Developing a Design Protocol for Low Air and Vapour Permeance Insulating Sheathing in Cold Climates

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ABSTRACT

Our company, a consulting engineering firm, was engaged to develop a design protocol for the application of insulating sheathing to low-rise buildings with high interior relative humidity (maximum 60%) for a range of degree-day locations across Canada. The protocol had to be consistent with requirements of the National Building Code of Canada (NBC) for sheathing with low air and vapour permeance applied to wood frame walls in cold climates.

A time variant, two-dimensional, heat-air-moisture (HAM) modeling program was selected to determine the hygrothermal performance of walls with a range of thermal insulation, air tightness and vapour permeance. The parametric study included a sparse matrix of material properties and outdoor environments. Air leakage paths included porous materials and gaps between non-porous materials. The results from the parametric study were analyzed for excessive moisture accumulation and developed a design protocol for the selection of insulating sheathing for buildings with high interior relative humidity in cold climates.

This paper presents the development of the model, parametric study and analysis.

INTRODUCTION

The National Building Code of Canada (NBC) is the basis for building regulation in Canada. It is a model building code that is developed by a consensus process to regulate the construction of new buildings, or the significant renovation of existing buildings. The NBC addresses a defined set of objectives, namely safety, health and fire and structural protection. A sub-objective of the health objective is control of condensation.

The NBC recognizes that there is an increased risk of condensation when low vapour permeance materials are installed on the exterior of insulated stud walls of buildings with elevated interior relative humidity (RH) in the heating season. To address this issue for 'small' buildings, the NBC sets prescriptive requirements of minimum 'Ratio of Outboard to Inboard Thermal Resistance' for buildings with low air and vapour permeance materials installed on the exterior of insulated stud walls (see Appendix A). The NBC sets performance-based requirements to address this issue for 'large' buildings.

Foam plastic insulating sheathing is a low air and vapour permeance material, and the NBC prescriptive requirement for 'small' buildings therefore sets a minimum thermal resistance of insulating sheathing relative to the thermal resistance of insulation in the stud cavity. These requirements apply to 'small' buildings with either planned interior RH less than 35% in the heating season in 'cold' climates or planned interior RH less than 60% in the heating season in 'mild' climates. (Note that 'large' and 'small' buildings and 'cold' and 'mild' climates are defined by the NBC.) In all other situations, e.g., planned interior RH between 35% and 60% in a 'cold' climate, walls with low air and vapour permeance materials have to be designed to control condensation according to the performance-based requirements for 'large' buildings.

The prescriptive requirements for 'small' buildings with planned interior RH less than 60% in the heating season in 'mild' climates was an extension that was introduced in the 2005 edition of the NBC. The requirements were developed based on hygrothermal analysis conducted by the National

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Research Council (NRC) (Chown & Mukhopadhyaya 2005). A manufacturer of both glass fibre and extruded polystyrene insulation was interested in extending the application further by developing a design protocol for the application of insulating sheathing on insulated buildings with planned interior RH less than 60% in the heating season in 'cold' climates. They retained our company, a consulting engineering firm, to develop such a protocol. The development was based on the premise that the analysis would extend the NRC hygrothermal analysis to colder climates, and it was understood that the new analysis would be calibrated against the previous NRC analysis and not against field data. Our project proceeded through the following four phases:

Development—Develop an experimental plan, including selecting a simulation program.

Calibration—Calibrate the program to demonstrate that the results can be used to develop a design protocol.

Parametric Study—Select a range of climates, materials and properties for a parametric study.

Analysis—Analyze the results from the parametric study to develop a design table.

DEVELOPMENT

Heat, Air, Moisture (HAM) Program

Following review of publicly available simulation programs, the computer program DELPHIN (version 4.5.5) was selected to simulate heat, air and moisture performance for this project. This program was developed by, and is maintained at, the Technical University of Dresden (TUD), and has been recognized as one of the "mature" hygrothermal modeling programs (Nofal, et al 2001).

DELPHIN is a time variant, two-dimensional, heat-air-moisture (HAM) computer simulation program that can simulate the combined effects of heat flow, airflow and moisture flow. Heat flow is by conduction, convection, radiation and phase change. Airflow is assumed to be laminar and a value is pre-calculated for individual user-defined elements in the version of the model used to complete the study. Moisture flow is by convection, vapour diffusion, capillary suction and adsorption, and includes moisture movement through common construction materials including air.

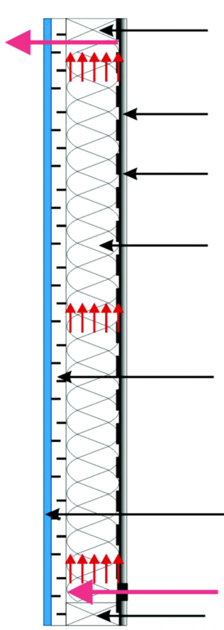

Figure 1 *Model of wall assembly with 38 × 89 mm (2 × 4 in.) studs.*

Wall Assembly

The wall assembly used in the simulations is based on wall assemblies that had been used previously for analysis of condensation from air leakage (Ojanen & Kumaran, 1992 & 1996; VTT, 1994). It is a cross-section of a wood stud wall with extruded polystyrene insulating sheathing, fiberglass insulation in the stud cavity, and a 60 ng/(Pa·s·m) [1 perm] vapour barrier and painted gypsum wallboard on the interior surface. Wood stud top and bottom plates are included in the 2-D wall assembly. Figure 1 illustrates the generic wall assembly with 38 × 89 mm [2 × 4 in.] studs.

Climates

The design protocol was to be developed for locations with climates that had a Mild Climate Indicator (MCI) greater than 6300, where the MCI is calculated according to the formula in Article 9.25.1.2. (NBC 2005, see Appendix A). Following review of Climatic Design Data from the NBC, the locations in Table 1 were selected for analysis. The locations

Table 1. List of Canadian Locations Included in Study

Location	Degree Days Below 18ºC	MCI
Toronto, ON	3650	7250
Yarmouth, NS	4100	6700
Halifax, NS	4100	7300
Montreal, QC	4250	8850
Ottawa, ON	4600	9600
Moncton, NB	4750	9150
St. John's, NL	4800	7600
Quebec City, QC	5200	10200
Sudbury, ON	5400	11000
Edmonton, AB	5400	11800
Winnipeg, MB	5900	12500
Saskatoon, SK	5950	12950
Prince Albert, SK	6450	13850
Fort McMurray, AB	6550	14350

were selected to include different regions, climate type (e.g., maritime, continental) and Degree Days, in addition to MCI.

CALIBRATION

Models

In order to provide confidence in DELPHIN as the simulation tool for development of the design protocol, DELPHIN was calibrated against results obtained previously by NRC and VTT (VTT 1994). The basis of the calibration was to establish that the heat and moisture flows predicted by DELPHIN were in general agreement with the results obtained previously by NRC/VTT (the previous analysis had not been calibrated against field data).

NRC/VTT. The base physical model for the NRC/VTT simulations was a section through a 2400 mm [96 in.] high, 38 mm x 140 mm [2x6] wood stud wall, with the stud cavity filled with RSI-3.5 (R-20) fiberglass insulation and top and bottom wood plates (Figure 1). The vapour permeance of the vapour barrier on the interior was 60 ng/(Pa·s·m) [1 perm] and the vapour permeance of the sheathing was 170 ng/(Pa·s·m) [3 perms]. The air leakage path in the NRC/VTT model included an opening low in the interior surface representing an electrical outlet and an air barrier material on the exterior surface. The rate of air leakage was a function of the air pressure difference across the assembly and the permeance of the air barrier material, and the air pressure difference was a function of the wind velocity and mechanical over pressurization of 10 Pa [0.04 in. H_2O]. The interior air was maintained at 21ºC [70ºF] when the exterior air temperature was less than 21ºC [70ºF], and equal to the exterior air temperature when it exceeded 21ºC [70ºF]. Interior vapour pressure was set at 900 Pa, which is equal to a little more than 35% RH at 21ºC [70ºF]. Exterior conditions were based on Ottawa weather data. The NRC/VTT parametric matrix included a range of air permeance of the air barrier material, interior RH of 50% in winter, and additional R-value (insulating sheathing) on the exterior surface.

DELPHIN. The base physical model for the DELPHIN simulations was the same as that for the NRC/VTT simulations. Interior RH was computed based on a moisture balance considering occupancy, weather and storage. The algorithm was one that had been used by NRC (Chown et al, 2005) and was based on an algorithm developed by Jones, et al (1993 & 1995). The algorithm is discussed in detail in the next section. The modeled airflow through the wall assembly was calculated based on the rated air leakage for the client's evaluated air barrier system and assuming laminar flow. Rated air leakage for the client's evaluated air barrier system, which was based on extruded polystyrene, was reported as 0.048 L/(s·m) at 75 Pa [0.01 cfm at 0.3 in. H_2O] (Di Lenardo 2003).

Calibration Results

To calibrate the model, the response of selected walls was simulated using Ottawa weather (DD = 4600) and the response predicted by DELPHIN was compared to published results from the NRC/VTT studies. The example wall assembly had an outboard to inboard thermal resistance ratio of 0.39, a ratio that is almost double the minimum ratio required by Part 9 of the NBC for interior RH less than or equal to 35% in winter (Appendix A, Table 9.25.2.1.).

Heat Flow. VTT reported that the convective heat loss increased when the air permeance of the air barrier increased, but the conductive heat loss through the interior surface decreased, apparently because the exfiltrating air warms the interior surface. The heat flows reported by VTT and calculated by DELPHIN compared favorably.

Moisture Flow. VTT reported that the RH in fiberglass insulation near the interface with the sheathing was normally in the range of 90% to 100% due to the sorption curve of the fiberglass insulation. Because the RH close to the exterior sheathing is significantly higher than the average value in the structure, it does not provide information that is easily comparable. For this reason, VTT reported only the total mass of moisture and localized moisture content of the fiberglass insulation. The moisture flows reported by VTT and calculated by DELPHIN compared favorably.

Acceptable Performance

A necessary metric for performance analysis is to decide whether the predicted quantity and duration of moisture accumulation is 'pass', 'marginal' or 'fail'. It is generally recognized that a limited amount of moisture that exists for a short duration will not lead to premature deterioration. Acceptable performance for the NBC 2005 work was established by comparing the total moisture content in a wood frame wall assembly with batt insulation and low vapour permeance insulating sheathing, to that in a wall assembly with batt insulation and code-compliant wood sheathing (Chown et al, 2005). The performance of a wall assembly with low vapour permeance insulating sheathing was deemed acceptable if the moisture content level in the wall cavity was 'comfortably' lower than the base case wall assembly. Following analysis of some preliminary results, we added two additional steps to our criteria for acceptable performance, as follows:

Step 1. Determine that the amount of moisture in the stud cavity was not increasing from year to year. In Figure 2, the total moisture mass in the stud cavity is plotted for 'Interior RH at 35%' and 'High Interior RH' (60%), and it can be seen that the minimum moisture mass does not increase over a year (from day 500 to day 850).

Step 2. Compare the performance of the generic wall assembly to that of the base wall assembly. In Figure 3, the total moisture mass in the stud cavity is plotted for the generic wall and the base case wall, and it can be seen that the moisture mass in the generic wall is comfortably less than that in the base wall, thus satisfying the acceptance criterion used for Table 9.25.1.2. in NBC 2005 (Chown et all, 2005).

Step 3. Examine the peak moisture content of the bottom plate, as this was determined to be the wood element with the highest moisture content. In Figure 4, the moisture content of

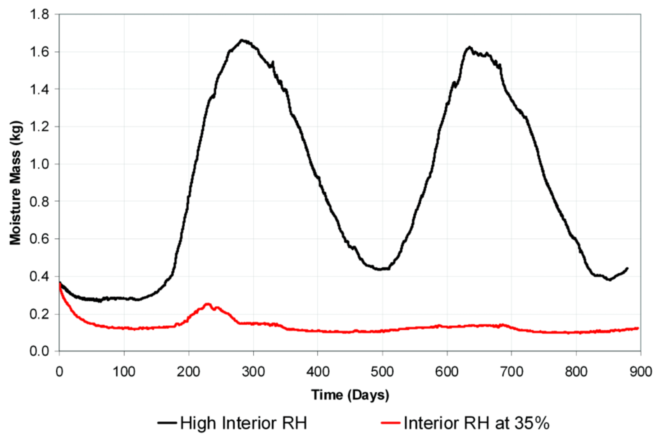

Figure 2 *Predicted total mass of moisture in the stud cavity for the insulating sheathing wall with 'High' (60%) and 35% Interior RH, and with Ottawa weather.*

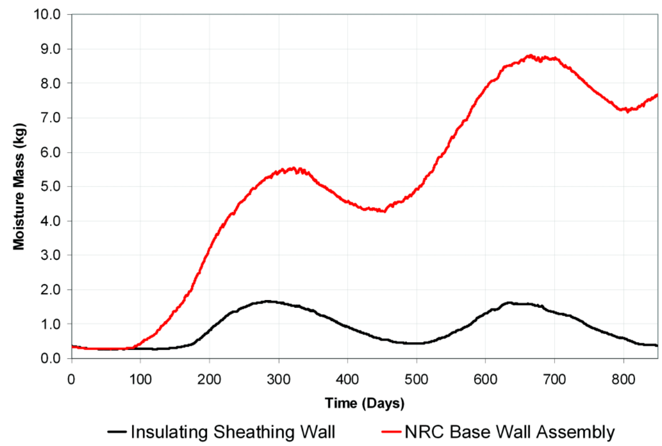

Figure 3 *Predicted total mass of moisture in the stud cavity for the insulating sheathing wall and for the NRC base wall, both with Ottawa weather.*

the bottom plate is plotted for the generic insulating sheathing wall assembly with 'Interior RH at 35%' and 'High Interior RH' (60%), and it can be seen that performance has 'failed', because the peak moisture content is well above fibre saturation (28%).

The preceding discussion highlights the fact that a wall assembly cannot be considered acceptable ('pass') solely on the basis of a comparison its predicted moisture content against the predicted moisture content a code-compliant base assembly. For this reason, the moisture content of the bottom wood plate and the moisture mass in the cavity were examined to determine wall assemblies with acceptable moisture performance for the selected configurations and modeled boundary conditions.

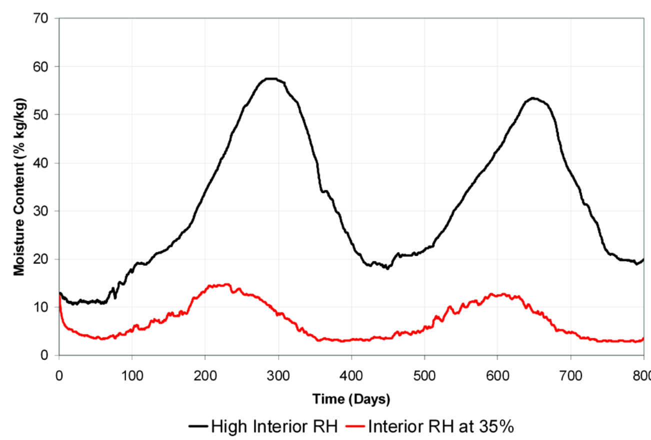

Figure 4 *Predicted moisture content (%) of the bottom wood plate for the insulating sheathing wall with 'High' (60%) and 35% Interior RH and with Ottawa weather.*

PARAMETRIC STUDY

Parametric Matrix

Following a review of the parameters in the generic wall assembly, the following were selected for the study:

- *Wood studs:*
  38 × 89 [2 × 4] and 38 × 140 [2 × 6]
- *vapour barrier:*
  60 ng/(Pa·s·m) [1 perm]
- *Stud insulation:*
  RSI-2.5 [R-14] fiberglass batt for 38 × 89 [2 × 4] studs
  RSI-3.8 [R-22] fiberglass batt for 38 × 140 [2 × 6]studs
- *Insulating sheathing:*
  25 [1 in.] / RSI-0.9 [R-5] / 48 ng/(Pa·s·m)
  38 [1.5 in.] / RSI-1.3 [R-7.5] / 32 ng/(Pa·s·m)
  50 [2 in.] / RSI-1.8 [R-10] / 25 ng/(Pa·s·m)
- *Air leakage rate:*
  0.048 L/(s·m) at 75 Pa (for rated air barrier system),
  plus 0.024 L/(s·m) at 75 Pa (measured for sealed and/or taped system),
  and 0.10 L/(s·m) at 75 Pa (suggested limit for Part 5 air barrier systems)
- *Weather for 14 Canadian locations:*
  Toronto, Yarmouth, Halifax, Montreal, Ottawa, Moncton, St. John's, Quebec City, Sudbury, Edmonton, Winnipeg, Saskatoon, Prince Albert, Fort McMurray

Combinations of stud cavity insulation thermal resistance and insulating sheathing thermal resistance were selected for analysis. Identification codes for the different wall constructions and the ratio of the outboard to inboard thermal resistance are presented in Table 2. A sparse matrix of insulating values was simulated for each climate to determine the minimum ratio of outboard to inboard thermal resistance that

Table 2. Wall Assembly Codes, Thermal Resistance, and Ratio of Outboard to Inboard Thermal Resistance

Code	Studs	Fiberglass R-Value	Sheathing Thickness/ R-Value	Outboard/ Inboard Thermal Resistance Ratio
B1	38x89 [2x4]	RSI 2.5 [R14]	25 / RSI 0.9 [1 in. / R5]	0.39
B2	38x89 [2x4]	RSI 2.5 [R14]	38 / RSI 1.3 [1.5 in. / R7.5]	0.55
B3	38x89 [2x4]	RSI 2.5 [R14]	50 / RSI 1.8 [2 in. / R10]	0.72
D1	38x140 [2x6]	RSI 3.8 [R22]	25 / RSI 0.9 [1 in. / R5]	0.25
D2	38x140 [2x6]	RSI 3.8 [R22]	38 / RSI 1.3 [1.5 in. / R7.5]	0.36
D3	38x140 [2x6]	RSI 3.8 [R22]	50 / RSI 1.8 [2 in. / R10]	0.47

Note that codes Ax and Cx were used in the study but are not discussed in this paper.

would provide acceptable moisture performance with the rated air barrier system.

Boundary Conditions

Interior Conditions. The indoor temperature was set at 22ºC when the exterior temperature was below 18.5ºC or 3.5ºC above the 24-hour running average of the exterior temperature when it was above 18.5ºC. The sensitivity of moisture accumulation to the indoor temperature during the non-heating season was investigated, and it was determined that the peak wood moisture content was slightly reduced by modeling the indoor temperature equal to the outdoor temperature during the non-heating season. The difference is not significant enough to affect the selection of the minimum outboard to inboard thermal resistance ratio. The indoor relative humidity was calculated using a moisture balance between the interior air and exterior air (Roppel, et al 2007). The following values of the governing parameters were selected because they produced a monthly average interior RH during the heating season between 50 and 60% for all the modeled climates:

Room dimensions:	2400 mm height (8.0 ft), 80 m (860 ft) area, 195 m (6890 ft) volume
Ventilation:	0.3 ACH = 0.0163 m/s (34 CFM) air exchange rate
Moisture generation:	6 L/day
Absorption/desorption:	alpha = 0.6, beta = 0.4

With the ventilation rate increased to 0.5 ACH, equivalent to 0.0271 m/s (57 CFM) air exchange rate, the monthly average interior RH during the heating season was between 45 to 50% for all climates.

Exterior Conditions. Hourly weather data records were obtained from Environment Canada for each of the fourteen locations for the years 1985 to 2005. The exterior boundary conditions for the DELPHIN model are temperature (°C) and relative humidity (%). (Note that the effect on air leakage of wind speed and direction were accounted for in the pre-calculated air leakage data—see Appendix B).). From the weather records, the degree-days below 18ºC (DD) were calculated for the heating season for each location, assuming a heating season from October 1 and April 30 for all the locations. The two contiguous years of weather data with the highest DD were selected for the simulations. For example, the highest DD for Ottawa was between October 1, 1993 and April 30, 1994. Therefore, simulations were run using weather data from the years 1993 and 1994. Simulations were started on July 1 and the weather data was cycled for the two selected years until a steady periodic response was achieved.

Air Leakage

Air leakage through the wall assembly was modeled as laminar flow. The path extended from an opening in the interior above the bottom plate, and through the stud cavity to an opening in the exterior below the top plate. The airflow rate was calculated based on the pressure difference across the wall assembly and the rated air leakage rate at 75 Pa for the simulated air barrier system. The air pressure difference was calculated using hourly weather data for wind velocity, stack effect, and assigned over pressurization of 10 Pa from mechanical equipment (see Appendix B). The air leakage rate was pre-calculated for each hour of the weather data file and provided as an input file.

Documents provided by the client showed a laboratory measured air leakage rate of 0.005 to 0.028 L/(s·m) at 75 Pa for an air barrier system constructed with insulating sheathing and sealant and/or tape. To determine the effect on moisture performance of the difference between these rates and the CCMC evaluated rates for the same assembly, we simulated the response for an air leakage rate of 0.024 L/(s·m) at 75 Pa for Fort McMurray weather data. The response for air leakage rates of 0.1 L/(s·m) at 75 Pa and 0.024 L/(s·m) at 75 Pa were also simulated for Ottawa weather data to assess the effect of a range of air leakage rates.

Material Properties

Material properties were derived from material properties supplied by the client for their materials and from NRC hygrothermal property databases (Kumaran, et al 2002b and Kumaran 2002c).

The basic material properties are summarized in Table 3. The effect of moisture content on a given transport mechanism for each material is summarized in Table 4. The parameters for the linear dependency of thermal conductivity are presented in Table 5. Graphs of the moisture storage function and the mois-

Table 3. Basic Material Properties

Property	Units	Material			
		Fiberglass Insulation	Gypsum Wallboard	Insulating Sheathing	Wood Stud (Spruce)
Porosity	m/m	0.99	0.45	0.60	0.90
Saturation Moisture Content	m/m	0.98	0.40	0.58	0.88
Density, ρ	kg/m	11.5	700	28	400
Heat Capacity, c	J/(kg K)	840	870	1470	880
Thermal Conductivity, λ	W/(m K)	0.036	0.16	0.027	0.088
Water Vapour Permeability	ng/(Pa·s·m)	170	39	1.2	4.9

Table 4. Moisture Dependency of Transport Mechanism

Transport Mechanism	Material			
	Fiberglass Insulation	Gypsum Wallboard	Insulating Sheathing	Wood Stud (Spruce)
Vapour Diffusion	constant	moisture dependent	constant	moisture dependent
Liquid Flow	zero	moisture dependent	zero	moisture dependent
Thermal Conductivity	moisture dependent	moisture dependent	constant	moisture dependent

ture dependency on transport mechanism for each material are given in Appendix C.

ANALYSIS

Simulation Results

As noted previously, a sparse matrix of combinations of climate (Table 1) and wall configuration (Table 2) were simulated; the combinations that were simulated were selected to identify wall configurations that would provide acceptable moisture performance. Each simulation result was judged to be 'pass', 'marginal' or 'fail' based on the criteria discussed in the section "Acceptable Performance" (above).

Graphs presenting moisture accumulation in the stud cavity, moisture content of the bottom wood plate, and moisture content of the batt insulation at the bottom air gap were generated for each combination simulated. The results for Ottawa are presented in Appendix D as examples of the output generated.

Effect of Air Leakage

To determine the effect of air leakage rate on moisture performance, the results for a B2 wall assembly (thermal resistance ratio = 0.55) in Ottawa were compared with air leakage rates of 0.024, 0.048 and 0.1 L/(s·m) at 75 Pa. The results show that, while the peak moisture mass in the stud cavity differed by as much as 2 kg during the heating season, it dried down to the same level in the summer. This shows that the acceptance criterion of zero net moisture accumulation over any year is met for a wide range of air leakage rates. However, an examination of the moisture content of the bottom wood plate shows that the acceptance criterion for the moisture content of the wood may not be met for the higher air leakage rate. Accordingly, the design requirements for air leakage rates greater than 0.048 L/(s·m) at 75 Pa will require further investigation. Conversely, assemblies with an air leakage rate on the order of 0.024 L/(s·m) at 75 Pa may require less outboard insulation.

Table 5. Moisture Dependency of Thermal Conductivity (Linear)
($\lambda_{moisture\ dependent} = \lambda_{dry} + \lambda_{moisture} \cdot MC$)

Thermal Conductivity	Material		
	Fiberglass Insulation	Gypsum Wallboard	Wood Stud (Spruce)
λ_{dry}	0.036	0.027	0.088
$\lambda_{moisture}$	0.6	0.191	1.1

Design Requirements

Design requirements should ideally include all 'pass' configurations identified in the simulations. The NBC requirements for low air and vapourvapour permeance sheathing with Interior RH≤35% and MCI≤6300 are presented in terms of the ratio of thermal resistance outboard of the material to the thermal resistance inboard of the material. Using a similar approach, a relationship between the outboard/inboard thermal resistance ratio and acceptable performance can be determined for wall configurations with the rated air leakage rate and both Interior RH≤60% and Interior RH≤50%. The analysis proceeded through the following steps:

1. Determine a linear relationship for the 'pass' simulation data points with Interior RH≤60% and with Interior RH≤50%.
2. Determine a relationship for Acceptable Performance for Interior RH≤50% that includes all 'pass' data points by

fitting the relationship through the data point furthest below the line, i.e., Halifax and Yarmouth.

3. Determine a relationship for Acceptable Performance for Interior RH≤60% that includes all 'pass' data points by fitting a line with slope of Interior RH≤50% through the data point furthest below the line, i.e., Halifax and Yarmouth (this assumes the same linear relationship for both Interior RHs).

The equations representing the Acceptable Performance relationships are as follows:

For Interior RH≤50%:

Thermal Resistance Ratio = 7.67×10^{-5} * DD + 0.03

For Interior RH≤60%:

Thermal Resistance Ratio = 7.67×10^{-5} * DD + 0.24

The results from the simulations are shown graphically in Figure 5, where the 'pass' and 'marginal' configurations are plotted for Design Degrees Days versus the outboard/inboard thermal resistance ratio. The solid lines are proposed as the limits of acceptable performance for Interior RH≤60% and Interior RH≤50%. Note that the solid line for Interior RH≤60% excludes the 'pass' for St. John's and includes the 'marginal' results for Winnipeg and Saskatoon.

The key to the graphical information presented in Figure 5 is as follows:

Interior RH≤60%

Solid data points—'pass' configurations

Open data points—'marginal' performance

Dashed line—linear fit through 'pass' configurations'

Solid line—line of acceptable performance with slope as for RH≤50% fitted through lowest point below line (Halifax & Yarmouth)

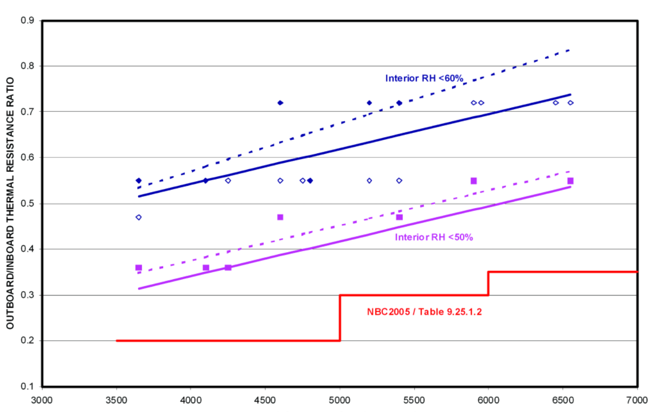

Figure 5 *'Pass' and 'marginal' simulation results for both Interior RH≤50% and Interior RH≤60%, plus limits set by NBC 2005 in Table 9.25.1.2. for RH≤35%.*

Interior RH≤50%

Solid data points—'pass' configurations

Open data points—'marginal' performance

Dashed line—linear fit through 'pass' configurations'

Solid line—line of acceptable performance with slope of linear fit fitted through lowest point below line (Halifax & Yarmouth)

NBC2005/Table 9.25.1.2

Limits set by Table 9.25.1.2. for interior RH≤35%

Design Tables

Tables 6 and 7 are derived from the analysis discussed above and the results presented in Figure 5.

CONCLUSIONS

A hygrothermal modeling study was conducted to develop a design protocol for the application of low air and vapour permeance insulating sheathing to wall assemblies on buildings with high interior relative humidity during the heating season in cold climates. The hygrothermal model DELPHIN was used to simulate heat transfer, moisture flow and air leakage. The approach for the design protocol was based on requirements for low air- and vapour-permeance materials contained in the National Building Code of Canada (NBC). The study involved a range of climates and of thermal design approaches for wood frame construction. Acceptable performance was assessed based on an analysis of the amount of moisture accumulation from condensation within the wall assembly - the condensation was consequence of the transport of interior moisture by air leakage and vapour diffusion. These results are dependent on the level of interior relative humidity, the amount of air leakage, and the climate.

The analysis indicated that insulating sheathing with thermal resistance of RSI 0.9 to RSI 1.8 was required to avoid moisture problems from condensation in wall assemblies of buildings with interior RH≤50% during the heating season. For buildings with interior RH≤60% during the heating season, insulating sheathing with thermal resistance of RSI 1.3 to RSI 1.8 was required with 38 × 89 mm[2 × 4 in.] stud walls, and thermal resistance greater than RSI 1.8 is required for 38 × 140 mm [2 × 6 in.] walls. Design tables similar to those in the NBC were developed for wall assemblies on buildings with interior RH≤50% and with interior RH≤60%.

The effect of three air leakage levels was examined and it was determined that, in general, moisture that accumulated during the heating season dried out in the non-heating season. However, in the cases with higher air leakage rates, the amount of accumulation during the heating season was sufficient to produce fibre saturation. Further investigation is required to determine the limits of air leakage on performance. As well, it may be useful to develop a relationship to determine the maximum indoor RH for a particular insulation ratio and design condition.

Table 6. Examples of Minimum Exterior Insulation Required for Interior RH≤50% during the Heating Season for Locations Included in Study

Location	DD Below 18ºC	Minimum Outboard/Inboard Thermal Resistance Ratio	Minimum Exterior Insulation	
			2x4 Stud w/RSI-2.5 [R14] Batt	2x6 Stud w/RSI-3.9 [R22] Batt
Toronto, ON	3650	0.31	RSI-0.9 [R5]	RSI-1.4 [R7.5]
Yarmouth, NS	4100	0.34	RSI-0.9 [R5]	RSI-1.4 [R7.5]
Halifax, NS	4100	0.34	RSI-0.9 [R5]	RSI-1.4 [R7.5]
Montreal, QC	4250	0.36	RSI-0.9 [R5]	RSI-1.4 [R7.5]
Ottawa, ON	4600	0.38	RSI-0.9 [R5]	RSI-1.8 [R10]
Moncton, NB	4750	0.39	RSI-0.9 [R5]	RSI-1.8 [R10]
St. John's, NL	4800	0.40	RSI-1.4 [R7.5]	RSI-1.8 [R10]
Quebec City, QC	5200	0.43	RSI-1.4 [R7.5]	RSI-1.8 [R10]
Sudbury, ON	5400	0.44	RSI-1.4 [R7.5]	RSI-1.8 [R10]
Edmonton, AB	5400	0.44	RSI-1.4 [R7.5]	RSI-1.8 [R10]
Winnipeg, MB	5900	0.48	RSI-1.4 [R7.5]	>RSI-1.8 [R10]
Saskatoon, SK	5950	0.49	RSI-1.4 [R7.5]	>RSI-1.8 [R10]
Prince Albert, SK	6450	0.52	RSI-1.4 [R7.5]	>RSI-1.8 [R10]
Fort McMurray, AB	6550	0.53	RSI-1.4 [R7.5]	>RSI-1.8 [R10]

Table 7. Examples of Minimum Exterior Insulation Required for Interior RH≤60% during the Heating Season for Locations Included In Study

Location	DD Below 18ºC	Minimum Outboard/Inboard Thermal Resistance Ratio	Minimum Exterior Insulation	
			2x4 Stud w/RSI-2.5 [R14] Batt	2x6 Stud w/RSI-3.9 [R22] Batt
Toronto, ON	3650	0.52	RSI-1.4 [R7.5]	>RSI-1.8 [R10]
Yarmouth, NS	4100	0.55	RSI-1.4 [R7.5]	>RSI-1.8 [R10]
Halifax, NS	4100	0.55	RSI-1.4 [R7.5]	>RSI-1.8 [R10]
Montreal, QC	4250	0.57	RSI-1.8 [R10]	>RSI-1.8 [R10]
Ottawa, ON	4600	0.59	RSI-1.8 [R10]	>RSI-1.8 [R10]
Moncton, NB	4750	0.60	RSI-1.8 [R10]	>RSI-1.8 [R10]
St. John's, NL	4800	0.61	RSI-1.8 [R10]	>RSI-1.8 [R10]
Quebec City, QC	5200	0.64	RSI-1.8 [R10]	>RSI-1.8 [R10]
Sudbury, ON	5400	0.65	RSI-1.8 [R10]	>RSI-1.8 [R10]
Edmonton, AB	5400	0.65	RSI-1.8 [R10]	>RSI-1.8 [R10]
Winnipeg, MB	5900	0.69	RSI-1.8 [R10]	>RSI-1.8 [R10]
Saskatoon, SK	5950	0.70	RSI-1.8 [R10]	>RSI-1.8 [R10]
Prince Albert, SK	6450	0.73	>RSI-1.8 [R10]	>RSI-1.8 [R10]
Fort McMurray, AB	6550	0.74	>RSI-1.8 [R10]	>RSI-1.8 [R10]

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REFERENCES

Chown, G.A. & P.Mukhopadhyaya. 2005. NBC 9.25.1.2.: The On-Going Development of Building Code Requirements to Address Low Air and vapour Permeance Materials. Proceedings of the 10th Canadian Conference on Building Science and Technology. Ottawa, ON.

Chown, G.A. 2003. Committee Paper on Application of NBC Part 9 Building Envelope Diffusion Requirements Depending on Indoor Relative Humidity. National Research Council Canada.

Di Lenardo, B. 2003. "CodeBoard® Air Barrier System". Canadian Construction Materials Centre Evaluation Report No.12935R. National Research Council Canada.

Jones, R. 1995. Indoor Humidity Calculation Procedures. Building Services Engineering and Technology, Vol 16, No 3, pp.119-126.

Jones, R. 1993. Modelling Water vapour Conditions in Buildings. Building Services Engineering Research and Technology, Vol 14, No 3, pp.99–106.

Kumaran, M.K. & J.C.Haysom. 2002. Low-Permeance Materials in Building Envelopes. Construction Technology Update No. 41. National Research Council Canada.

Kumaran, M.K., J.C. Lackey, N. Normandin, D. Van Reenen, and F. Tariku. 2002. Summary Report From Task 3 of MEWS Project at the Institute for Research in Construction - Hygrothermal Properties of Several Building Materials. Research Report 110. National Research Council Canada.

Kumaran, M.K. 2002. A Thermal and Moisture Transport Database for Common Building and Insulating Materials. ASHRAE Research Project RP-1018, sponsored by TC 4.4 Building Materials and Building Envelope Performance. National Research Council Canada.

Nofal, M., M.Straver & M.K.Kumaran. 2001. Comparison of Four Hygrothermal Models in Terms of Long-Term Performance Assessment of Wood-Frame Constructions. NRCC-44690. National Research Council Canada.

Ojanen, T. & M.K.Kumaran. 1992. Air Exfiltration and Moisture Accumulation in Residential Wall Cavities. Thermal Performance of Exterior Envelopes of Whole Buildings V, Proceedings of ASHRAE/DOE/BTECC Conference, pp. 491-500. Clearwater Beach, FL.

Ojanen, T. & M.K.Kumaran. 1996. Effect of Exfiltration on the Hygrothermal Behaviour of a Residential Wall Assembly. Journal of Thermal Insulation and Building Envelopes, Volume 19, pp.215-227.

Roppel, P.J., M.D.Lawton & W.C. Brown. 2007. Modelling of Uncontrolled Interior Humidity for HAM Simulations of Residential Buildings. Thermal Performance of Exterior Envelopes of Whole Buildings X, Proceedings of ASHRAE/DOE/BTECC Conference. Clearwater Beach, FL.

VTT. 1994. TCC2D - Simulations on the Performance of Air Barriers in Ottawa, An Interim Report.

APPENDIX A—EXCERPTS FROM NATIONAL BUILDING CODE OF CANADA 2005

Section 9.25. Heat Transfer, Air Leakage and Condensation Control

9.25.1. Scope

9.25.1.1 Application

1. This Section applies to thermal insulation and measures to control heat transfer, air leakage and condensation.
2. ....

9.25.1.2 General

1. Sheet and panel-type materials shall be installed in accordance with Sentence (2), if the material
   a. has an air leakage characteristic less than 0.1 L/(s·m) at 75 Pa,
   b. has a water vapour permeance less than 60 ng/(Pa·s·m) when measured in accordance with ASTM E96, "Water Vapour Transmission of Materials," using the desiccant method (dry cup), and
   c. is incorporated into a building assembly required by Article 9.25.2.1. to be insulated.
2. Sheet and panel-type materials described in Sentence (1) shall be installed
   a. on the warm face of the assembly (see also Article 9.25.4.2.),
   b. except as provided in Sentences (3) to (5), at a location where the ratio between the total thermal resistance of all materials outboard of its innermost impermeable surface and the total thermal resistance of all materials inboard of that surface is not less than that required by Table 9.25.1.2., or
   c. outboard of an air space that is vented to the outdoors and, for walls, drained.
3. Wood-based sheathing materials no more than 12.5 mm thick and complying with Article 9.23.16.2. need not comply with Sentence (1).
4. Where the mild climate indicator, determined in accordance with Sentence (6), is greater than 6300, the position of low air- and vapour-permeance materials within the assembly relative to the position of materials providing thermal resistance shall be determined according to Part 5, where
   a. the intended use of the interior space requires the indoor relative humidity to be maintained above 35% over the heating season and the ventilating and air-conditioning system is designed to maintain that relative humidity, or

Table 9.25.1.2. Ratio of Outboard to Inboard Thermal Resistance [Forming Part of Sentence 9.25.1.2.(2)]

Heating Degree-Days of Building Location, Celsius Degree-Days	Minimum Ratio, Total Thermal Resistance Outboard of Material's Inner Surface to Total Thermal Resistance Inboard of Material's Inner Surface
Up to 4 999	0.20
5 000 to 5 999	0.30
6 000 to 6 999	0.35
7 000 to 7 999	0.40
8 000 to 8 999	0.50
9 000 to 9 999	0.55
10 000 to 10 999	0.60
11 000 to 11 999	0.65
12 000 or higher	0.75

a. the intended use of the interior space will result in an average monthly indoor relative humidity above 35% over the heating season and the ventilating and air-conditioning system does not have the capacity to reduce the relative humidity to 35% for any period over that period.

5. Where the mild climate indicator, determined in accordance with Sentence (6), is less than or equal to 6300, the position of low air- and vapour-permeance materials within the assembly relative to the position of materials providing thermal resistance shall be determined according to Part 5, where
   a. the intended use of the interior space requires the indoor relative humidity to be maintained above 60% over the heating season and the ventilating and air-conditioning system is designed to maintain that relative humidity, or
   b. the intended use of the interior space will result in an average monthly indoor relative humidity above 60% over the heating season and the ventilating and air-conditioning system does not have the capacity to reduce the relative humidity to 60% over that period.
6. The mild climate indicator (MCI) shall be calculated according to the following formula:

MCI = abs(2.5% JMT)·200 + DD

where

abs(2.5% JMT) = absolute value of 2.5% January mean temperature and

DD = degree-days

APPENDIX B—DEVELOPMENT OF AIR LEAKAGE VALUES

In the model, the airflow is uniformly distributed through each vertical element in the stud cavity. The equation for volumetric airflow rate through a sharp-edge orifice is as follows:

$$Q = C_d \cdot A \cdot \left(\frac{2\Delta P}{\rho}\right)^{0.5}$$

where

Q = the air flow (m^3/s)

A = the area of the orifice (m^2)

ρ = the density of air (kg/m^3)

ΔP = the pressure difference (Pa)

C_d = the discharge coefficient (/(2 +) for sharp edge orifice)

Using this formula, the equivalent orifice area was calculated for the rated leakage rate (0.048 L/(s·m) at 75 Pa). Then the same equation was used to calculate the airflow for a pressure difference produced by hourly wind velocity, stack effect and mechanical ventilation.

The wind-induced pressure difference was calculated using the stagnation pressure equation (from Bernoulli's equation) as follows:

$$\Delta P = \frac{1}{2} \cdot C_p \cdot \rho \cdot v^2$$

where

ΔP = the pressure difference (Pa)

C_p = the wind surface pressure coefficient (-)

ρ = the density of air (kg/m^3)

v = the wind speed (m/s)

The average wind pressure coefficient was utilized as VTT reported (1994) by the following equation:

$$C_a = \sum_0^4 c_i \theta^i$$

where

c_0 = 0.587888

c_1 = 6.41584×10^{-3}

c_2 = -4.48460×10^{-4}

c_3 = 3.68668×10^{-6}

c_4 = -8.65351×10^{-9}

θ = the angle between wind direction and normal to the wall surface (degrees)

The stack effect pressure difference was calculated using the following formulae (ASHRAE Handbook of Fundamentals 2005):

$$\Delta P = \rho_o \cdot \left(\frac{T_o - T_i}{T_i}\right) \cdot g \cdot (H_{NPL} - H)$$

where

ΔP = the pressure difference (Pa)

ρ_o = the density of air (kg/m^3)

T_o = the outdoor temperature (^{o}C)

T_i = the indoor temperature (^{o}C)

g = the gravitational acceleration (9.81 m/s^2)

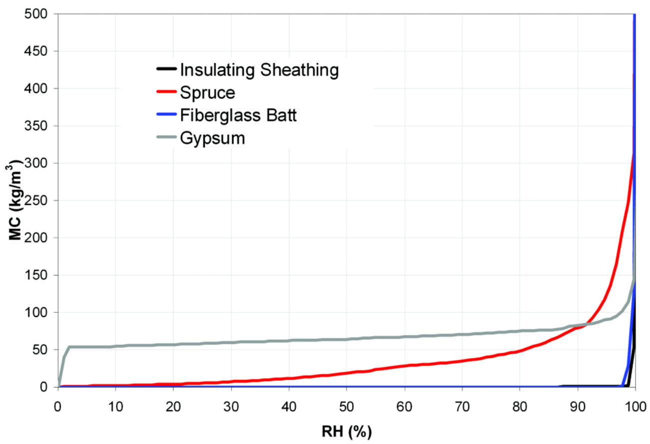
H = the height above reference plane (m)

H_{NPL} = the height of neutral pressure level above reference plane (m)

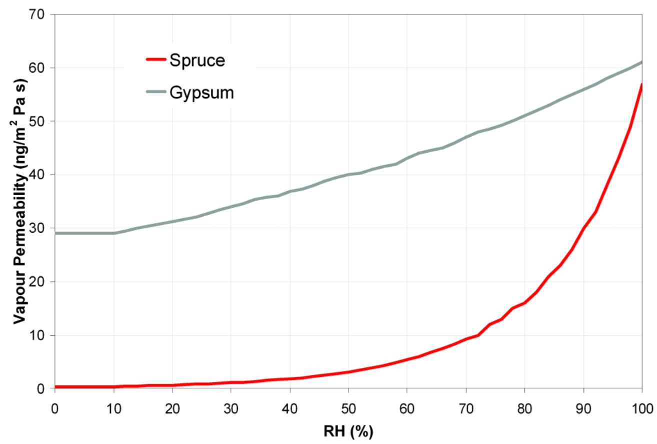
The mechanical ventilation pressure difference was set to a depressurization value of 10 Pa, as it had been for the previous NRC/VTT work.

APPENDIX C—MATERIAL PROPERTIES

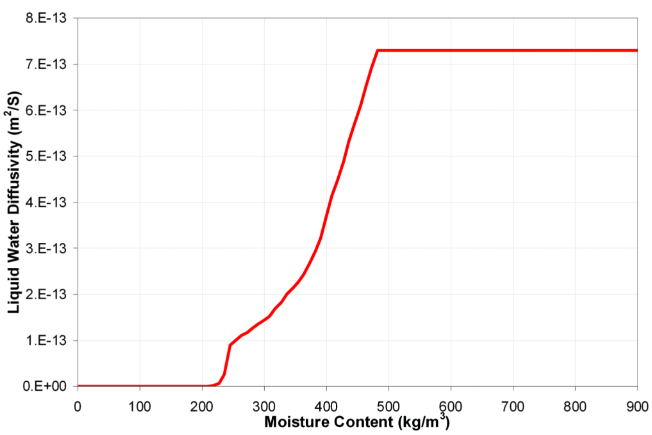
These figures graphically present the hygrothermal properties of the materials used in the simulated wall assembly (Figure 1).



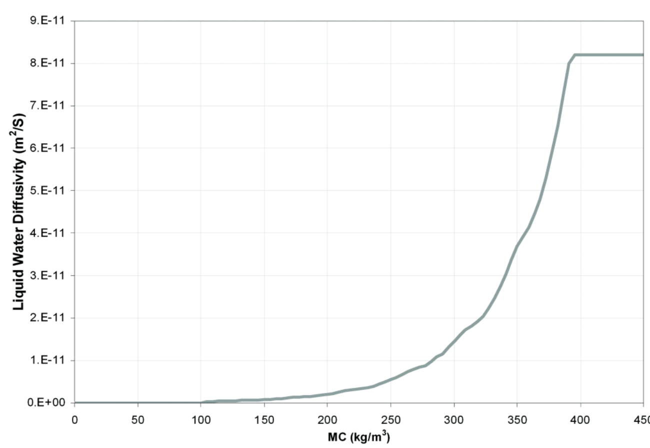
Moisture Storage Functions



Vapour Permeability



Spruce Liquid Flow



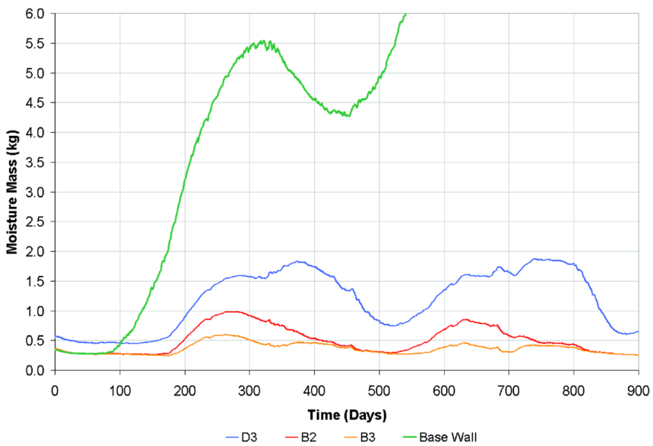
Gypsum Liquid Flow

APPENDIX D—EXAMPLES OF GRAPHICAL PRESENTATION OF RESULTS

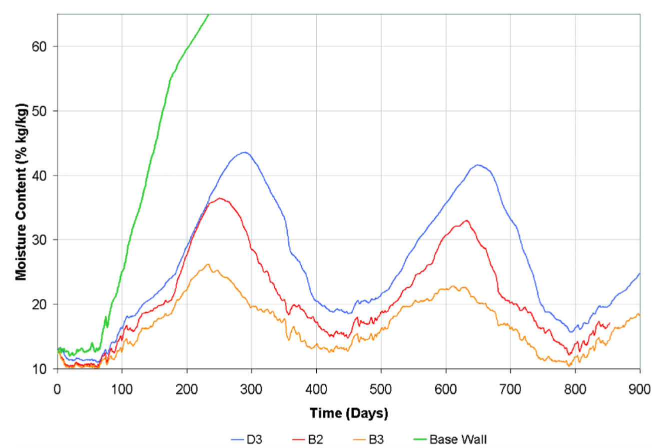
These figures graphically present an example of the simulation results obtained for four wall configurations in one location (Ottawa).

City: Ottawa

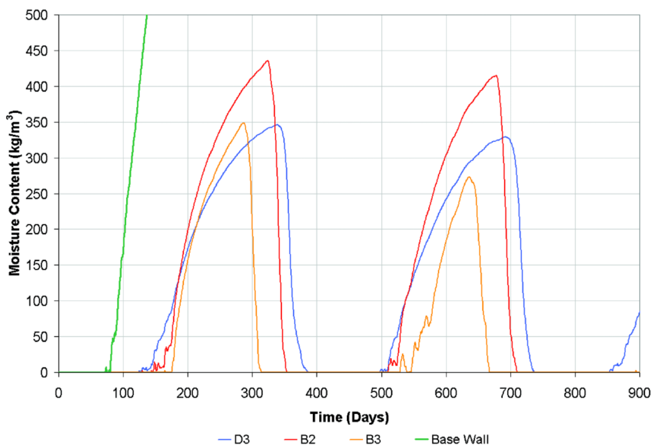
DDD: 4600



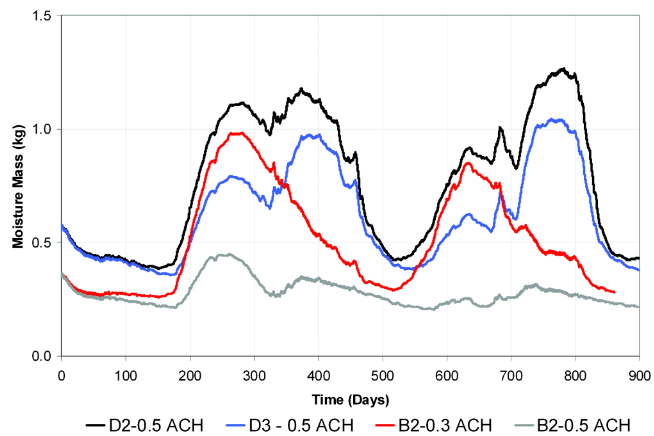
Ottawa Moisture Mass in Stud Cavity (Wood Plate and Batt) for Base Case



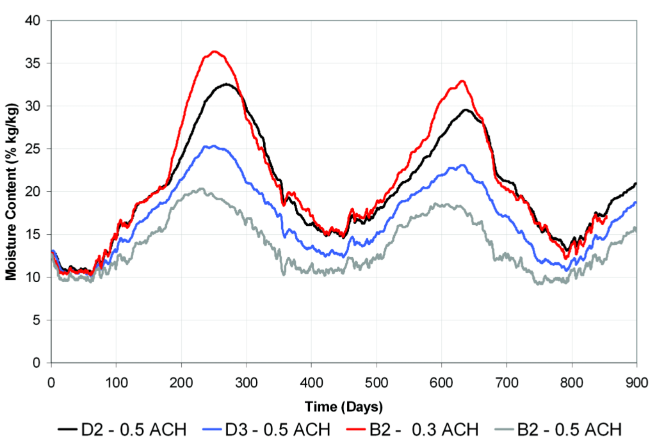
Ottawa Bottom Plate Moisture Content at Sheathing-Batt Interface for Base Case



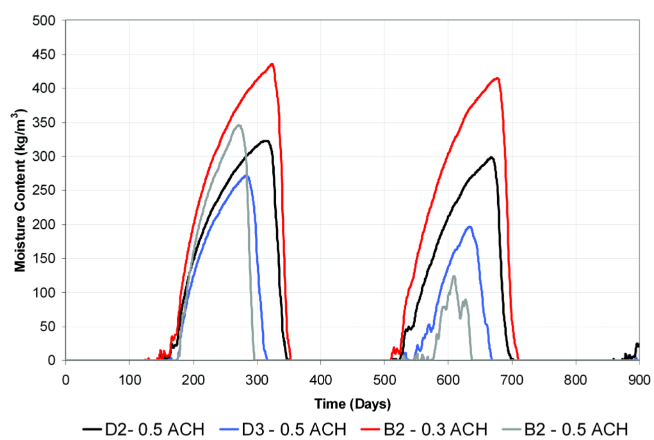
Ottawa Batt Insulation Moisture Content at Bottom of Cavity for Base Case



Ottawa Moisture Mass in Stud Cavity (Wood Plate and Batt) Comparing the Indoor Humidity



Ottawa Bottom Plate Moisture Content at Sheathing-Batt Interface Comparing the Indoor Humidity



Ottawa Batt Insulation Moisture Content at Bottom of Cavity Comparing the Indoor Humidity

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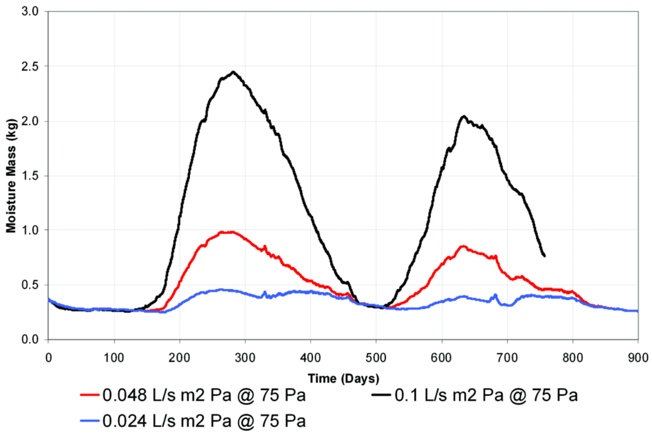
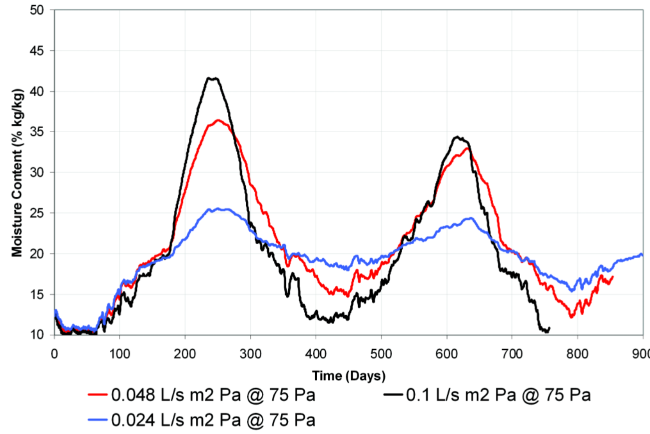
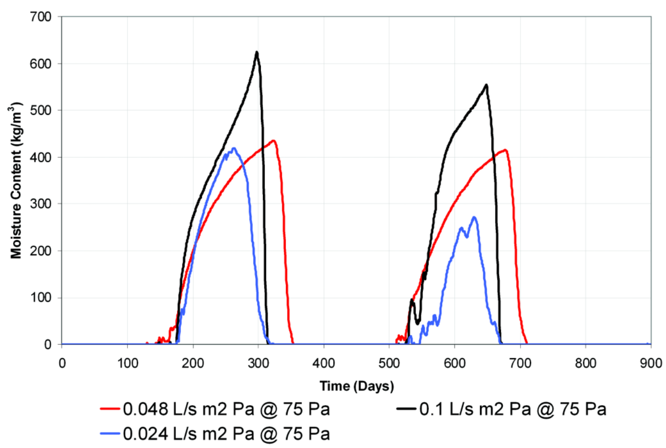
DDD: 4600



Ottawa Moisture Mass in Stud Cavity
(Wood Plate and Batt) Comparing the Air Leakage Rate



Ottawa Bottom Plate Moisture Content at
Sheathing-Batt Interface Comparing the Air Leakage Rate



Ottawa Batt Insulation Moisture Content at
Bottom of Cavity Comparing the Air Leakage Rate