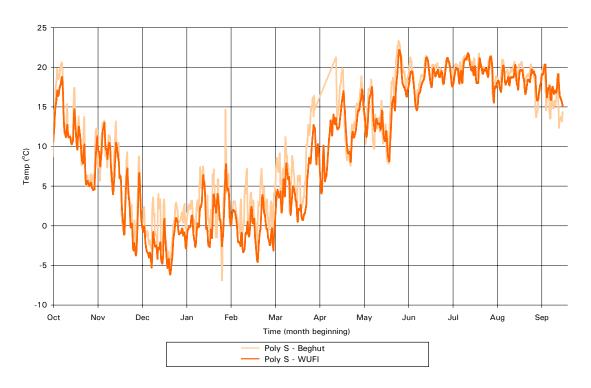


Figure 1.5: Poly South, Mid Fiberglass Batt Dew point

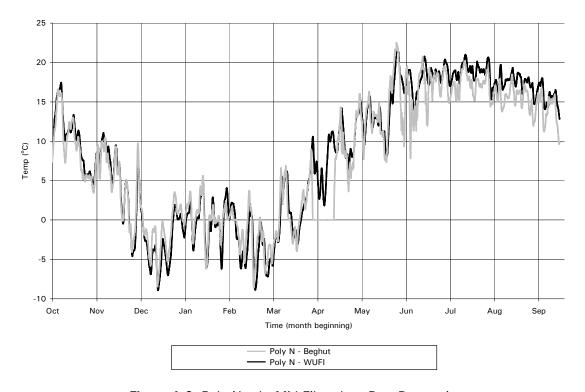


Figure 1.6: Poly North, Mid Fiberglass Batt Dew point



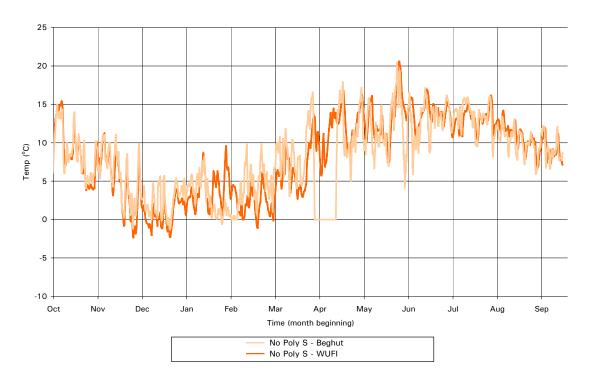


Figure 1.7: No Poly South, Mid Fiberglass Batt Dew point

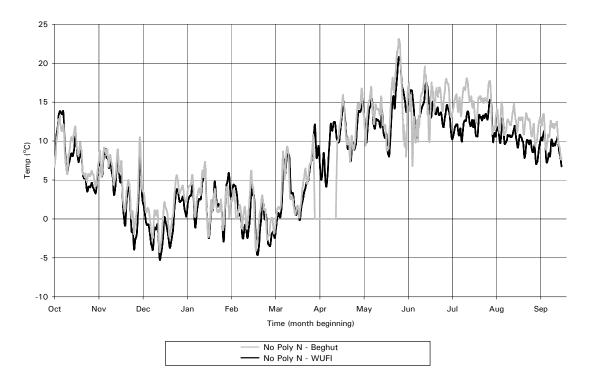


Figure 1.8: No Poly North, Mid Fiberglass Batt Dew point



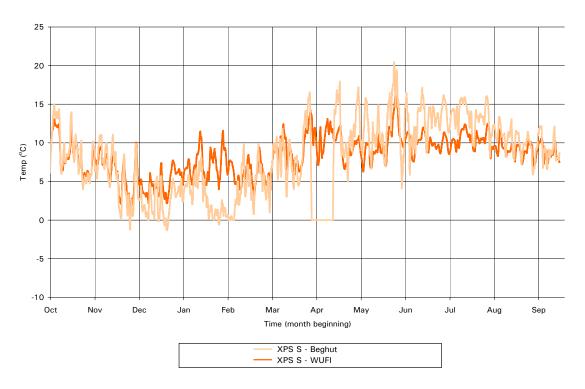


Figure 1.9: XPS South, Mid Fiberglass Batt Dew point

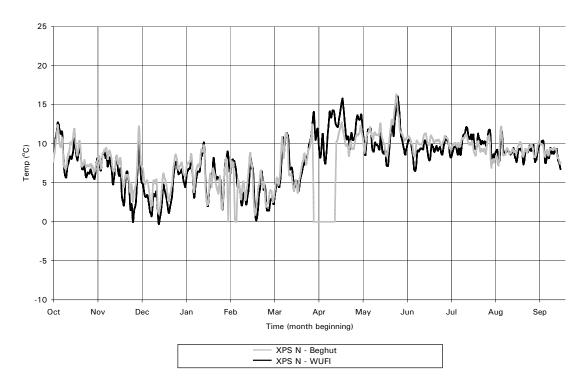


Figure 1.10: XPS North, Mid Fiberglass Batt Dew point



# APPENDIX D2 - MODELLING ASSUMPTIONS/VALIDATION, BASEMENT



#### 1.0 VALIDATION SIMULATION

The validation simulations are broken into two sections: the above-grade and below-grade portions. It was necessary to create both boundary conditions (exterior and interior), and starting moisture levels for the assembly. Results from initial models were used to iteratively tune these input conditions. Then, the results were compared with monitored data. When a lack of correspondence was found, possible reasons for this difference were proposed, and the applicability of simulation results was examined.

# 1.1 Above-Grade Validation Simulations

# 1.1.1 Boundary Conditions

The uppermost portion of the wall is exposed to above-grade conditions, as reflected by exterior air temperature and relative humidity measurements taken at the Kitchener site. However, additional weather data (rainfall, wind, and solar radiation) is required to create a climate file for a WUFI simulation. Therefore, weather data from Building Engineering Group exposure facility (BEGHut) was substituted to generate these conditions; this weather station is roughly 15 km (9 miles) northwest of the Kitchener site. Comparison of temperatures at the two sites shows close correlation, suggesting weather patterns are sufficiently similar.

Interior boundary conditions were provided by measured data. Conditions were relatively dry throughout the year, due to a combination of low moisture generation, ventilation with exterior air (winter), and/or running of the air conditioner (summer). Interior relative humidity was in the 25-35% range in wintertime, which was equivalent to a dewpoint in the 0-5° C range; summertime humidity levels were approximately 60%, or a 10° C dewpoint (interior temperatures were cooler than 20° C).

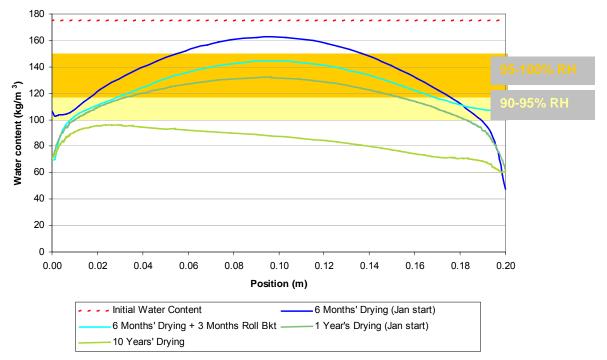
A southeast-facing wall was used in the validation runs, matching the test setup. The rain exposure of the test walls is not well characterized: the adjacent building shields the side of the house, but the effect varies between the test panels. Although the test walls are close to the ground (low exposure), they might be subject to splashback of rain coming off the building, hitting the ground. As a first estimate, WUFI default values of R1 = 0.0 and R2 = 0.07 (short building up to 10 m) were used. This is roughly equivalent to a rain deposition factor (RDF) of 0.32, which is in line with exposures seen at the bottom of the wall (RDF < 0.35, Straube 2005). Solar short-wave absorptivity ( $\alpha$ ) was set to 0.6, which is the value given for "concrete, rough" (ASHRAE 2005); long-wave emissivity ( $\alpha$ ) was set to 0.9. No additional coatings or surface transfer coefficients were specified.



# 1.1.2 Assembly Initial Conditions

Unlike lighter framed wall assemblies, the built-in construction moisture of a basement wall is a significant source for in-service problems. Therefore, characterizing this moisture load (and its distribution) is necessary to simulate performance. Starting with an initial moisture content of 175 kg/m³ (free water in fresh concrete, according to WUFI documentation), the wall was allowed to dry in WUFI with the described boundary conditions. Note that this is a conservative approach that underestimates the drying of the concrete, as the building would not have been dried in and conditioned for that full period.

Figure 1.1 shows some moisture profiles generated under various drying conditions and periods; the exterior side is the left, and interior right. The initial moisture content is shown by the red dotted line (175 kg/m³); the equivalent relative humidity (via the sorption isotherm in material properties) is indicated by shading. Unless noted otherwise, the wall had no interior finishes during drying.



**Figure 1.1:** Moisture content profiles through concrete thickness (exterior = left; interior = right)

The plot shows that drying occurs to both interior and exterior, even though the wall is exposed to rain. However, drying progresses relatively slowly: even after a year, the majority of the wall's thickness is above 90% RH. This shows that the construction moisture loading can be significant, even after a year of drying. After ten years' of drying, the wall has dried below 90% through its thickness; however, based on additional simulations, it appears that little drying will occur below this level. The asymmetric drying profile at 10 years is due to the fact that rain moisture is introduced at the exterior side, and dries to the interior.



In initial simulations, the profile of six months' drying (January-June) of unfinished wall was used. Simulations of test walls showed a small humidity rise in the insulation cavity at the beginning of the year (September-October), followed by a much larger one at the end of the year (August-September). In contrast, in monitored data, these spikes were of comparable size. It was realized that the roll blanket insulation was applied to the upper part of the wall during the construction process, inhibiting drying to the interior. Therefore, a simulation was run with six months of uncovered wall (January-June), followed by three months with the roll blanket in place (July-September). The resulting profile is shown above: the high humidity front "advances" inwards through the concrete when an impermeable material is placed inboard of the wall. This modification produced moisture "spikes" of similar magnitude for the two summer/fall seasons.

## 1.1.3 Test Assembly Details

After completion of this setup, simulation of the test walls could begin. Onedimensional simplifications of three assemblies were simulated: 50 mm (2") extruded polystyrene (Wall 1), the fiberglass roll blanket with polyethylene (Wall 2), and the framed 2x4 wall with fiberglass insulation, gypsum board, and latex paint (Wall 4). Most of these materials are already well characterized in WUFI; however, the latex paint was simulated as a separate layer with a vapour diffusion resistance factor (VDRF) that varied with relative humidity, instead of a fixed one (i.e., specifying a interior vapour resistance sd-value). NRC-IRC data (Kumaran 2002) for "painted" and "unpainted" gypsum board was compared; the painted sample was gypsum wallboard with one coat primer and two coats of latex paint. The net difference in permeance between these the painted and unpainted data was calculated, as shown in Figure 1.2. These values were then made into a 1 mm fictitious layer in WUFI, and applied to the interior side of gypsum board ("interior gypsum board" from ASHRAE TRP 1018); this material has performance very similar to the NRC-IRC data. This approach retains the moisture storage properties of the gypsum board; it also models the vapour resistance of the latex paint at its correct location, at the innermost layer.



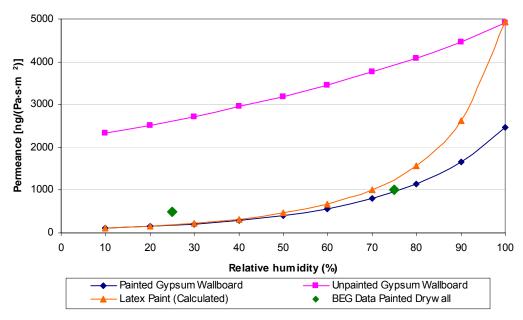


Figure 1.2: Gypsum wallboard permeability data (painted and unpainted) from Kumaran (2002)

However, it should be noted that Building Engineering Group is taking permeability measurements of similar latex paint/gypsum board samples (also plotted in Figure 1.2). Preliminary results are showing slightly different results: wet cup (75% average RH) measurements are in the 1000 ng/(Pa·s·m²) or 18 perm range, which match NRC-IRC's data. However, dry cup measurements are approximately 400-600 ng/(Pa·s·m²) (7-10 perms), compared to the 150-200 ng/(Pa·s·m²) (2.6-3.5 perm) values stated in the literature. Further testing is still in progress; after completion and vetting of these results, they may be applied to simulations.

As a final note, the difference in monitored performance seen between the roll blanket wall and the stud frame/polyethylene wall is worth examining here. The dewpoint at the upper portion of the wall (daily average data) is plotted for the roll blanket, the stud frame with polyethylene, and the stud frame with gypsum/latex paint in Figure 1.3. The performance of the stud frame-polyethylene wall seems to lie between that of the other two walls, changing between seasons (closer to the roll blanket in the summertime, and latex-gypsum in wintertime).



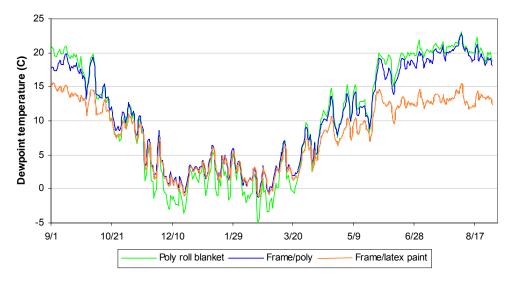


Figure 1.3: Daily average dewpoint (upper portion) comparison of Kitchener walls

There are several possible reasons for this difference. First, 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. Using the range of 0.58-7.8 ng/(Pa·s·m) for wood, 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.

# 1.1.4 Temperature Comparison Between Model and Monitored Data

The first step in validating simulations against data is to compare corresponding temperatures; the thermal performance is often captured more accurately than moisture performance. In the monitoring package, there are sensors located at the "upper" location, which is roughly at exterior grade height. The temperature at the interface between the concrete wall and the interior insulation at this upper location was compared. Figure 1.4 shows the comparison between monitored and modeled temperatures; the dewpoint temperature in the wall cavity is also included for reference. That plot shows a lack of correspondence between the pattern and range of these temperatures: the modeled temperature is less damped and shows greater extremes than the monitored data. This behavior is most clear during the winter: a detail for November through January



is shown in Figure 1.5. Monitored winter air temperature minimums are about  $2^{\circ}$  C range, while modeledresults are about of  $-8^{\circ}$  C.

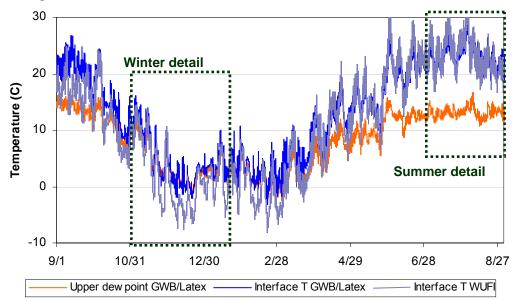


Figure 1.4: Upper height concrete temperature, monitored vs. model (full year)

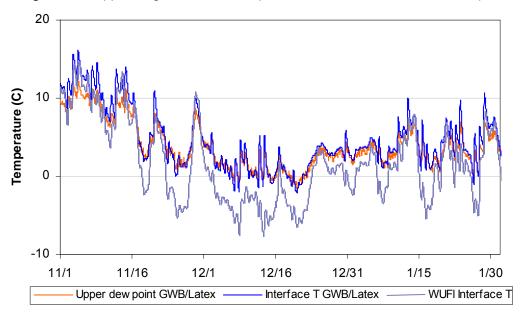


Figure 1.5: Upper height concrete temperature, monitored vs. model (winter detail)

The disagreement between the monitored data and the simulation in summertime is much smaller, as shown in Figure 1.6; the largest mismatches are on the order of 2-3° C, typically during daytime peaks. The monitored data for the framed walls (frame/polyethylene and frame/latex paint) are a close match to the model, while the remaining walls (roll blanket and XPS) show disagreement due to the shading from the adjacent house. In addition, the closer correspondence between monitored and simulated data may be due to the smaller  $\Delta T$  operating across the wall.



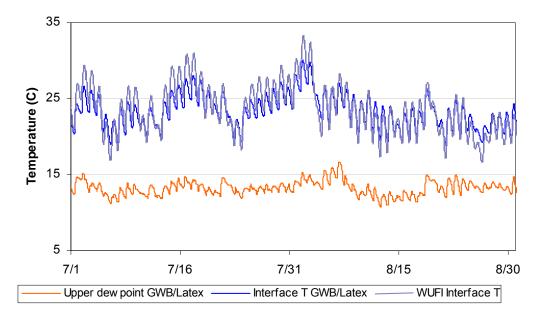


Figure 1.6: Upper height concrete temperature, monitored vs. model (summer detail)

The reason for the strong mismatch between monitored data and simulation (particularly in winter) was examined in more detail. The first approach looked at the possibility that the assembly thermal conductivities (U values) were not set properly; for instance, the insulation might have been compacted or wet, or the concrete drier (and therefore more insulative) than modeled.

The U values of the concrete and fiberglass insulation were used to calculate the relative contributions to the overall R-value of the assembly; these fractions give the temperature drop ( $\Delta T$ ) across each component of the assembly, and therefore the interface temperature under static conditions. According to these calculations, 3-6% of the overall  $\Delta T$  occurs through the concrete, with the remainder in the fiberglass insulation (for a full analysis, see Section 1.2.1).

Then, this contribution of concrete to the overall  $\Delta T$  was graphed for both the monitored data and the model, as shown in Figure 1.7. There is a great deal of scatter, due to the effects of thermal mass and solar gain. However, the modeled data is centered on the 3-6% range, as predicted by the static calculation. In contrast, the monitored data seems centered on the 20-30% range, which is much too large to be explained by variations in component U values.



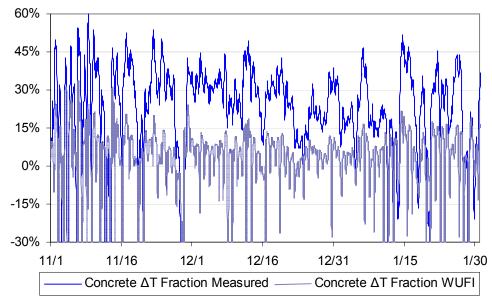


Figure 1.7: Concrete  $\Delta T$  as % of overall wall  $\Delta T$  (winter detail); monitored vs. model

Instead, the most likely explanation of the data is that the exterior air conditions recorded in weather data do not reflect the temperature difference that is operating across the wall. Inspection of the details of the wall assembly at this location indicates that it is likely that two-dimensional effects are significant (see Figure 1.8). 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.

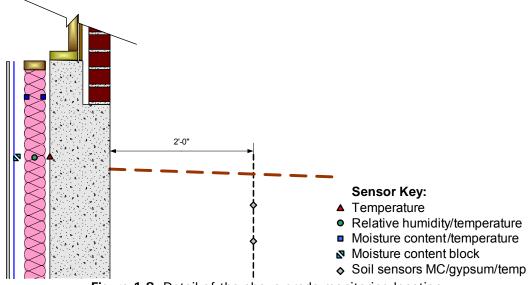


Figure 1.8: Detail of the above-grade monitoring location



Further evidence of two-dimensional effects can be found by plotting the soil temperature at the 150 mm (6") depth with the wall interface temperature and exterior air temperature, as shown in Figure 1.9. The interface temperature tracks much more closely to the shallow soil temperature than the exterior air temperature. In fact, a closer approximation to the concrete interface temperature can be made using a weighted average of the air and soil temperatures ("Weighted Shaded T").

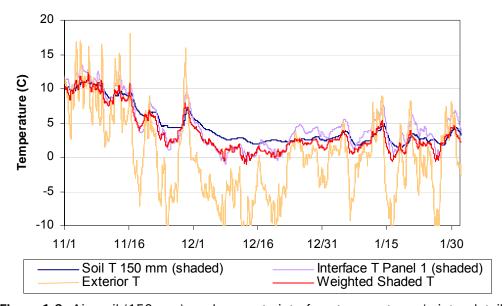


Figure 1.9: Air, soil (150 mm), and concrete interface temperatures (winter detail)

However, this level of extrapolation becomes increasingly difficult to justify; for instance, if this temperature were used as an exterior air temperature, this would require generation of modified exterior relative humidity, rain, and solar radiation levels, thus adding rather questionable boundary conditions.

Another question is whether the specific placement of the temperature sensor (at grade level) causes this poor correspondence when using above-grade boundary conditions. For instance, it seems possible that the upper portions of the above-grade concrete wall are closer to modeled behavior. First, dewpoint behavior shows that this is unlikely. The dewpoint in an assembly cavity with high vapour permeability (e.g., fiberglass batt) tends to be "pulled down" to the lowest temperature that the cavity is exposed to, when coupled to a hygrically massive material such as concrete. Therefore, if the upper parts of the wall are much colder, the dewpoint should reflect this effect. As shown in Figure 1.5, the dewpoint falls somewhat below the concrete surface temperature, but not by a large margin—nowhere near the  $-8^{\circ}$  C lows seen in the simulation.

Secondly, a vertical temperature gradient of the wall was taken during a wintertime (late January 2007) field visit to the experimental site. Temperatures were measured using an infrared thermometer, from the top of the wall to the "mid-height" location, as shown in Figure 1.10 and see Figure 1.11. Exterior temperature was in the -8 to  $-9^{\circ}$  C range during these measurements.



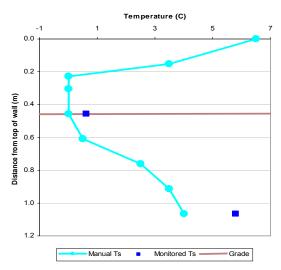




Figure 1.10: Vertical temperature gradient in frame-latex wall

Figure 1.11: Measurement of concreteinsulation interface temperatures

Just as for the monitored data, a large portion of the  $\Delta T$  (-8 or 9° C exterior; 20° C interior) occurs through the concrete. Also, the uppermost portions of the concrete-insulation interface are warmer (not colder) than the monitored T. This is likely due to the insulative effects of the brick airspace, as shown in the Figure 1.81.8. The U-value of 1" of still air (the brick drainage/ventilation space) is 1.2 W/m²•K, while 8" of concrete is an order of magnitude greater at 7-13 W/m²•K.

The data for a Chicago-area basement site was similarly examined; it also showed higher wintertime temperatures at the concrete-insulation interface than would be predicted by a one-dimensional model. This basement had an even smaller portion exposed above grade (150-200 mm/6-8") than the Kitchener basement.

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.



#### 1.2 Below Grade Validation Simulations

Like the above-grade validation simulations, the below-grade simulations required the development of boundary conditions and initial conditions.

# 1.2.1 Boundary Conditions

Soil temperatures were measured at multiple depths outside of the basement; the intent was to create exterior below-grade boundary conditions from this data. However, as shown in Figure 1.8, the soil measurement locations do not line up directly with the wall monitoring locations. In addition, no soil sensors were placed at a depth matching the "lower" wall position. Therefore, an alternate approach to creating exterior boundary conditions was used.

The temperature at the interior concrete surface (the interface between the insulation and concrete) was measured at all three monitoring heights (low, middle, high), parallel to other wall measurements. Given the low insulating value of the concrete, it seemed likely that the temperature on the interior of the concrete would be similar to the temperature at the exterior. Therefore, the relative R-values of the concrete and insulation were compared; the fractional contributions determine the temperature drop across each component. The concrete wall and RSI-2.3 (R-13 imperial) batt insulation were compared. Using thermal conductivity values for concrete of 1.4 to 2.6 W/m·K, the temperature drop across the concrete should be 3-6% of the total  $\Delta T$ . Given this small contribution, it appears that this approach will provide reasonable results. Since temperatures at the deepest "lower" locations varied on the order of 1-2° C between walls, 3-6% of the  $\Delta T$  across a wall would be smaller than this variation. In addition, at the below grade monitoring locations, the diurnal variations have been completely damped out; this should allay concerns of inaccuracies due to the thermal mass of the concrete.

The exterior below-grade relative humidity was set to a constant 100%. No rain was included in these climate files, which would have been used to simulate liquid water wetting from poor drainage, incomplete dampproofing, or other capillary sources.

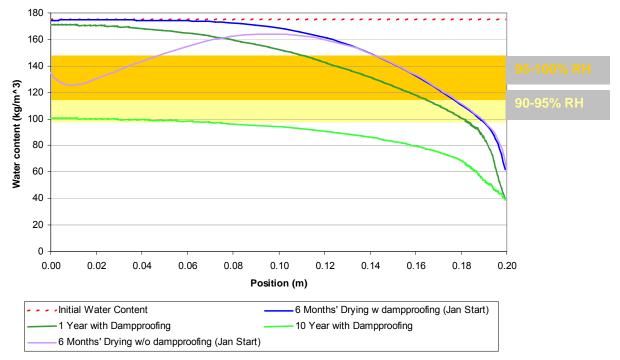
Like the above-grade wall, it seems possible that two-dimensional effects might reduce the accuracy of the simulation: for instance, the lower location could be affected by thermal bridging at the floor slab and/or footing. The fact that the temperature gradient varies continually with height is also a concern.

# 1.2.2 Assembly Initial Conditions

Like the above-grade wall, the starting moisture content of the concrete needed to be estimated, due to the moisture load it adds to the assembly. Drying simulations were run using the below-grade boundary conditions. First, several



parametric simulations were run to determine the effects of some extrapolations beyond the monitored walls, as shown in Figure 1.12.



**Figure 1.12:** Concrete moisture content; parametric drying studies (exterior = left; interior = right)

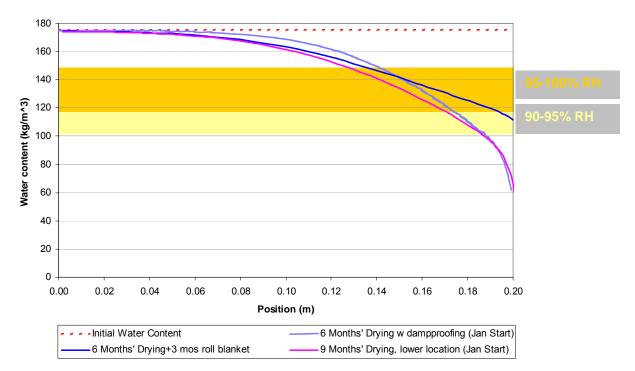
Initially the wall (at mid height) was dried for six months, one year, and ten years. Like the above grade wall, after six months, the majority of the wall is still over 90% relative humidity; and this is still the case after a year of drying. After ten years, the wall has largely dried below this level.

Due to the exterior dampproofing layer all drying must be to the interior (assuming that the damproofing is essentially vapour impermeable). To investigate the role of the damproofing a simulation with the dampproofing removed was also conducted. This simulation shows drying to the exterior, which is unexpected, given that the exterior is at 100% RH. However, there is a thermal gradient across the wall (the interior is warmer than exterior); this creates a vapour pressure gradient that results in the outwards drying. Note that this is by no means a recommendation for the elimination of dampproofing. The effect of liquid water as a boundary condition was not included in these simulations; without dampproofing, any liquid water due to poor drainage, clogged footing drains, etc., would result in wetting of the concrete from the exterior, and act as a significant moisture loading.

The moisture profiles used as initial conditions for the simulations are shown in Figure 1.13. At the "middle" height of the wall, the roll bag insulation was installed before installation of the test walls; the effects are shown ("6 Months' Drying + 3 Months' Roll Blanket"): the higher concrete moisture levels redistribute towards the interior side, since that interface is no longer in



equilibrium with dryer interior conditions. At the lower location, no insulation was installed before the test walls, so the profile for nine months of drying was used.



**Figure 1.13:** Concrete moisture content; initial conditions for simulation (exterior = left; interior = right)

# 1.2.3 Test Assembly Details

The simulated test assemblies were identical to their above-grade counterparts, except for the addition of dampproofing to the exterior of the concrete. Dampproofing options used in industry include cutback asphalt and asphalt emulsion products; in both cases, a 1/16" (1.6 mm) coating is recommended in manufacturer's specifications. Therefore, a 1/16" layer of cutback asphalt was simulated; ASHRAE Fundamentals (2005) gives a value of 8 ng/(Pa·s·m²) or 0.14 perms.

The wall assembly, as simulated, did not include the use of the dimple mat drainage board. Since liquid water capillarity from the exterior was not simulated, it should not make any difference. Furthermore, simulating the air space would decrease accuracy of the boundary conditions generated by concrete interface temperatures.

In the simulation, transfer coefficients were set for below-grade conditions: the exterior temperature was directly coupled to the wall's exterior surface, without a heat transfer coefficient (i.e., "Basement" condition); no coatings or special transfer coefficient were used.



# 1.2.4 Simulation Results and Analysis: Mid Height

After running simulations, the simulation results were compared with monitored data. Due to the setup of the boundary conditions, temperature correspondence was high. The critical metric for moisture performance, however, is relative humidity. The monitored relative humidity data at the mid-height location, at the concrete-insulation interface, is shown in Figure 1.14.

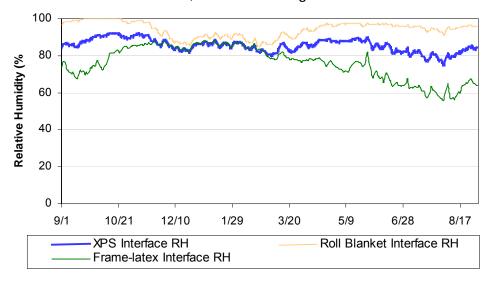


Figure 1.14: Monitored data: mid-height RH sensors at concrete-insulation interface

Behavior patterns are briefly described here, to see if they are matched in the model. The roll blanket, being the least permeable, has the consistently highest relative humidity levels. The interface is near saturation in fall, spring, and summer, dropping to  $\sim\!90\%$  RH in winter. The XPS wall shows moderately steady behavior, in the 80-90% RH range. And the fiberglass stud/latex paint wall has the driest behavior; it is at its peak during winter when the concrete wall is coldest. These three assemblies are generally ordered (wettest to driest) in the order of least permeable to most permeable.

There are moisture content surrogate sensors ("wafers") at the same location as these relative humidity sensors (concrete-insulation interface, mid height). The moisture content measurements can be related to relative humidity using the sorption isotherm for wood (Straube and Burnett 2005); the resulting data (using a curve fit) is plotted in Figure 1.15.



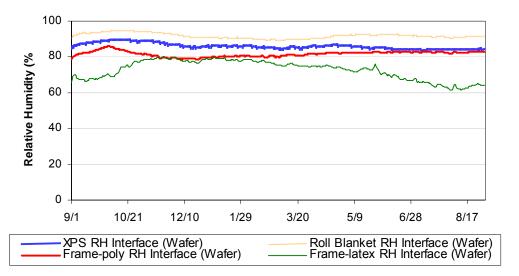


Figure 1.15: Monitored data: mid-height wafer sensors (calculated RH) at concrete-insulation interface

The wafer data shows a reasonable correlation with the relative humidity behavior shown in Figure 1.14 (such as the relative order and annual curve shape), but with slightly lower values and less response to transient changes. Note that this plot also includes wafer data for the frame-polyethylene wall, which was unavailable in the RH data. Also, similar to the data shown in Figure 1.3, the frame-polyethylene wall shows behavior between the roll blanket and frame-latex walls.

The corresponding data from the simulation is shown in Figure 1.16. 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 concreteinsulation interface. 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 of the panel was discussed above; this would also cause drying. Finally, it is possible that more drying of the concrete occurred before the installation of the insulation than simulations would indicate. The significant influence of the sorption isotherm in the high RH range also makes the simulations highly sensitive to the material property data input. Needless to say, all of these RH levels are high and cause for concern.



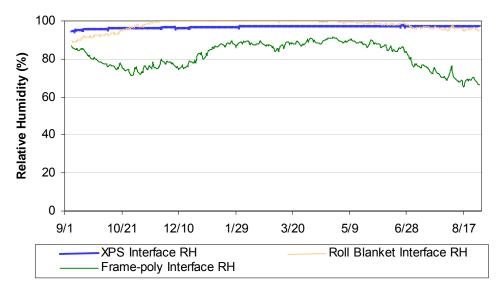


Figure 1.16: Simulation data: mid-height RH at concrete-insulation interface

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

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

# 1.2.5 Simulation Results and Analysis: Lower Height

A similar examination was made for the data at the lower wall location; however, correlations were hampered by the limited data available in the field monitoring. Lower-height relative humidity sensors were only installed in the frame walls (polyethylene and latex paint), and moisture surrogate "wafer" sensors were installed in the XPS and roll blanket walls. However, the roll blanket "wafer" sensor did not return valid data until a modification made during a recent field visit. The monitored data is shown in Figure 1.17.



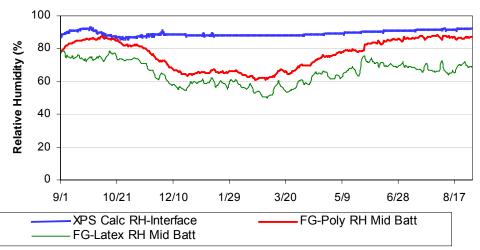


Figure 1.17: Monitored data: lower-height RH at interface and mid-batt

Note that this graph plots data from two different wall locations: the concrete-insulation interface (in the XPS wall), and mid-thickness in the batt (in the frame walls). The corresponding simulated data is shown in Figure 1.18.

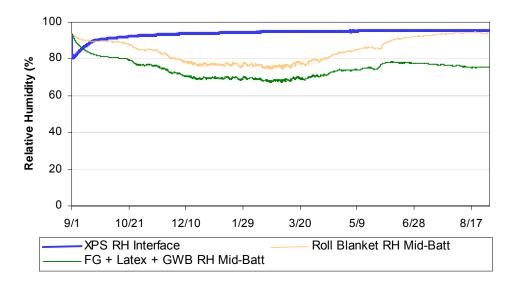


Figure 1.18: Simulation data: lower-height RH at interface and mid-batt

Again, the simulation captures the relative relationships between the relative humidity in the assemblies, but there is less accuracy in the absolute magnitudes. Note that unlike the "middle" height work, the roll blanket simulation is being compared to data from the framed wall with polyethylene.

In both the polyethylene and gypsum wallboard/latex paint simulations, the difference in performance can be explained by reasons stated earlier. The frame/fiberglass/polyethylene wall showed some evidence of moisture storage or bypass of the vapour control material, either by air leakage, flanking diffusion, or a drier initial state of the assembly.



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.



# **APPENDIX E1 - MODELLING RESULTS, ABOVE GRADE**



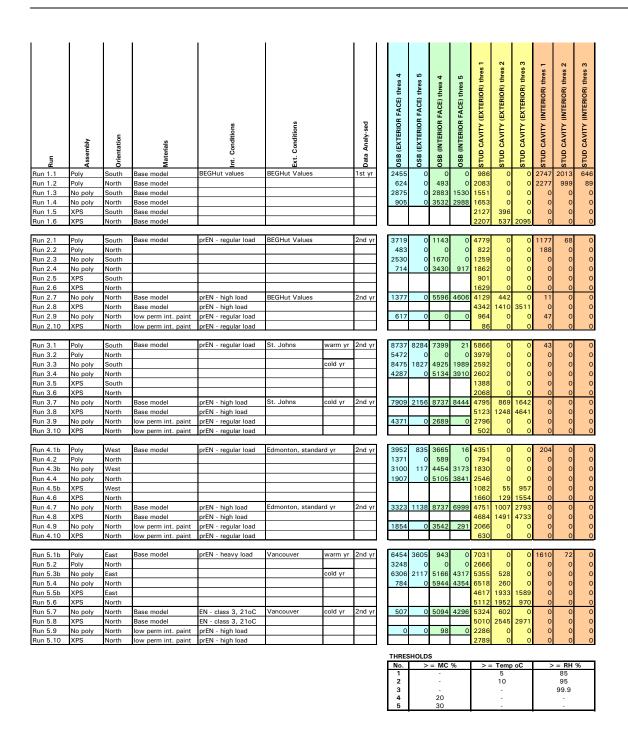


Figure 1.1: Record of Runs and Results (Ordered by City)
Time (Hrs) above indicated thresholds at given monitoring positions



Run 2.1 Run 3.1 Run 4.1b Run 5.1b	Poly Poly Poly Poly Poly	South South South West East	Wat er tal	BEGHut values prEN - regular load prEN - regular load prEN - regular load	BEGHut Values BEGHut Values St. Johns warm yr Edmonton, standard yr Vancouver warm yr	Pose Pued Programme Progra	2455 3719 8737 874 874 874 874 874 874 874 874 874 87	98 8 8 9 9 8 (EXTERIOR FACE) thres 5 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9	0 OSB (INTERIOR FACE) thres 4	O D L C O O UNTERIOR FACE) thres 5	0.000 STUD CAVITY (EXTERIOR) thres 1 10.000 STUD CAVITY (EXTERIOR)	STUD CAVITY (EXTERIOR) thres 2	STUD CAVITY (EXTERIOR) thres 3	9191 9192 8TUD CAVITY (INTERIOR) thres 1	22 0 0 89 89 27UD CAVITY (INTERIOR) thres 2	O O O O O O O O O O O O O O O O O O O
Run 1.2	Poly	North	Base model	BEGHut values	BEGHut Values	1st yr	624	0	493	0		0	0	2277	999	89
Run 2.2	Poly	North North		prEN - regular load	BEGHut Values St. Johns warm yr	2nd yr 2nd yr	483 5472	0	0	0		0	0	188	0	0
Run 3.2 Run 4.2	Poly Poly	North		prEN - regular load prEN - regular load	St. Johns warm yr Edmonton, standard yr	2nd yr	1371	0	589	0	3979 794	0	0	0	0	0
Run 5.2	Poly	North		prEN - high load	Vancouver warm yr	2nd yr	3248	0	0	0	2666	0	0	0	0	0
	1			<b></b>	I							. 1				
Run 1.3 Run 2.3	No poly No poly	South South	Base model	BEGHut values prEN - regular load	BEGHut Values BEGHut Values	1st yr 2nd yr	2875 2530	0	2883 1670	1530	1551 1259	0	0	0	0	0
Run 3.3	No poly	South		prEN - regular load prEN - regular load	St. Johns cold yr	2nd yr	8475	1827	4925	1989	2592	0	0	0	0	0
Run 4.3b	No poly	West		prEN - regular load	Edmonton, standard yr	2nd yr	3100		4454	3173		0	0	0	0	0
Run 5.3b	No poly	East		prEN - high load	Vancouver cold yr	2nd yr	6306	2117	5166	4317	5355	528	0	0	0	0
				L	I											
Run 1.4	No poly	North North	Base model Base model	BEGHut values	BEGHut Values	1st yr	905 714	0	3532	2988 917	1653	0	0	0	0	0
Run 2.4 Run 2.7	No poly No poly	North	Base model	prEN - regular load prEN - high load	BEGHut Values BEGHut Values	2nd yr 2nd yr	1377	0	3430 5596	4606	1862 4129	442	0	11	0	0
Run 2.9	No poly	North	low perm int. paint	prEN - regular load	BEGHut Values	2nd yr	617	0	0	0	964	0	0	47	0	0
Run 3.4	No poly	North	Base model	prEN - regular load	St. Johns cold yr	2nd yr	4287	0	5134	3910	2602	0	0	0	0	0
Run 3.7	No poly	North	Base model	prEN - high load	St. Johns cold yr	2nd yr	7909		8737	8444	4795	869	1642	0	0	0
Run 3.9	No poly	North	low perm int. paint	prEN - regular load	St. Johns cold yr	2nd yr	4371	0	2689	0	2796	0	0	0	0	0
Run 4.4 Run 4.7	No poly No poly	North North	Base model Base model	prEN - regular load prEN - high load	Edmonton, standard yr Edmonton, standard yr	2nd yr 2nd yr	1907 3323	1138	5105 8737	3841 6999	2546 4751	1007	2793	0	0	0
Run 4.9	No poly	North	low perm int. paint	prEN - regular load	Edmonton, standard yr	2nd yr	1854	0	3542	291	2066	0	0	0	0	0
Run 5.4	No poly	North	Base model	prEN - high load	Vancouver cold yr	2nd yr	784	0	5944	4354	6518	260	0	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 5.9	No poly	North	low perm int. paint	prEN - high load	Vancouver cold yr	2nd yr	0	0	98	0	2286	0	0	0	0	0
Run 1.5	XPS	South	Base model	BEGHut values	BEGHut Values	1st yr					2127	396	0	0	0	0
Run 2.5	XPS	South	Base model	prEN - regular load	BEGHut Values	2nd yr					901	0	0	0	0	0
Run 3.5	XPS	South	Base model	prEN - regular load	St. Johns cold yr	2nd yr					1388	0	0	0	0	0
Run 4.5b	XPS	West	Base model	prEN - regular load	Edmonton, standard yr	2nd yr					1082	55	957	0	0	0
Run 5.5b	XPS	East	Base model	prEN - high load	Vancouver cold yr	2nd yr					4617	1933	1589	0	0	0
Run 1.6	XPS	North	Base model	BEGHut values	BEGHut Values	1st yr					2207	537	2095	0	0	0
Run 2.6	XPS	North	Base model	prEN - regular load	BEGHut Values	2nd yr					1629	0	0	0	0	0
Run 2.8	XPS	North	Base model	prEN - high load	BEGHut Values	2nd yr					4342	1410	3511		0	0
Run 2.10	XPS	North	low perm int. paint	prEN - regular load	BEGHut Values	2nd yr					86	0	0	0	0	0
Run 3.6 Run 3.8	XPS XPS	North	Base model	prEN - regular load	St. Johns cold yr St. Johns cold yr	2nd yr 2nd yr					2068 5123	0 1248	0	0	0	0
Run 3.8	XPS	North North	Base model low perm int. paint	prEN - high load prEN - regular load	St. Johns cold yr	2nd yr					502	1248	4641 0	0	0	0
Run 4.6	XPS	North	Base model	prEN - regular load	Edmonton, standard yr	2nd yr					1660	129	1554	0	0	0
Run 4.8	XPS	North	Base model	prEN - high load	Edmonton, standard yr	2nd yr					4684	1491	4733	0	0	О
Run 4.10	XPS	North	low perm int. paint	prEN - regular load	Edmonton, standard yr	2nd yr					630	0	0	0	0	0
Run 5.6	XPS	North	Base model	prEN - high load	Vancouver cold yr	2nd yr					5112	1952	970	0	0	0
Run 5.8 Run 5.10	XPS XPS	North North	Base model low perm int. paint	EN - class 3, 21oC prEN - high load	Vancouver cold yr Vancouver cold yr	2nd yr 2nd yr					5010 2789	2545	2971	0	0	0
5.10	,,,,,		now point int. paint	p. z. riigir ioda	cold yi	,1					2700	J	J	J	- 3	
							THRES	SHOLDS	8							

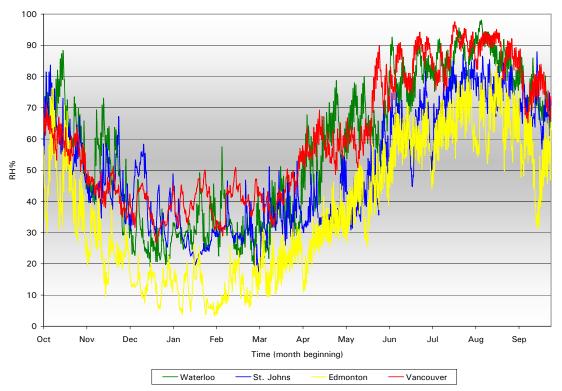
85 95 99.9

5 10

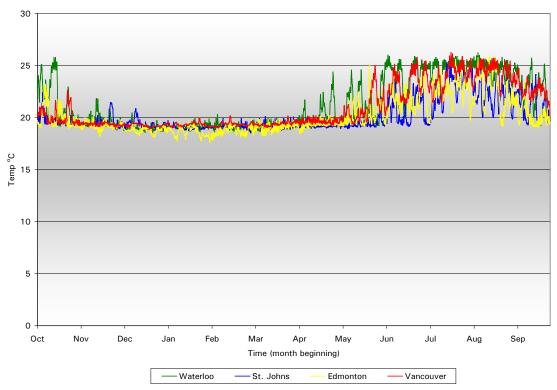
= RH %

Figure 1.2: Record of Runs and Results (Ordered by Wall Type) Time (Hrs) above indicated thresholds at given monitoring positions





**Figure 1.3:** Relative humidity Versus Time Poly S/E/W, Outboard face of Poly



**Figure 1.4**: Temperature Versus Time Poly S/E/W, Outboard face of Poly



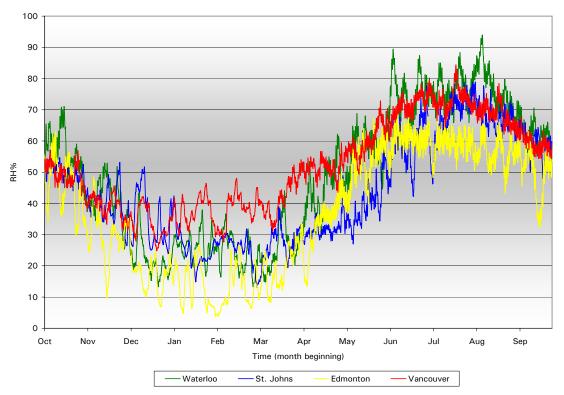


Figure 1.5: Relative humidity Versus Time Poly North, Outboard face of Poly

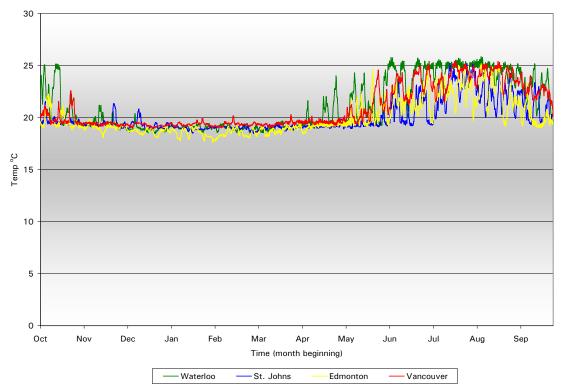
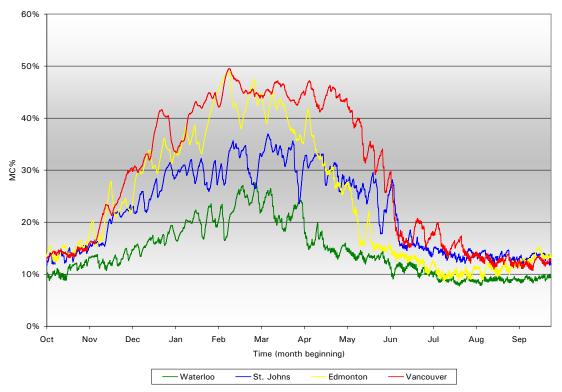
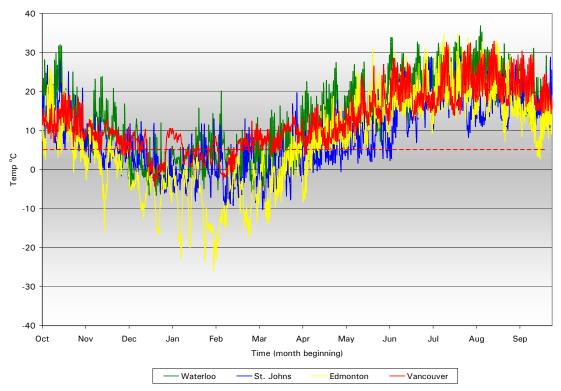


Figure 1.6: Temperature Versus Time Poly North, Outboard face of Poly





**Figure 1.7:** Moisture Content Versus Time No Poly S/E/W, Inboard face of OSB



**Figure 1.8:** Temperature Versus Time No Poly S/E/W, Inboard face of OSB



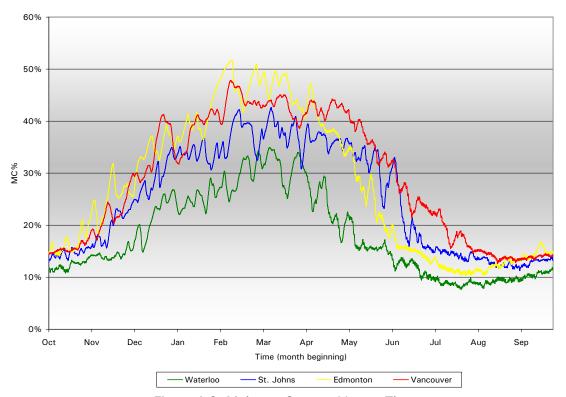
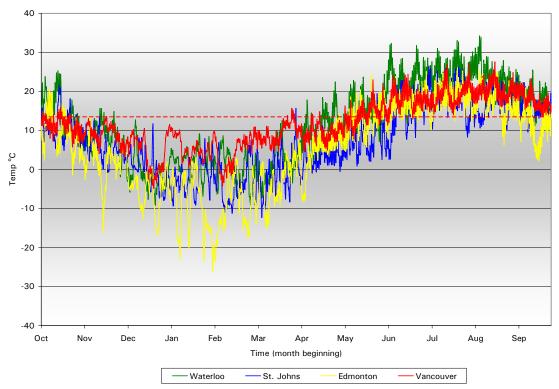


Figure 1.9: Moisture Content Versus Time No Poly North, Inboard face of OSB



**Figure 1.10:** Temperature Versus Time No Poly North, Inboard face of OSB



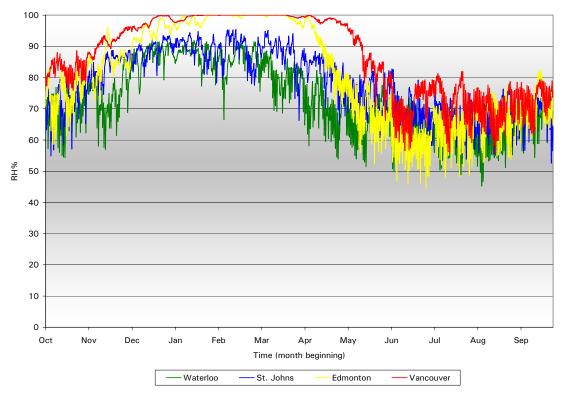


Figure 1.11: Relative Humidity Versus Time XPS S/E/W, Inboard face of XPS

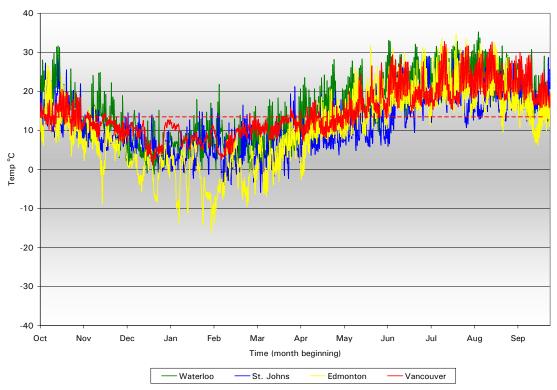


Figure 1.12: Temperature Versus Time XPS S/E/W, Inboard face of XPS



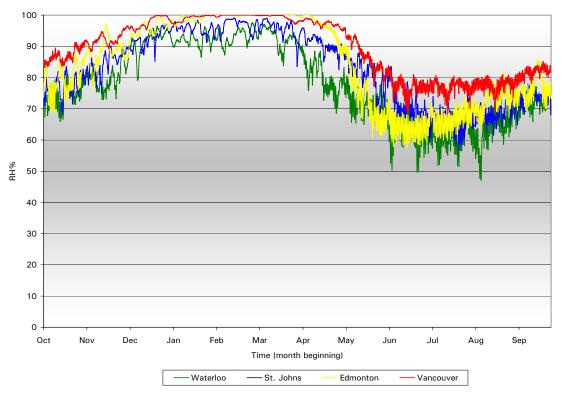


Figure 1.13: Relative Humidity Versus Time XPS North, Inboard face of XPS

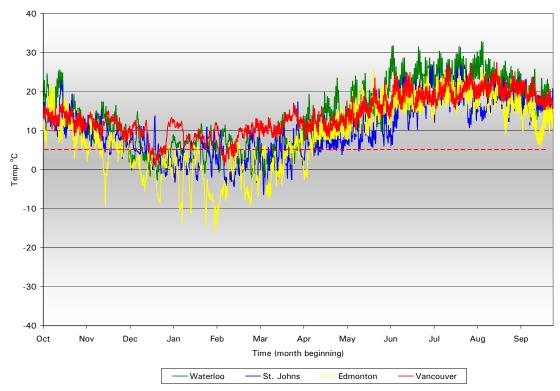


Figure 1.14: Temperature Versus Time XPS North, Inboard face of XPS



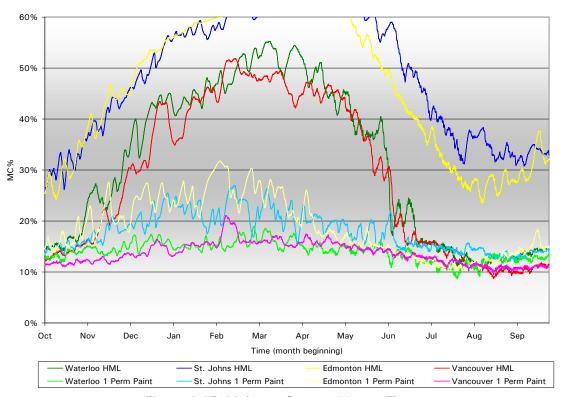


Figure 1.15: Moisture Content Versus Time
No Poly North, Inboard face of OSB (HML - Heavy Moisture Load)

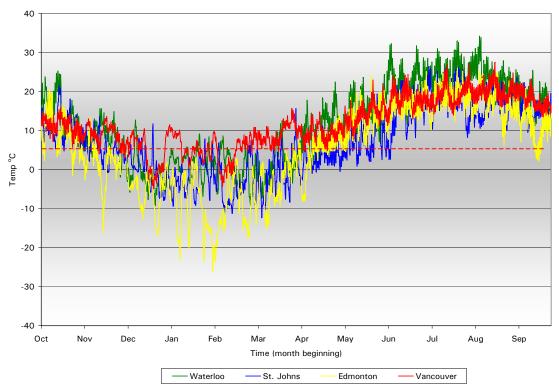


Figure 1.16: Temperature Versus Time
No Poly North, Inboard face of OSB (HML - Heavy Moisture Load)



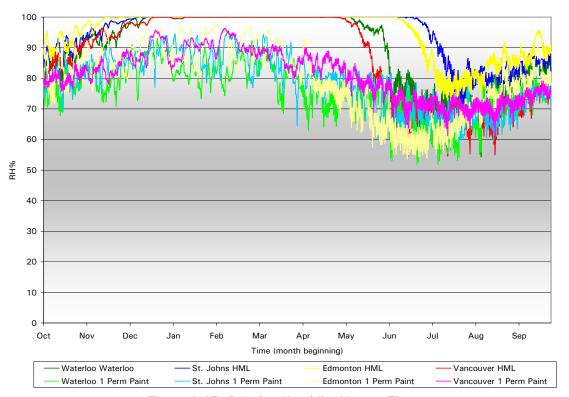


Figure 1.17: Relative Humidity Versus Time XPS North, Inboard face of XPS (HML - Heavy Moisture Load)

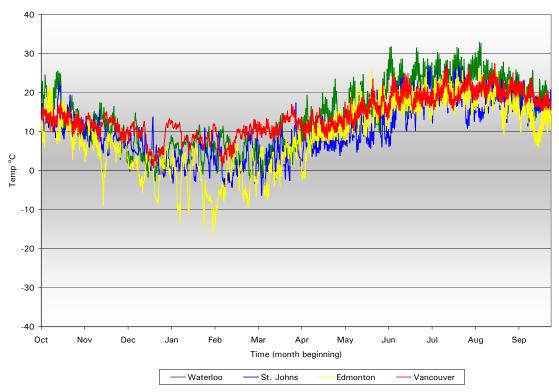


Figure 1.18: Temperature Versus Time XPS North, Inboard face of XPS (HML - Heavy Moisture Load)



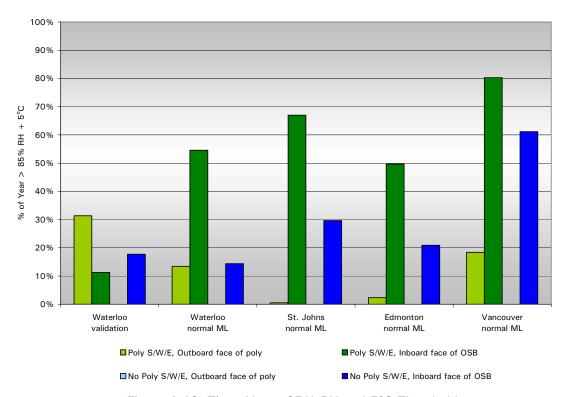


Figure 1.19: Time Above 85% RH and 5°C Threshold Poly & No Poly S/W/E

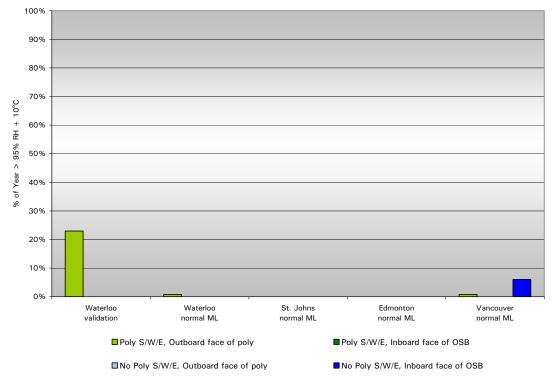


Figure 1.20: Time Above 95% RH and 10°C Threshold Poly & No Poly S/W/E



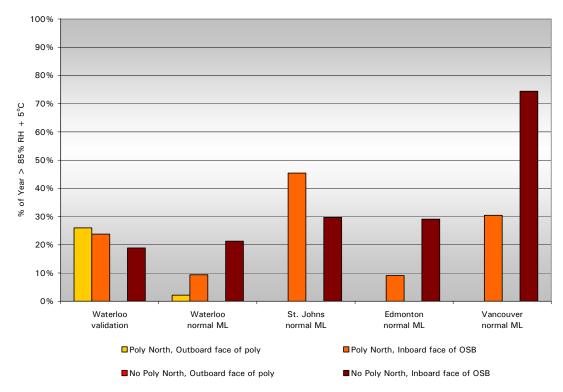


Figure 1.21: Time Above 85% RH and 5°C Threshold Poly & No Poly North

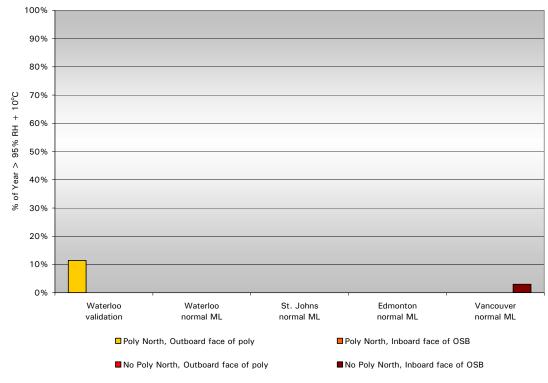


Figure 1.22: Time Above 95% RH and 10°C Threshold Poly & No Poly North



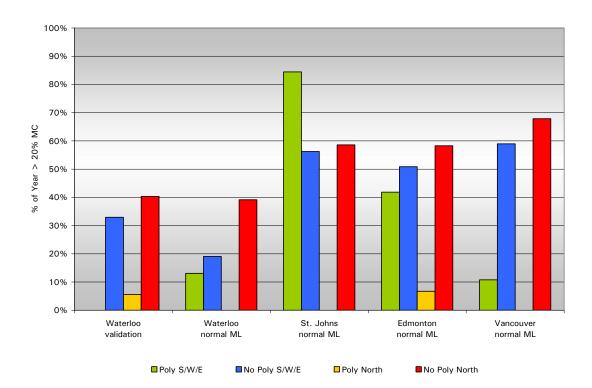


Figure 1.23: Time Above 20% MC Threshold Poly & No Poly, Inboard Face of OSB

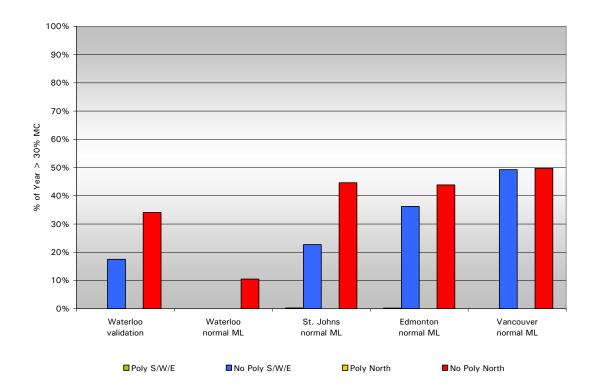


Figure 1.24: Time Above 30% MC Threshold Poly & No Poly, Inboard Face of OSB



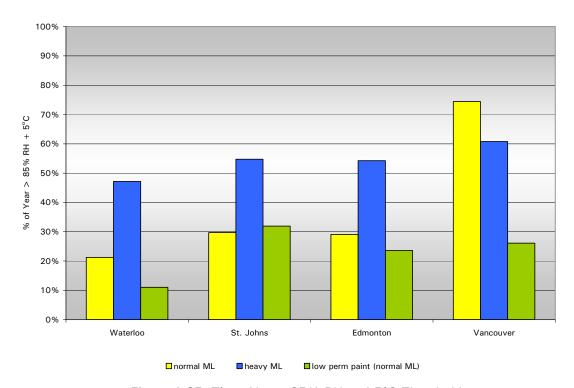


Figure 1.25: Time Above 85% RH and 5°C Threshold No Poly North, Inboard face of OSB

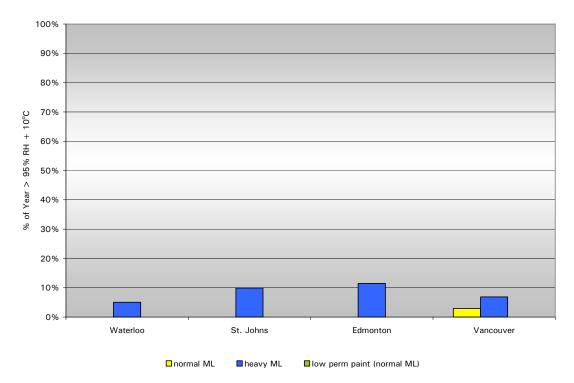


Figure 1.26: Time Above 95% RH and 10°C Threshold No Poly North, Inboard face of OSB



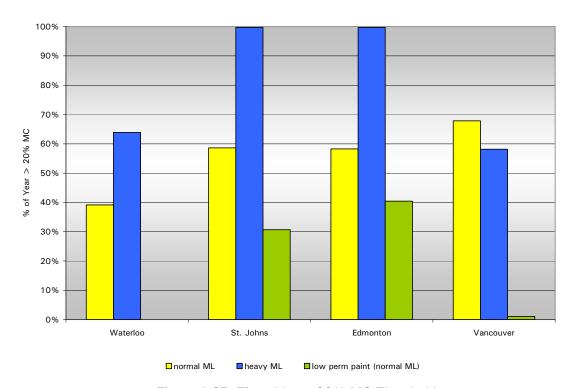


Figure 1.27: Time Above 20% MC Threshold No Poly North, Inboard face of OSB

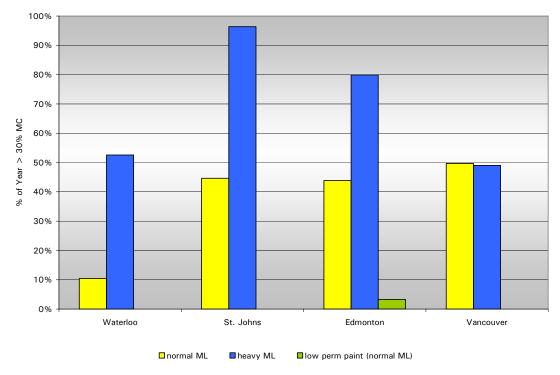


Figure 1.28: Time Above 30% MC Threshold No Poly North, Inboard face of OSB



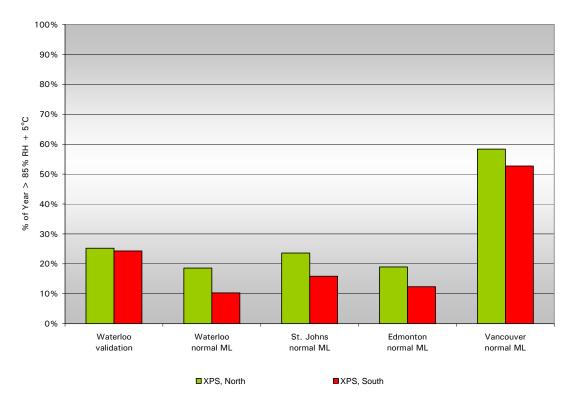


Figure 1.29: Time Above 85% RH and 5°C Threshold XPS, Inboard face of XPS

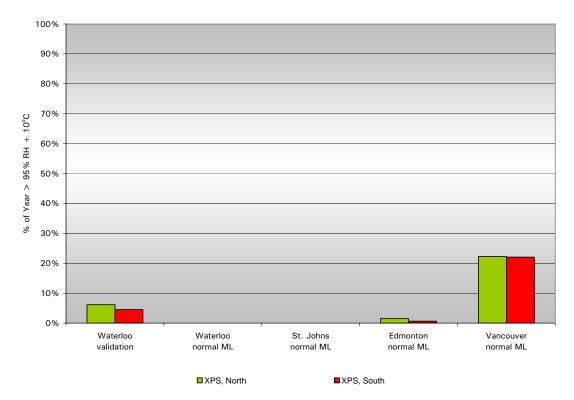


Figure 1.30: Time Above 95% RH and 10°C Threshold XPS, Inboard face of OSB



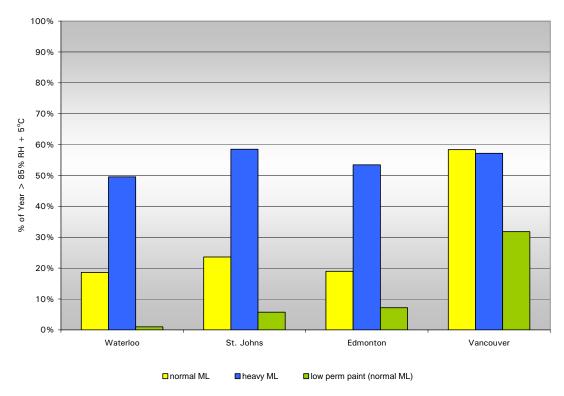


Figure 1.31: Time Above 20% MC Threshold XPS North, Inboard face of OSB

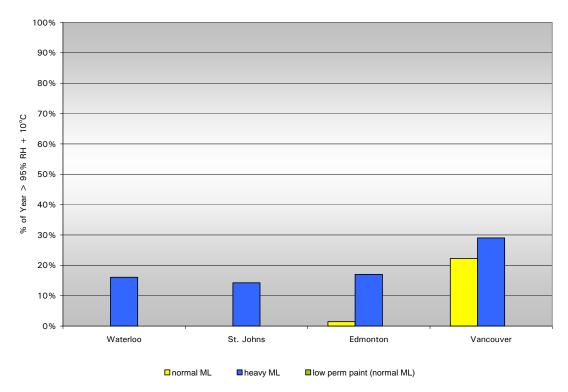


Figure 1.32: Time Above 30% MC Threshold XPS North, Inboard face of OSB



# APPENDIX E2 - MODELLING RESULTS, BASEMENT



#### 1.0 EXTRAPOLATION SIMULATIONS

The extrapolation simulations use the walls developed earlier with different interior and exterior conditions. However, two topics are discussed before proceeding with the full complement of simulations. First, due to the lack of temperature correspondence between the Kitchener site data and simulations, the runs using site data are presented here under extrapolations. Second, in analyzing the results, it was useful to develop an indicator of likelihood of condensation and/or rundown of moisture accumulation at an interface, due to the strong effects of liquid water on mold growth. Specifics on incorporating this tool into the simulation and interpretation of results are discussed.

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).

#### 1.1 Above Grade Simulations for Kitchener Site

Due to the lack of temperature correspondence between simulations and monitored data at the above-grade portion of wall, these simulations are presented under extrapolation. However, there were some similarities noted between the simulations and monitoring, when channels were available.

A comparison of relative humidities at the interface between the concrete and insulation is shown in Figure 1.1 (simulated data for roll blanket and fiberglass/GWB/latex paint) and Figure 1.2 (monitored data for roll blanket, fiberglass/poly, and fiberglass/GWB/latex paint). This interface is of particular interest because it is the likely location for wintertime condensation.

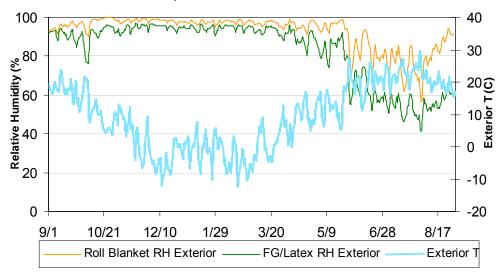




Figure 1.1: Simulation data: relative humidity at concrete-insulation interface, above-grade

A caveat must be noted for the monitored data: this is a calculated relative humidity value, based on the dewpoint temperature measured at the middle of the insulation, and the temperature of the concrete surface. However, the vapour resistance of batt insulation is very low, so this is a reasonable assumption for the purposes of this calculation.

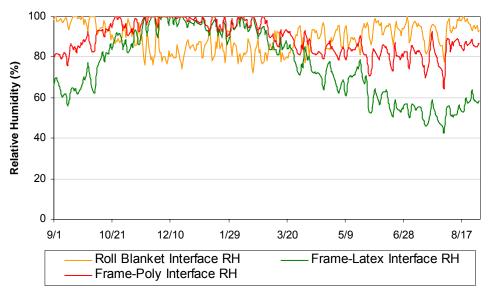


Figure 1.2: Monitored data: relative humidity at concrete-insulation interface; above-grade

Overall, relative humidity correspondence is relatively low, as would be expected by the lack of temperature correspondence. In the simulation, the polyethylene (roll blanket) and latex paint walls both show extended periods at high (90% +) relative humidity; this continues through the spring, until the temperature gradient shifts inward (mid-May). At that point, both relative humidity levels drop, and the latex paint wall shows lower humidity than the polyethylene wall, since it allows drying to the interior.

In contrast, the monitored data for the two frame walls shows a shorter period of high wintertime RH, dropping in mid-March. This can likely be ascribed to the warmer temperatures seen at this interface, due to the two-dimensional effects mentioned earlier. In the winter, the roll blanket wall has humidity levels substantially lower than the simulated wall (~80-90% RH, vs. 90% + RH). At the end of the winter, the latex paint wall RH falls (like the simulation); however, the polyethylene-based walls (roll blanket and frame-poly) remain at higher levels.

Similar plots are shown for relative humidity at the interface between the insulation and the interior vapour control layer (polyethylene, or exterior face of gypsum board), to show the possibility of summertime condensation due to inward vapour drives. The interface between the concrete and XPS is also included in these plots. In the test walls, moisture content wafers were placed



at these locations; therefore, a plot showing calculated relative humidity is shown for comparison. This metric introduces a fair amount of error; however, it is useful for examining high humidity conditions. The simulated data is shown

in Figure 1.3, and the monitored (wafer) data in Figure 1.4.

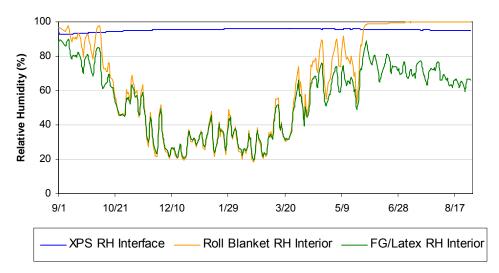


Figure 1.3: Simulation data: upper-height relative humidity at interior interface

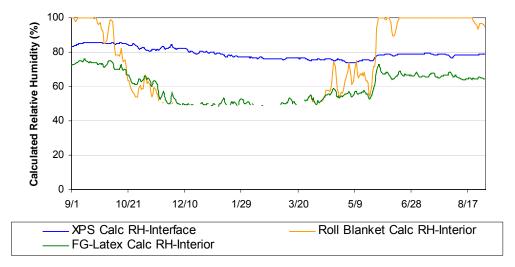


Figure 1.4: Monitored data: upper-height wafer sensors (calculated RH) at interior interface

These summertime comparisons seem to be a slightly closer match than the previous comparisons. Like the comparison between simulated and monitored data at the below-grade portion of the wall (Appendix D2, Sections 1.2.4 and 1.2.5), the XPS wall has higher sustained RHs in the simulation. The summertime plots of the roll blanket and fiberglass/latex paint walls have similar patterns: summers with high relative humidity are seen in the roll blanket wall, while the latex paint wall allows drying.

However, the simulation has much lower relative humidity levels during the winter. Again, this can be explained by the lower temperatures seen at the concrete in the simulations (relative to monitored data). The cold concrete will



"pull down" the dewpoint in the fiberglass insulation, resulting in humidity levels in the 20-40% range.

Overall, similar behavior patterns are seen between the simulation and monitored data; however, the lack of temperature correlation impedes the direct validation of the model.

# 1.2 Condensation Layer Diagnostic Tool

#### 1.2.1 Development of the Condensation Layer

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 of assemblies.

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/m² for non-absorptive materials, or 1000 g/m² 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/m². 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.

With this limit in mind, a useful criterion to estimate the risk of a wall assembly is to determine the maximum condensation seen in the simulation, and to compare it with this limit. This was done in WUFI by creating a fictitious "condensation layer" material with a very steep moisture storage function (sorption isotherm); the storage at 100% RH was set to the condensation rundown limit. This fictitious layer was specified as 1 mm thick, which simplified setup, and was given the equivalent storage capacity of 500 g/m².

The remaining properties were set to minimize the impact of this layer on the simulation. The diffusion resistance factor (DRF, [-]) was set to 0.5 (twice as permeable as a layer of "still air," similar to the "Air Layer" materials in the WUFI database). The specific heat was set to a small figure (100 J/kg·K). All of the remaining hygric extensions (material properties) were left blank.



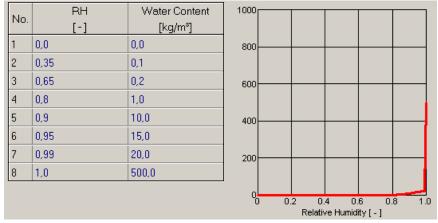


Figure 1.5: Sorption isotherm for WUFI imaginary condensation layer

This material was incorporated in simulations at interfaces likely to have condensation, based on monitored data.

#### 1.2.2 Sample Use of the Condensation Layer

A sample use of this condensation layer is shown in the figures below, which examine the relative humidity at the interface between the concrete and insulation at the upper portion of walls with roll blanket insulation, fiberglass/latex paint, and no vapour control (but no air transport/bypass). In the whole-year plot (Figure 1.6), the high wintertime humidity levels are difficult to read.

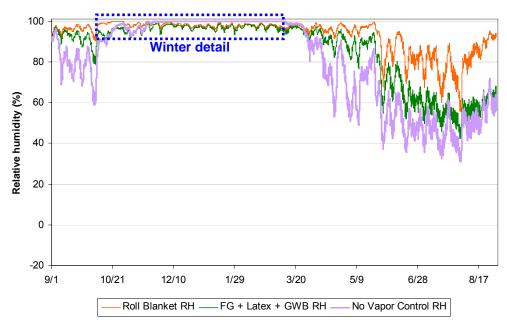


Figure 1.6: Simulation relative humidity at concrete-insulation interface, above grade portion

Greater resolution can be seen in the winter detail (Figure 1.7): it shows that the "no vapour control" wall remains at 100% RH for much of the winter, while the



other walls vary between 95-99% RH. Although this suggests that condensation is occurring at the "no vapour control" wall, it does not give an indication of the magnitude of the accumulation.

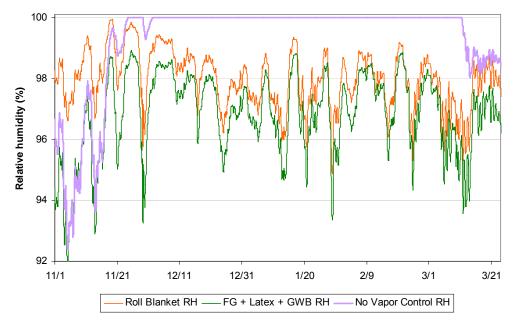


Figure 1.7: Simulation relative humidity at concrete-insulation interface, winter detail

The relative performance of these walls is much clearer when the moisture content of the condensation layer is plotted in Figure 1.8 below; the accumulation can be compared with the  $500 \text{ g/m}^2$  limit used in the DIN 4108 standard. Exterior temperature is plotted for reference.

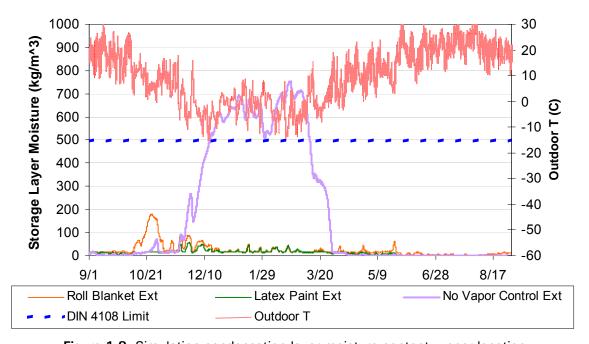


Figure 1.8: Simulation condensation layer moisture content, upper location



The results indicate a significant accumulation of wintertime condensation at the concrete-insulation interface in a wall without any interior vapour control; this amount exceeds the rundown storage limit of the layer. This representation also shows the drying of this layer in the spring.

The small spikes seen in late October can be explained as well. In the roll blanket (polyethylene) wall, some moisture accumulated in the insulation space at the end of the fall, due to the inward vapour gradient. This spike is due to the drop in temperatures seen at the concrete interface, at the onset of winter. A similar but smaller spike is seen in the "no vapour control" wall, corresponding to the extended period of cold weather in early November.

#### 1.2.3 Condensation Layer Response in Above-Grade Field Measurements

As mentioned in Appendix D1, Section 1.1.4, the simulated temperatures did not match the monitored data at the above-grade portions of the Kitchener model. However, this was noticeably worse for the winter portion of the simulation; the summer data was a closer match. Therefore, the simulated condensation layer was run in the Kitchener above-grade model, to try to correlate predicted accumulation levels with the effects seen in the data and in disassembly.

First, the winter (i.e., less accurate) data was plotted (Figure 1.9); it shows minimal accumulation, even though the concrete-insulation interface is noticeably colder than reality. Note the moisture content spike in late October in the roll blanket wall; this is likely due to moisture that has accumulated in the insulation space at the tail end of the summer, which is shifted to the exterior by the change in temperature gradient. Neither the latex paint nor the roll blanket wall show condensation over the rundown limit in this simulation, which matches observations made during disassembly.



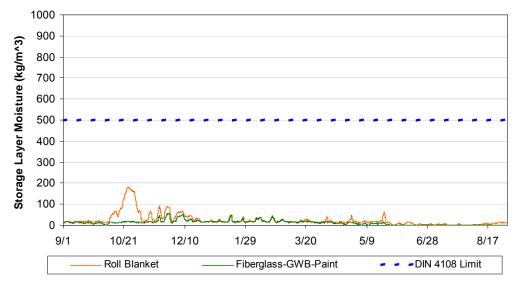


Figure 1.9: Concrete-insulation interface condensation layer MC, Kitchener data, above grade

This is followed by a plot of the accumulation at the condensation layer located between the insulation and either the polyethylene or the interior side of the gypsum board (Figure 1.10). The first summer is dry for both walls; however, during the second summer, the polyethylene roll blanket shows accumulation that exceeds the DIN 4108 limit, peaking over 900 g/m². This matches monitored data and disassembly observations: the moisture content wafer at this location in the roll blanket wall clearly showed the presence of liquid water, well over the 100% RH level.

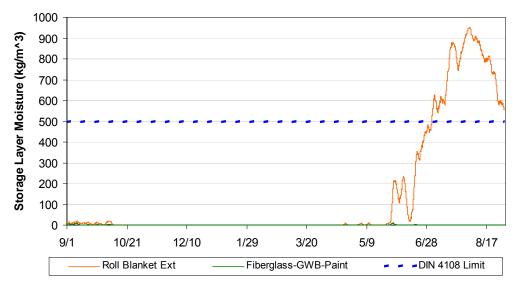


Figure 1.10: Vapour barrier condensation layer MC, Kitchener data, above grade



# 1.3 Boundary Conditions for Extrapolations: Exterior

## 1.3.1 Above Grade Boundary Conditions

The exterior conditions used for extrapolation simulations were several representative Canadian climates, which included Vancouver, BC; St. John's, NL; and Edmonton, AB. A summary of the Environment Canada is shown in Table 1.1 and Figure 1.11 below; the graph includes the historical data for Waterloo, ON.

Although the weather can be quickly compared in the monthly average graph, the patterns should be briefly described. Vancouver, BC represents a maritime coastal climate, and has both temperate winters and summers. St. John's, NL is a northern Maritime climate, and has winters roughly equivalent to Waterloo; however, it has greater rainfall (1500 mm vs. 900 mm), and cooler summers. Edmonton, AB represents a cold plains climate; it has significantly colder winters than Waterloo, and cooler summers. As shown by the cooling degree data, all three of these climates have minimal cooling loads (80 CDD 18° C or less).

In addition, three other climates (Toronto, ON, Montreal, QC, and Minneapolis, MN) are shown in Table 1.1 for reference. The average Environment Canada data for Toronto is similar to the monitored year in Waterloo, and the Montreal and Minneapolis data are included for later use.

**Table 1.1:** Climate data for extrapolation locations

			Average T	Monitored T	
	HDD 18° C	CDD 18° C	(°C)	Avg.	
Waterloo (monitored				_	
year)	3558	349	9.2		
Waterloo, ON	4288	338	6.7	-2.5	
Vancouver, BC	2926	80	10.1	+0.9	
Saint John's, NL	4881	58	4.7	-4.5	
Edmonton, AB	5708	51	2.4	-6.8	
Toronto, ON	3570	359	9.2	-0.1	
Montreal, QC	4891	158	5.0	-4.2	
Minneapolis, MN	4376	388	7.5	-1.8	



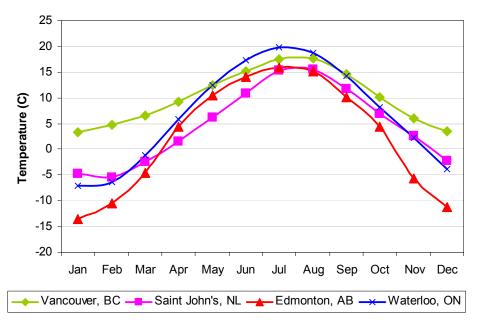


Figure 1.11: Monthly average temperatures for climate locations (Environment Canada data)

The historical data is compared with BEGHut weather conditions in Table 1.1 and Figure 1.12; the experimental year was warmer than average, especially in January 2006.

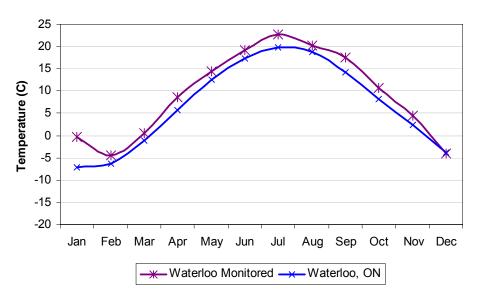


Figure 1.12: Comparison of monitored and climate average monthly temperatures for Waterloo

Next, it was necessary to choose simulation parameters to provide worst-case conditions. Risk of wintertime condensation at the upper portion of the wall is related to the temperature of the concrete surface, which in turn is linked to the exterior temperature. The worst-case conditions would be north facing or with



no solar exposure; in locations with a "warm" and "cold" weather year (Edmonton, Vancouver, Toronto), the "cold year" was chosen.

Summertime inward vapour drives are related to the temperature of the saturated material, and thus, they are tied to exterior temperatures and orientation. Therefore, the highest solar exposure (south orientation) and the "warm" year climate file were used in these simulations. Simulation work by Swinton and Karagiozis (1995) demonstrated the worst vapour drives on the south orientation in a Montreal climate, but problems still occurred on the north orientation. One matter of curiosity is whether sufficiently cool summers will render inward vapour drive problems negligible or not.

## 1.3.2 Below Grade Boundary Conditions

The extrapolation boundary conditions for the below grade portions of the wall pose some issues: soil temperatures are not only a function of outdoor temperature, but also the soil's thermal diffusivity (ratio of thermal conductivity and volumetric heat capacity), and therefore soil composition and moisture content. Since there are too many unknowns to give definitive soil conditions, the following approach was used to do some form of geographic extrapolation.

The constant deep ground soil temperature is typically 2-6° C above the mean annual air temperature (Hutcheon and Handegord 1983); the monitored data from the Kitchener site follows this general trend. The sinusoidal temperature variation at 900 mm soil depth is centered at roughly 12° C, and the lower wall at roughly 14° C, which is within the range of 9° C (average annual temperature, Table 1.1) + 2 to 6° C. Therefore, for geographic extrapolation, the temperature profile at the lower concrete interface was offset by the mean annual temperature difference (between locations), and used as the exterior condition. However, this does not address the amplitude of the seasonal sinusoidal pattern, which would be a function of the annual climate swing and soil conditions.

These boundary conditions lend themselves to a simple initial analysis before proceeding with hourly hygrothermal models, which is to compare the concrete surface temperatures with interior dewpoints. If the surface temperature never exceeds dewpoint, there is no chance of condensation. However, even if this is the case, it is worthwhile to run hygrothermal modeling to demonstrate relative drying rates between assemblies.

# 1.4 Boundary Conditions for Extrapolations: Interior

Interior boundary conditions were also varied in the extrapolation simulations: relative humidity was the significant experimental variable. Sinusoidal annual humidity profiles were created to provide "low," "middle," and "high" humidity loadings, as shown in Table 1.2 and Figure 1.13.



Table 1.2: Interior humidity conditions used in extrapolation simulations

	Low	Mid Humidity:	High
	<b>Humidity:</b>	40%	<b>Humidity:</b>
	30%	low/60% hi	<b>50</b> %
	low/60% hi		low/65% hi
Waterloo, ON	•	•	•
Vancouver, BC		•	•
Saint John's, NL	•	•	•
Edmonton, AB	•	•	

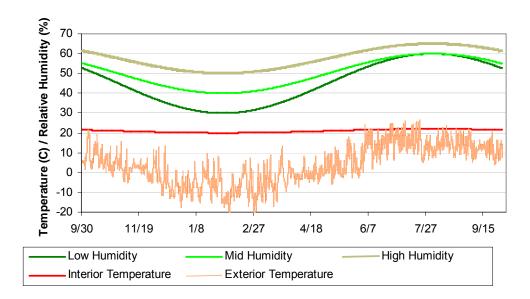


Figure 1.13: Summary of interior conditions (temperature and RH) with Waterloo exterior T

Not all humidity profiles were not used in all locations, as shown in Table 1.2. The Vancouver coastal climate is expected to have relatively high wintertime interior dewpoints, due to climate patterns, low ventilation rates, and high occupancy. Edmonton has very cold winters, resulting in low wintertime dewpoint temperatures (thus the elimination of the "high" humidity condition).

These interior humidity profiles are shown in terms of dewpoint in Figure 1.14. Interior temperature varies sinusoidally over the year from 20 to 22° C.



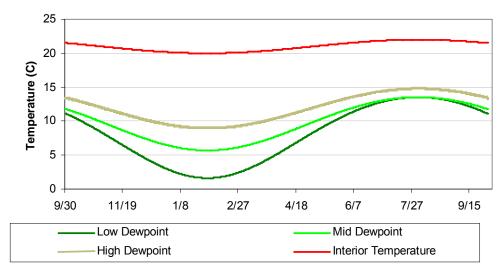


Figure 1.14: Interior conditions, shown as temperature and dewpoint (° C)

These interior conditions were compared to previous measurements. The Ruest et. al. (1993) measurements of basement wintertime dewpoints across Canada were mostly in -5 to 5° C range (corresponding to "low" humidity conditions or drier). The exception was dewpoints in British Columbia, which were mostly in the 5-10° C range ("mid" to "high" humidity conditions).

Interior wintertime dewpoints collected by Building Science Corporation in the Chicago area were centered on the 5-8° C range, but with variations up above 12° C and down to near 0° C. The majority of the data is similar to the "mid" and "high" humidity ranges. It is worth noting, however, that these were recently constructed houses in their first season of occupancy. Summertime dewpoint data indicated that window ventilation was used for cooling in most houses; this resulted in dewpoints in the 15-20° C range, with peaks above this level. This is higher than the summertime interior conditions to be used in the simulations (13-15° C dewpoint).

## 1.5 Above-grade Extrapolations

At the above-grade portion of the wall, simulations were run for the three climate locations, as well as for Toronto. Toronto weather was used instead of Waterloo data for two reasons: a "cold" year and "warm" year were available, and being a larger population center, it might provide greater perceived applicability.

In addition to the three materials used in the Kitchener test basement, four other assemblies were simulated. As a bounding condition, a wall with fiberglass insulation and no interior vapour control was used. WUFI does not account for the bulk air transport that would occur through low-density insulation, but it does show the effect of vapour diffusion through this permeable material. Second, in the United States, the roll blanket material is available with a



permeable perforated polypropylene facer attached the fiberglass. This facer has been tested by Building Engineering Group (as detailed in Appendix D), giving values of 720 ng/(s·m²·Pa)/13 perms (dry cup) to 790-850 ng/(s·m²·Pa)/14-15 perms (wet cup). Third, a fiberglass batt with a Kraft facer was simulated as well; the variable permeability of this material was simulated, ranging from 17 ng/(s·m²·Pa)/0.3 perms (dry cup) to 34 ng/(s·m²·Pa)/0.6 perms (wet cup). Finally, in some simulations, a bare un-insulated concrete wall was used as a comparison.

#### 1.5.1 Toronto Simulations

The first set of simulations examined the risk of wintertime condensation at the above-grade portion of the wall. As mentioned earlier, these simulations are conservative, given the warmer temperatures seen at the concrete in the monitored data, due to two-dimensional effects. 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 these graphs: early simulations indicated superior performance compared to these cavity walls even at the worst conditions; success of this assembly in the field is evidence that the simulation captures the behavior correctly.

The accumulation at the fictitious condensation layer is shown for these walls under "low" (Figure 1.15), "mid" (Figure 1.16), and "high" (Figure 1.17) humidity conditions; the DIN 4108 500 g/m² threshold is shown on the graphs as a proposed pass/fail criterion.



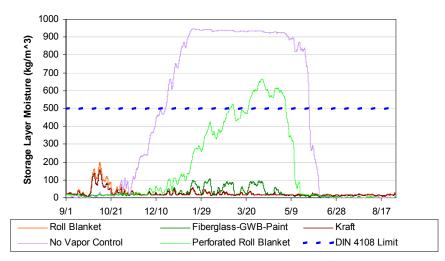


Figure 1.15: Condensation layer MC, Toronto AG, low RH

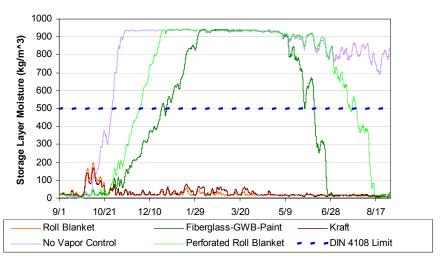


Figure 1.17: Condensation layer MC, Toronto AG, high RH

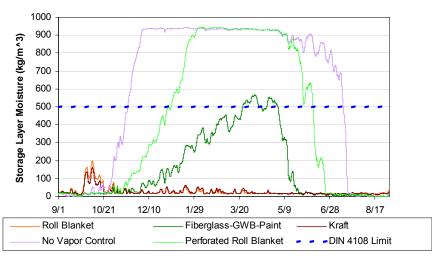


Figure 1.16: Condensation layer MC, Toronto AG, mid RH

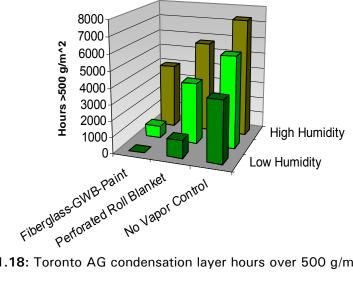


Figure 1.18: Toronto AG condensation layer hours over 500 g/m<sup>2</sup>

The results show consistent patterns: the walls with polyethylene or Kraft paper, which are classified as vapour barriers (less than 57 ng/(Pa·s·m²)/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 500 g/m². 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 500 g/m² 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 Figure 1.18, showing the increase in hours over the condensation limit with increasing permeability, and with increasing interior humidity.

Another phenomenon simulated here 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. A condensation layer was placed on the exterior side of the vapour control layer; the resulting moisture accumulation levels are shown in Figure 1.19. It 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. Note that the inward vapour drive failure shown here 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.



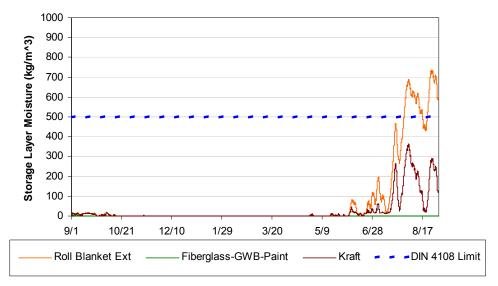


Figure 1.19: Interior cavity side condensation layer MC, Toronto AG, mid RH

Another way to compare these walls is to show the temperature and humidity conditions (isopleths) at a given monitoring location; the conditions at the concrete-insulation interface for the roll blanket and fiberglass-latex paint walls are shown in Figure 1.20 and Figure 1.21, respectively. These are the results for the "mid" humidity condition; note that the y-axis changes between these plots.

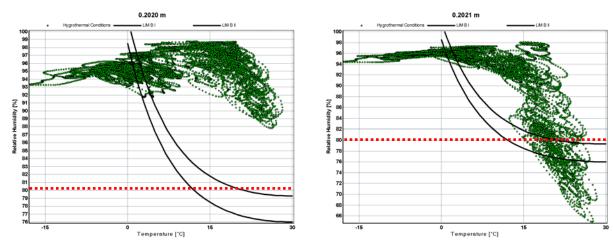


Figure 1.20: Roll blanket isopleth at concreteinsulation interface, "mid" humidity

Figure 1.21: Latex paint-gypsum isopleth at concrete-insulation interface, "mid" humidity

These plots indicate that this interface has extended periods at high RH. The proposed ASHRAE 160P Standard (2006) defines mold growth failure when the RH exceeds 80% RH (shown by dotted red line) for one month. All of these walls fail this metric; however, the vulnerability of the assembly components should be accounted for. For instance, the XPS wall has materials at the high humidity interface with minimal nutrient value for mold growth, compared to wood studs in the frame walls.



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 LIMBau I level (biodegradable materials such as wallpaper, plasterboard) and the LIMBau II level (porous substrates such as mineral building materials and some woods). These two curves are shown in Figure 1.20 and Figure 1.21: both of these walls show significant portions of the year above the LIMBau II level. Although these limits are known to be generally conservative, these isopleths indicate the risk of placing moisture-sensitive materials such as wood framing at this location.

#### 1.5.2 Vancouver Simulations

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" (Figure 1.22) and "high" (Figure 1.23) interior humidity levels. 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 limit at the "high" level.

In addition, 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: values peaked near 200 g/m $^2$ , as shown in Figure 1.24.



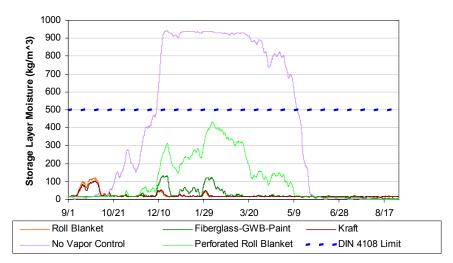


Figure 1.22: Condensation layer MC, Vancouver AG, mid RH

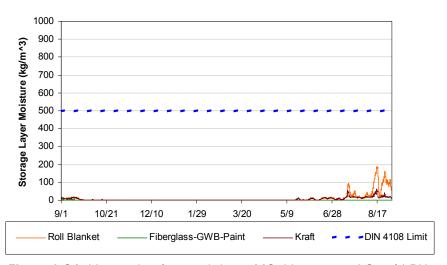


Figure 1.24: Vapour barrier cond. layer MC, Vancouver AG, mid RH

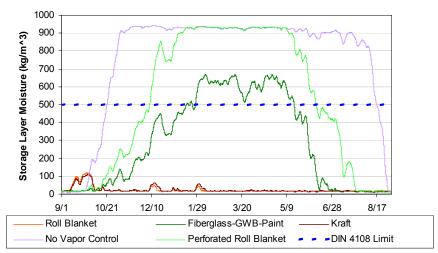


Figure 1.23: Condensation layer MC, Vancouver AG, high RH

#### 1.5.3 St. John's Simulations

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 Figure 1.26 through Figure 1.29). The latex paint wall remained below the accumulation threshold only at "low" humidity conditions; all other combinations exceeded this 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/m², compared to over 700 g/m² in Toronto. 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.

#### 1.5.4 Edmonton Simulations

Edmonton is a substantially colder climate (5708 HDD 18° C) than St. John's (4881 HDD 18° C). Therefore, it is unsurprising that the wintertime condensation performance of the permeable assemblies is even worse: as shown in Figure 1.25, even the fiberglass-latex paint assembly under "low" humidity conditions has significant hours over the 500 g/m² threshold. 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<sup>2</sup>.

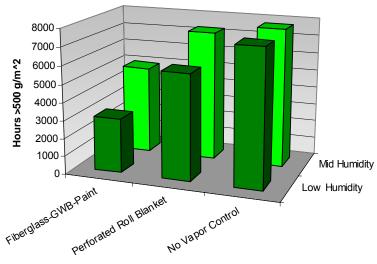


Figure 1.25: Edmonton AG condensation layer hours over 500 g/m<sup>2</sup>



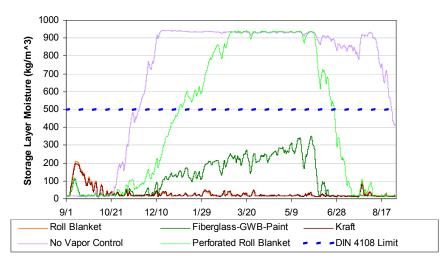


Figure 1.26: Condensation layer MC, St. John's AG, low RH

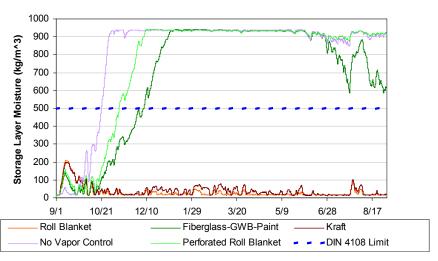


Figure 1.28: Condensation layer MC, St. John's AG, high RH

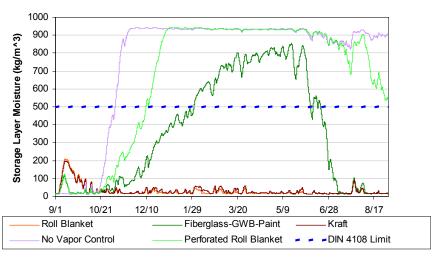


Figure 1.27: Condensation layer MC, St. John's AG, mid RH

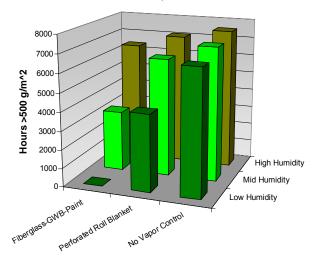


Figure 1.29: St. John's AG condensation layer hours over 500 g/m<sup>2</sup>

1.6 Below-grade Extrapolations

# The first step for the below-grade extrapolations was to narrow the focus on the most informative cases to model. As per previous cases, the interior relative

humidity was varied, and several interior insulation assemblies were used. However, it is notable that the worst case below grade situations will typically be at the "lowest" location: it has the greatest thermal lag, and therefore the coldest temperatures (and greatest chances of condensation) under summertime high dewpoint conditions. Any wintertime issues seen at the "middle" height would occur in worse form at the "upper" or above grade location. Therefore, the first set of simulations uses the "lowest" boundary conditions for the Kitchener field site, and varies interior RH and assemblies.

In addition, the synthesized "Edmonton" soil conditions (as described in Section 1.3.2) were used as a second set of boundary conditions. Edmonton was the coldest climate in the selection, so it is used as a "bounding" condition. The applicability of an extensive set of simulations in all climates would be questionable, given that they would all be synthesized below-grade conditions, simply offset by the difference in average annual temperature, without regard for amplitude changes.

#### 1.6.1 Simulations Using Kitchener Boundary Conditions

The first cursory analysis was to plot the interior and exterior boundary conditions over the year, as shown in Figure 1.30. It is notable that the interior temperature is always higher than the lower wall temperature, showing an outward thermal gradient throughout the year. Second, the exterior boundary conditions (100% RH at the "Wall T Lower" temperature) are at a higher dewpoint (absolute moisture content) for almost all of the year, demonstrating a largely inward vapour gradient. Even though the concrete is not entirely at 100% RH, it is at 90% RH or higher through most of its thickness; we can infer that drying of the concrete to the interior will occur. There appears to be close to no chance of interior moisture condensing on the concrete surface; there is a minimal overlap in late winter.



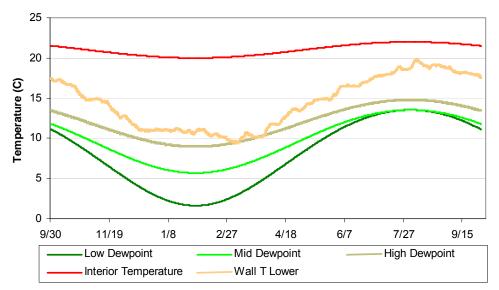


Figure 1.30: Interior dewpoint extrapolation conditions, and lower wall temperature

After examining the initial results of the hygrothermal simulations, it was necessary to create criteria to interpret and compare them. The results were first compared using the "condensation layer" approach used at the above grade simulations, as shown in Figure 1.31. The simulations were run over a period of six years at the "high" relative humidity condition; the plot shows the condensation layer at the concrete-insulation interface. All of the walls except for the roll blanket show minimal accumulation, with the Kraft paper wall showing a small rise during the winter seasons. However, the polyethylene roll blanket shows a seasonally ratcheting pattern of increasing accumulation due to movement of moisture from the concrete into the fiberglass batt space. Although the polyethylene peaks increase towards the 500 g/m² limit, it does not reach the limit during the six years simulated here. These results show that thermal and moisture drives in the below-grade environment are less powerful and dynamic than the above-grade portion.



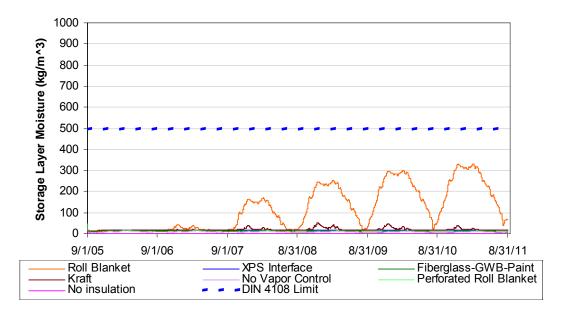


Figure 1.31: Condensation layer accumulation for lower location, "high" relative humidity

Since the condensation layer approach does not differentiate the assemblies well, the isopleths at the concrete-insulation interface were compared, as shown for the least and most permeable assemblies (roll blanket and no vapour control; Figure 1.32 and Figure 1.33). Although the roll blanket wall shows much higher sustained moisture levels, both of these assemblies remain above LIMBau II for the majority of the year. Although the more permeable option could be considered "better" (drying below the LIMBau II state for part of the year), this method does not provide much differentiation between assemblies.

Since the interface conditions are not at condensation, but are at sustained high relative humidity levels, another approach was considered.

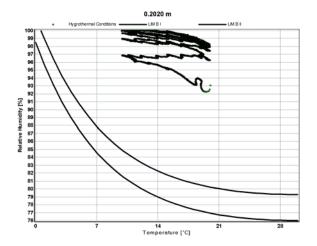


Figure 1.32: Roll blanket isopleth at concreteinsulation interface, "mid" humidity

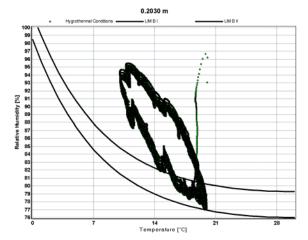


Figure 1.33: No vapour control isopleth at concrete-insulation interface, "mid" humidity



Another way to compare these assemblies was to record the drying of the concrete to the interior. The water content of the concrete wall is plotted in Figure 1. 34 ("low" humidity conditions) and Figure 1. 35 ("high" humidity conditions). As one might expect, the drying of the concrete increases with greater permeability of the interior insulation, given that the damp-proofing prevents drying to the exterior. One simulated option to leave the concrete bare (i.e., no interior insulation); as expected, it shows the fastest drying, but is only slightly faster than the most permeable options (no vapour control and perforated roll blanket). In addition, lower interior relative humidity increases the drying rate for the more permeable assemblies, but not by a large margin.

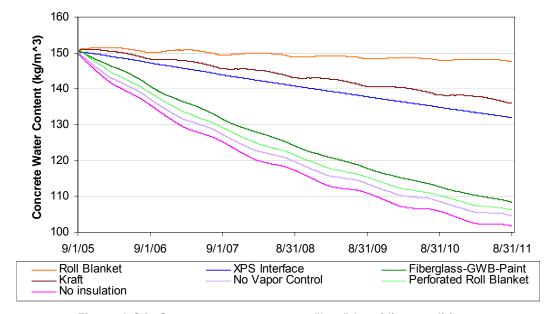


Figure 1.34: Concrete water content, "low" humidity conditions



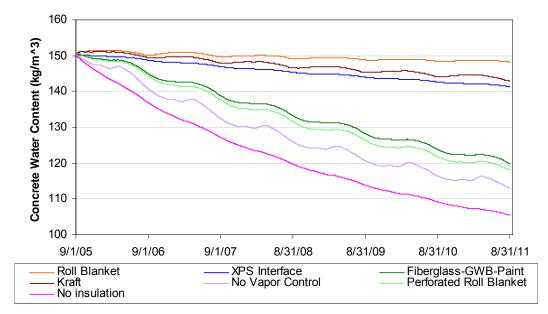


Figure 1.35: Concrete water content, "high" humidity conditions

It can be argued that the drying of the concrete has little relevance to actual performance, given that even the most permeable options show high relative humidity levels at the concrete-insulation interface, even after several years of drying (as per Figure 1.33). However, the least permeable material (polyethylene) shows rising humidity levels at the interface heading towards condensation (Figure 1.32), which is a much more dangerous condition for mold growth than high RH levels. If nothing else, faster-drying assemblies will be at lower risk levels sooner.

One traditional argument for low permeance materials at the below-grade portion of the wall is to reduce moisture flux into the basement, resulting in higher interior humidity levels and mold. The moisture introduced from the concrete can be compared with typical interior moisture generation rates, to understand the relative magnitudes. Over the six years, the greatest drying is seen in the "no insulation" option, drying from 150 to 100 kg/m<sup>3</sup>. For the 0.20 m (8") concrete wall and a 30 by 40 foot (9.1 m x 12.2 m) basement with 8foot (2.4 m) high walls, this gives an average rate of 0.5 liters/day. Note that this is a rough estimate, ignoring the differences at the above-grade part of the wall, which dries to interior and exterior. This rate can be compared to average moisture generation rates of a family of four, at 10-15 liters/day (Straube and Burnett 2005). Seasonal desorption effects are listed at 3-8 liters/day (depending on house construction). As another comparison point, a person generates 0.75 to 1.2 liters/day (from sedentary to average). So although the drying of the concrete construction moisture can add noticeable amounts of water, it is not a large increase in moisture generation that would result in substantially higher interior humidity levels by itself. It is more of a concern in



terms of the moisture accumulation within interior insulation assemblies, where it can cause much greater damage.

Note that the calculated moisture release rate only includes drying of the concrete's construction moisture, as opposed to vapour transmission from the soil through the concrete: the impermeable exterior dampproofing keeps this from occurring in the simulation. Separate WUFI simulations were run comparing vapour diffusion with capillary transport through an 8" concrete wall at isothermal conditions. The moisture transport rate due to capillary transport (i.e., exterior precipitation conditions every hour) was over an order of magnitude higher than the rate with the exterior at 100% relative humidity. This demonstrates the vital importance of bulk water drainage and capillary separation between the soil and the concrete wall.

# 1.6.2 Simulations Using Edmonton Simulated Boundary Conditions

Below grade simulations were run using the "synthesized" Edmonton soil conditions; i.e., the Kitchener temperature profile, offset by the mean annual temperature difference between the two climates. These boundary conditions are shown in Figure 1.36. As per the above-grade runs, only "low" and "mid" humidity levels were used.

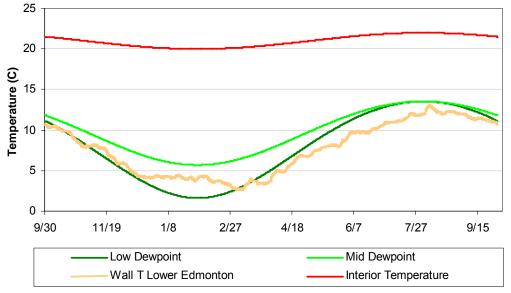


Figure 1.36: Interior dewpoints and lower wall T for Edmonton extrapolation

Again, the thermal gradient is always outward. But in contrast with the Kitchener relationships, the interior dewpoint is higher than the exterior or concrete dewpoint for most or all of the year. These conditions would cause wetting or condensation on the concrete, as opposed to the drying seen in the Kitchener simulations.



The simulations were first examined using the condensation layer at the concrete-insulation interface; results are shown for "low" (Figure 1.37) and "mid" (Figure 1.38) humidity conditions. In the "low" humidity simulation, the higher permeability options (no vapour control, perforated facer, latex paint) quickly accumulate moisture and rise above the 500 g/m² limit. However, the vapour control options (polyethylene, Kraft paper, XPS) also show a ratcheting rise towards this limit. The only option that does not show condensation/accumulation at the interface is the "no insulation" option, which leaves that surface open to the interior.

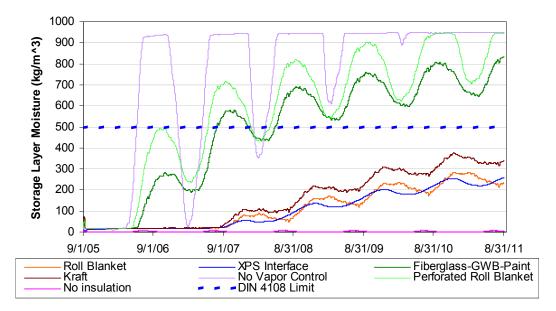


Figure 1.37: Accumulation at storage layer, Edmonton extrapolation, "low" humidity

Running the simulations at "mid" humidity levels result in an even faster failure for all of the walls, except for the "no insulation" option, which remains dry.



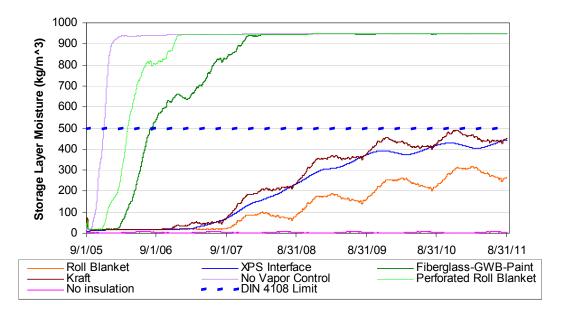


Figure 1.38: Accumulation at storage layer, Edmonton extrapolation, "mid" humidity

The difference in behavior of Kitchener and synthesized Edmonton conditions is shown in another form in Figure 1.39. When the interior dewpoint and the exterior boundary condition temperatures are plotted in Figure 1.30 and Figure 1.36, the difference between the two could be "integrated" into a dewpoint degree-hour total for the year. For instance, when the "low" humidity condition is compared with the Edmonton exterior condition, it will dry the wall part of the year, and wet it for the remainder: this calculation demonstrates the net effect over the year.

As shown in the plot, the Kitchener boundary conditions always result in drying of the wall, with a smaller drying potential at higher relative humidity. In contrast, in the synthesized Edmonton conditions, there is always a net wetting potential over the course of the year.



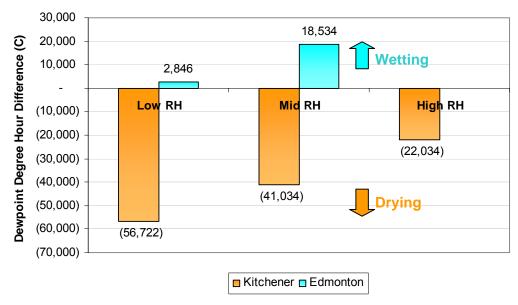


Figure 1.39: Dewpoint degree hour differences between concrete & interior conditions

As a final comparison, the concrete moisture content over the six year modeled period is shown in Figure 1.40 for the "low" humidity conditions. All of the higher permeability options (no vapour control, perforated facer, latex paint) show strong moisture accumulation in the concrete. The vapour control options (polyethylene, Kraft) show a small rise, but appear to be stable. The only option that shows drying is the "no insulation" option.

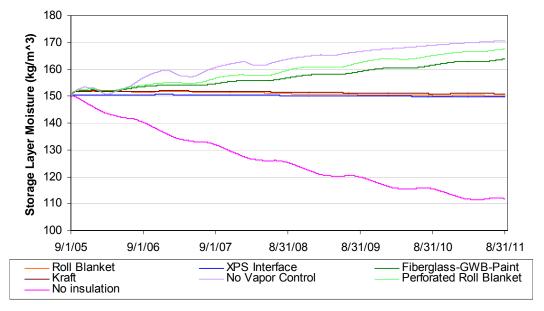


Figure 1.40: Concrete water content, "low" humidity conditions



However, these 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 relative humidity levels in these assemblies are generally not high enough to cause widespread problems. Third, Edmonton has an extremely dry climate; a modified version of the dewpoint-temperature comparison (Figure 1.36) is shown with average Edmonton weather exterior dewpoints (Figure 1.41).

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 is more likely, resulting in similar inside and outside dewpoints. If anything, monitored data typically shows 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.

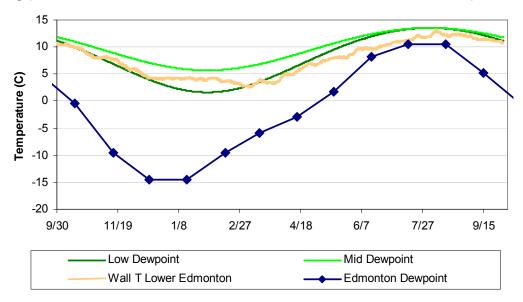


Figure 1.41: Interior dewpoint, lower wall temperature, and Edmonton exterior dewpoint



# 1.6.3 Simulations Using High Summertime Interior Relative Humidity

Additional simulations were run to examine situations that might cause condensation at the lower part of the wall using the Kitchener boundary conditions. Summertime interior conditions are typically drier than exterior conditions due to air conditioning; infiltration of exterior air would raise interior dewpoints. Therefore, the worst likely scenario is interior air that is at exterior dewpoint conditions.

Exterior dewpoint is plotted with the temperature of the lower portion of the wall in Kitchener in Figure 1.42. Unlike previous simulations of the lower Kitchener wall, this dewpoint rises above the wall surface temperature (compare with Figure 1.30), as seen in the summertime spikes.

Therefore, these conditions were simulated by using an interior climate file with temperatures as per monitored conditions, but with dewpoints identical to exterior for the summer months. When the dewpoint went over interior air temperature, humidity was set to 100%. The assemblies tested in previous work were compared using these conditions; the results are plotted in terms of accumulation at the fictional condensation layer, as shown in Figure 1.43.

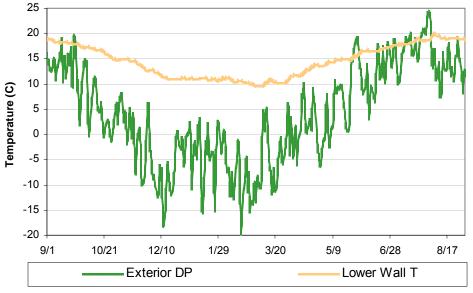


Figure 1.42: Exterior dewpoint and lower wall temperature from Kitchener data



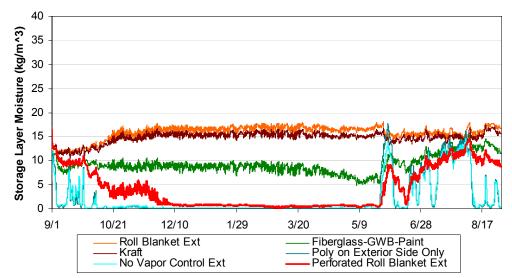


Figure 1.43: Results of Kitchener simulation with elevated summertime interior humidity

This plot shows that accumulation is minimal: it is nowhere near the 500 g/m2 rundown limit described earlier. This zoomed-in plot shows that the less permeable assemblies (polyethylene and Kraft paper) have slightly greater accumulation levels; the more permeable assemblies show summertime spikes, but are able to dry quickly. XPS is not included in this analysis, given the lack of danger seen in previous simulations.

The question then becomes whether or not these boundary conditions are realistic or representative of typical conditions. For further comparison, the exterior dewpoint and lower wall temperature are plotted for the Huntley site for 2004 and 2005, in Figure 1.44. It shows a similar behavior pattern: exterior dewpoint exceeds the wall temperature in discontinuous spikes, although Huntley shows longer periods of condensation risk.

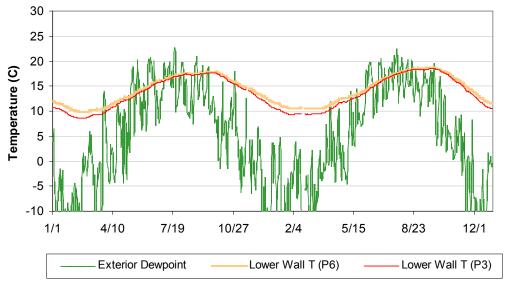


Figure 1.44: Exterior dewpoint and lower wall temperature from Huntley data



This analysis is not meant to imply that that high humidity levels could not cause condensation at the lower portion of the wall, due to soil thermal lag effects. A set of simulations was run with much higher interior dewpoint levels; sinusoidal conditions were set up with a peak condition of 80% RH at 26° C in early August. These conditions resulted in dewpoints above wall temperature for a large portion of the year (roughly April through October). Simulations showed moisture accumulation above the rundown limit in all of the vapour permeable assemblies, and minimal accumulation in the polyethylene and Kraft assemblies, similar to the Edmonton results.

However, these conditions are very unlikely, since they would require significant summertime moisture generation to raise interior dewpoints this far above exterior conditions, not to mention summertime heating of the basement to reach that temperature. Note that to some degree, condensation on the lower portion of the wall is somewhat self-protecting due to climate relationships. Climates that have high summertime exterior dewpoints are also likely to have warmer temperatures at the lowest portion of the wall, therefore reducing the risk. Likewise, locations with colder temperatures at the bottom of the wall will likely have lower summertime dewpoints.

Note that none of these simulations account for air transport: it seems quite possible that summertime condensation issues at the lower portion of the wall could be related to the absence of an air barrier.

