Hygrothermal modelling benchmark: comparison of hygIRC simulation results with full scale experiment results: report to Research Consortium for Wood and Wood-Hybrid Mid-Rise Buildings

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Publisher's version / Version de l'éditeur:
https://doi.org/10.4224/21274575
Client Report (National Research Council of Canada. Construction), 2014-12-31

NATIONAL RESEARCH COUNCIL CANADA

REPORT TO RESEARCH CONSORTIUM FOR WOOD AND WOOD-HYBRID MID-RISE BUILDINGS

Hygrothermal Modelling Benchmark: Comparison of hygIRC Simulation Results with Full Scale Experiment Results

CLIENT REPORT: A1-100035-03.6

December 31, 2014

National Research Council Canada
Conseil national de recherches Canada

Canada

REPORT TO RESEARCH CONSORTIUM FOR WOOD AND WOOD-HYBRID MID-RISE BUILDINGS

Mid-rise Wood Constructions – Hygrothermal Modelling Benchmark: Comparison of hygIRC Simulation Results with Full Scale Experiment Results

Steven M. Cornick and David Van Reenen

Report No. A1-100035-03.6
Report date: December 31, 2014
Contract No. B-7000 (A1-100035)
Prepared for Canadian Wood Council
FPInnovations
Régie du bâtiment du Québec
HER MAJESTY THE QUEEN IN RIGHT OF ONTARIO as represented by the Minister of Municipal Affairs and Housing

22 pages

ACKNOWLEDGMENTS

The research consortium has been supported by Natural Resources Canada and the Ontario and Quebec building authorities, with research being conducted by the National Research Council (NRC), Canadian Wood Council (CWC) and FPInnovations (FPI). Two working groups were established, with participants from NRC, CWC, FPI and Municipal Affairs and Housing (Ontario) – one on fire and building envelope and the other on structure and acoustics. Working group meetings have been held on a biweekly basis to develop and design test methods, design test assemblies and select materials for the test arrangements. The results of tests are discussed on an ongoing basis.

The following staff members of project partner/collaborator organizations have contributed to the working groups and this progress report:

CWC: Rodney McPhee, Ineke Van Zeeland, Peggy Lepper;

FPI: Richard Desjardins, Mohammad Mohammad, Christian Dagenais, Chun Ni, Lin Hu, Lindsay Osborne, Ling Lu, Ciprian Pirvu; Julie Frapper (Nordic);

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NRC: Khaled Abdulghani, Steve Cornick, Bruno Di Lenardo, Gnanamurugan Ganapathy, Michael Lacasse, Wahid Maref, Travis Moore, Phalguni Mukhopadhyaya, Mike Nicholls, Hamed Saber, Mike Swinton, and David Van Reenen

EXECUTIVE SUMMARY

hygIRC 1D and 2D are hygrothermal simulation models developed at NRC Construction. hygIRC 1D is a one-dimensional version of hygIRC 2D. The objective of the task described in this report was to compare the results derived from the use the hygrothermal simulation models hygIRC 1D and hygIRC 2D to the results of a laboratory experiment (conducted as part of Task 5) to measure the drying rate of a specific wall assembly when subjected to nominally steady state conditions in an environmental chamber. The intended outcome was to duplicate the laboratory results as closely as possible as a means of benchmarking the simulation models both of which were subsequently used as part of the parametric simulation task (Task 6).

In this task, a combination of one-and two-dimensional models were used to calculate, on the basis of simulation results, the change in weight of a wall configuration model for a specified wall assembly. The wall configuration that was modelled using the same materials and geometry as the wall specimen tested. The boundary conditions on either side of the wall assembly were provided by environmental chambers that mimicked exterior and interior conditions; the conditions that prevailed in these chambers over the course of the experiment were used as input to the simulations.

Several variations of the basic wall configuration models were evaluated through simulations, however the most useful simulation results when compared to the experimental data were those derived from the initial base case model and another configuration model that included an air gap, the latter model meant to replicate gaps observed between the spray polyurethane foam (SPF) insulation and wood framing. The modelling exercise, while not precisely matching the experimental results, did sufficiently predict the drying out of the wood frame assembly, given the information available from the experiment, to warrant the use hygIRC for the parametric simulation task, Task 6, of the midrise wood project.

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Hygrothermal Modelling Benchmark: Comparison of hygIRC Simulation Results with Full Scale Experiment Results

S.M. Cornick and D. Van Reenen

Introduction

The objective of this task was to compare the results of the hygrothermal simulation tools hygIRC 1D and hygIRC 2D, to be used as part of the parametric simulation task, to the results of the laboratory experiment conducted as part of Task 5 and documented in Maref et al. [1]. The laboratory experiment measured the drying rate of a wall in an environmental chamber. A schematic of the modelled configuration of the wood frame wall assembly is shown in Figure 1Figure 1. The wall tested had dimensions of: 2438 x 2438 x 140mm and is comprised of the components listed in Table 1. The wood framing was saturated by immersing it in a water tank. The saturated wood frame wall assembly was subsequently foamed with spray polyurethane foam insulation, covered with an interior grade gypsum panel, and installed in an environmental chamber (NRC's Envelope Environmental Exposure Facility - EEEF). The benchmark wall was installed between two controlled environments in the EEEF, one side simulating the conditions of indoor temperature and RH, the other side simulating outdoor temperature and RH in the winter. The moisture content of the initially saturated wood studs was tracked over time when subjected to the above differential in environments. The temperature and RH of the two sides of the EEEF were also tracked, and this data was used as the boundary conditions for the simulations.

hygIRC 1D and 2D are hygrothermal simulation tools developed at NRC Construction [2][3]. hygIRC 1D is a one-dimensional version hygIRC 2D with an no heat, air, and moisture transfer along the top and bottom boundary, i.e. no heat or mass flow in the y-direction. Both hygrothermal simulation tools were used to model the drying experiment conducted in the laboratory. The objective of the task was to compare the results derived from the use the hygrothermal simulation models hygIRC 1D and hygIRC 2D to the results of a laboratory experiment (conducted as part of Task 5) to measure the drying rate of a specific wall assembly when subjected to nominally steady state conditions in an environmental chamber. The intended outcome was to duplicate the laboratory results as closely as possible as a means of benchmarking the simulation models both of which were subsequently used as part of the parametric simulation task (Task 6).

Methodology

The methodology used was as follows:

- Both one- and two-dimensional models were used in combination to predict the weight of a digital configuration of the wall assembly similar to the test specimen;
- hygIRC 1D was used to model the drying of the top and bottom plates of the wall section; the assumption was that there was little to no moisture transfer between the wood studs and adjacent spray polyurethane foam insulation, since the 1-D representation of the wall could not account for lateral moisture transfer in any case.
- hygIRC 2-D was used to model the drying of the stud elements of the wood frame wall assembly, while also accounting for possible moisture transfer between the studs, OSB, polyurethane foam and air spaces in the assembly.
- Both hygrothermal simulation models returned the moisture content of the materials within the assembly, including the studs: the weight of water in the specimen was calculated from the volume and the dry density of the material.

Modeling Assumptions

The following parameters were accounted for in the modelling:

- Wood-frame wall assembly and model configurations;
- Material properties;
- Boundary conditions – including environmental conditions simulating interior and exterior conditions and as well those that relate to conditions at the periphery of the test specimen;
- Transfer coefficients (heat and moisture);
- Initial conditions;
- Simulation sets.

Each of these items is briefly described below.

Wood-frame wall assembly and model configurations

A schematic of the wood frame wall assembly is shown in Figure 1Figure 1. The wall had dimensions of: 2438x 2438 x 140mm and is comprised of the components listed in Table 1. From left to right in the figure the material layers are; oriented strand board, wood stud frame (eastern white pine), spray-in-place polyurethane foam insulation (SPF) between the studs, 10 mm air gap in the stud cavity between the foam and the gypsum, and finally 12.7mm interior grade gypsum panel (unfinished). The benchmark assembly did not include a polyethylene sheet between the SPF and gypsum.

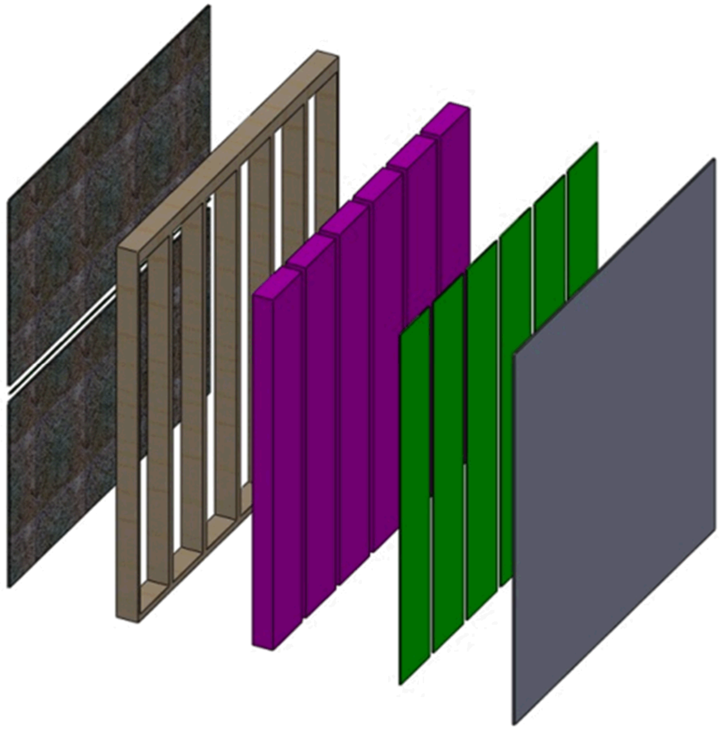


Figure 1 – Schematic of Wall Configuration used in Model.

Table 1 – Components of Wood-Frame Wall Assembly Test Specimen.

Component	Description
Vertical wood studs	Five of: 2324.4 x 140 x 38mm on 406mm centers
Wood headers	Three headers of: 2434.4 x 140 x 38mm; double top plate, single bottom plate
Framing wood studs	Two framing studs 2434.4 x 140 x 19mm at both ends
Exterior sheathing panels	Two OSB 2434.4 x 1219.2 x 11mm panels
Spray-in-place foam insulation	406mm cavities* between vertical studs (6) filled with SPF
Interior sheathing panels	Two gypsum 2434.4 x 1219.2 x 11mm unfinished panels

* – For modelling purposes, each cavity was assumed to have a 10mm air space between the surface of the framing stud and the exterior surface – of the interior finish. The 10mm spacing was based on a gap analysis performed on the laboratory benchmark wall.

Model configurations

The following simulation model deployment strategy was used to construct a 3-dimensional wall specimen drying result using a combination of 2-D and 1-D hygIRC simulation tools.

Figure 2 shows the 2-dimensional model representation, based on the test specimen described in Figure 1, which was used to predict drying curve. The figure shows the stud cavity in plan view. Half a stud cavity was modelled, taking advantage of symmetry. The left and right boundaries represent the exterior (weather) and interior side of the test chamber respectively. There was no heat, air, and moisture transfer allowed at the top and bottom boundaries. To estimate the weight of the vertical stud/insulation/cavity portion of the wall at time step of the simulation, the weight of the modeled portion at each time step was multiplied by 12; i.e. six stud cavities times two half sections. Figure 3 shows the one-dimensional model of the top and bottom plates. The figure shows a section of the plates as well as the one-dimensional model representation. As with the 2-D model, the left and right represent the exterior and interior boundaries, while there is no heat, air, and moisture transfer through the top and bottom boundaries. The weight of the top and bottom portions of the wall was estimated by multiplying the weight of the 1-D model result at every time step by the width of the wall and the height of the respective plate.

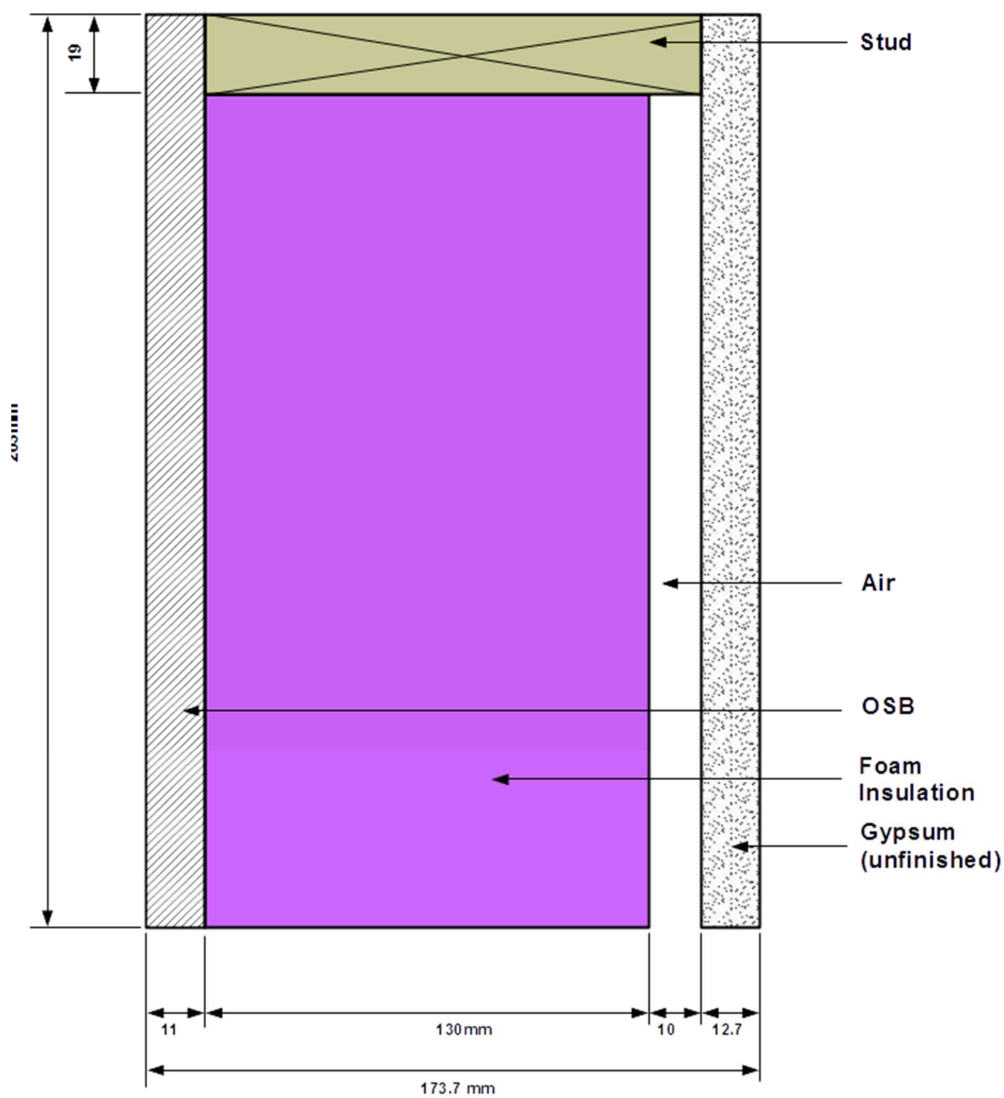


Figure 2 – Plan view of two-dimensional model of the wood-frame wall assembly; the model represents ½ a stud cavity. The left was the exterior boundary. This was the Base Case.

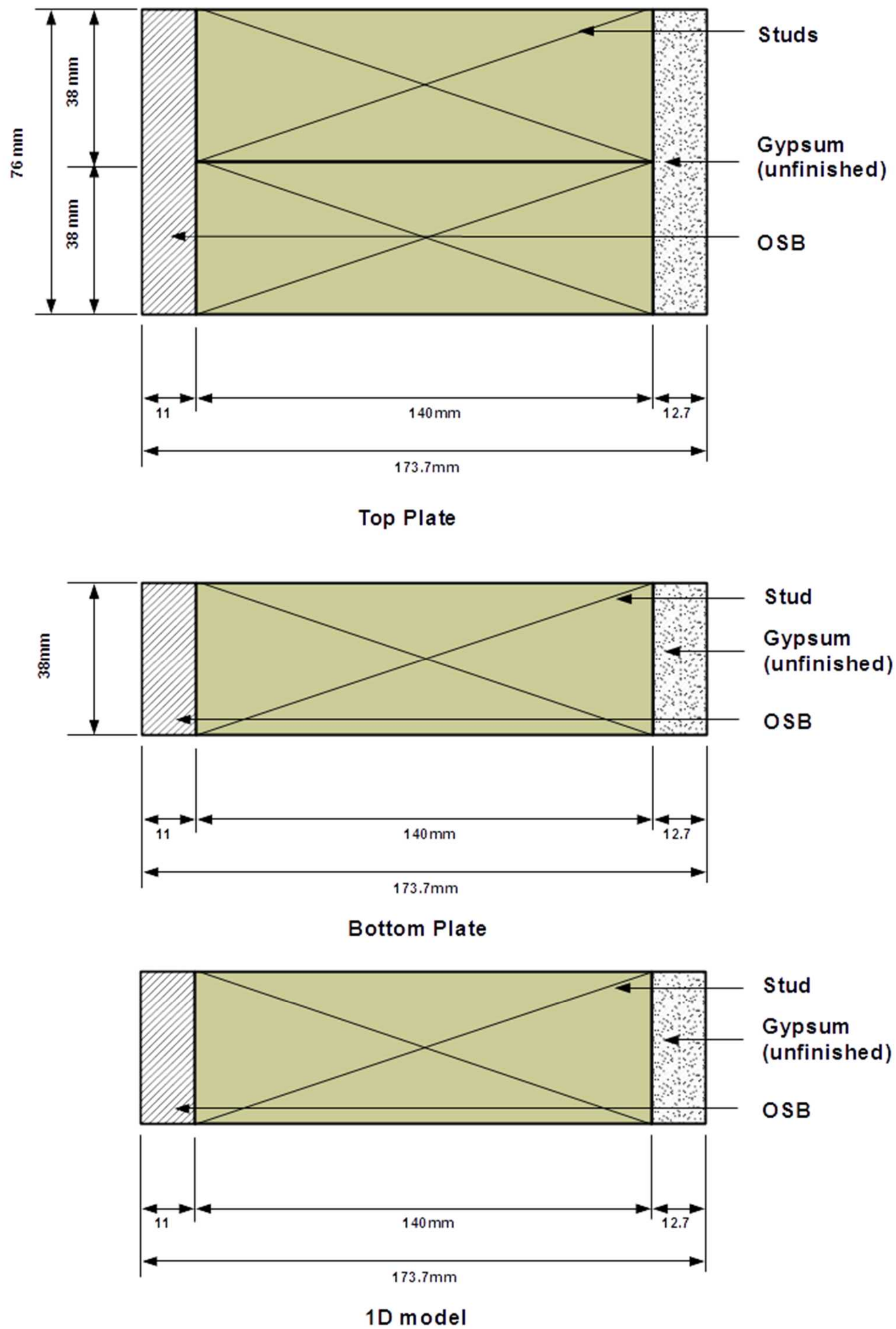


Figure 3 – Section view of top and bottom plates of the wood-frame wall assembly. The bottom section represents the one-dimensional model used. The left was the exterior boundary.

The total weight of the simulated wall at every time step was the calculated sum of 2-D and 1-D results described above.

Materials

Materials for the modeling task were taken from the existing hygIRC materials properties database with the exception of the spray polyurethane foam, properties for which were determined as part of the mid-rise wood project [4]. The materials used were:

1. OSB 11mm averaged material properties – hygIRC Database,
2. Unfinished Gypsum, 12.7 mm – hygIRC Database,
3. Air, 10 mm – hygIRC Database,
4. SPF – mid-rise wood project.

The hygrothermal properties of materials for the different components listed and provided in Table 1 are given in the Appendix.

Boundary Conditions

Boundary conditions relate to those environmental conditions that exist over the course of the test on either side of the wall assembly and as well, assumed conditions at the extremities of the wood-frame wall assembly, specifically along the periphery of the test specimen. Information for each of these boundary conditions is described in turn.

Environmental Conditions Simulating Interior & Exterior Boundary Conditions

Boundary conditions on either side of the wall test specimens were based on environmental measured conditions that prevailed in the respective chambers of the envelope environmental exposure facility (EEEF) over the course of the benchmarking experiment; simulated exterior conditions of -10°C and 60% RH were set in the primary climate chamber of the EEEF whereas conditions simulating the interior of a wall assembly were set at 24°C; no predetermined degree of RH was set in this latter chamber as the RH in the chamber was permitted to vary according to indoor lab conditions that prevailed over the course of the test.

A record of the temperature and relative humidity within the primary (cold side) chamber of the EEEF and in which exterior conditions were controlled over the course of the test is given in Figure 4. Temperature and RH within the environmental chamber serving to maintain interior conditions is given in **Error! Reference source not found.**.

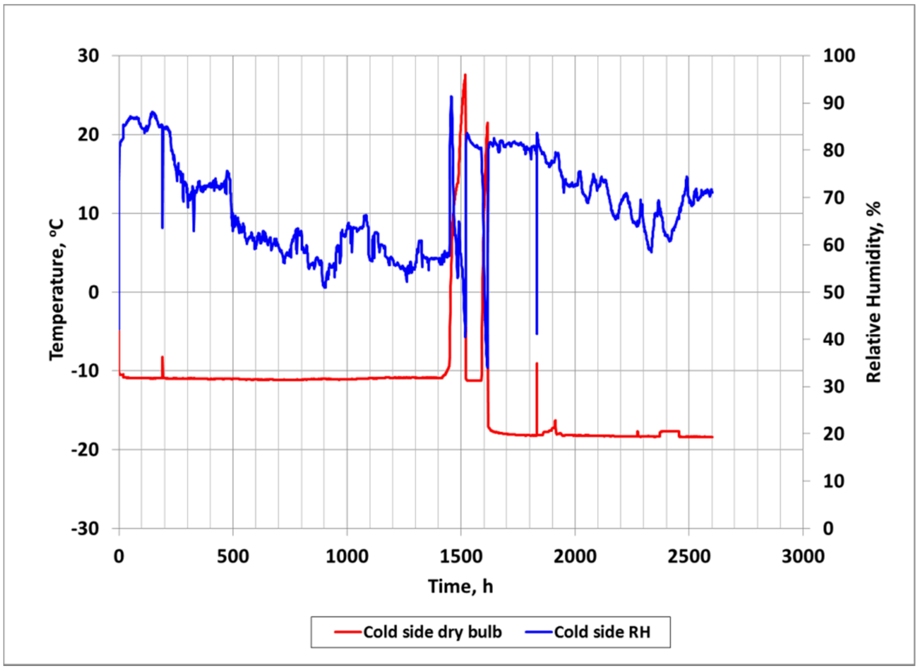


Figure 4 – The temperature and relative humidity within the cold side of the environmental chamber (EEEF) as a function of exposure time (hours) in which was installed the full-scale wood-frame test specimen.

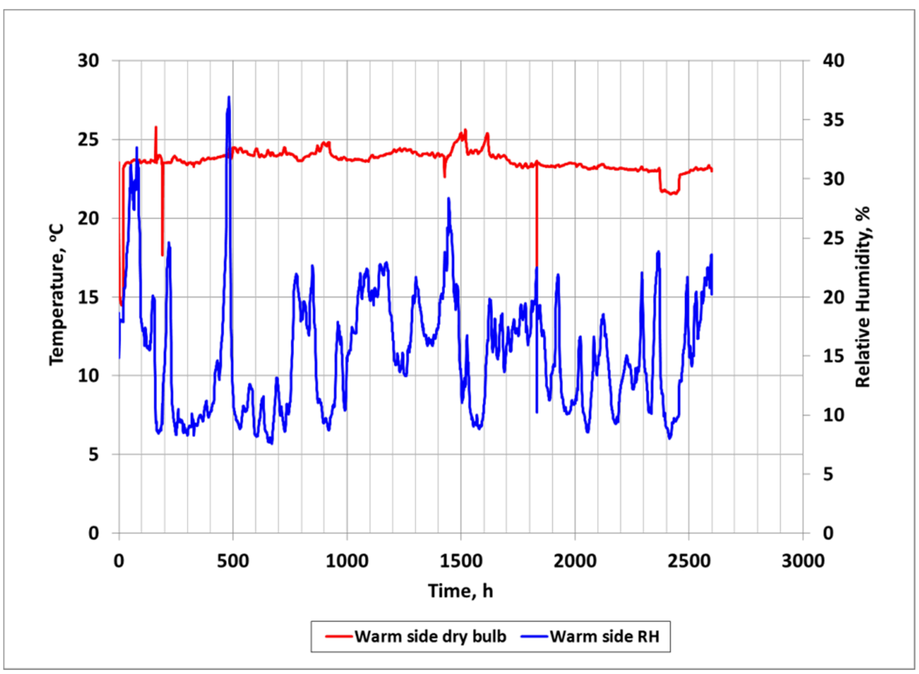


Figure 5 – The temperature and relative humidity within the warm side of the environmental chamber serving to maintain interior conditions as a function of exposure time (hours) in which was installed the full-scale wood-frame test specimen.

Top and Bottom Plates
Assumed boundary conditions at the top and bottom plates were as follows: no heat, air, and moisture transfer along the top and bottom plates along the y-axis; i.e. in the vertical direction when viewed in section.

Transfer coefficients
The heat and moisture transfer coefficients were assumed to be constant for the duration of the experiment. The following values were used for the heat and moisture transfer coefficients respectively:

- Heat transfer coefficient, exterior/interior: 10.00 $W/m^2 \cdot K$
- Moisture transfer coefficient, exterior/interior: 7.40E-08 $kg/m^2 \cdot s \cdot Pa$

Initial conditions
Except for the wood frame the initial conditions of the wall materials were determined from the conditions in the laboratory the beginning of the experiment. The OSB, gypsum, SPF were assumed to have equilibrated to laboratory conditions; before the wall was placed into the environmental chambers the conditions were measured to be 15% RH and 23.6°C. The moisture content of the wood frame was obtained by weighing the dry frame and the weight of the frame after prolonged soaking. The moisture content was determined to be 46.16% kg water/kg dry material. Details are given in Maref et al. [1]

The initial conditions under which the simulations completed were:

- Initial temperature: 23.6°C for all materials,
- Initial moisture content: 15% RH for OSB, Gypsum, and spray-in-place PUR, and
- Initial moisture content: 46.2% MC or 99.2% equivalent RH.

List of Simulation Sets
There were several sets of simulations that were completed to permit adequately benchmarking the simulation to the experimental results. A number of simulations were carried out at different initial moisture contents for the wood as these were found to affect to a significant degree the response of the assembly to moisture dissipation.

It was observed following the test that in certain stud cavities a gap appeared between the vertical face of the wood studs and the SPF. Accordingly, simulations were undertaken to determine the extent to which moisture dissipation from the vertical stud was affected by the presence of such gaps in proximity to the face of the wood studs.

Another set of simulations was done to investigate the variations in material properties data. Wood materials demonstrate a considerable degree of variability in material properties. Two sets of simulation runs were done with the water vapour permeance and liquid diffusivity of the wood materials varied by plus or minus 25%. The properties were either all increased or decreased, rather than in combination.

Given these scenarios the following set of simulations was completed:

1. Base Case, Initial MC in Pine 46.2%,
2. With Air Gap Adjacent to Stud, Initial MC in Pine 46.2%,
3. Change in experimental/simulation start time,
4. Parametric runs; water vapour permeance and liquid diffusivity of wood materials increased and decreased by 25%.

Summation of Moisture to obtain total moisture in wall

The calculation of the weight of water in the wall model for comparison with the weighing experiment is straightforward. The hygrothermal simulation tools, hygIRC 1D and hygIRC 2D return the total moisture content of the entire wall section as well as the total moisture content of the individual materials in terms of weight of water per unit length as output.

To estimate the weight of water in the wall or individual materials for the two-dimensional simulation the total moisture content of the modelled portion was multiplied by the height of the stud in the modelled portion. In this case the height was 2324.4 mm (an 8 foot stud minus the thickness of 3 2x6 plates). Since the modelled portion represented ½ of the wall, the final weight was multiplied by 12 to estimate the weight of water in the studs, SPF, gypsum and OSB. Moisture contents were obtained by dividing by the dry densities of the individual materials or the dry density of the wall portion modelled.

To estimate the weight of water or moisture content in the 1-D case a similar procedure was used. The 1-D case was simpler in that there was no y-dimension; consequently it was only necessary to multiply by the length of the top or bottom plates, (2.438.4 mm) and the thickness of the top or bottom plate to obtain the desired information.

The total change in moisture content at any time step from the initial moisture content was used to compare with the laboratory measurements, the moisture content being the summation of the 1-D and 2-D simulation results.

Comparison of Results Derived from Simulation with the Laboratory Experiment

Base Case, Initial Moisture Content in Pine 46.2%

The Base Case simulations assumed that the initial moisture content of the wood framing elements was 46.2% (RH ~ 99.2%). The relative humidity of all other materials was assumed to be in equilibrium with the laboratory conditions and thus the moisture contents of the respective materials were determined on the basis of the corresponding relative humidity in-laboratory. The temperature was assumed to be the initial temperature in the environmental chamber. For the Base Case the models used were those shown in Figure 2 and Figure 3. Figure 6 shows a comparison between the experimental results and the Base Case simulation. The chart shows the total moisture loss in the wall assembly from time zero over a 100-day period (2400 hours). The simulation results underestimated the drying out of the wall assembly. As well, the simulation showed that there was a substantial amount of moisture pickup during the simulation period whereas the experimental showed that the weight was more or less monotonically decreasing.

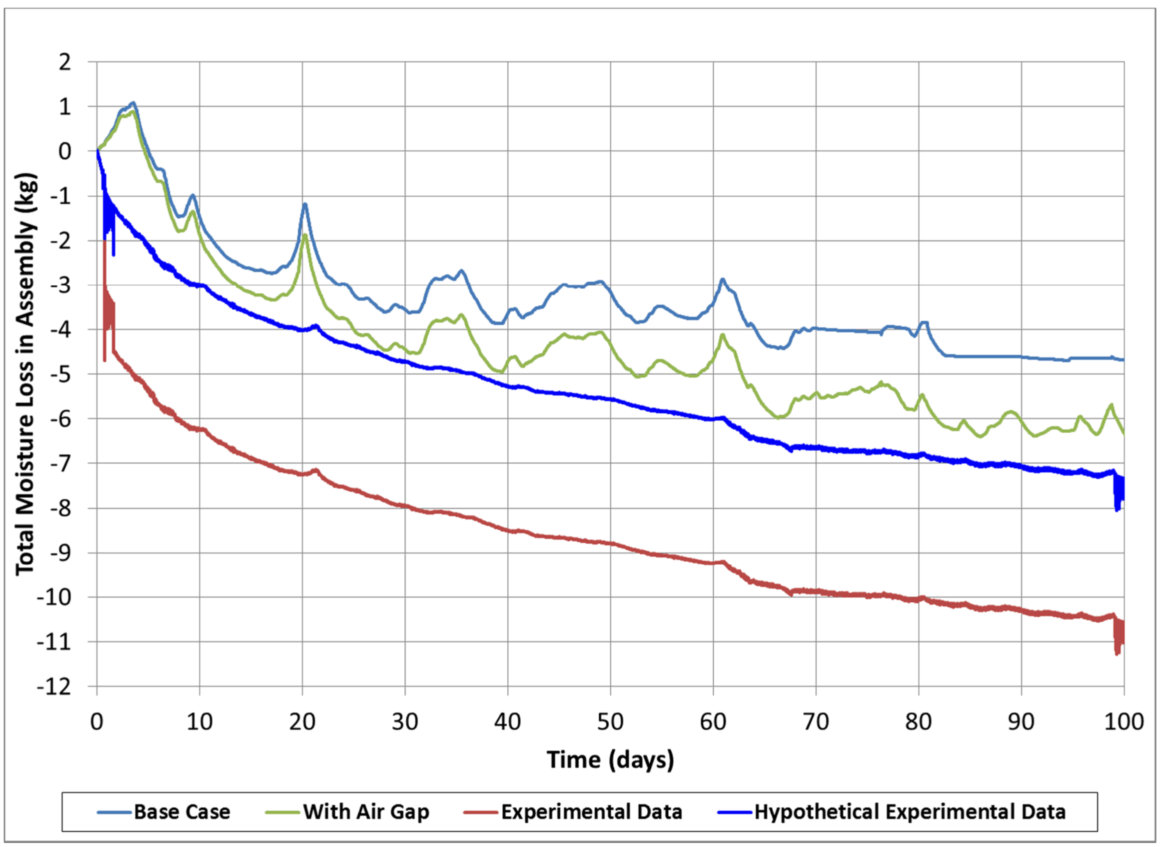


Figure 6 – Total moisture loss in the wall assembly. Initial moisture content of wood frame 46.2%, Base Case and Air Gap Case compared with experimental data and corrected experimental data.

Correction of experimental drying curve

A closer examination of Figure 6 shows that there are two significant losses in weight over short time periods. Figure 7 (a) shows the specimen weight over the time of the experiment whereas Figure 7 (b) shows the weight of the specimen during the first 168 hours. These weight losses, as occurred between hours 12 and 24 and hours 36 and 42 (Figure 8 (a) and (b) respectively), are large (> 3.5 kg between 12 and 24 hours) and occur in a short period of time. The drops are significantly different from the normal expected data acquisition system signal noise that occurred during the experiment. Such signal noise can be seen in Figure 8 as characterised by sharp drops that return to the normal tracking of the weight loss curve (range from ~ 0.3-0.4 kg);. Hygrothermal conditions on both sides of the environmental chamber could perhaps have accounted for the amount and suddenness of the weight loss, however the two weight losses were subsequently attributed to measurement difficulties inherent to the experimental setup; the combination of data acquisition system, the weighing system, and the load cells.

In order to account for what was considered to be an experimental error a new drying curve was thereafter developed by adding the weight lost after each respective change in weight for which four correction factors were identified over the course of the experiment; these are given in Figure 9. Figure 6 shows the comparison between the simulation results and the corrected experimental data.

Table 2.. The uncorrected weight loss of the wall was reported as 10.6 kg whereas the corrected weight loss of the wall was calculated to be 7.37 Kg. A corrected drying curve to which comparisons were made to those of the hygrothermal simulation results is given Figure 9. Figure 6 shows the comparison between the simulation results and the corrected experimental data.

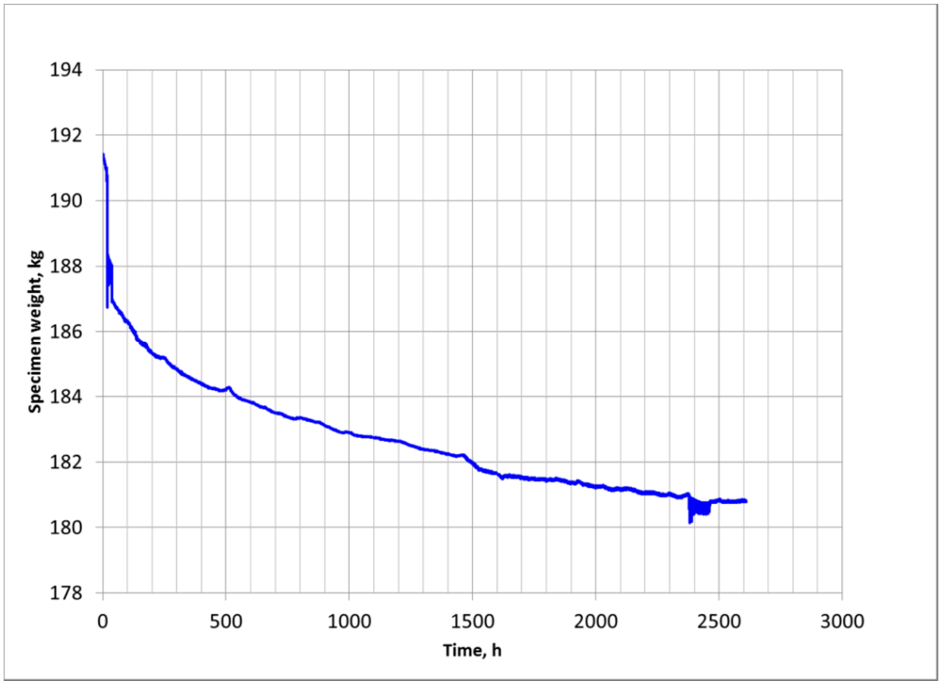
Table 2 – Weight correction factors

Correction factors, kg	
Corr1	1.85968
Corr2	0.88120
Corr3	0.54970
Corr4	1.03725
Total weight. correction	4.32783

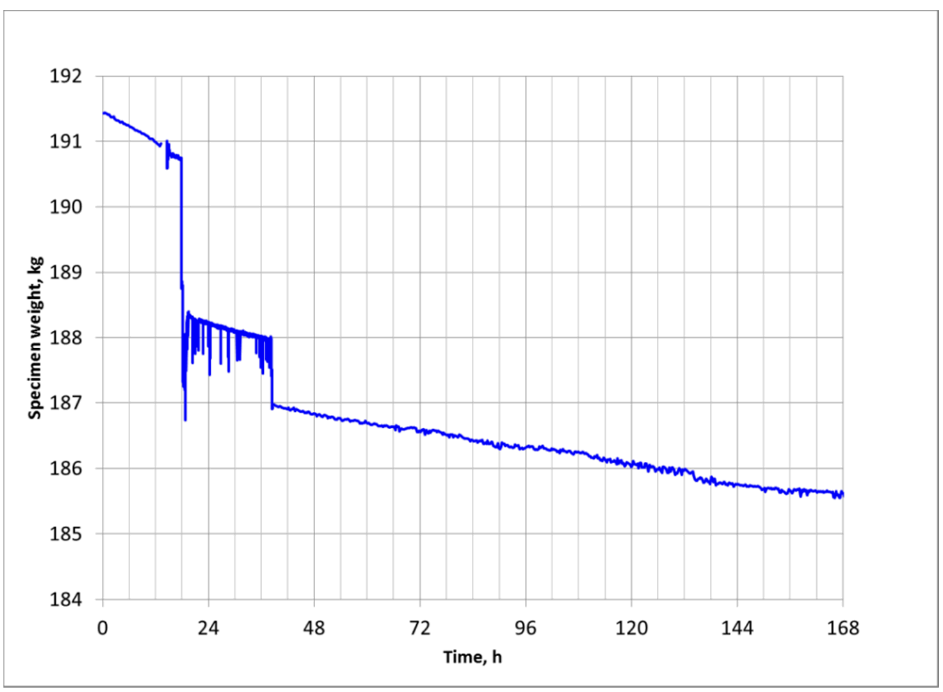
Air Gap Adjacent to Stud, Initial MC in Pine46.2%

Prior to commencing the experiment a detailed examination of the wall specimen was conducted. It was noted that there had been a considerable amount of separation between the SPF and the vertical studs of the wood frame assembly. This was due to the fact that the wood studs were much wetter when the SPF was applied than foam manufacturers recommend. Consequently in many places the foam did not properly adhere to the wood studs. This is shown in Figure 10.

This gap potentially provided another path for moisture to dry from the studs. Consequently a second 2-D simulation model was created to assess the impact of foam separation on the drying of the wood studs; a 2mm gap was assumed between the stud and the foam. A schematic of the revised 2-D wall model is shown in Figure 11. The result of simulation from this variation is shown in Figure 6, and is referred to as the Air Gap Case. The assumed gap produces an increase in the drying rate of the wood frame and it is also shown that this curve more closely approximates that of the corrected experimental drying curve.

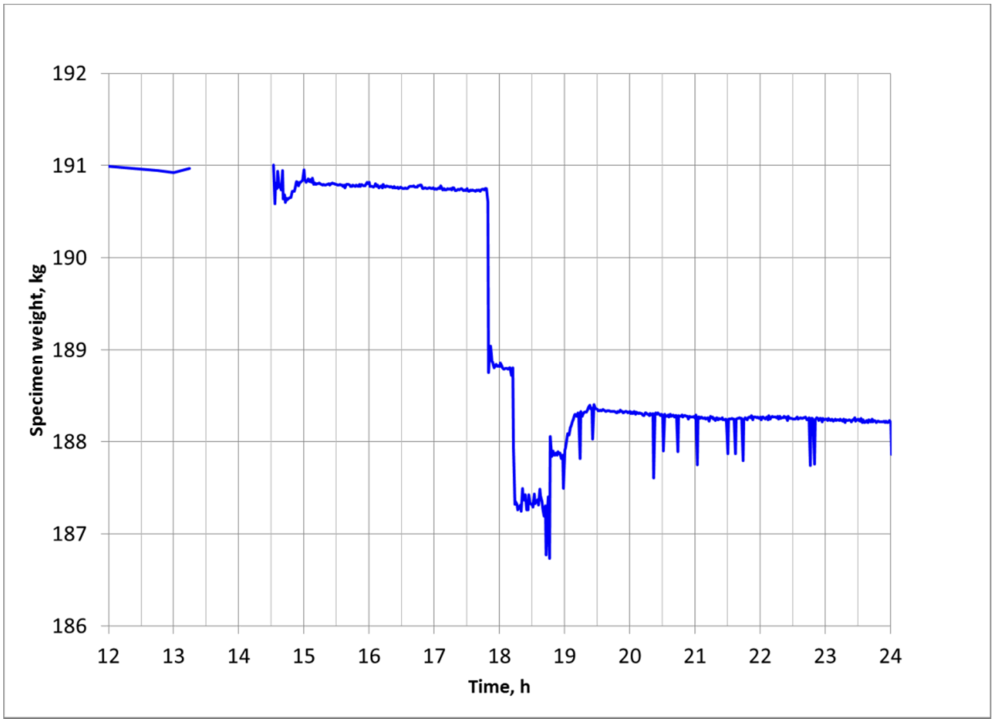


(a)

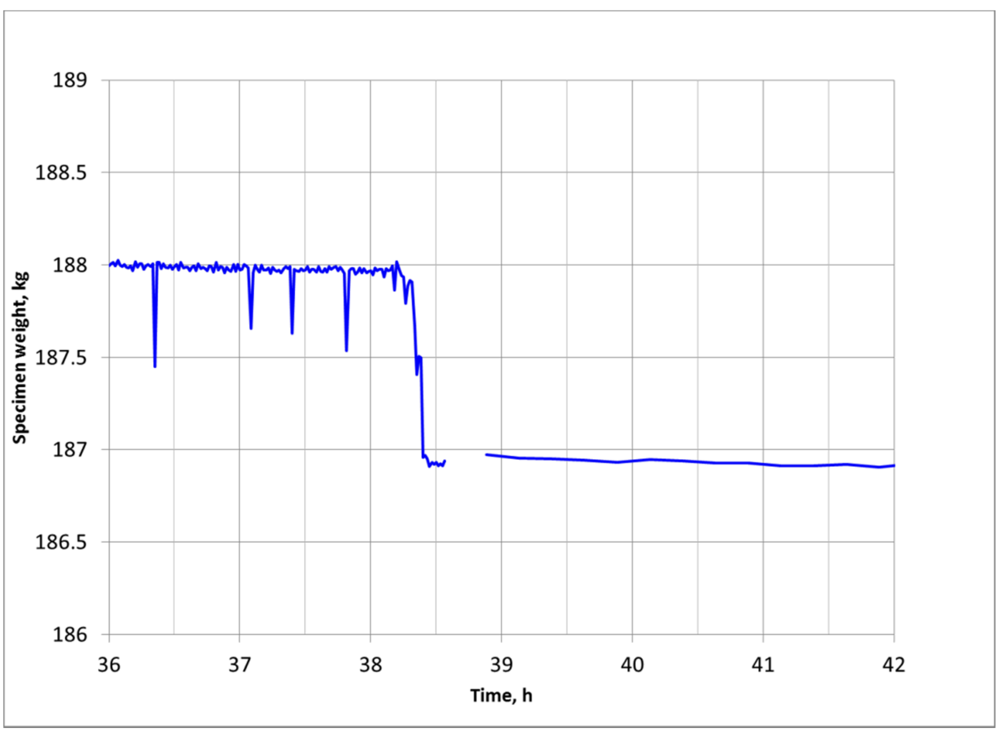


(b)

Figure 7 – Moisture Dissipation from test specimen as a function of time as derived from results of laboratory experiment over (a) the entire drying experiment and (b) the initial 168 hours.



(a)



(b)

Figure 8 – Weight of wall assembly as a function of time. (a) Weight between 12 and 24 h from start of experiment; initial loss in weight not due to chamber conditions but to experimental setup; (b) Weight between 36 and 42 h from start of experiment; loss in weight not due to chamber conditions but to experimental setup.

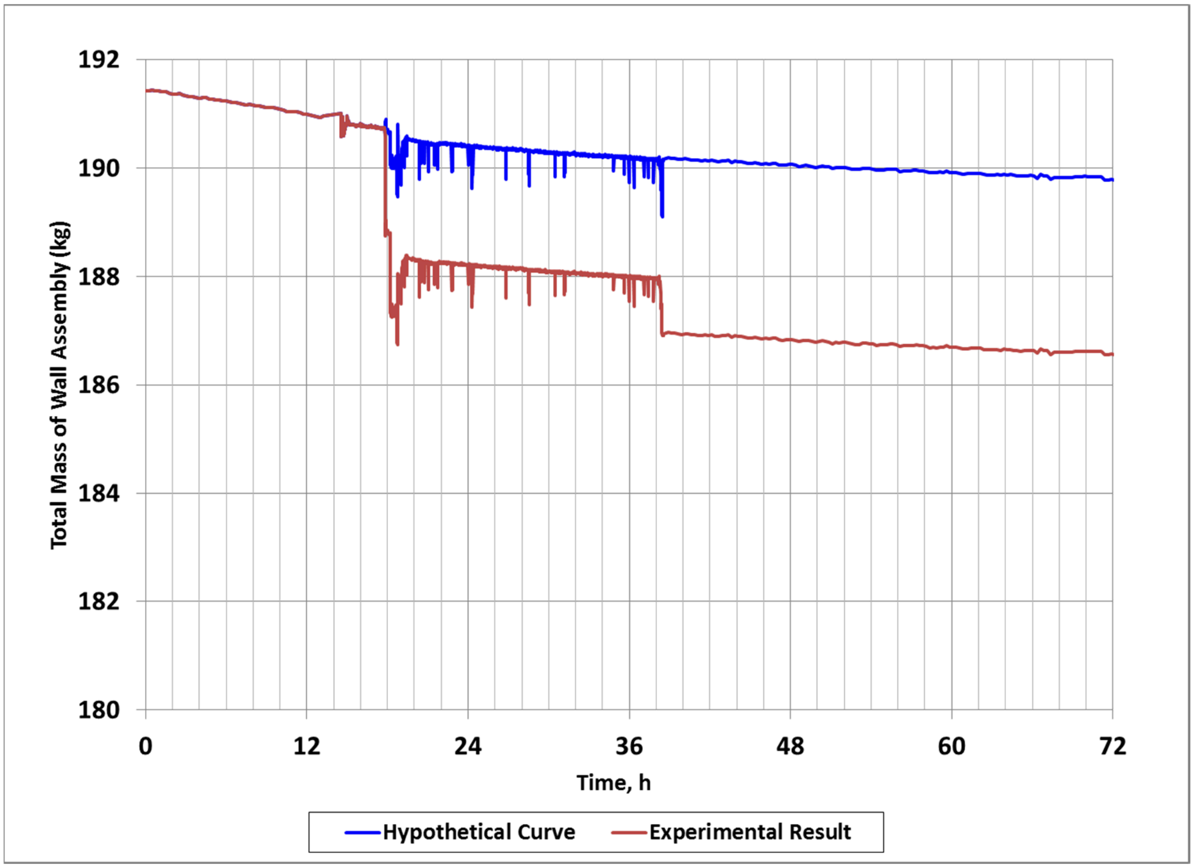


Figure 9 –Weight of wall assembly as a function of time – corrected and experimental values.

Figure 10 – Separation of SPF from framing due to higher than normal moisture content in studs. [1]

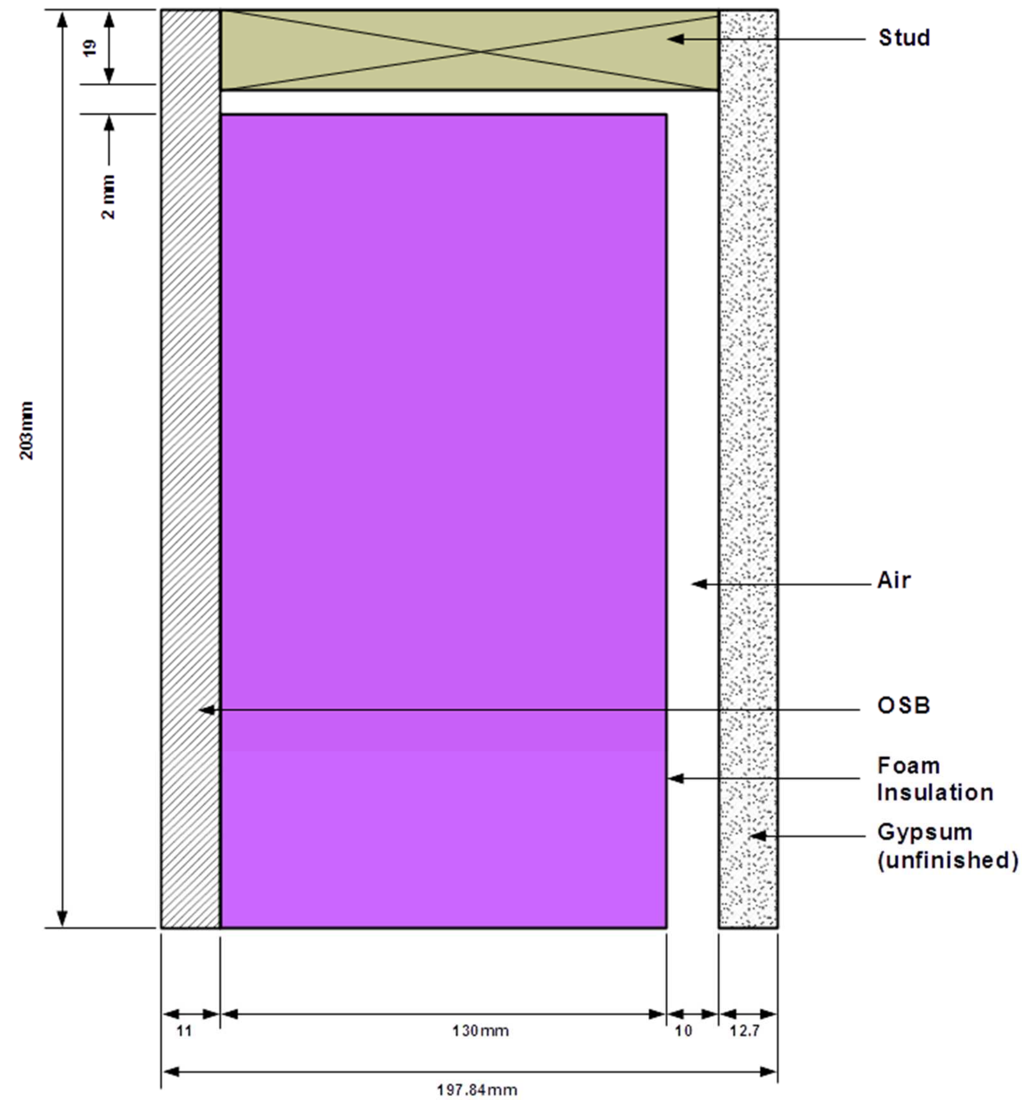


Figure 11 – Plan view of two-dimensional model of the wood-frame wall assembly; model represents ½ a stud cavity. In this case a 2mm gap was assumed to model the effect of separation between the foam and the stud.

Change in simulation start time

Several simulation runs were conducted where the start time of the simulations was delayed. The simulation start times were moved to the point after the weight drops noted in the previous section. Although these results seemed at first to better than the results presented here the assumptions were not felt to be defensible.

Parametric runs

Finally, a series of parametric runs were conducted to examine the effect of uncertainty in the values of the material properties. Two properties were selected for variation, specifically the water vapour permeance (WVP) and liquid diffusivity (LDiff) of the wood materials. The materials properties for gypsum and SPF were assumed to lie within a narrow band due to quality control of the respective products. Instead of a complete matrix of simulation runs, 8 in this case, only two variations were completed; these included an increase of 25% in the WVP and LDiff in both the OSB and wood framing and a decrease of 25% in the WVP and LDiff of the OSB and wood framing. These two variations were chosen to bracket the potential increased and decreased moisture transfer due to uncertainty in material property values. A comparison of the results of the parametric runs, using 46.2% initial moisture content for the framing, the base case model, and the corrected experimental data is shown in Figure 12. Based on these variations, there appeared to be little change in the drying rate the assembly.

Consideration of the framing only

Figure 13 shows the comparison between the simulated results for the Base Case and Air Gap Case at 46.2% initial moisture content and the corrected experimental results. In this case only the simulated moisture content of the framing was considered; i.e. the weight changes in the gypsum and OSB were removed from the total change in weight. The figure shows a considerable improvement in weight change prediction. Cleary the majority of variation in the simulation was caused by changes in weight of the gypsum and the OSB. Simple one-dimensional indicates that the majority of the variation can be attributed to the change in moisture content of the gypsum (see Figure 14).

Discussion

In this task, a combination of one-and two-dimensional models were used to calculate, on the basis of simulation results, the change in weight of a wall configuration model for a specified wall assembly. The wall configuration that was modelled used the same materials and geometry as the wall specimen tested. The boundary conditions on either side of the wall assembly were provided by environmental chambers that mimicked exterior and interior conditions; the conditions that prevailed in these chambers over the course of the experiment were used as input to the simulations.

Several variations of the basic wall configuration models were evaluated through simulations, however the most useful simulation results when compared to the experimental data were those derived from the initial base case model and another configuration model that included an air gap meant to replicate gaps observed between the SPF insulation and wood framing following the completion of the experimental. In both of these simulation runs the initial moisture content for the framing was assumed to be 46.2%.

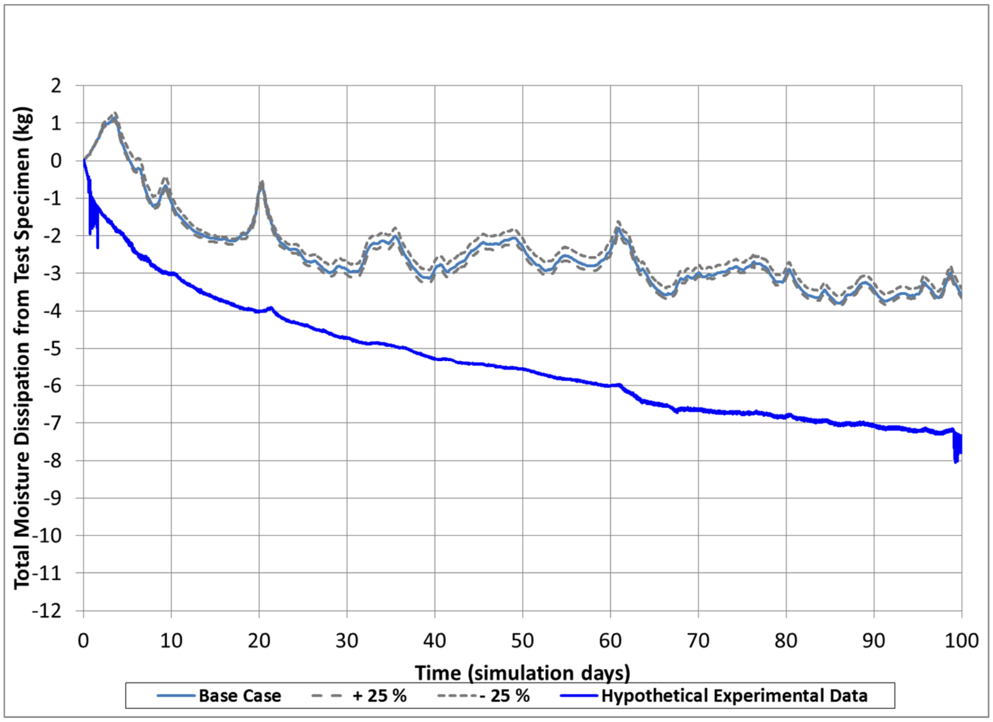


Figure 12 – Results of a 25% parametric variation in water vapour permeance and liquid diffusivity for the wood materials in the base case model.

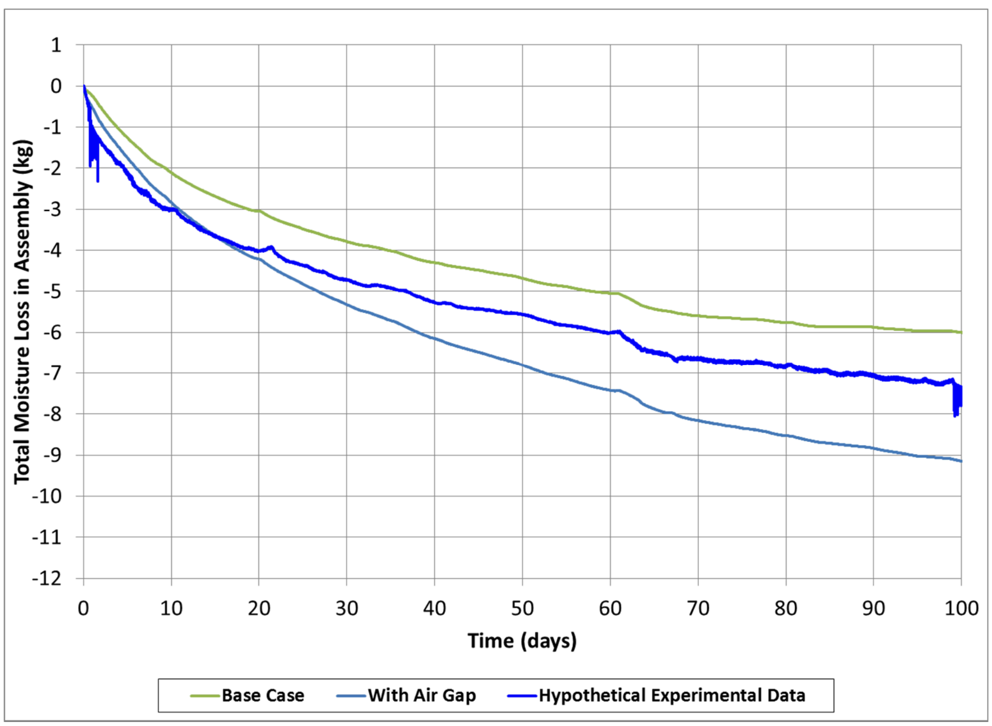


Figure 13 – Comparison of simulation results with corrected experimental results; only simulated change in weight of framing considered.

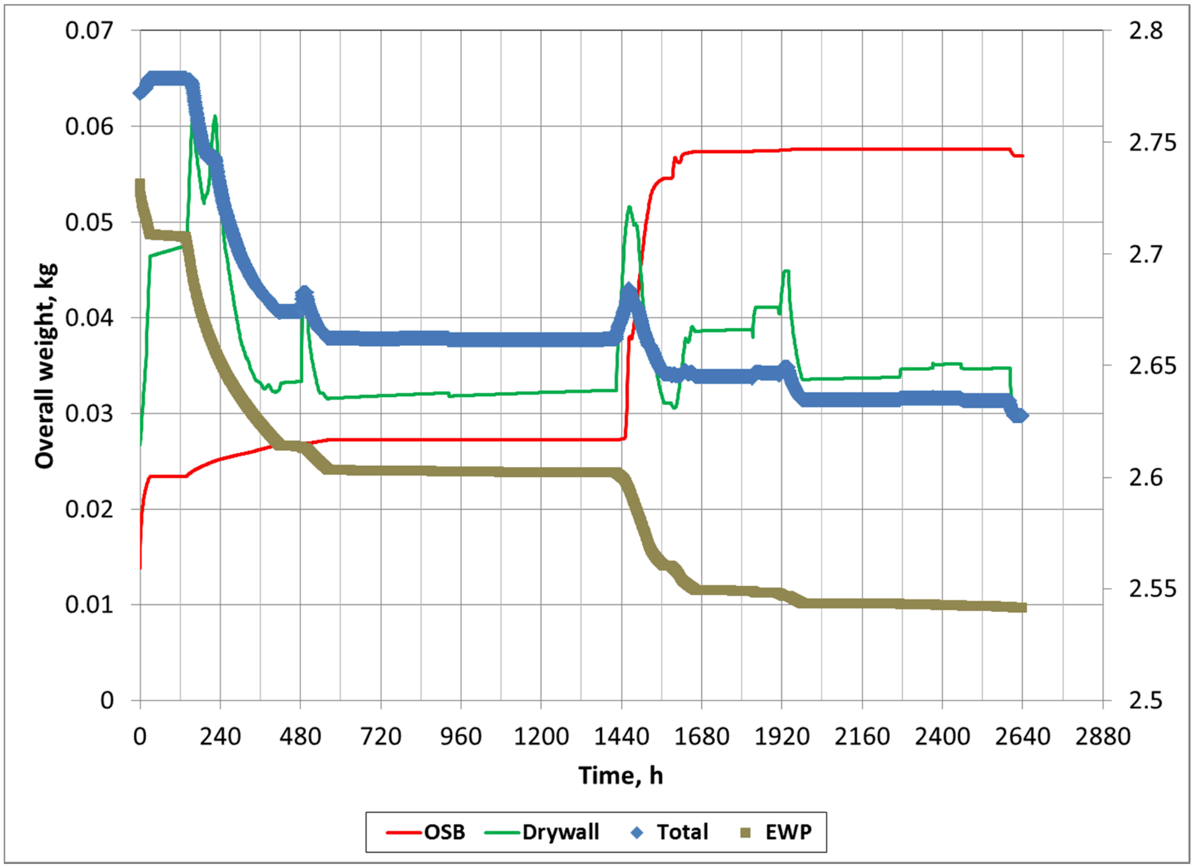


Figure 14 – One-dimensional modelling using laboratory boundaries conditions shows that variations are due to moisture pick up and release by the interior gypsum. (EWP refers to …)

These results compared best with the corrected experimental results and they represented variations for which the fewest assumptions were made and thus considered to be the most defensible. The overall weight change as estimated by simulation was nonetheless underestimated and hence the drying out of the frame was likewise underestimated. Possible improvements to the simulation results could perhaps be gained by attempting to model the gap between the two horizontal sheets of gypsum as such an approach could provide a clear path from the wood frame to the interior of the chamber; this however was not investigated.

The simulated drying curve also showed weight increases whereas the experimental drying curve was essentially monotonically decreasing. When the OSB and particularly the gypsum were removed from the simulated results the concordance between the change in measured weight of the wall and the predicted change in weight was much improved. In fact the corrected experimental data was bracketed by simulation results derived for the Air Gap Case and Base Case models. It was suggested that the discrepancy was due to the difficultly of correctly modelling moisture transfer at free surfaces of components using hygIRC.

This same phenomenon was previously encountered by Maref et al. [5] when using hygIRC to benchmark full scale wall specimens. In those experiments a saturated specimen of OSB was dried in an environmental chamber and the subsequent modelling exercise of the drying of the OSB specimen there were challenges in adequately modelling the drying of the free surface of a saturated component. However as the wall specimens became increasingly complex and the saturated OSB layer was placed in the middle of several layers of the wall assembly, the simulation results better matched the experimental results. The reason put forward for this was that the moisture transfer through material layers that were in close contact was better modelled in hygIRC than the moisture transfer between a material and air through a free surface. The results of the experiment referred to by Maref et al. [**Error! Bookmark not defined.**] reported on the total moisture content of the OSB rather than the entire specimen. Thus the results of the current exercise were consistent with previous exercises designed to benchmark hygIRC 1-D and hygIRC 2-D. In conclusion, the modelling exercise whilst not precisely matching the experimental results, did sufficiently predict the drying out of the wood frame assembly, given the information available from the experiment, to warrant the use hygIRC for future tasks in the midrise wood project, Task 6.

References

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Appendix

Material properties

A list of materials used in the hygrothermal simulations and the respective relevant hygrothermal properties in given in Table A1. A comparison of the water vapour permeance, sorption/desorption isotherm, liquid diffusivity, and conductivity properties is shown in Figures A1 through A4. The properties were primarily derived from tests that were completed for the MEWS project [1] and subsequently reported in the ASHRAE project [2].

Table A1 – Material Properties

Material	Density (kg/m^3)	Heat Capacity (J/kg·K)	Air permeability (m^2)
OSB (11 mm thickness)	600	1880	3.12×10^{-12}
Gypsum sheathing panel (12.7mm thickness unpainted)	700	870	5.66×10^{-14}
Wood (Eastern White Pine)	460	1880	2.13×10^{-17}
Spray polyurethane foam [3]	40.3	1470	3.83×10^{-14}

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[2] Kumaran, M. K; Lackey, J. K; Normandin, N.; Tariku, F.; and, van Reenen, D. (2002), "A Thermal and Moisture Transport Property Database for Common Building and Insulating Materials: Final Report from ASHRAE Research Project 1018-RP".

[3] Mukhopadhyaya, P., S. Bundalo-Perc, D. van Reenen and J. Wang (2013), "REPORT TO RESEARCH CONSORTIUM FOR WOOD AND WOOD-HYBRID MID RISE BUILDINGS, Characterization of Hygrothermal Properties" Report A1-100035-03.4, National Research Council Canada, Ottawa, 29 p.

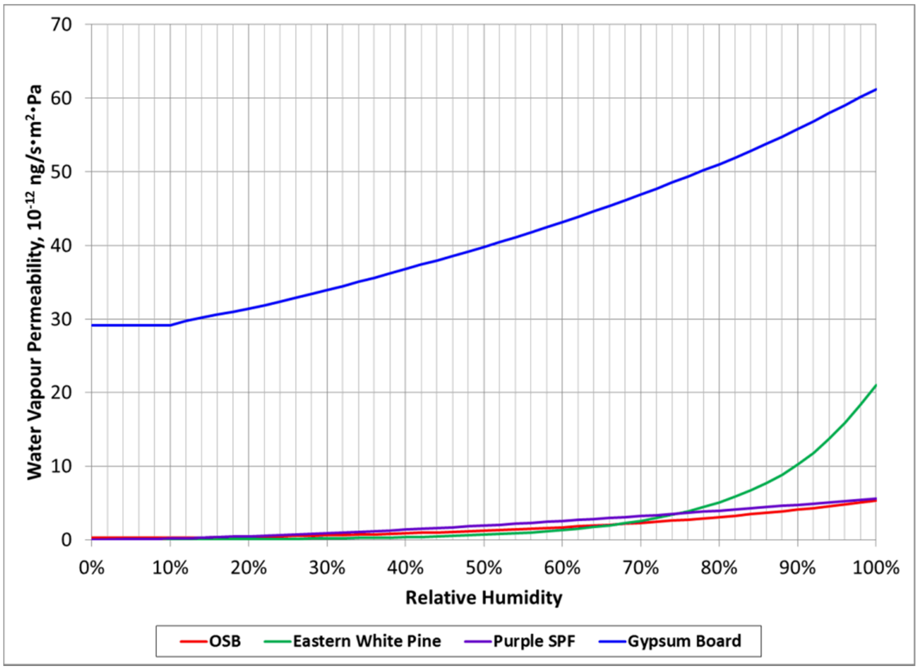

Figure A1 – Water vapour permeability property of materials used in the modelling exercise.

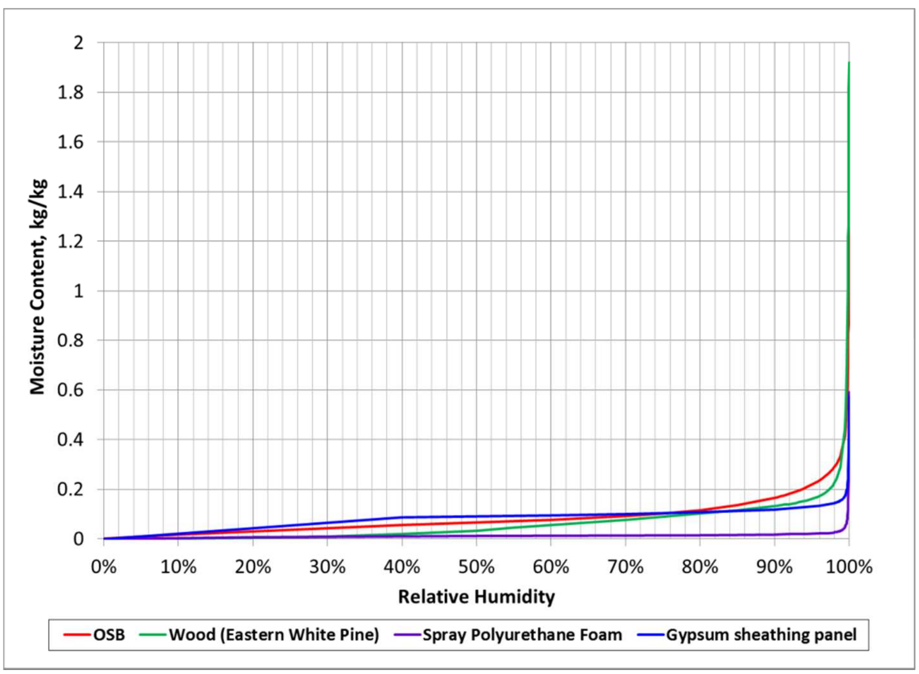

Figure A2 – Sorption/Desorption isotherm property of materials used in the modelling exercise.

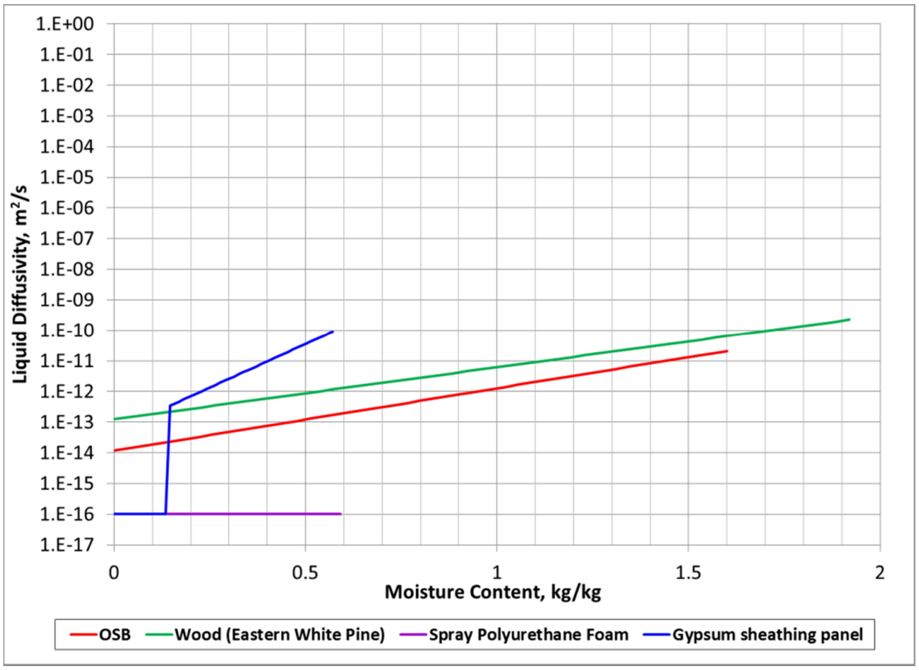

Figure A3 – Liquid Diffusivity property of materials used in the modelling exercise.

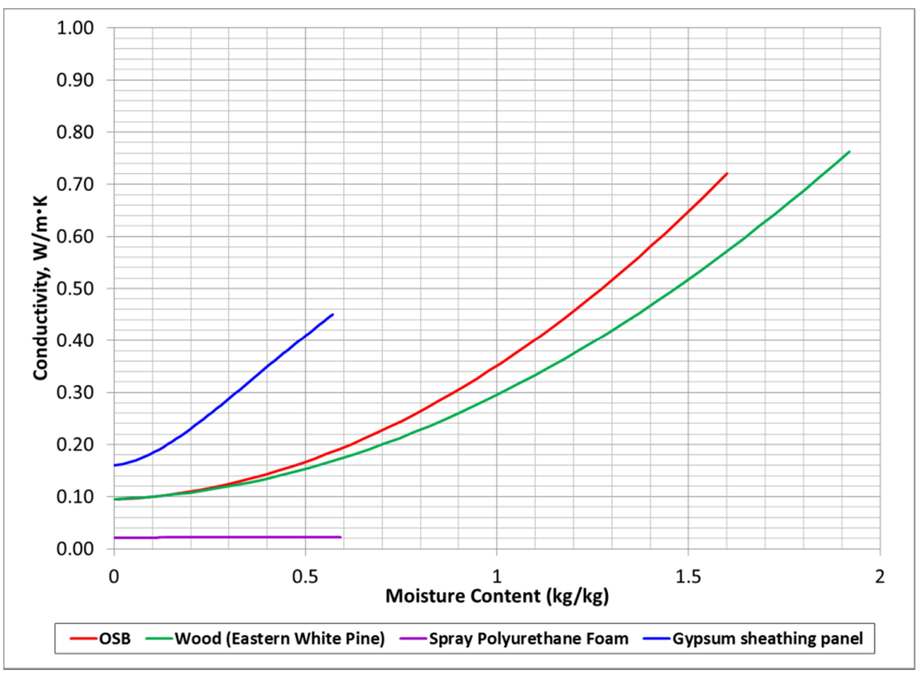

Figure A4 – Conductivity property of materials used in the modelling exercise.