HYGROTHERMAL PERFORMANCE OF HIGHLY INSULATED WOOD FRAME WALLS WITH AIR
LEAKAGE: FIELD MEASUREMENTS AND SIMULATIONS

By

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Ryerson University, Toronto

ABSTRACT

This thesis examines the hygrothermal performance of six types of high thermal resistance (High RSI) wall assemblies during environmental exposure and an air leakage (exfiltration) simulation test. These walls were installed in the Building Engineering Group's test facility (BEG Hut) located at the University of Waterloo. The High-RSI wood-frame walls were assessed by analyzing condensation, mould, and decay risks using the moisture content, temperature, relative humidity and heat flux data collected during the field test. These field-measured data were also used to calibrate one-dimensional WUFI® simulation models for each of the High-RSI assembly for use in future durability assessments using a range of North American climates. Methods were investigated to improve the predictive capacity of these simulation models as well as to increase their utility as a research tool. The design, construction and instrumentation details of the High-RSI study were also documented.

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1 INTRODUCTION

Climate change and increasing commodity prices have led to governments mandating greater energy efficiency in building codes throughout Canada and the US. Increased energy efficiency requires higher levels of insulation in envelope assemblies beyond what is now achieved with traditional 38 x 88 mm and 38 x 140 mm wood framing and cavity insulation. Increased insulation thicknesses will lead to dramatic changes in building design, which may unintentionally affect the long-term durability of wood-based structural elements. Whether the efficiency gains are achieved through deeper framing cavities or externally insulated traditionally framed wall assemblies, understanding the risks of interstitial condensation arising from moisture loads and air leakage is necessary in order to determine design limitations.

To investigate these potential risks and design limitations, six high thermal resistance (RSI) wall assemblies were constructed at a field test facility at the University of Waterloo's Building Engineering Group's test facility (BEG Hut). This High RSI wall study is part of the NSERC strategic research Network for Engineered Wood-based Buildings Systems (NEWBuildS). NEWBuildS is a multi-disciplinary network of researchers focused on various aspects of engineered wood products, their integration and advancement in modern construction. An important technical goal of this network is the development of technical tools and design criteria for use by engineers, researchers, and product manufacturers. The high RSI wall study was part of NEWBuildS Theme 4: Building systems – durability, sustainability and enhanced products. The goal of this project is the development of advanced knowledge and best practices in the construction and design of energy efficient, cost effective and sustainable residential buildings with ensured long-term durability.

1.1 *Overview of the High RSI wall study*

Recent research (Armstrong, Maref, Rousseau, Lei and Nicholls, 2010) has identified the potential for moisture related damage arising from air leakage in conventional light wood framed walls installed with low water vapour permeability exterior-insulation. The need for performance details related to the impact of air leakage and the drying capacity of not only exterior insulated walls, but deep cavity walls has also been identified (Straube, 2010). The High RSI wall project was designed to document the moisture performance and durability of exterior insulated and deep cavity walls concurrently in a typical Canadian cold climate with active air leakage and water leakage testing.

The High RSI wall assemblies used in this study were allowed to acclimate during a baseline period or passive phase where climatic moisture responses of the wood-based materials could be assessed prior to active moisture loading. The active moisture loads were applied by simulating exfiltration through the injection of interior air into the central stud bay of each test assembly and by injecting liquid water behind the air barrier on the exterior surface of the sheathing. The impacts of increased insulation levels on the moisture content (MC) of wood-based components were monitored using electric moisture content sensors placed in the sheathing and framing plates. Through the inclusion of a Part 9 Ontario Building Code compliant datum wall in the study, the risks associated with increased insulation levels could be quantified relative to current code compliant practices.

In addition to the MC-data, temperature, relative humidity (RH), heat flux data, as well as climate data were collected for analysis. These datasets were used to calibrate the hygrothermal simulation models (WUFI®) with the climate data in order to optimize the predictive capacity of the models and increase their utility as a research tool. Using the hygrothermal simulation models calibrated to full-scale field test data; this study assessed condensation risks, drying potential and in-service durability with the intent of developing climate-sensitive design guidelines. These guidelines will help ensure the compliance of high RSI value wall assemblies with increasingly stringent building codes.

1.2 Material selection and design

The High RSI walls selected for this study target the design and construction of OBC Part 4 platform wood-frame and wood-hybrid buildings (including mid-rise) as well as OBC Part 9 for residential houses and small buildings. The wall types selected for this study are readily adaptable to meet the anticipated 50% increase to current building code requirements of RSI 3.9 to RSI 6.

The different ways to achieve higher thermal resistance levels include increased wall widths to accommodate thicker cavity insulation as well as the combination of different types of insulation materials like rigid or semi-rigid exterior insulation. The hygrothermal behaviour of each wall assembly varies according to climatic conditions, which results in different performance and durability profiles. From these performance data, the potential weaknesses of the selected High RSI wall assemblies can be identified.

Dense-pack cellulose insulation was chosen for two of the deep cavity wall types because of its hygroscopic nature and moisture buffering capacity as well as its cost profile. The framing designs used

in these deep cavity walls included a double stud wall and an I-Joist stud wall. Thermal bridging in the double stud wall was reduced by the insulated space between the two stud frames, while the thin, 11.1 mm OSB web of the I Joist wall was the limiting factor for thermal bridging in this wall type.

Another deep cavity wall was also included in this study that used 38x184 mm framing installed with 160 mm of closed-cell spray polyurethane foam (ccSPF). The purpose of this wall was to contrast the high thermal resistance of the ccSPF foam with the thermal bridging effects of the 184 mm framing.

The exterior insulated walls were constructed using the same 38x140 mm framing as the datum wall and fitted with fibreglass cavity insulation because of its greater susceptibility to moisture damage than mineral wool. The three exterior insulation types were selected from common materials that could readily increase the thermal resistance of the datum wall by 50% (~RSI 2.1). The thickness of each insulation type was designed to add approximately equivalent amounts of thermal resistance to each wall. Two of the three exterior insulation types selected were rigid products (extruded polystyrene [XPS] and polyisocyanurate) with low water vapour permeance values at their installed thicknesses. These two insulation types were contrast with the high water vapour permeability of the third, semi-rigid insulation composed of mineral wool.

1.3 Experiment methodology

The six high RSI wall assemblies used in this study were installed at the BEG Hut test facility in Waterloo, Ontario during the July and August 2012. Of the six high RSI wall designs in this study, three investigated the relative performance of exterior insulation (polyisocyanurate, extruded polystyrene and mineral wool) on traditional 38 x 140 mm framed walls with fibreglass cavity insulation. The installed thermal resistance of these test walls averaged RSI 6.0. Two other wall types investigated the performance of the deep framing cavities filled with dense-pack cellulose insulation. These deep cavity walls were constructed using 286 mm cavity double stud or 241 mm cavity I-Joist stud framing that accommodated installed thermal resistances of RSI 6.8 and RSI 5.8 respectively.

Two test panels of each of these five wall types were built and installed on north and south facing orientations in order to compare the effects of direct solar radiation on moisture transport and storage. The data from these two orientations help to create a more complete estimation of each wall's expected in-service durability. A standard 38 x 140 mm framed wall with fibreglass cavity insulation (RSI 3.87) type was also included as a performance datum for both the north and south facing wall assemblies.

Finally, a third deep cavity wall was constructed with 38 x 184 mm framing and insulated with 152 mm of closed-cell polyurethane spray foam insulation (ccSPF) for an installed thermal resistance of RSI 6.4. Due to space limitations at the BEG Hut, this wall was only oriented with a southern exposure.

The drying capacity of each wall was assessed under typical indoor conditions and climatic exposure. In addition, each wall was evaluated with an air injection test to simulate air leakage and an exterior water leakage test to simulate rain infiltration. The moisture content of the oriented strand board (OSB) sheathing was used as the primary performance criterion for the determination of durability and drying potential.

1.4 *Experimental approach*

The six high RSI wall and the datum test wall used in this study were represented by 1.2 x 2.4 m test panels installed in the north and south facing walls of the BEG Hut test facility. The BEG Hut facility was designed to maintain a controlled indoor climate while exposing the test panels to exterior climate conditions. The test panels were designed to hygrothermally isolate one full-scale framing cavity of each wall type, which were then monitored using temperature, relative humidity (RH) and moisture content sensors to show their response to the environmental conditions.

The test panels were instrumented with moisture sensors to monitor the moisture content of the wood-based framing and sheathing of the central framing cavity, while RH sensors were installed in the centre of the framing cavity and the exterior drainage space to determine vapour pressure differentials across the wall components. Temperature sensors were placed with each moisture content and RH sensors as well as on the interior and exterior surfaces.

Data collected from these sensors were evaluated based on wall type and orientation through three distinct study intervals:

1. A fall/winter baseline period from October to mid-February,
2. A wintertime air leakage test from mid-February to early April, and
3. A springtime drying period extending from early April to early June

The variability of vapour pressure in response to climatic conditions was monitored and its effect on the moisture content of the OSB sheathing was evaluated over the three study intervals. Selected weather events were examined to determine the ability of each wall assembly to manage specific instances of

environmental moisture load. Extensive modeling was then performed to determine model sensitivities to boundary conditions, input parameters, and material properties. The datum wall was used to refine and calibrate the initial WUFI® model prior to expanding it to the high RSI wall designs.

1.5 Thesis objectives

The objective of this thesis was the documentation of the experimental setup, data acquisition and analysis of the High RSI walls through three segments of the study period. The High RSI and datum walls were analysed for mould and decay risks during the baseline period, the air injection period, as well as the subsequent drying period.

To meet the High RSI wall study's objective of developing climate-sensitive guidelines for each test wall, accurate hygrothermal simulation models were required to assess the performance of each wall when subjected to the range of North American climates. Literature indicated the absence of a well-documented approach to establishing accurate hygrothermal models of light wood frame walls. The secondary objective of this thesis was to encapsulate the physical principles required to simulate wall performance with a high level of precision and to develop an approach for the creation and calibration of hygrothermal simulation models.

The creation of well-calibrated hygrothermal models will also permit experimentation with wall designs to explore potential solutions to durability issues. These models will also assist in planning future work related to more advanced High RSI walls.

1.6 Thesis outline

This thesis presents a review of the properties of wood-based materials, the role of vapour retarders in moisture management, the methodology of electric moisture sensors, and the risk factors relating to wood-based materials in Chapter 2. Chapter 3 contains the experimental design and test procedures along with the instrumentation details. The hygrothermal analyses of the High-RSI wall assemblies presented in Chapter 4 include vertical temperature and moisture content variations, condensation, mould and decay risks, as well as inter-wall performance comparisons and thermal analysis using the heat-flux sensor data. The calibration methodology and results of the hygrothermal simulations are presented in Chapter 5.

The data collected during the study period were used to assess the thermal and moisture performance of High RSI walls. The vertical temperature profiles were examined to determine the typical temperature variability and its implications for data quality and moisture content interpretation. The vertical variability of moisture content was also assessed to determine wall-related performance issues like the initial moisture content of cellulose insulation. The moisture content data were further analysed with the temperature and relative humidity data to determine mould and decay risks for each of the test walls during three phases of the wall study. The thermal performance of a four wall types were also investigated using the heat-flux sensor data. The role of vapour drive with respect to drying potential was also examined.

Hygrothermal models of the High RSI test walls were created to examine the interactions between climatic conditions, material properties, electrical sensor measurement, and simulated air leakage. The models were calibrated to the measured data recorded between October 4, 2012 and June 3, 2013. During the calibration process, the seasonal variations of the surface transfer coefficients were investigated and their effect on the temperature and relative humidity regimes explored. The simulation models used in this study were configured to allow various investigations of the factors influencing the flow of heat and moisture through the High RSI walls. The aim of this model study was to create reliable simulation models that could be applied to regional performance studies as well as material and component oriented investigations.

2 BACKGROUND AND LITERATURE REVIEW

2.1 Energy efficiency and code standards

Energy use in Canada is tracked by natural resources Canada (NRCan) through the office of energy efficiency (OEE). The residential sector accounts for 17% of the secondary energy use in Canada, of which, 63% of the energy consumed was used for space heating. Energy consumption in the residential sector has grown since 1990 due to increased sector activity, which was driven by population growth and the combined trends of larger house sizes with fewer occupants (OEE, 2012). As the amount of floor space per occupant increases, the impact of more energy efficient wall systems can have a greater

Canadian Households by Type of Dwelling, 2008

Source: oee.nrcan.gc.ca/corporate/statistics/neud/dpa/handbook_res_ca.cfm?attr=0

Figure 2-1 Distribution of Canadian residential housing types as of 2008

influence on the energy efficiency gains for both new construction and upgrades to existing structures. Figure 2-1 shows the distribution of residential Canadian housing units as of 2008. The largest portion of Canadian housing occupies single detached homes, which means that envelope improvements to this segment will be most effective in reducing overall energy demand.

Energy efficiency requirements for buildings within national, provincial, and municipal building codes across Canada and the US have been rapidly changing in recent years to

address building envelope efficiency. In 2012, Supplementary standard SB-12 was enacted for the Ontario Building Code (OBC) to increase the energy efficiency of new buildings (OMMAH, 2011). SB-12 accomplishes this through prescriptive compliance packages that designate acceptable levels of thermal resistance in the various components of the building envelope based on heating equipment, fuel type and location. The thermal insulation requirements for above grade walls listed in the compliance packages range from RSI 3.87 to 5.11 (R22 to R29) with no consideration for thermal bridging through framing members (OMMAH, 2011). The OBC SB-12 is intended to be an alternative for EnerGuide rating 80 for building enclosures and streamlines the process for designers/ builders through the adoption of compliance packages. The thermal insulation component of the high RSI walls in this study ranged from

RSI 5.75 to 6.80 (R33 to R39) and are compared to a 38 x 140 mm framed wall with RSI 3.87 cavity insulation as a datum.

The EnerGuide rating system is a standard measure for energy efficiency in housing that provides a rating between 0 and 100 based on a standard set of operating assumptions. A rating of 0 signifies a structure with serious air leakage, poor to no insulation and its consequent high levels of energy consumption; essentially an uninhabitable building. The EnerGuide rating for new houses built to code standards is typically between 65 and 72. A rating of 100 is achieved with levels of insulation and air sealing such that the building does not require the purchase of external energy in normal operation (OEE-NRC, 2010). The objectives of 'Net Zero ready' and carbon neutral construction would require EnerGuide ratings between 91 and 100, which render the current building practices and code standards insufficient to meet these energy efficiency demands through light wood framing and cavity insulation alone. The changes in building design and materials that will arise from increased energy efficiency targets, may have unintended consequences with respect the building envelope's ability to manage moisture and increase the risk of decay in structural wood components.

2.2 Wall assemblies - functions and control layers

The primary function of building envelopes is to isolate the controlled environment of the interior space from the ever-changing exterior climatic conditions. In performing this task, the envelope is required to be durable enough to withstand the elements and manage moisture while maintaining the aesthetics of the building. N.B. Hutcheon identified the need for systematic design and careful consideration of how different building materials interact and perform their functions within the building envelope. Hutcheon realized that building science could resolve building failures in an effective, timely and cost effective manner (Hutcheon, 1953).

The principal functions of a wall are to control the flow of heat, air and water vapour. The wall must also control the penetration of rain, light, solar radiation, noise and fire from the exterior. In doing so, the wall must also provide strength, rigidity, durability, and economy. Depending on the climate or geographic location, each of these functions will vary in importance (Hutcheon, 1963). In areas that are frequently windy, or prone to hurricane and tornado damage, strength and impact resistance are very important considerations. Historical communities may place aesthetics above other considerations and most importantly, if the wall system is prohibitively expensive, then it will not be built.

Figure 2-2 Control layers of the perfect wall design (Lstiburek, 2007)

The perfect wall approach builds on these wall functions and states that there are four principal layers in a perfect wall (listed in order of importance) that control rain, air, water vapour and heat (Lstiburek, 2007). In its simplest form, the perfect wall is composed of the cladding, control layers and the building's structural frame as shown in Figure 2-2. The cladding protects the structure and its more sensitive components from the effects of solar radiation, wind and minor impacts, insects, and can offer fire resistance depending upon its composition. The cladding is not intended to be an impenetrable barrier to rain, but rather, it is designed to shed the majority of precipitation and sunlight.

The drainage space is placed between the cladding and the WRB drainage layer to regulate air and vapour pressures through the ventilation ports as well as along the cladding joints in many types of siding. Air and vapour pressures in the drainage space are influenced by solar heating, ambient temperature and humidity as well as wind.

The drainage layer as defined by Straube (2005) consists of a sealed water resistive barrier (WRB) that is placed between the drainage space and the structure. Since this barrier is protected from the elements by the cladding, its integrity and effectiveness is maintained for as long as possible. When the water resistive barrier is properly sealed, an air barrier is also created and the first two criteria of the perfect wall are met. The presence of the air barrier on the outside of the structure eliminates air leakage and wind washing of air permeable insulation materials, which optimizes the thermal performance of the assembly. This approach is also known as a drained-screened wall system, which was developed from rainwater control theory based on the fact that rain in contact with a wall can be shed, stored by the cladding or transmitted further into the wall. Ideally, water is controlled as each successive layer of the assembly reduces the transmission of water to zero.

The water vapour and thermal control layers need to be considered together as the moisture storage capacity of air is directly related to temperature. As the temperature within an assembly changes with variations in the exterior and interior temperatures (temperature profile), the moisture capacity of the air within the wall also changes, this can lead to condensation within the wall should the inner wall

temperatures fall below the dew point of the air. In cold climates, the warm, moist interior air creates a partial pressure differential that causes the outward flow of water vapour from the interior. For this reason, the water vapour control layer is typically applied to the warm in winter side of the assembly to restrict the outward flow of water vapour into the wall where it will condense on the colder sheathing surfaces. Only one vapour control layer should be installed, as more vapour barriers would inhibit drying in the event of accidental water leakage.

The vapour control layer in Canada is generally composed of a 6-mil polyethylene sheet applied and sealed between the framing and interior drywall. The vapour control layer need not be polyethylene as some low vapour permeance foams like closed cell spray polyurethane foam (ccSPF), extruded polystyrene (XPS) or foil faced polyisocyanurate can provide vapour control provided they are installed correctly. The insulation should be continuous and sealed across the entire wall with proper detailing at wall openings. In addition, the insulation thickness should be sufficient to ensure that the temperature of its interior surface remains above dew point. The Ontario Building Code (OBC) prescribes minimum thermal resistance ratios of outboard to inboard insulation in Part 9.25.1.2 of the residential and small housing section of the OBC (OMMAH, 2006). These ratios are based on the number of heating degree-days at the geographical location of the building. Thermal insulation installed on the exterior of the structure also protects it from variations in temperature that can cause shifting, swelling or shrinkage and cracking.

2.3 Water vapour transport

The transport of water vapour in air and porous media occurs through the two dominant processes of diffusion and convective airflow (advection). These processes, as explain by Straube (2005) are driven by pressure or density gradients caused by temperature imbalances, wind or mechanical systems. Convective airflow can occur within a wall through air permeable insulation where the vertical temperature profile is stratified. This form of air movement is driven by the density gradients caused by a temperature imbalance and it can cause convective loops within the wall cavity. When the stud cavity is connected to the interior and / or exterior spaces, then air leakage takes place, which has the potential to move large amounts of moisture into and out of the wall space.

2.3.1 Diffusion

Water vapour molecules disperse in air through the process of diffusion, which is similar to the convection transport process on a molecular scale. The rate at which diffusion occurs is governed by the concentration gradient through space, which in the case of water vapour in air, is defined as the partial pressure of water vapour relative to atmospheric pressure. The mass flow rate of a solute (water vapour) through a stationary medium (air) can be described using the general mass flow equation for diffusion of a solute into a medium as defined by the change of mass per unit time using a form of Fick's Law, derived as follows in Straube, (2005):

$$\frac{dm}{d\theta} = -D \cdot \nabla C \quad [1]$$

$\frac{dm}{d\theta}$ = mass flow per unit time (ng/s)

- D = proportionality constant including the medium's permeability and area ($\mu \cdot A$)

C = the concentration of the solute (water vapour), Pa

∇ = the divergence 'del' operator ($\nabla = i \frac{\partial}{\partial x} + j \frac{\partial}{\partial y} + k \frac{\partial}{\partial z}$),

D represents the diffusion coefficient or diffusivity. Diffusivity is the proportionality constant between the flux and the gradient. The negative sign indicates that the mass of the solute flows from high to low concentrations. The divergence or 'del' operator represents the change in concentration (scalar) throughout the 3-dimensional basis vector field (i, j, k) of the medium. For one-dimensional flow, Fick's Law can be rewritten as (Hutcheon, 1983):

$$\frac{dw_x}{d\theta} = -\bar{\mu} \cdot A \cdot \frac{dP_w}{dx} \quad [2]$$

$\frac{dw_x}{d\theta}$ = mass flow of water vapour per unit time (ng/s)

$\bar{\mu}$ = the average permeability of the medium (ng/Pa·s·m)

A = area through which the solute (mass) is transported (m²)

$\frac{dP_w}{dx}$ = the concentration gradient of the solute in the direction 'x' (Pa/m)

The average vapour permeability of a material is determined through standardized laboratory tests like ASTM E96 Standard Test Methods for the Water Vapour Transmission of Materials (ASTM, 2005). These tests are conducted on representative samples of the material with a defined thickness (<32 mm) under specific boundary conditions. The test sample is sealed against the open side of a test dish that contains anhydrous calcium chloride for the Desiccant Method or Dry Cup test, or distilled water for the Water Method or Wet Cup test. The sample, sealed to the test dish, is placed in a test chamber with a

controlled environment of 50% RH and an applicable temperature for the material's usage (ASTM, 2005). The test cup is periodically weighed to determine the rate of vapour flow through the specimen.

The results of the ASTM E96 test are used to calculate the water vapour permeability of the material over its test thickness, generally 25.4 mm, which yields a unitized permeability known as permeance. Permeance (M) has the units of $\text{ng}/(\text{Pa}\cdot\text{s}\cdot\text{m}^2)$ and is determined by:

$$M = \frac{\bar{\mu}}{l} \quad [3]$$

Where, l = the length (m) of the flow path through the material. Building codes specify transmission rates for vapour retarders using permeance values. The 2006 Ontario Building Code (OBC) requires vapour retarding materials to have a water vapour permeance less than $60 \text{ ng}/(\text{Pa}\cdot\text{s}\cdot\text{m}^2)$, as measured by ASTM E96 (desiccant method). Water vapour permeance and permeability are also defined in US perms and the Water Vapour Diffusion Resistance (WVDR) Factor. The US perm is based on the imperial system of measurement; one US perm is the equivalent of $57.2 \text{ ng}/(\text{Pa}\cdot\text{s}\cdot\text{m}^2)$.

2.3.1.1 *Diffusion control - vapour retarders*

The control of water vapour diffusion is accomplished using water vapour retarders. Vapour retarders are classified as follows (Lstiburek, 2006):

- Class 1 – less than 0.1 perm { $< 5.72 \text{ ng}/(\text{Pa}\cdot\text{s}\cdot\text{m}^2)$ }
- Class 2 – less than 1.0 perm and greater than 0.1 perm { between 57.2 and $5.72 \text{ ng}/(\text{Pa}\cdot\text{s}\cdot\text{m}^2)$ }
- Class 3 – greater than 1.0 perm { $> 57.2 \text{ ng}/(\text{Pa}\cdot\text{s}\cdot\text{m}^2)$ }

A vapour barrier is considered to be a class 1 vapour retarder such as 6-mil polyethylene sheeting, which has a water vapour permeance of $3.4 \text{ ng}/(\text{Pa}\cdot\text{s}\cdot\text{m}^2)$ (ASHRAE, 2009). The 6-mil polyethylene provides a level of vapour control an order of magnitude higher than the minimum prescribed in the OBC ($60 \text{ ng}/(\text{Pa}\cdot\text{s}\cdot\text{m}^2)$).

2.3.2 *Water vapour diffusion resistance factor*

For hygrothermal modeling using the German modeling software WUFI®, the WVDR factor is used to define the water vapour permeance of building materials in lieu of permeance or permeability values more commonly used in North America. The diffusion of water vapour through porous materials can be considered the same process as diffusion through air with the exception that diffusive flow is obstructed within the material by access to open porosity, adsorption at the pore walls and the degree of tortuosity along the interconnected pore paths (WUFI®, 2009). For this reason, the μ -value defines the water

vapour permeability of building materials relative to the water vapour diffusion coefficient in stagnant air. The μ -value [-] is defined as follows (Kumaran, 1998):

$$\mu = \frac{\delta_{\alpha}}{\delta} \quad [4]$$

δ_{α} = the water vapour permeability of stagnant air (kg / Pa·s·m)

δ = the water vapour permeability of the building material (kg / Pa·s·m)

The values of δ_{α} and δ use to determine the μ -value should be for the same temperature and atmospheric pressure. The water vapour permeability of stagnant air is difficult to measure in the laboratory, in part due to the relative pressures of water vapour and the atmosphere. A consistent value for δ_{α} has not been determined since the results of theoretical calculations are regularly higher than the results determined through experimental measurements (Kumaran, 1998). The standard equation adopted for use in WUFI® is as follows (Schirmer, 1938 from WUFI®, 2009):

$$\delta_{\alpha} = 2.0 \cdot 10^{-7} \cdot T^{0.81} / P_{atm} \quad [5]$$

T = absolute ambient temperature (K)

P_{atm} = the atmospheric pressure (Pa)

Equation [5] was used to determine the values of δ_{α} over the -20° to +38°C (253 to 309 K) temperature range. The average value for δ_{α} was 190 ng / (Pa·s·m) within a range from 175 to 205 ng / (Pa·s·m).

Like the value of δ_{α} , the δ -value for a porous building material also depends on air pressure and temperature since the water vapour diffusion through porous materials occurs through the air in open pores. For this reason, WUFI® uses the units of water vapour flux density and retains the δ_{α} term by dividing by the μ -value. Rearranging Equation [2], the water vapour flux density for a porous medium is (WUFI®, 2009):

$$g_v = -\frac{\delta_{\alpha}}{\mu} \cdot \frac{dP_w}{dx} \quad [6]$$

$g_v = \frac{1}{A} \cdot \frac{dw_x}{d\theta}$ = the water vapour flux density (kg / s · m²) in porous media

For materials like vapour barriers and surface coatings, WUFI® calculates the thickness of air (s_d) that provides an equivalent resistance to diffusion as a porous material with a thickness (s) using the relationship:

$$s_d = \mu \cdot s \quad [7]$$

The s_d –value does not require that the thickness of the material to be defined, so this property can be used in all aspects of the program other than just the component assembly.

The μ -value and $\bar{\mu}$ that is used to represent a material's average water vapour permeability should not be confused as the μ -value is a dimensionless coefficient whose value is relative to the water vapour permeability of air. Water vapour permeability is also referred to as the water vapour diffusion coefficient in WUFI® simulation program. This term should not be confused with the proportionality constant 'D' (diffusivity) from Equation 1.

2.4 Moisture content and storage

Moisture content influences the physical properties and behaviour of wood through dimensional, thermal and elasticity changes. Wood is an anisotropic material that is created by the addition of circular growth rings throughout the life of the tree as it grows in height and diameter. The physical properties of wood-based materials depend on the principal growth directions – longitudinal, radial and tangential. Each of these principal directions interacts differently with either liquid water or water vapour based on geometry and exposure of the underlying cell structure. As an example, shrinkage coefficients for several selected wood types indicate that the maximum dimensional change caused by moisture content occurs in the tangential direction. The radial direction is also affected but is generally less than 60% of the tangential change while dimensional changes in the longitudinal direction are insignificant by comparison (Glass and Zelinka, 2010). This mechanism is responsible for many interior problems like sticking doors and drawers as well as splits, checks and cracks in flooring, trim and furniture.

Moisture content (MC) is calculated as ratio between the mass of water in the specimen and the mass of dry wood as follows (Glass and Zelinka, 2010):

$$MC = \frac{m_{water}}{m_{wood}} \cdot (100\%) \quad [8]$$

Moisture may be present in the cell voids (lumina) as mobile liquid water (free water) or water vapour. The moisture contained in the cell walls is called bound water as it is captured by the matrix of the cellular material. The fibre saturation point (FSP) occurs when the moisture content of the cell walls is at a maximum and the RH of the air in the lumen is at 100%. Any further additional water will be added to the wood as free water. Above the FSP, the physical and mechanical properties are no longer directly a

function of moisture content (Glass and Zelinka, 2010). Fibre saturation happens at about 30% moisture content, but it varies among tree species and is not necessarily uniform.

2.4.1 Water vapour sorption and capillary water

The ability of porous hygroscopic materials to exchange molecules of water vapour with the ambient air is an important aspect of building envelope durability. This exchange is known as moisture storage and it occurs through the process of adsorption. Adsorption is governed by the relative humidity of the air

Figure 2-3 Moisture storage in hygroscopic materials (Straube, 2006)

contained in the envelope assembly and the pores of hygroscopic materials. The polarity of the water molecule enables it to bond with the pore surfaces of hygroscopic materials. The storage of moisture in this manner acts as a buffer that moderates the flow of water vapour through a wall assembly by raising the moisture content of hygroscopic wall components. The important concerns for durability are the storage capacity of the material, the exchange rates, and the length of time that the moisture can be stored without the onset of deterioration. The storage of moisture in this manner is significantly affected by the amount of open pore space and surface area.

Figure 2-3 illustrates the process of moisture storage in a hygroscopic material. In the figure, adsorption begins from the dehydrated state at 0% RH through the adsorptive regions 'A' & 'B' until liquid water condenses within the pore spaces of the material in region 'C'. The material's water content (W) is determined by the relative humidity (of air) throughout the regions 'A', 'B', and 'C'. Region 'D' begins at the critical water content (W_{crit}) where the process of water accumulation is controlled by capillary forces.

The adsorption of water begins with a single-layer of molecules that adhere to the surface of the medium. As water molecules accumulate, multiple layers are formed. Each successive layer is more

weakly bound to the medium than the initial, single layer. As a result, the built-up multi-molecular layers interact with one another to create capillary condensation or unbound liquid water as the relative humidity rises. Pore space condensation begins in the smallest pores and proceeds until all but the largest pores are filled. This point is known as the critical moisture content (W_{crit}) as it is the point at which capillary forces begin to dominate moisture storage and the rate at which water is accumulated by the medium. The critical moisture content is material dependent but is generally considered to occur in equilibrium with 93-98% RH air as reported by Straube (2005). From W_{crit} to the capillary saturation point, W_{cap} , capillary action forces water into the porous medium. Above this point, external forces are required to drive water into the material.

2.4.2 Equilibrium moisture content (EMC)

In the sorption region, the equilibrium water content of the porous medium is attained through a balance of the absolute humidity and temperature. Increased water vapour concentrations deposit more water molecules on the surface of the medium while increased temperatures desorb the water molecules. As a result, the water content below the fibre saturation point (FSP) is determined by the relative humidity of the air temperature.

This process is gradual and as a result, daily temperature and RH fluctuations only tend to affect the wood's surficial moisture content as the wood equilibrates with its surroundings. Longer-term temperature and RH trends have a greater effect on the overall moisture content of wood because full equilibration can require several weeks depending on the material's thickness and the degree of moisture imbalance. The EMC is reached when the wood no longer exchanges moisture with the air. The time required to reach the EMC is influenced by the tree species, wax and extractive content (resin) of the wood. The EMC varies slightly between species and is determined using metric units through the following relationship (Glass and Zelinka, 2010):

$$EMC (\%) = \frac{1800}{W} \cdot \left[\frac{K \cdot h}{1 - K \cdot h} + \frac{K_1 \cdot K \cdot h + 2 \cdot K_1 \cdot K_2 \cdot K^2 \cdot h^2}{1 + K_1 \cdot K \cdot h + K_1 \cdot K_2 \cdot K^2 \cdot h^2} \right] \quad [9]$$

Where h is the relative humidity of the air, W and K , K_1 and K_2 are temperature dependent functions (T in °C) as follows:

$$\begin{aligned} W &= 349 + 1.29 \cdot T + 0.0135 \cdot T^2 \\ K &= 0.805 + 0.000736 \cdot T - 0.00000273 \cdot T^2 \\ K_1 &= 6.27 - 0.00938 \cdot T - 0.000303 \cdot T^2 \\ K_2 &= 1.91 + 0.0407 \cdot T - 0.000293 \cdot T^2 \end{aligned}$$

Equation 9 was used to calculate the EMC for the wood plates in the high RSI wall study to determine if the moisture sensors were functioning correctly and measuring moisture content values within the expected range.

A typical sorption / desorption isotherm is shown in Figure 2-4 (Glass and Zelinka, 2010), this plot shows the change in moisture content with relative humidity for a constant temperature. Wood is considered to be 'green' prior to drying or seasoning and the initial desorption line (Figure 2-4) represents the drying curve from the 'green' state at equilibrium with 100% RH (roughly the FSP) to equilibrium at 0% RH. The resorption or adsorption curve represents the wood's response to increasing moisture content from a dried state at 0% RH. The difference between these drying and wetting curves is known as hysteresis.

Figure 2-4 Typical sorption and desorption curves starting from 'green' lumber. (Glass and Zelinka,, 2010).

The EMC of the lumber is highest when 'green' and the material equilibrates at lower EMC for the next adsorption cycle (Glass and Zelinka, 2010). The oscillating vapour pressure desorption curve represents conditions between desorption and adsorption that represents practical applications. The plot of EMC versus RH represents the moisture storage function (MSF) used by WUFI® to define the storage capacity of a material. The MSF is obtained from sorption isotherms from 0 to ~90% and from pressure plate measurements above 95%.

During the manufacture of products like OSB, the wood fibres are compressed and adhered with thermoplastic resins that reduce the amount of pore space and the available surface area for water vapour. This reduction in surface area also reduces the amount of water adsorbed from the air and results in average moisture content measurements that are about 3-4% lower (Forintek observations from Straube et al, 2002) in OSB than unaltered wood of the same species under similar conditions. The addition of wax and adhesives impedes the rate of sorption while adding dry mass that does not adsorb.

2.4.3 Absorption

The process of adsorption continues until the addition of multi-molecular layers begins to condense liquid capillary water in the pores. Some of this pore water is held or bound by surface tension with the cell walls while the remainder is driven into the pore space by the capillary suction pressure created by the surface tension of the water-air contact (Glass and Zelinka, 2010). Capillary pressure is inversely proportional to the effective radius of the pore throat, which means that smaller pores create greater capillary pressures. The absorption process is capable of raising the moisture content above the fibre saturation point. Absorption also occurs through contact with liquid water that results from rain leakage or condensation. This rapidly increases the moisture content of wood framing materials and it is limited by access to liquid water and the rate at which air escapes the lumina. The absorption of liquid water is also highly anisotropic in wood with the highest rates occurring along the longitudinal axis – in the direction of sap flow. The absorption of water continues until the capillary pressure has diminished and the capillary saturation point is reached, W_{cap} , in Figure 2-3. The principal grain directions of wood are shown in Figure 2-5 on the following page.

Water absorption is measured by tests that restrict the exposure of water to a single side of the test sample. The sample is partially immersed in water and weighed at set time intervals. The mass of water absorbed per unit area of the sample's exposed surface are plot versus the square root of time. The slope of this curve (linear portion) is the water absorption coefficient, A_w . The A_w -values for softwood range from 10-16 g /m²s^{1/2} in the longitudinal direction and 1-7 g /m²s^{1/2} in the transverse direction (Glass and Zelinka, 2010). The A_w -values for the panel surface of OSB range from 1.1 to 3.3 g /m²s^{1/2} (Kumaran, Lackey, Normandin, Tariku, van Reenen, 2003).

The rate at which liquid water flows through a porous material is measured by the parameter, D_w (m²/s) – liquid water diffusivity. Liquid water diffusivity is defined as the moisture content (kg/m³) through a unit thickness, m. The liquid transport coefficients for suction and redistribution (D_{ws} , D_{ww}) that were used in the WUFI® modeling were approximated using the following equation (WUFI®, 2009):

$$D_{ws}(w) = 3.8 \cdot \left(\frac{A}{w_f}\right)^2 \cdot 1000 \left(\frac{w}{w_f}\right)^{-1} \quad [10]$$

D_{ws} = liquid transport coefficient for suction (m²/s)

A = water absorption coefficient (kg /m²s^{1/2})

w = moisture content (kg/m³)

w_f = free water saturation (kg/m^3)

The test method used to determine the liquid water diffusivity of OSB products (Kumaran et al, 2003) may involve the edge wood of the OSB sample. Since the edge wood is biased with longitudinal grains, the resulting diffusivity values are not necessarily applicable to the panel face in a sheathing application. For this reason, liquid water transport coefficients approximated with water absorption coefficients determined from the materials' planar surfaces may be more appropriate for modeling sheathing type applications.

2.5 Thermal properties of wood-based materials

2.5.1 The influence of structure

The structure of wood varies with species and type, whether it is a hardwood or softwood. The terms hard and soft are misnomers in a sense because there are hard softwoods like Douglas fir, and soft hardwoods like balsa or poplar. Generally, hardwoods are deciduous, broad-leafed plants whose seeds are produced in the ovary of a flower and enclosed such as with a fruit or nut. These types of plants are called angiosperms. Hardwoods contain pores and their cell structure is composed of vessel elements with open ends that stack to form a continuous tube.

Softwoods differ from hardwoods in that their seeds are not enclosed; these are referred to as gymnosperms. Softwoods are often cone bearing, have needles or scaly leaves and do not have a porous cell structure like hardwoods (Glass and Zelinka, 2010). Three predominant types of softwoods are used

Figure 2-5 Longitudinal, tangential and radial grain directions in wood (Wengert, 1993)

for framing in house construction – spruce, pine and fir. Oriented strand board is made from the fast growing hardwood species – aspen and poplar, although pine is used by some manufacturers.

The thermal and moisture characteristics of wood-based products are influenced by the anisotropy of wood's grain structure. The thermal conductivity (k-value) of wood is directionally dependent with respect to grain. The orientation of wood grain is defined as longitudinal (L), tangential (T) or radial (R) and illustrated in Figure 2-5. The tangential k-value is generally somewhat less than the radial k-value depending on the amount of ray cells in hardwood and the ratio of earlywood to latewood in softwoods. Earlywood refers to the fast wood growth of the spring while latewood refers to the slower wood grown after seeds and leaves have been produced.

The following two images in Figure 2-6 illustrate the difference in grain structure between hardwoods (left image) and softwoods (right image). The ray cells of the hardwood are shown in section on the tangential face of the image. The primary functions of ray cells change with the seasonal demands of the tree and are related to the transport and storage of fluids. In both hard and softwoods, the cellular make up resembles bundles tubes that transport sap to and from the roots through capillary forces. The open cell voids are known as lumina (singular – lumen).

The right-hand image of soft wood cell structure most clearly illustrates the difference between early wood and latewood. Early wood is more porous to enhance fluid transport in spring for bud formation and defines the rate of longitudinal absorption of fluids.

Figure 2-6 Microscopic wood grain structures in hardwoods (left) and softwoods (right) no scale available. Note. Adapted from Monteiro, P.,(nd)

The frequency of ray cells in growth rings determines the magnitude of the difference between tangential and radial thermal conductivities in hardwoods (Kollmann, 1951 (from Sonderegger, 2009)) and the relative volumes and density differences of early wood versus latewood govern thermal anisotropy in softwood lumber (Chudinov, 1968 (from Steinhagen, 1977)).

The microscopic variations in wood grain indicate that wood's anisotropic thermal properties arise from porosity distribution and cell wall densities. Thermal conductivity is highest in the longitudinal direction where the cell cavities are open and the cell walls are continuous. Suleiman et al (1999) attribute this to the fact that the cellulose in the cell walls is arranged in microfibrils that are aligned with the longitudinal axis and conduction occurs preferentially along the microfibril rather than across it. The continuity of longitudinal cell and pore structures promotes thermal conduction and potentially convection within air-filled pore space. When viewed in transverse and radial sections, the cell pores appear as discrete air pockets that function as insulators to inhibit heat transfer in the transverse and radial directions.

2.5.2 Influence of moisture content on thermal properties

The microstructure shown in Figure 2-6 illustrates the relationship between moisture content and thermal conduction. As moisture content increases, the fibres of the cell wall swell to the saturation point. The microfibrils that comprise cell walls can contain bound water up to ~28% (by weight) on average. Above 28% free water begins to appear within the pore space where it is transported longitudinally by capillary forces as it fills the pores. The moisture content of wood is related to the thermal conductivity by the following equation developed by Wilkes (1979) from (ASHRAE, 2009):

$$k = 0.1791 + \frac{(1.874 \times 10^{-2} + 5.753 \times 10^{-4} \cdot M) \cdot \rho}{1 + 0.01M} \quad [11]$$

M = Moisture content (%)

ρ = Density of moist wood in (kg/m³)

The cell wall thickening reduces the open pore size and its insulating effect. Greater cross-sectional area of the wall increases thermal conduction while the bound water increases the cell wall density.

2.5.3 Influence of density on thermal properties

The dry density of wood depends on the cell structure and its porosity. Wood porosity affects heat transfer through the presence of air or moisture within the cells (Suleiman et al, 1999). Research

conducted by Kollmann (1951) established relationships between heat flow in the parallel and perpendicular grain directions as a function of wood density at 27°C and 12% MC. For thermal conductivity in the longitudinal direction or parallel ($k_{||}$) to the grain, the k-value is calculated as follows (Sonderegger, 2009):

$$k_{||} = 0.026 + 0.46 \cdot \rho \cdot 10^{-3} \quad [12]$$

For thermal conductivity in the radial direction or perpendicular to the grain, the k-value is calculated using this relationship:

$$k_{\perp} = 0.026 + 0.195 \cdot \rho \cdot 10^{-3} \quad [13]$$

On average, the longitudinal thermal conductivity is greater than radial thermal conductivity by a factor of 1.8 over a reported range of 1.5 to 2.8 (Glass and Zelinka, 2010) for a variety of trees species.

2.5.4 Influence of temperature on thermal properties

For temperatures between 20°C and 100°C, tests indicate that thermal conductivity increases approximately 14% to 24% for the longitudinal and transverse axes in light to medium hardwood. However, different wood samples under similar temperature conditions exhibited distinct variations in their thermal conductivity profile. This finding further suggests that the wood grain type and its orientation influence thermal conduction (Suleiman et al, 1999).

2.6 Electrical properties of wood-based materials

The conduction of electricity occurs only in materials that have freely moving electron charge carriers. Electrical charge can be carried either by electrons in electronic conduction or by ions in ionic conduction. In all other materials, electric fields induce polarization, which displaces or reorients charged particles within the electric field (Keller and Frischknecht, 1966). The bond strength of the molecules within a medium and the field strength determine the extent of polarization.

In metallic conductors, electrons are free to move throughout the metal's atomic structure. The electrons in the metallic atom's outer shell dissociate and move easily within the lattice structure of the material. The electrical field produced by an applied voltage potential drives the dissociated electrons from the high electron potential terminal (negative) to the low electron potential terminal (positive). This type of current flow is known as electronic conduction. Ionic conduction occurs through the movement of ions (charge carriers) through the molecular structure of a solid or through ions in

aqueous solution. In ionic conduction, the mobility of the charge carrier is directly related to temperature unlike electronic conduction where temperature is inversely related to charge carrier mobility.

The electrical conductivity of wood-based materials depends primarily on their moisture content. Other influencing factors include temperature, grain direction and the dielectric constant.

2.6.1 Temperature

When moisture content levels are above 10%, the wood's electrical conductance doubles for every 10°C increase in temperature. This relationship indicates that ionic conduction is involved in the flow of electrons (James, rev. 1988)) as the mobility of the charge carriers increases with temperature.

2.6.2 Moisture content

While temperature has a direct influence on electrical conductance, temperature has an inverse effect on moisture content as the EMC of wood strongly depends on its temperature. Drying wood from the fibre saturation point down to near zero increases the electrical resistance of wood by a factor of 10^{10} or higher. The resistivity of oven dry wood is in the order 10^{15} to $10^{16} \Omega \text{ m}$ while wood at fibre saturation is in the range of 10^3 to $10^4 \Omega \text{ m}$ (Glass and Zelinka, 2010). Logarithmic plots of moisture content versus electrical resistance have a linear relationship throughout this range. Further, above the FSP up to the capillary saturation point, there is a poor relationship between MC and electrical resistance. In this region ('D' from Figure 2-3), drying reduces the electrical resistance by only a factor of 50 to 100 over a narrow range of relative humidity (James, rev. 1988)).

The reduced influence of moisture content and poorer correlation with electrical resistance above FSP likely arises from the increased continuity of water within the pore structure. As the pore spaces fill with fluid, the electrical conductance of the wood and moisture approach the limits of conduction in aqueous solution. Above FSP, the dominant influence on electron flow is determined by the ionic potential of the dissolved mineral content. The ionic potential may also be related to the water solubility of the extractive content within the wood.

2.6.3 Dielectric constant

The ability of a material to polarize and establish an internal electric field is measured by its dielectric strength. The dielectric strength or absolute permittivity is determined from the amount of charge (Q) per volt (Farad) stored by the material over the charge separation distance. The dielectric constant is a

relative measure of the material's dielectric strength to the dielectric strength of a vacuum. The dielectric constant is an important consideration for materials like wood and cellulose insulation that have extremely receptive surface areas for the adsorption of polarized water molecules.

As the moisture content of hygroscopic materials like wood and cellulose increase, adsorption advances from the well bonded, single molecular layer to the more weakly bonded, multiple molecular layers. It follows that an applied voltage field will have an increased effect on the polarization of the more weakly bonded adsorbed water molecules added at higher relative humidity. Wood's dielectric strength increases with increasing moisture content (James, rev. 1988)).

2.6.4 Grain direction

Wood fibres with adsorbed water molecules conduct current through ionic conduction and polarization while the open pore spaces act as insulators to resist the flow of electricity. Grain direction influences conductivity the most along the grain in the longitudinal direction. Electrical conduction in the tangential and radial directions is roughly half that of the longitudinal direction.

2.7 Electrical resistance and moisture content

The moisture content of wood and wood-based products can be determined using electrical resistance measurements and mathematical relationships to correct for wood species and temperature. Empirical research by the forest products industry developed equations relating electrical conductivity to moisture content. Douglas fir became the industry standard for moisture sensing equipment and most meters are calibrated to Douglas fir at 21°C (70°F). Further research developed the mathematical relationships

Figure 2-7 Photo illustrating the positioning of moisture sensor pins in framing plates

between the industry standard and various other wood species and wood products (Straube et al, 2002).

The resistance of wood cannot be measured by common hand-held multimeters since the resistance of wood is very high in typical applications. Specially designed, high resistance, hand-held moisture meters have evolved over the years for use in the lumber industry. These devices are calibrated and work well for industry applications. For in-situ measurements, the principals of the hand-held moisture sensor have been adapted for use with a datalogger. The datalogger can record data from wired sensor pins specially placed and embedded in building assemblies. This technique is non-destructive and relatively non-invasive. The photo in Figure 2-7 illustrates the positioning of the MC sensor pins with a 25.4 mm separation, their signal wires and the associated thermistor (on left) for temperature measurements.

Figure 2-8 Schematic drawing of the moisture sensor measurement circuit

The datalogger applies 12 V potential of direct current across the circuit and measures the voltage drop across the sensor resistor, V_{sensor} . The voltage measured across the 10k Ω sensor resistor wired in series with the pins. This measured voltage can then be used in the voltage divider formula to calculate the electrical resistance of the wood at the MC sensor pin location.

The voltage divider formula derived using Ohm's Law in Floyd (2010):

$$R_{\text{total}} = \left(\frac{V_{\text{supply}}}{V_{\text{sensor}}} \right) \cdot R_{\text{sensor}} \quad [14]$$

R_{total} = the total resistance of the measurement circuit ($R_{\text{wood}} + R_{\text{sensor}}$) (Ω)

V_{supply} = the supply voltage applied across the measurement circuit (12 V)

V_{sensor} = the voltage measured by the datalogger across the sensor resistor (Ω)

R_{sensor} = the measured resistance of the 10k Ω sensor resistor (Ω)

The total the sum of resistances in a series circuit can be determined from:

$$R_{total} = R_{wood} + R_{sensor} \quad [15]$$

R_{wood} = the resistance of the wood at the MC sensor pins (Ω)

Equations 14 and 15 are combined to determine the resistance of the wood at the sensor pin location:

$$R_{wood} = [(V_{supply}/V_{sensor}) \cdot R_{sensor}] - R_{sensor} \quad [16]$$

The calculated value for R_{wood} can then be used to determine the uncorrected moisture content in terms of Douglas fir with the following relationship (Straube et al, 2002):

$$\log_{10}(MC_u) = 2.99 - 2.113 \cdot [\log_{10}(\log_{10}R_{wood})] \quad [17]$$

MC_u = uncorrected moisture content in terms of Douglas fir (%_{mass})

Once the moisture content in terms of Douglas-fir is calculated, the MC_u value can be corrected for temperature and species. As discussed previously, the conductivity wood doubles for every 10°C temperature change. Studies by Forintek Canada investigated the relationships of Canadian tree species, temperature and correlation to Douglas-fir. These studies produced correction tables and developed a numerical relationship for the conversion to facilitate the correction of large amounts of data. The relationship is as follows (Garrahan, 1988 and detailed in Straube et al, 2002):

$$MC_c = \left(\frac{(MC_u + 0.567 - 0.0260 \cdot T + 0.000051 \cdot T^2)}{0.881 \cdot (1.0056)^T} - b \right) / a \quad [18]$$

MC_c = corrected moisture content for species and temperature (%_{mass})

T = wood temperature (°C)

a, b = regression coefficients from species correction

The values for coefficients 'a' and 'b' are species dependent. The values used in the high RSI study were selected from a table of coefficients (Straube et al, 2002). The coefficients for Eastern white pine / Norway spruce were used to correct moisture content calculation of framing lumber ($a = 0.702$ and $b=0.818$). The coefficients used to correct the OSB MC-data were derived by laboratory testing performed by Forintek Canada, these values were $a = 1.1114$ and $b = 0.366$ (Straube et al, 2002).

2.8 Air leakage

Air tightness in buildings is essential to control undesired airflows through building envelopes. The uncontrolled movement of air through wall assemblies is a contributor to moisture related building

problems. Air leakage introduces damaging moisture that promotes the growth of fungi and contributes to poor indoor air quality. Sufficiently high and sustained moisture levels in wall assemblies lead to the decay of structural wood framing components as well. The proper design and installation of air barriers can eliminate the damaging effects of air leakage.

Air leakage occurs through cracks and holes, around penetrations, and within the large pore spaces of some insulating materials, as shown in Figure 2-9. Interior and exterior air can mix in the attic space (A) and leak into the wall cavities through gaps between the top plate and the drywall as well as any electrical wiring holes drilled through the plates (B). In buildings without an intact water resistive barrier (WRB) or exterior air barrier, air leakage can enter through gaps in the sheathing shown at (C). Interior electrical boxes (D) allow air to circulate into the wall cavity. Gaps at the bottom plate with the drywall and subfloor (E) allow airflow across the wall into the wall cavity. Vents and other penetrations (F & G) can allow interior air to enter the wall cavity or escape directly to the exterior. If penetrations are not properly sealed, they can act as entry points for rain leakage and insects as well. Other connections at floor headers and sill plates (H) can also permit airflow across wall assemblies.

Figure 2-9 Air leakage paths through wall assemblies. Note. Condensed from Conservation Technology (2008)

2.8.1 *Air leakage mechanisms*

The air pressure differentials that drive air leakage are primarily caused by wind, stack effect, and mechanical air handling systems (Hutcheon, 1983). Unlike ventilation, air leakage is uncontrolled, which means that it is not filtered or conditioned and may introduce harmful contaminants or allergens to the indoor air. Uncontrolled airflows also transport problematic amounts of heat and moisture into sensitive areas of the building enclosure.

Air leakage occurs when the interstitial air of framing cavities mixes and circulates with the interior or exterior air through upper and lower openings on the same side of the wall assembly (Hutcheon, 1983). In winter, the introduction of warm, moist interior air into a wall cavity creates moisture damage as the air mass loses heat to the exterior and moisture is deposited as condensation on the sheathing. Air leakage from outdoor air has a drying effect in winter as the cooler winter air warms within the assembly and removes moisture. In summer, outdoor air has a wetting effect warm, humid air condenses on the internal vapour barriers of air-conditioned spaces. Air leakage reduces energy efficiency as it lowers the effective thermal resistance of air permeable insulation.

Warm air infiltrating during the summer and exfiltrating in winter has the potential to deposit its entrained moisture as condensation within the wall. Conversely, under the proper conditions, air leakage can help to dry out a moisture laden wall assembly. The significant energy costs associated with air leakage and its adverse effects on thermal comfort, air quality and wall durability have driven the modern approach of limiting flow of air across an assembly to near zero (Straube, 2005).

Moderate fluctuations in relative humidity and the moisture content in envelope assemblies regularly occur as the envelope equilibrates with changes to the interior and exterior climates. As moisture loads pass through, hygroscopic materials respond by adsorbing or desorbing water molecules towards their EMC. Air leakage can carry high moisture loads that disturb the moisture balance within the assembly. Damage from excessive moisture occurs when the interstitial RH remains elevated for extended periods. This damage can be compounded if the internal wall temperatures drop below the dew point.

2.8.2 Calculating airflows and leakage

The flow of air across a building envelope occurs through discrete cracks and openings as shown in Figure 2-9. The airflow can be characterized as orifice flow, large crack flow or small crack flow (tortuous). The complexity of defining the size and distribution of each crack and orifice has led to the assumption of diffuse flow through enclosure components (Straube, 2005). Whole-building air leakage tests measure the combined flow rate of all the of the leak types in the building under a specific pressure differential. The general power law equation is used to fit these data (Baker et al, 1987):

$$Q = C \cdot (\Delta P)^n \quad [19]$$

Q = volumetric flow rate

P = pressure (Pa)

C = flow coefficient

n = flow exponent (0.5 < n < 1.0)

To determine the flow rate at different pressures for the same test, the conversion is as follows:

$$Q_2 = Q_1 \cdot \left(\frac{\Delta P_2}{\Delta P_1} \right)^n \quad [20]$$

The value of the flow exponent helps to indicate the dominant type of airflow through the enclosure. Lower flow exponent values (~0.5) indicate turbulent flow while exponent values of 1 indicate that the flow is laminar and the flow rate is linearly related to the change in pressure.

2.8.3 Air leakage flow rates and standards

As building codes raise the requirements of thermal resistance in building envelopes, limited progress has been made in creating mandatory airtightness testing in housing and currently airtightness requirements do not exist for multi-unit residential buildings (MURBs) (RDH, 2013). Building codes like the 2010 National Building Code (NRC IRC, 2010) and the 2011 National Energy Code of Canada for Buildings (NRC IRC, 2011) or the 2006 OBC (OMMAH, 2006) and its 2012 Supplementary Standard SB-12 (OMMAH, 2011) all specify the required properties for air barrier materials as well as continuity details. According to these codes the air barrier must have an air permeability of less than 0.02 L/s·m² as tested according to CAN/ULC-S742, "Air Barrier Assemblies – Specification," (SCC, 2011) under a pressure differential of 75 Pa. These building codes also supply details regarding the condition and integrity of the air barrier as well as requirements to ensure the proper sealing of edges and connections with adjoining

materials; they do not, however, specify any required test to ensure compliance and determine the actual air leakage of the building (RDH, 2013). Such a requirement would be analogous to the pressure testing plumbing or natural gas lines prior to use.

The United States Army Corps of Engineers (USACE) mandate air leakage tests for their newly commissioned buildings to ensure compliance with construction standards. USACE consistently achieve air leakage rates of $1.27 \text{ L/s}\cdot\text{m}^2$ of enclosure area at 75 Pa because of testing procedures and performance standards (RDH, 2013). In contrast, selected typical mean NLR_{75} air leakage data for selected Canadian building types (CMHC, 2001) is summarized as follows:

- Multi-Unit Residential Building (MURB) – $3.19 \text{ L/s}\cdot\text{m}^2 @ 75 \text{ Pa}$
- Office Buildings – $2.48 \text{ L/s}\cdot\text{m}^2 @ 75 \text{ Pa}$
- Schools – $1.48 \text{ L/s}\cdot\text{m}^2 @ 75 \text{ Pa}$
- Commercial – $1.35 \text{ L/s}\cdot\text{m}^2 @ 75 \text{ Pa}$
- Institutional – $0.86 \text{ L/s}\cdot\text{m}^2 @ 75 \text{ Pa}$

All aspects of residential housing from single detached to multi-unit residential buildings (MURBs) would benefit from mandatory whole-building air tightness standards. Air leakage limits and testing would give industry targets and the impetus for compliance. The resulting improved energy efficiency and lower upfront costs from smaller heating, ventilation and air conditioning (HVAC) systems would serve to offset increased expenditures associated with the evaluation of building air tightness. Improved air quality and thermal comfort could be considered a bonus.

2.8.4 Air leakage units of measurement

Whole-building airtightness is expressed differently throughout the building industry. The units of measurement include the airflow or leakage rate and a specified pressure differential that is often related to the volume or surface area of the building. As summarized in Finch, Straube and Genge, (2009) air-leakage test results are reported as:

- Fan flow rate (L/s, cfm) required to establish a specific pressure drop (50, 75 Pa)
- Equivalent leakage area (ELA) that results from a specific flow rate and pressure differential
- Air exchange rate (ACH, $\text{m}^3/\text{hr}/\text{m}^3$) at a specified pressure differential

Reporting test data as an ELA combines all of the openings that contributed to the leakage and summarizes them as an equivalent rectangular opening that can be readily compared between

buildings. Test data reported as an air exchange rate are normalized to the building volume (ACH), floor area or total envelope area. The National Research Council of Canada (NRC) uses the Normalized Leakage Rate (NLR) to quantify air leakage in buildings. The standard NLR_{75} is defined as the total air leakage divided by the total envelope area using an indoor to outdoor pressure differential of 75 Pa.

Airtightness standards and methods to achieve low air leakage rates are constantly evolving. As previously discussed, building codes outline materials and requirements for air barriers but they do not establish a desired degree of overall building airtightness. Some organizations have developed airtightness targets for buildings and the following are some examples of equivalent normalized leakage rates (ASHRAE, 2009):

- ASHRAE – Tight enclosure = $0.5 \text{ L/s}\cdot\text{m}^2 @ 75 \text{ Pa}$
- ASHRAE – Average enclosure = $1.5 \text{ L/s}\cdot\text{m}^2 @ 75 \text{ Pa}$
- ASHRAE – Leaky enclosure = $3.1 \text{ L/s}\cdot\text{m}^2 @ 75 \text{ Pa}$
- Int'l Energy Conservation Code (IEEC) = $2.0 \text{ L/s}\cdot\text{m}^2 @ 75 \text{ Pa}$
- NBC 2005 for building assemblies (curtain wall) = $0.15 \text{ L/s}\cdot\text{m}^2 @ 75 \text{ Pa}$
- Air Tightness Testing and Measurement Association (ATTMA 2007) = $0.83 \text{ L/s}\cdot\text{m}^2 @ 50 \text{ Pa}$ for best practice construction of dwelling enclosures.

Common reference pressure differentials for airtightness testing are 4, 10, 25, 50 and 75 Pa. The pressure differences closest to those actually experienced across building envelopes are in the range of 4 to 10 Pa. While the leakage data at low pressures may be more representative of actual conditions, achieving repeatable leakage test data at these low pressures is not feasible at this time. Differences in test method or technique as well as small calibration errors result in larger errors when the data are extrapolated to 4 Pa (ASHRAE, 2009).

2.9 Mould and decay

The assessment criteria for moisture related damage are determined by the amount of time moisture sensitive building materials are exposed to elevated RH levels or liquid moisture. The consequences of excessive moisture accumulation and retention are well known – corrosion of fasteners, bacterial growth, mould and staining, decay fungi and the favourable conditions for insects, but the boundaries of the limiting conditions are less well understood. Nofal and Morris (2003) discussed the need for a damage function to integrate with hygrothermal models in order to facilitate the prediction of strength

degradation associated with decay. The authors proposed that damage be considered in terms of a loss of strength to the assembly as well as the potentially hazardous effects of biological damage on the health of the occupants.

Fungi are some of the earliest organisms on earth and their spores can be found virtually everywhere. Over a million species of fungi exist on the planet and they grow under a variety of conditions. Some species are hazardous to human health and destructive to building assemblies. Fungi require oxygen, moisture and favourable temperatures to multiply. When all of these conditions are met, they are capable of decomposing organic material such as paper, adhesives, wood, and cellulose. The rate of fungal growth depends on surface area and access to nutrients. High surface area materials like particleboard, fibreboard, ceiling tiles and paper facings have the highest growth rates. Wood-based products like lumber, plywood and OSB have slower growth rates but can be significant under the right conditions.

Since fungal spores are ubiquitous, it is most likely that they are built into enclosure assemblies. Kiln drying lumber is an improvement over air-drying in that it eliminates any spores that may be present at the time of drying. Air dried lumber was often infected with fungal spores, and if not spaced properly, could initiate the decay process prior to drying. Storage, transportation and installation of lumber products also yield opportunities for contamination by fungal spores. Even once the building enclosure is completed, rainwater and air leakage can introduce more spores as well as the moisture to help them grow.

The proliferation of decay related organisms is complex process. The establishment of wood-rotting basidiomycetes is a function of the aforementioned growth requirements as well as competition from bacteria, moulds, and staining fungi that are effective at colonizing wet wood as well. The decay process can, however, be simplified to the three stages of establishment, growth and decay, and survival. Since these stages can be limited by controlling humidity and temperature, establishing boundary conditions for these parameters will help hygrothermal models more effectively predict enclosure durability.

2.9.1 Thresholds

Defining thresholds for mould growth and decay processes require limiting conditions for the relative humidity and temperature of the internal wall environment. The ideal temperature conditions for mould growth are species dependent but the average range is from 20° to 35° C. Fungal growth slows outside of this range and generally stops below 5°C and above 50°C. The fungal spores can survive outside of

this range so growth can resume when favourable conditions return. Most fungal species that attack building materials require a surface RH of 75-80% for slow growth and 90-95% for fast growth. Above 95%, fungal growth slows as oxygen is depleted within the pore space (Straube, 2005).

For decay related damage, there is consensus that maintaining wood below 20% MC provides a good margin of safety against fungus damage (ASHRAE, 2009;). Using Equation 9 for EMC, prolonged periods at 90% RH translate into 20-21% EMC for most species of wood between 5°C and 30°C. At 95% RH, the EMC of wood averages 24% between 5°C and 30°C. The EMC for OSB is approximately 3-4% lower than that of wood (Straube et al, 2002) under similar conditions. The physical factors that reduce the moisture content of OSB could also limit mould growth. These factors include the wax and adhesives used to bind the strands together, as well as the smooth, compacted interior face of the sheathing that minimizes the amount of surface area available for growth to occur. The higher density of OSB also lowers the porosity of the material, which removes some of the air from within the wood's structure as well as potential storage for the adsorbed and absorbed moisture that enables mould growth.

The rate of decay depends on the fungus and tree species as well as whether or not it is heartwood or sapwood. The generally accepted onset point where active decay begins is above 26-28% MC (at or near the fibre saturation point) although it has been shown that marginal infection can also occur as low as 25% MC (Morris and Winandy, 2002). Further, Morris and Winandy (2002) also reported that Forintek confirmed that OSB decay could be initiated at 27% MC when exposed to 99.9% RH and 20°C for 8.5 months and inoculation every 2 weeks. Once decay is initiated above the 26-28% threshold, decay will continue down to 20% MC before ceasing.

3 EXPERIMENTAL SETUP

To investigate the risks associated with reduced drying capacity, thirteen test panels were built and inserted into the exterior walls of the University of Waterloo's Building Engineering Group test facility (BEG Hut) in Waterloo, Ontario, Canada. Construction and installation details are provided in Appendix A.

3.1 Building Engineering Group test facility

The thirteen test panels include five high RSI value wall assemblies built with north (N) and south (S) facing orientations; one high RSI value wall assembly built on a south facing orientation only and one datum wall assembly built with both north and south facing orientations. The datum wall assembly was a currently code-accepted wall design that met the OBC 2012 minimum for thermal resistance.

Figure 3-1 Test panel positions on south and north elevations and climate sensor locations

The BEG Hut test facility had space for seven south facing test panels and only six north facing test panels. For this reason, wall Type 4 was selected for southern exposure only. Figure 3-1 shows the north and south elevations of the BEG Hut and the placement of the 13 test panels. The test panels were numbered from the east on both the north and south elevations.

The BEG Hut test facility is a 10.5 m square building with each of its exterior walls aligned with one of the four principal directions. The building has a 3.0 m floor to ceiling height with a 1:3 pitch hip roof. The post and beam construction maximizes the wall space available for test panels.

A pipe mast is anchored to the roof that supports the weather station 10 m above

grade. The BEG Hut is conditioned with an air-to-air heat pump, humidification system and four ceiling fans to maintain a uniform temperature of 21° and 40% relative humidity throughout the building. The 200 mm roof overhang was de-signed to prevent shading and incorporates a drip-edge in lieu of eavestrough to optimize exposure.

The building is located on flat land adjacent to a university parking lot. The base of the test panels are between 160 and 220 mm above grade with the exterior siding lapping over the built-up wall curb at the edge of the BEG Hut floor slab.

3.1.1 BEG Hut weather data instrumentation

The weather station installed at the BEG Hut facility collected the ambient exterior temperature, wind speed and direction, as well as relative humidity data from a height of 10 m above grade. Incident solar radiation was measured with a pyranometer that was located lower on the instrumentation mast at roof height (shown in Figure 3-1) with the tipping-bucket rain gauge.

Weather data from the nearby Environment Canada - University of Waterloo Class A weather station was available for substitution in the instance that weather data was not collected at the BEG Hut weather station.

3.1.2 Wall type identification

The seven wall assemblies were identified by their type and orientation. Their locations in the BEG Hut exterior are shown in Figure 3-1. The deep cavity walls and the datum wall were designated as follows:

- Type 1 (S1, N1) – Double Stud with dense-packed cellulose
- Type 2 (S2, N2) – I-Joist Stud with dense-packed cellulose
- Type 3 (S3, N3) – 38x140 mm Datum with fibreglass cavity insulation
- Type 4 (S4) – 38x184 mm (Spray Foam)

The remaining three wall types were constructed using the base Type 3 Datum framing and configured with three different types of exterior insulation. These three wall assemblies were identified as:

- Type 5 (S5, N5) – 38x140 mm with 50 mm (RSI 2.18) Polyisocyanurate
- Type 6 (S6, N6) – 38x140 mm 64 mm (RSI 2.21) Extruded Polystyrene
- Type 7 (S7, N7) – 38x140 mm 76 mm (RSI 2.11) Mineral Wool

The installed thickness of each exterior insulation type was chosen to result in approximately equivalent RSI values of RSI 2.2, 2.2 and 2.1, respectively. Detailed construction drawings of the test panels are provided in Appendix B.

3.2 Test panel installation and isolation.

The rough openings of the BEG Hut were finished with 38 mm XPS insulation, 12.5 mm plywood and wrapped with self-adhering water proof membrane on the exterior edge. The plywood was fastened to the building posts, beams or floor curb through the insulation. The plan view diagram in Figure 3-2 illustrates how the test panels were inserted into BEG Hut walls, hygrothermally isolated and sealed.

Figure 3-2 Hygrothermal isolation of the test panels in the exterior walls of the BEG Hut (typical).

The test panels were hygrothermally isolated using 305 mm I-Joists placed vertically between the test panels. Each I-Joist web was filled with 12.5 mm thick XPS insulation to make the side of the I-Joist flush with the edge of the flange. Waterproof membrane was then wrapped around the exterior edge of the I-Joist. The openings were sized to allow for a 19 to 25 mm space around each test panel to accommodate the sensor wires and tubing as well as provide adequate space for the foam to penetrate the gap and make an airtight seal.

3.3 Test panel design

The test panels were designed with the overall dimensions of 1.22 x 2.44 m and were framed on 600 mm centres with double top plates. The framing is predominantly 38 mm thick spruce lumber with varying widths depending on the wall design. Table 3-1 summarizes the framing, insulation type with

cavity RSI value and vapour control details. The basic design of the test panel includes three cavities – the central 571.5 mm wide cavity and the two 277 mm side cavities. The side cavities were designed as hygrothermal buffers for the central cavity. To this end, the two outermost studs were framed using 9.5 mm spruce plywood in order to maintain proportional thermal performance. The RSI values shown for each wall represent the “Installed Insulation RSI”, which is the sum of the insulation product RSI values as defined by Christian and Kosny, (1995). The installed insulation value is generally cited by building codes and used by industry participants. The RSI values presented in Table 3-1 do not reflect the effects of thermal bridging. The thermal analysis of the centre-of-cavity and clear wall RSI-values is presented with the heat flux data in Section 4.8.

Table 3-1 Summary table of wall design details

Wall ID	Wall framing*	Insulation	RSI	6-mil VR**
S1, N1	140 mm exterior frame; 89 mm interior	286 mm cavity with dense pack cellulose	6.8	Yes
S2,N2	241 mm I-Joist stud; 241 mm plates	241 mm cavity with dense pack cellulose	5.8	Yes
S3,N3	140 mm framing	140 mm fibreglass insulation	3.9	Yes
S4	184 mm framing	152 mm closed cell spray polyurethane foam (ccSPF)	6.4	No
S5,N5	140 mm framing	140 mm fibreglass insulation; 50 mm PI	6.1	No
S6,N6	140 mm framing	140 mm fibreglass insulation; 64 mm XPS	6.1	No
S7,N7	140 mm framing	140 mm fibreglass insulation; 76 mm mineral wool	6.0	Yes

* All framing using 38 mm thick Spruce-Pine-Fir (SPF) lumber; studs are installed 600 mm OC with two nominal 300 mm side cavities for total frame width of 1.22 m. Wall framing includes single bottom and double top plate except the single interior frame top plate in walls S1 and N1.

**6-mil vapour retarder (VR) indicates the use of 6-mil polyethylene in the assembly.

The Type 2 wall used 241 mm I-Joists in lieu of solid spruce lumber to isolate the three stud cavities. The I-Joists were built on-site using an 11 mm oriented strand board (OSB) web and 38x64 mm SPF flanges. The I-Joist webs were connected to the flanges via 11x12.5 mm dadoes, fastened with construction adhesive and clamped overnight to ensure good adhesion. The Type 1 double stud wall, by nature of its design, was the only wall where the central cavity was connected to the side cavities through the 57 mm insulated space (thermal break) between the interior and exterior frames.

The general framing elevation diagram for all of the wall assemblies is located in Figure 3-3. This figure shows the layout of the central stud cavity and indicates the dimensions as well as the locations of sensors, the exterior wetting sheet and the air injection / exhaust ports. For detailed diagrams, please refer to Appendix B.

- ☒ Moisture Content and Temperature Sensor
- ☒ Heat Flux Transducer
- ⊗ Air Injection and Exhaust Ports

Figure 3-3 General framing elevation for test panels

- △ Temperature Sensor
- ▣ Moisture Content and Temperature Sensor
- ⊗ Relative Humidity and Temperature Sensor
- ▤ Heat Flux Sensor

Figure 3-4 Exploded cross sectional diagram of typical test panel configuration

Table 3-2 Wall component details from Figure 3-4

ID	Wall component
A	11 mm Fibre cement siding
B	19 mm strapping / drainage space
C	Exterior Insulation (if installed)
D	SBPO air barrier and water resistive layer
E	11 mm OSB Sheathing
F	140, 184 or 241 mm framing as required
G	6-mil polyethylene (if installed)
H	12.5 mm drywall
I	Air injection port
J'-J	Sensors through wall insulation cavity
K	Air exhaust port
L	Exterior water injection wetting sheet

The exploded cross section shown in Figure 3-4 on the preceding page illustrates the installed sensor locations relative to each wall layer. Wall components are identified alphabetically and listed in Table 3-2. The instrumentation and monitoring details are located in Section 3.6.

3.4 Test panel control components

In addition to the building controls and side cavity buffer zones, each wall assembly was designed to hygrothermally isolate the central stud cavity using common control layers. The control layers common to each assembly were:

- Exterior drained-screened wall system
- 11 mm OSB sheathing
- Interior 12.5 mm drywall with
- Two coats of latex paint

These common components limited the factors affecting hygrothermal performance and facilitated comparisons between the high RSI walls and the Type 3 datum.

3.4.1 Drained-screened exterior assembly

The drained-screened exterior was assembled with 8 mm fibre cement siding, 19 mm strapping / air layer (drainage space) and drainage plane.

The drainage plane or water resistive barrier (WRB) was provided by the spun bonded polyolefin (SBPO) installed on the exterior side of the OSB sheathing. A slightly oversized 1.2 x 2.4 m sheet of SBPO was sealed to the waterproof membrane on the finished wall openings with construction tape. Penetrations in this layer for sensor wires were sealed with acoustical sealant and tape. The air space around the test panel was filled with polyurethane foam (window grade) to complete the air, water and thermal sealing.

The exterior insulation used in Wall Types 5 and 6 provided an additional drainage plane in these walls. The exterior mineral wool insulation of Wall Type 7 increased the drainage space from 19 mm to 57 mm.

3.4.2 Exterior insulation

Walls should have at least one direction of drying provided to deal with accidental and construction moisture. In the walls with extruded polystyrene (permeance of 18 ng/Pa·s·m² at 64 mm thickness) and foil-faced polyisocyanurate (permeance less than 1 ng/Pa·s·m² due to the aluminium facer material), the interior 6-mil polyethylene was removed to allow a drying path to the inside.

The mineral wool exterior insulation used in wall Type 7 had a high water vapour permeance in excess of the OBC minimum requirement for water vapour control. The 6-mil polyethylene vapour retarder was located between the stud cavity and the interior drywall in wall type 7.

3.4.3 Air barrier

Several of the materials used in the various test panels will perform the function of an air barrier as well as the SBPO layer, but this air barrier and its location are common to each wall type. For the purposes of the air injection test, further air sealing was provided for the central stud cavity. Acoustical sealant was applied around the air injection port to provide an air seal between the 6-mil polyethylene and drywall. Where 6-mil polyethylene was not used for vapour control, acoustical sealant was applied around the perimeter of the drywall to ensure that the injected test air exited the cavity from the 25 mm diameter exhaust port drilled into the centre of the top plates.

3.4.4 OSB sheathing

The 11.1 mm OSB sheathing was installed in two pieces with the horizontal joint 600 mm above the bottom plate. Since the OSB sheathing is moisture sensitive, its moisture content was the primary performance indicator. Changes in OSB MC were monitored to determine the effects of climatic exposure and the air injection test in order to determine the drying potential and durability of each wall assembly. To monitor moisture content, the sheathing was instrumented with temperature and

moisture sensors as shown in Figure 3-3 and Figure 3-4 as well as the more detailed construction drawings in Appendix B.

3.5 Cavity insulation

There are three types of cavity insulation used in this study:

- Fibreglass batt
- Closed cell Polyurethane Spray Foam (ccSPF)
- Dense-pack cellulose

The fibreglass batt insulation was installed in the stud cavities the 38x140mm framed walls. It is a very common insulating material in North American residential construction because it does not require any specialized installation knowledge. In contrast, the ccSPF insulation used in wall Type 4 must be installed professionally as it requires special equipment and experience.

The ccSPF installation required three applications each separated by a cooling period to obtain the required 152 mm thickness. The foam cured through an exothermic reaction that caused the temperature in the stud cavity to rise above 65° C on an average hourly basis, while the peak temperature on a 15-minute basis reached a high of 75°C. Figure 3-5 shows the change in OSB and S4 central cavity temperatures before, during and after the installation of the ccSPF insulation. Prior to the installation, the cavity and OSB were exposed to the interior climate, which resulted in the stable

Figure 3-5 OSB and cavity temperatures in S4 associated with ccSPF installation

temperatures prior to November 15. After the foam installation, daily temperature fluctuations can be observed.

The final type of cavity insulation used in this study was dense-pack cellulose insulation. Blown cellulose insulation is most often used in attic type spaces where settling is not a major concern. However, in wall applications, the cellulose must be installed with sufficient density to resist settling, as any compaction post installation will result in a loss of thermal protection in the upper portion of the stud cavity.

3.5.1 Cellulose installation procedure

The dense-pack cellulose insulation was installed using industry best practices under the instruction of Chris Schumacher at Building Science Labs. The installation of the cellulose used a standard hopper and blower apparatus and the only specialized equipment required was a 38 mm tapered hose adapter to reduce the 100 mm diameter main hose. The cellulose was installed in the following order – S2, S1, N1, and N2.

The insulation was installed with final average densities of 64 kg/m³ in the Type 1 double stud walls and 68 kg/m³ in the Type 2 I-Joist walls. The cellulose was easier to pack into the separated stud cavities of the I-Joist wall as the lateral connection between the side and central stud cavities of the double stud wall allowed air to circulate through all of the stud cavities, which made compaction more difficult. The installed cellulose densities are located in Table 3-3.

Table 3-3 Cellulose density for wall types 1 & 2

	<u>Installed Cellulose Density</u>	
	<i>lbs/ft³</i>	<i>kg/m³</i>
<i>S1</i>	4.0	64.3
<i>N1</i>	4.1	64.9
<i>S2</i>	4.3	68.5
<i>N2</i>	4.2	67.8

Prior to installation, the rough framed test panels were prepared with 250 mm wide strips of 6-mil polyethylene sealed to the outer edges of each assembly. These strips were used to attach and sealing the final sheet of 6-mil poly vapour barrier. A 1.22 x 2.44 m piece of air permeable fabric was then installed across the entire face of the test panel to hold the cellulose in position and allow the air to

Figure 3-6 Strapping and air permeable membrane cellulose installation (wall S2)

escape. Next, the face of the test panel was strapped horizontally with 19 x 64 mm spruce on 400 mm vertical centres to support the fabric and ensure a planar surface for the drywall.

The cellulose insulation was weighed and blown into the walls through 75 mm 'X' slots cut into the air permeable fabric. The installation proceeded in 800 mm vertical increments so the installed insulation mass could be tracked with an incremental wall volume. This stepwise process ensured that the desired insulation density was achieved. Following installation, the access holes were sealed with construction tape; the 250 mm polyethylene strips were folded around the strapping and sealed to the final sheet of 6-mil polyethylene. The exterior perimeter of the polyethylene was packed with acoustical sealant to prevent the edges and corners of the strapping from piercing the vapour retarder.

Figure 3-6 shows the S2 test wall after the installation of the cellulose. The fabric is visibly stretched from the packed cellulose but held in place well by the strapping. The access holes in the fabric were sealed with technical tape upon completion.

3.6 Instrumentation and monitoring

The centralized data acquisition unit (DAU) installed at the BEG Hut was configured with five Campbell Scientific AM16-32B multiplexers (MUX), a main CR 1000 data logger and a 12 volt backup battery. In total, 220 sensors were used to monitor the 13 test panels in this study – 121 T-sensors, 65 moisture

sensors, 26 relative humidity sensors and 8 heat flux transducers. Each test panel had 9 temperature, 2 relative humidity and 45 moisture content sensors installed (as detailed in Appendix B).

All sensors were connected to the DAU with CAT 3 communications cables from terminal strips located beside each test panel. The datalogger was programmed to acquire hourly averaged data with sample intervals at 15 minutes. Detailed MUX wiring diagrams are located in Appendix C. The sensor code and wiring diagrams are located in Appendix D. The datalogger program is presented in Appendix E. The datalogger program was created using subroutines authored by Chris Schumacher of Building Science Corporation. The subroutines are noted with 'CJS' in the remark statements associated with each subroutine.

3.6.1 Exterior climate sensors

The BEG Hut weather station uses a Vaisala™ HUMICAP® HMP 35C to measure relative humidity and temperature. The HMP 35C probe is shielded from both scattered and direct solar radiation as well as precipitation. The HMP 35C relative humidity sensor has a measuring range from 0.8 to 100% RH (0.002 to 1 VDC) and an accuracy at +20°C of $\pm 2\%$ RH (0 to 90% RH) and $\pm 3\%$ RH (90 to 100% RH). The long-term stability is typically $<1\%$ RH / year and the temperature dependence sensor is $\pm 0.04\%$ RH/°C. For temperature, the HMP 35C uses a platinum Pt 100 RTD (IEC751 1/3 Class B) with a resistance of 100 Ω at 0°C and a measurement range from -40° to +60°C (0 to 1 V DC). The overall accuracy of this sensor through the range of -24°C to 48°C is $\pm 0.4^\circ\text{C}$.

Incident solar radiation is monitored using a Kipp & Zonen Model CM11 pyranometer. The accuracy of the pyranometer is $\pm 10 \text{ W/m}^2$ with a sensitivity to temperature dependence of $<1\%$ from -10°C to +40°C. Pyranometers measure total radiation, direct and diffuse, independent of wavelength and angle of incidence. The BEG Hut pyranometer is mounted in an unobstructed, horizontal position.

Wind speed and direction is monitored using the RM Young Wind Sentry 03002-10A. The anemometer has an operating range of 0 to 50 m/s with an accuracy of $\pm 0.5 \text{ m/s}$. The output frequency is 0.75 m/s per Hz. The balanced wind direction vane uses a 10k Ω transducer that operates with 1% linearity and an accuracy of $\pm 5^\circ$. Precipitation is measured with a 0.1 mm/count tipping bucket rain gauge.

3.6.2 Relative humidity sensors

The relative humidity (RH) sensors used in this study were Honeywell model HIH-3610-004 series. Each RH sensor was bundled with a T-sensor and wrapped with spun-bonded polyolefin for protection against

liquid water. These sensor bundles were mounted mid-depth in both the central stud cavity and the exterior drainage space, as shown in Figure 3-4. They were secured with nylon line and building tape to maintain their positioning while the insulation was installed.

The HIH-3610 sensors have an accuracy of $\pm 2\%$ RH from 0 to 100%RH under non-condensing conditions while exposure to $\geq 90\%$ RH with condensing conditions causes a reversible shift of $\pm 3\%$ RH. Placement of the RH sensors in the centre of the insulation cavity limited the sensors exposure to $> 90\%$ RH. The interchangeability accuracy of these sensors is $\pm 5\%$ RH, 0-60%RH and $\pm 8\%$ @ 90%RH with other performance details as follows:

- RH Linearity – $\pm 0.5\%$ RH typical
- RH Hysteresis – $\pm 1.2\%$ span maximum
- RH Repeatability – $\pm 0.5\%$ RH
- RH Stability – $\pm 1\%$ RH typical at 50% RH in 5 years
- $V_{\text{supply}} = 5 \text{ V DC}$

The sensor RH data was processed to correct for temperature using the temperature compensation equation (T in $^{\circ}\text{C}$):

$$\text{True RH} = (\text{Sensor RH}) / (1.0546 - 0.00216 \cdot T) \quad [21]$$

The effect of this temperature correction is $\pm 0.007\%$ RH/ $^{\circ}\text{C}$ at 0%RH and -0.22% RH/ $^{\circ}\text{C}$ at 100%RH.

3.6.3 *Temperature sensors*

The temperature sensors used in this study were precision Fenwal Unicurve® 10k Ω (25°C) thermistors wired in series with a 1000 Ω fixed resistor. Temperature was calculated from the voltage difference measured across the fixed resistor using the following relationship (R in Ω):

$$T = -0.101 \cdot R^3 + 4.346 \cdot R^2 - 77.18 \cdot R + 446.05 \quad [22]$$

Each T-sensor had a tolerance of $\pm 0.2^{\circ}\text{C}$ and operated with a supply voltage of 2.5 V. These T-sensors were installed with each relative humidity, moisture content, and heat flux sensor as well as on the interior and exterior surfaces of the assemblies. The thermistor measurement circuit is detailed in Appendix F.

3.6.4 *Wood moisture*

The moisture content (MC) sensor pins were installed to a depth of 5 mm in the OSB sheathing and framing. The MC sensors installed in the plates were 9.5 mm from the exterior edge of the framing. The sensors were located at elevations of 285, 1200 and 2040 mm along the vertical centreline of the central cavity as measured from the top of the bottom plate as shown in Figure 3-3 and Figure 3-4

The electrical resistance of the wood between the MC sensor pins was determined from the voltage measured across a 10k Ω resistor in series using Ohm's law and the voltage divider. This electrical resistance was then used to calculate the moisture content based on the mathematical relationships between species and temperature, as detailed in Section 2.7.1.

3.6.5 *Interior climate sensors*

The interior climate was monitored for temperature and relative humidity using an RH/T bundle similar to those used within the test panel assemblies. The sensors were centrally located at a height of 1.8 m above the floor and recorded with the CR-1000 DAU.

3.6.6 *Heat flux*

Two heat flux (HF) transducers were installed on four south facing walls each to measure the variation in heat flux through the insulation cavity and the stud. These sensors were installed on the cavity side of the drywall to limit the effects of air movement on the sensor output. A shallow notch the thickness of the transducer (3 mm) was cut into the stud to allow the heat flux sensor to lie flush with the stud face and not interfere with the placement of the drywall. Temperature sensors were installed directly over the heat flux transducers on the interior surface of the drywall at both the cavity centre and stud locations. Heat flux transducers were installed on S2, S3, S4 and S5. The locations of heat flux sensor are illustrated Figure 3-3 and Figure 3-4.

3.7 *Moisture sensor trouble-shooting*

Trouble-shooting of the data acquisition system began with the initial data collection during the first week of October 2012. The MC sensors were tested for accuracy by placing a 9.6 M Ω resistor across the sensor leads and compared with the value of the datalogger output. This process also verified the wiring and programming by ensuring that the datalogger recorded the measurements at the correct sensor location.

On October 22, two malfunctioning T-sensors associated with the lower OSB MC sensors in S1 and S7 were replaced. This work was completed at the same time as the installation of the MC sensor isolators in walls S1, S2, N1, and N2.

3.7.1 Isolation of moisture content sensors in cellulose walls

The initial data indicated that the framing and OSB MC measurements in wall Types 3-7 were within expectations and compared well between test panels as well as with the calculated EMC. The MC measurements in wall Types 1 & 2, however, were generally higher due to decreased resistance between the MC sensor pins.

The shafts of the MC pins were painted with non-conductive paint; however, the soldered wire contacts with the MC pin were in fact bare. Further investigation revealed that a sample of cellulose insulation compacted to 64 kg/m³ and placed between the MC sensors resulted in lower resistivity measurements and higher calculated MC. These non-insulated electrical connections caused a bypass circuit through the cellulose. The cellulose had a higher than expected electrical conductivity that appears to be related to the moisture content of the cellulose. Silicone isolators were installed on the affected MC sensors to eliminate this source of error. Once installed, the calculated MC for these sensors was reduced by 3-5%. The isolator installation is detailed in Appendix G.

The data from some of the OSB and framing MC sensors in walls S1, S2, N1, and N2 indicated a rise in moisture content about one week after the isolators were installed. After two weeks, some MC readings were higher than before the isolators were installed but this correlates with cooler weather and condensation within walls S1, S2, N1, and N2. The connection between these MC measurements, condensation and the initial RH are discussed further in Section 4.4.

3.8 Moisture loading protocol

The High-RSI wall study included two types of induced moisture loading in addition to the climatic loads resulting from natural exposure. The first induced moisture load was applied during the wintertime using a constant-volume flow rate of interior air that was injected into each of the test assemblies (excluding S4). The second type of induced moisture load was applied during late spring and mid-summer to simulate rainwater leakage. The rainwater leakage assessment was beyond the scope of this thesis.

3.8.1 *Simulated air leakage test*

The air leakage test was administered through the lower access port in the test walls as shown in Figure 3-3 and Figure 3-4. The air was piped from a centralized location through 25 mm polyethylene tubing to a flow meter placed at each wall. The air pump is shown in Figure 3-8a and a typical wall connection is shown in Figure 3-8b. The exhaust port in the upper plate was accessed with a 25mm drill bit through the interior drywall and 6-mil polyethylene to allow the injected air to leave the wall cavity and return to the BEG Hut interior.

Figure 3-8a Central air pump used for injection test

Figure 3-8b Air injection port at test wall

The central air pump maintained the flow and pressure on the piping system while the injection rate was adjusted individually at each wall through the flow meter. The air injection test was started on February 19, 2013 at 16:30 hours with the constant flow rate set to 0.315 l/s (40 SCFH). Weekly inspections noted that once the flow rate was set at the wall, the injection rate held steady and no fluctuations in flow rate were observed. The moisture content of the OSB and plates were monitored throughout the test and once the walls were subjected to a sufficient degree of wetting, the airflow was removed and the top exhaust ports were covered with building tape to eliminate air movement. The walls were then monitored throughout the drying period.

The air injection system maintained the 0.315 L/s flow rate through each of the test walls wall at a low pressure of approximately 5 Pa, which is characteristic of natural pressure differentials that typically occur across wall assemblies in the absence of an elevated stack effect or high wind velocity. The 0.315

Table 3-4 Natural pressure NLR₅ for selected target air leakage rates (from Section 2.8.4)

	NLR Leakage Rate	
	$L/s \cdot m^2$ at 75 Pa	$L/s \cdot m^2$ at 5 Pa
USACE	1.27	0.22
ASHRAE Tight	0.50	0.09
ASHRAE Average	1.50	0.26
ASHRAE Leaky	3.10	0.53
IEEC	2.00	0.34
ATTMA 2007	0.83	0.14

L/s flow rate was normalized to the central wall cavity area (1.31 m^2) and the total wall panel area (2.9 m^2) in order to determine its NLR₅ for comparison with the air tightness target NLRs from Section 2.8.4. These NLR₅ data were $0.24 \text{ L/s} \cdot \text{m}^2$ for the central cavity and $0.11 \text{ L/s} \cdot \text{m}^2$ for the total test panel area. The central

cavity NLR₅ applies to most of the High RSI wall types with the exception of wall Type 1.

The stud cavities of wall type 1 are connected by the 57 mm space between the interior and exterior framing assemblies, which enables air to flow between the stud cavities. However, the placement of the upper exhaust port in the upper plates above the central cavity represents the path of least resistance for airflow, which may have bias flow through the central cavity. The actual flow rate for the Type 1 wall is uncertain but it will fall between the 0.11 and $0.24 \text{ L/s} \cdot \text{m}^2$ NLR₅ values.

In order to compare the air injection rate with the air tightness targets, the NLR₇₅ data were converted to NLR₅ data using equation 20. These NLR₅ data are presented in Table 3-4. The central cavity NLR₅ injection rate of $0.24 \text{ L/s} \cdot \text{m}^2$ compares well with the target value for the USACE as well as the ASHRAE target for average enclosures.

The NLR leakage rates specified in Table 3-4 represent building leakage rates, which include windows and other openings as well as assembly penetrations. The simulated air leakage test considers that all air leakage associated with penetrations enters the wall cavity, which may be considered a worst-case investigation of a $0.24 \text{ L/s} \cdot \text{m}^2$ NLR₅ air leakage rate.

3.8.2 Air tightness test data

Prior to the air leakage test, each wall assembly was tested for air tightness using suction test with flow rates from 0 to 200 CFH (0 to 1.6 L/s). The maximum pressure drop ranged from 80 to 91 Pa in walls S1 & N2 up to 436 Pa in wall N7. The air tightness data are presented in Figure 3-9. This chart compares the wall types and orientation using the air leakage rate at 75 Pa and normalized with the surface area of the test panels ($\text{L/s} \cdot \text{m}^2$). The data in Figure 3-9 show that the two deep cavity walls, Types 1 & 2, have similar leakage rates with the exception of the north facing double stud (N1), which has an air leakage

Figure 3-9 Air tightness comparison based on wall type and orientation (L/s · m² at 75 Pa)

rate about 30% lower. Similar differences were also noticed in the datum wall (Type 3) pair as well as the XPS wall (Type 6) pair. The suction test data are presented as pressure response versus flow rate charts in Figure 3-10. The pressure data for N7 indicate that a blockage of the air leakage path occurred during the test or some equipment related failure occurred that rendered these data uncertain.

The difference in air leakage rates between the north and south facing walls highlights the variation that occurs in construction even when great care is taken during construction. Other sources of uncertainty associated with the air tightness data relate to the measurement procedure during the test as well as any leakage that may have occurred at the air injection port's seal with the 6-mil poly or drywall. In addition, although the central cavities of wall Types 2-7 were hygrothermally isolated by the two side cavities, air leakage between the central and side cavities could occur between the plates and the studs as well as through the 3 mm expansion space at the sheathing joint.

Figure 3-10 Air tightness data for the north (Top) and south (Bottom) wall assemblies

4 HYGROTHERMAL ANALYSIS

The central stud cavity within each wall assembly was instrumented with three OSB MC-sensors (lower, middle, upper) and two framing MC sensors in the upper and lower plates. An RH/T bundle was also located in the centre of the stud cavity. The data collected from these sensors were evaluated based on wall type and orientation through three distinct study intervals:

1. A fall/winter baseline period from November 20 to February 19
2. A wintertime air leakage test from February 19 to April 8
3. A springtime drying period extending from April 8 to June 3

The variability of vapour pressure in response to climatic conditions was determined and its effect on the OSB and framing moisture content was evaluated over each of these three study intervals. Each wall assembly was also compared between wall types, orientation as well as with the relevant datum wall.

The wall assembly components and their wall identification numbers are re-stated here for convenience. The deep cavity walls and the datum wall are designated as follows with colour codes used in graphing:

- Type 1 (S1, N1) – Double Stud with dense-packed cellulose
- Type 2 (S2, N2) – I-Joist Stud with dense-packed cellulose
- Type 3 (S3, N3) – 38x140 mm Datum with fibreglass cavity insulation
- Type 4 (S4) – 38x184 mm (Spray Foam)

The remaining three wall types were constructed using the Type 3 Datum framing as a base with fibreglass cavity insulation and configured with three different types of exterior insulation. These three wall assemblies are identified as:

- Type 5 (S5, N5) – 38x140 mm 50 mm (RSI 2.18) Polyisocyanurate
- Type 6 (S6, N6) – 38x140 mm 64 mm (RSI 2.21) Extruded Polystyrene
- Type 7 (S7, N7) – 38x140 mm 76 mm (RSI 2.11) Mineral Wool

4.1 *Weather*

Several important weather statistics are summarized below in Table 4-1. The water vapour pressure differentials were calculated using the difference between the exterior and interior partial vapour pressures (RH/T data). These pressure differentials express the outward flow of water vapour as

positive. The vapour drive was predominantly outward during the three analysis periods; however, the drying period experienced a greater percentage of inward vapour drives because of the warmer wet weather in the spring. The relative amount of time that an outward vapour drive occurred during the baseline, air injection and drying phases were 91%, 98%, and 67% respectively.

The average wind speed was 3 m/s with an average westerly wind direction during each of these analysis periods. The complete weather dataset is presented in Appendix H.

Table 4-1 Summary of weather data for the analysis periods

Analysis Period	Days	Temperature Average (Max Min) (°C)	Average Relative Humidity (%)	H _z . Solar Radiation Ave (Peak) (W/m ²)	Total Rainfall (mm)	Vapour Pressure Differential Ave (Max, Min) (Pa)
Nov 20 to Feb 19	91	-2.0 (14.9,-19.3)	78%	109 (672)	135.0	233 (674, -561)
Feb 19 to Apr 8	49	-1.1 (13.7, -13.1)	73%	220 (840)	41.6	364 (658, -256)
Apr 8 to Jun 3	55	12.1 (28.4, -3.4)	63%	298 (926)	173.4	32 (722, -1074)

4.2 Vertical temperature profiles

Data from the five central cavity OSB and framing T-sensors were compared to determine the vertical temperature profile of each test wall. Overall, the temperature differences between the lower and upper OSB sensors averaged 0.3-1.4 °C. The maximum daytime temperature differences ranged from 2.3°C on cloudy days to 12.1°C on sunny days for the south orientation. The maximum daytime temperature differences of the north-facing walls were between 2.1 to 3.9°C. The overnight temperature differences for both orientations were less than 0.5°C.

During the baseline period, the largest vertical temperature differences were observed in wall Types 1-4. The maximum temperature differences in these walls ranged from 7°C to 12°C in the south facing walls to between 3°C and 4°C for the north facing walls. Lower vertical temperature differences were observed in wall Types 5-7. Generally, the differences between the upper and lower sensors of the OSB were 2-5°C for the south walls and 2-3°C for the north. The top and bottom framing plates exhibited similar behaviour between the wall types. The exterior-insulated walls had lower temperature gradients between the upper and lower plates than the walls with un-insulated sheathing while the north-facing

Figure 4-1 Typical vertical OSB temperature profile for south facing wall Types 1-4 (S1 Data shown)

walls had lower vertical temperature gradients than the south walls and less variation between wall types.

The temperature gradients of the framing plates ranged between 8-15°C in walls S1-4 and 4 to 6°C in walls S5-7. Their vertical temperature gradients between the upper and lower plates of the north facing walls ranged between 2 to 4 °C in walls N1-7.

The graphs in Figure 4-1 and Figure 4-2 show the vertical OSB temperature profile in S1 and N1 during two clear sunny days separated by a cold, -15°C night (February 9-11, 2013). These data in these figures are representative of the walls without exterior insulation.

Figure 4-2 Typical vertical OSB temperature profile for north facing wall Types 1-3 (N1 Data shown)

Figure 4-3 Typical vertical OSB temperature profile for south facing wall Types 5-7 (S7 Data shown)

Further analysis of walls S1-4 showed that the middle and upper temperatures tracked closely together and, with the exception S3, the upper temperature was generally slightly higher. During periods of solar heating, the lower OSB T-sensor data were consistently cooler than the upper and middle data on the south orientation. In contrast, the lower OSB T-sensor data of walls N1-3 were consistently higher than the upper and middle T-sensor data. Reasons for these temperature differences include convection in the drainage space, mass effect of the ground, solar angle and albedo as well as wind effects.

Figure 4-3 and Figure 4-4 show the typical vertical OSB temperature profiles for exterior insulated walls during the same February time interval. These temperature data indicate that the exterior insulation resulted in a lower temperature gradient when compared to the datum wall since the exterior insulation

Figure 4-4 Typical vertical OSB temperature profile for the north facing wall Types 5-7 (N7 Data shown)

significantly reduced the daily temperature fluctuations of the OSB sheathing. For further comparisons between each wall type, the temperature profiles during this analysis period are presented in Appendix I along with the associated wind, temperature and solar radiation data. These vertical temperature profiles also illustrate the stabilizing effect of the exterior insulation on the temperature oscillations of the sheathing. This reduction in the severity of these daily temperature oscillations could enhance durability by minimizing the number of freezing cycles experienced by the OSB and hence, less stress on the glued strands as the adsorbed water vapour changes phase. This effect would be more pronounced at higher moisture contents with some critical moisture content above which damage is likely to occur.

4.2.1 Vertical temperature profiles - air injection test

The vertical temperature profiles of the OSB and plates were influenced by the heat associated with the injected air. This effect was most noticeable on the lower portion of the OSB and was quantified using the average value of the temperature differences between the upper (U) and lower (L) T-sensors for both the OSB and framing plates.

These data were compared between a pre-test period and the injection test interval. To reduce the effects of seasonal influences, the pre-test period immediately preceded the air injection test and was limited to 49 days (same duration as the injection test). The resulting data are expressed as temperature change in °C and summarized below in Table 4-2 for the OSB and Table 4-3 for the framing plates.

Table 4-2 OSB – Vertical ΔT (L- U) –average difference between air injection test and baseline (°C)

<i>S1</i>	<i>S2</i>	<i>S3</i>	<i>S4</i>	<i>S5</i>	<i>S6</i>	<i>S7</i>	<i>N1</i>	<i>N2</i>	<i>N3</i>	<i>N5</i>	<i>N6</i>	<i>N7</i>
0.7	0.4	1.5	0.3	1.9	2.0	1.9	0.3	0.1	1.5	1.9	2.1	2.2

Table 4-3 Plates – Vertical ΔT (L- U) –average difference between air injection test and baseline (°C)

<i>S1</i>	<i>S2</i>	<i>S3</i>	<i>S4</i>	<i>S5</i>	<i>S6</i>	<i>S7</i>	<i>N1</i>	<i>N2</i>	<i>N3</i>	<i>N5</i>	<i>N6</i>	<i>N7</i>
0.4	-0.2	1.0	0.1	1.1	1.1	0.1	0.1	-0.6	1.2	0.4	0.4	0.5

Since test panel S4 (ccSPF) was not included in the air injection test, its average vertical ΔT value represents the seasonal error associated with the temperature change estimations. The negative ΔT values for the plates of S2 and N2 indicate that the upper plates were warmer than the lower plates. These negative data coincide with the heavy (38x241mm) plates used in the Type 2 wall assembly.

To illustrate the effect of the injected air, Figure 4-5 is presented with the vertical ΔT -data of the north-facing assemblies. The upper data plot illustrates the vertical ΔT of the deep cavity walls relative to the

Figure 4-5 OSB vertical ΔT before and during air injection test

datum while the lower plot shows this temperature effect on the exterior-insulated walls. Figure 4-5 shows that the temperature effect of the air injection test was the highest on the walls with shallow stud cavities since there was less insulation between the air injection point and the sheathing. The stud cavity depths for wall Types 1 & 2 were 286 mm and 241 mm respectively as opposed to the 140 mm stud cavities of wall Types 3, and 5-7. These vertical temperature gradients were also affected by the path of the injected air within the cavity and the air tightness of the wall assembly.

Data plots of the vertical ΔT -data for OSB and plates of each wall are presented in Appendix J

4.3 Vertical moisture content profiles

The vertical moisture content profiles of each test assembly were assessed to determine the variation between the OSB MC-sensors and the framing plate MC-sensors. This analysis was performed using the baseline, air injection, and drying periods. Figure 4-6 presents the full term OSB MC-data for test walls N2, N3 and N7 while Figure 4-7 presents the full term framing plate data for test wall N2, N3 and N7. These data represent the vertical MC-data profiles of a cellulose-insulated, datum, and exterior insulated wall. The complete sets of OSB and framing plate MC-data are located in Appendix K.

The vertical moisture content distribution was quantified by calculating the average moisture content for each MC-sensor during the baseline, air injection and drying periods. The standard deviations were calculated for both the OSB (L, M, and U) and framing plate (B, T) datasets. These standard deviation data functioned as divergence indicators for the MC-sensor data. In addition, the average MC ranges for the OSB and plate sensors were determined along with the maximum MC for the OSB and plates during each analysis period. These data are presented in Table 4-4 for the baseline period, Table 4-5 for the air injection period and Table 4-6 for the drying period.

Figure 4-6 Vertical OSB MC-profiles for test walls N2, N3, and N7

Figure 4-7 Vertical framing plate MC-profiles for test walls N2, N3, and N7

4.3.1 Vertical moisture content profiles – baseline period

The framing and OSB MC-data varied less significantly on a daily basis than the temperature data. Three of the four cellulose-insulated test panels however, developed a 7-12% MC difference between the upper and lower sensors over the duration of the baseline analysis period (from Nov 20 to Feb 19). Table 4-4 contains the intra-sensor variation statistics for the baseline period. The red highlight indicates the most poorly performing walls, while the yellow highlight indicates a value moderately higher than the datum value. The green highlight indicates the lowest value for the category and best performance.

The standard deviation data indicate that the OSB MC-sensors generally varied within less than 0.5% MC during the baseline period. The largest standard deviations occurred in the walls S1 and N2 with 2.5% and 2.9% respectively. The plates also varied less than 1% for every wall except S1. Most walls experienced minor to negligible MC variations in between the assembly components during the baseline period.

Table 4-4 Moisture content variation statistics for the baseline period (MC %)

OSB	S1	S2	S3	S4	S5	S6	S7	N1	N2	N3	N5	N6	N7
Std. Dev.	2.5	0.2	0.0	0.1	0.4	0.3	0.0	0.7	2.9	0.2	0.3	0.2	0.0
Ave. Range	6.6	2.7	2.9	2.8	4.6	2.6	1.5	2.8	9.8	2.0	5.6	3.9	1.2
Max MC	17.3	8.8	8.5	8.6	11.7	9.9	7.4	8.6	21.1	8.9	12.7	11.5	7.5
Plates	S1	S2	S3	S4	S5	S6	S7	N1	N2	N3	N5	N6	N7
Std. Dev.	3.8	0.8	0.0	0.0	0.1	0.7	0.4	0.4	0.6	0.1	0.4	0.1	0.0
Ave. Range	8.1	4.8	3.8	2.5	3.2	2.5	1.8	7.7	8.8	2.5	3.2	3.0	1.5
Max Top Plate	24.3	16.9	12.1	12.5	13.2	13	11.4	19.7	21.4	12.5	14.4	14.0	11.1
Max Btm Plate	12.9	12.5	12.1	12.2	14.6	11	10.8	18.8	19.4	12.6	13.3	13.0	10.9

In terms of variability, the cellulose-insulated walls generally performed more poorly than the other wall types. The widest variability in the OSB MC data occurred in the north facing I-Joist wall (N2) and the south facing double stud wall (S1). The moisture content difference between the lower and upper sensors was 7-8% in both S1 and N2 during the final week of the baseline period. In addition, the MC differences between the upper and lower framing plates of walls N1, N2, and S2 were between 2-4% while the test wall S1 had a ~12% MC difference develop during the baseline period.

The OSB MC sensors of wall Types 5 and 6 showed slightly more MC-variation than the datum wall. These variation correlate to changes in the interior RH of the BEG Hut since the 6-mil polyethylene vapour barrier was not installed in the Type 5 and 6 walls. Moisture content variability was not observed in the either of the north or south-facing Type 7 walls.

The typical OSB moisture content variability for selected test walls is shown in the following figures from Figure 4-8 through Figure 4-11. Figure 4-8 shows the near-identical OSB MC profiles for the three OSB

Figure 4-8 OSB MC Profile of the south datum wall

Figure 4-9 Vertical OSB MC-profile of walls S5-7 - typical for both north and south orientations

MC sensors within the S3 Datum test panel. This moisture profile was also typical for the north and south orientations of wall Type 7 and the south orientation of wall Type 4.

Figure 4-9 shows the typical moisture content variability within wall Types 5-7 for both the north and south facing orientations. The three OSB MC-data plots of wall Type 7 (Bottom) were essentially identical while the OSB MC-data of S5 (Top) and S6 (Middle) demonstrated slight variations between the three OSB MC sensors. These slight variations of the vertical MC-profiles may have resulted from the absence of the 6-mil polyethylene vapour barrier.

Figure 4-10 Baseline OSB MC-profiles of I-Joist test wall N2 (Top) and S2 (Bottom)

Figure 4-10 presents the wide separation of the N2 OSB data in contrast to the tight correlation of the S2 OSB MC-data. This figure illustrates the difference between a 2.9% standard deviation in N2 and the 0.2% standard deviation in S2 as shown in Table 4-4.

Similar patterns were also observed in the Double Stud wall; however, the greatest separation of the OSB MC data occurred in the south facing wall, S1 as opposed to the north-facing wall. The OSB MC data for the Double Stud walls N1, S1 are shown in Figure 4-11.

Figure 4-10 and Figure 4-11 demonstrate that the variability in the OSB MC between the walls of Type 1 & 2 is not necessarily a direct result of orientation or wall type given the similar stratification observed in S1 and N2. The standard deviation data presented in Table 4-4 also indicate that this degree of moisture content stratification was not present in each of the walls that used exterior insulation or fiberglass insulation in the stud cavity. The ccSPF also had a uniform OSB MC distribution. In addition, the temperature data from the OSB and plate MC/T-sensors located in wall Types 1 & 2 indicated that these MC variations were not a result of vertical temperature differences.

Figure 4-11 Baseline OSB MC-profiles of the north (Top) and south (Bottom) Double Stud walls N1 and S1

Factors that may have influenced these variations are not limited to the following:

- Variations in the sorption isotherm of OSB
- Variations in OSB density
- Variations in cellulose density and its sorption isotherm
- Variations in the initial moisture content of the cellulose
- Electrical / conductivity effects of the fire retardant used on the cellulose

More RH/T sensors installed vertically within the cellulose cavity would assist in understanding the cause of these variations in the OSB MC-profile. The initial moisture content of the cellulose insulation should also be confirmed in future tests in order to rule out this factor out as a possibility. The relationship between OSB density and its sorption isotherm would also help to reduce uncertainty.

4.3.1.1 *Cellulose installation note*

The cellulose insulation used in these walls was recycled from a previous project and stored in large, vapour permeable bags. During long-term storage and prior to use, the lower portions of the bags were in contact with the cooler temperatures near the cement floor, which *may have* stratified in the moisture content of the cellulose within the bags.

The cellulose insulation was installed in the walls in the following order – S2, S1, N1, and N2. The lowest moisture content cellulose was in the top of the bag, which was installed in S2. The lower portion of that bag, with a higher moisture content level was then blown into S1 and wall N1 received the top of the next bag while N2 was filled with the remainder of the higher-MC cellulose that was closest to the floor at the bottom of the bag. This does not indicate the cause of the OSB MC variations in wall Types 1 & 2; it merely indicates a potential source of uncertainty and possible contributing factor.

Note: When these vertical MC profiles were first observed, the sensor wires and connections were tested and re-verified as well as the DAU programming to ensure that the datalogger had recorded the correct data from the intended sensor location – all connections were found to be correct.

4.3.2 Vertical moisture content profiles – air leakage test

The intra-sensor variation statistics for the air injection period are presented in Table 4-5. The red highlight indicates the most poorly performing walls, while the yellow highlight indicates a value moderately slightly at-risk or higher than the datum value. The green highlight indicates the lowest value for the category and best performance.

The vertical OSB MC profiles of the cellulose-insulated walls N1-2 and S2, as well as the north datum wall N3 were inverted during the air leakage test. The lower OSB MC data in these walls were consistently higher than the data collected from the middle and upper OSB MC sensors because of the proximity of these MC-sensors to the air injection point. In addition, the average values of the OSB MC-data collected in the south facing walls were lower than the data collected from the north facing walls, which indicates that solar heating was an important performance factor during this test. The vertical

Table 4-5 Moisture content variation statistics for the air injection period (MC %)

OSB	S1	S2	S3	S4	S5	S6	S7	N1	N2	N3	N5	N6	N7
Std. Dev.	0.9	2.2	0.8	0.1	1.2	1.0	0.5	3.7	2.2	4.0	1.1	2.0	1.0
Ave. Range	5.8	5.4	6.7	1.3	3.7	2.4	1.5	9.1	8.0	11.3	4.4	3.9	3.2
Max MC	16.7	19.0	15.6	8.2	12.3	10.9	9.0	31.4	27.8	29.3	13.0	15.6	12.5
Plates	S1	S2	S3	S4	S5	S6	S7	N1	N2	N3	N5	N6	N7
Std. Dev.	3.2	0.3	3.1	0.1	0.6	1.7	0.7	9.7	6.0	1.5	1.9	1.2	0.3
Ave. Range	13.8	5.9	10.0	1.6	4.7	2.7	3.1	17.1	12.0	9.0	7.1	4.6	3.2
Max Top Plate	23.8	17.7	16.3	12.3	17.0	16.0	14.4	19.9	22.1	18.5	22.5	18.2	13.6
Max Btm Plate	35.8	20.4	24.8	12.2	16.6	11.1	12.0	50.2	37.4	22.7	17.8	14.7	12.8

Figure 4-12 OSB MC-data for walls S1 and N2 during the air injection and drying periods

OSB MC profiles were also less well defined in the S1 and N2 walls as the injected air increased the moisture load within the cellulose insulation of the lower portion of the wall cavity (shown in Figure 4-12).

The MC-data (shown in Table 4-5) indicate that the largest increase in framing plate MC occurred in the north-facing cellulose-insulated walls. During the air injection period, the MC of the lower N2 plate rose to over 35% MC and the MC of the lower N1 plate increased to over 50%. The higher MC in the Double stud walls resulted from the thermal break between the two framing layers that isolated the exterior 38x140mm plate members. These plate data are presented in Appendix K.

The exterior-insulated walls performed well during the air injection test. In contrast to the cellulose-insulated and datum walls, the lower OSB MC-data were only slightly affected by the injected air since the exterior insulation of wall Types 5-7 maintained much higher OSB temperatures in the lower section of the cavity. In general, the middle and upper OSB sensors responded to the injected air with similar increases in moisture content.

The OSB MC of wall Types 5-7 indicated that the sheathing of these walls were safe during the air injection test. The plate data reveal, however, that the upper and lower plates of N5 did not perform as well since the peak MC readings of upper plate was 22.5% and the lower plate was 17.8%. The upper plate MC in N6 peaked at 18.2% during this test period. By comparison, the upper and lower plates in walls S7 and N7 remained below 15%. These plate data are presented in Figure 4-13.

Figure 4-13 Plate MC-data for walls N5-7 during the baseline, air injection and drying periods

4.3.3 Vertical moisture content profile – drying period

The intra-sensor variation statistics for the air injection period are presented in Table 4-6. The maximum moisture content data were replaced by the minimum or lowest moisture content recorded at the end of the drying period. The red highlight indicates the most poorly performing walls, while the yellow highlight indicates a value moderately slightly at-risk or higher than the datum value. The green highlight indicates the lowest value for the category and best performance.

The data in Table 4-6 show that the vertical OSB MC profiles of walls S1 and N2 converged to less than 1% standard deviation, which eliminated the wide vertical MC profile that existed during the baseline period (see Figure 4-12). In contrast, the vertical OSB MC profiles of test walls N1 and N3 increased after the air leakage test because of the interstitial condensation. The moisture content of the lower framing plates in walls N1-3 also remained elevated at the end of the drying period relative to the upper plate because of the extensive condensation that occurred during the air injection period.

The MC-data for test walls N1-2 are presented in Figure 4-14 to illustrate the extent of the wetting that occurred in during the air injection test.

Table 4-6 Moisture content variation statistics for the drying period (MC %)

OSB	S1	S2	S3	S4	S5	S6	S7	N1	N2	N3	N5	N6	N7
Std. Dev.	0.8	0.8	0.0	0.1	0.5	0.5	0.1	2.7	0.6	1.7	0.3	0.4	0.1
Ave. Range	5.0	3.2	2.7	1.8	1.7	1.4	1.1	1.8	10.9	4.7	2.3	1.8	1.2
Min MC	7.6	7.1	6.3	6.2	6.8	6.7	6.0	6.2	10.6	9.4	7.0	6.7	6.0
Plates	S1	S2	S3	S4	S5	S6	S7	N1	N2	N3	N5	N6	N7
Std. Dev.	0.9	0.1	0.8	0.1	0.8	0.9	0.6	8.6	4.8	3.0	0.5	0.2	0.2
Ave. Range	10.3	5.9	4.3	1.9	2.4	2.0	1.6	12.4	11.5	5.3	4.0	3.0	2.0
Min Top Plate	14.2	10.5	9.4	10.0	11.6	10.0	9.7	13.8	12.6	10.3	11.8	10.2	9.5
Min Btm Plate	12.6	10.7	10.2	10.0	10.2	8.9	8.9	24.3	18.2	15.6	11.2	10.3	9.3

The OSB and framing plate MC profiles in each of the south facing walls varied by less than 1% MC standard deviation. Both orientations of the exterior insulated walls performed well during the drying period and the Type 7 wall had the best overall performance.

Figure 4-14 Framing plate MC-data test walls N1 and N2

4.4 Condensation risk assessment

The water vapour pressure and condensation potential for each wall were determined using the RH and T sensor data from the main stud cavity. For OSB condensation, the saturation vapour pressure was

determined using the T sensor data associated with the OSB MC sensors and the relationship (ASHRAE, 2009):

$$P_{ws} = 611.2 \cdot e^{\left(\frac{17.67 \cdot t}{t + 243.5}\right)} \quad [21]$$

P_{ws} = saturation vapour pressure, Pa
 t = temperature, °C

To determine the water vapour partial pressure (P_w) for the air in the stud cavity, P_{ws} was calculated using Equation 21 and the temperature data from the RH/T sensor bundle located in the centre of the stud cavity as well as the relationship (ASHRAE, 2009):

$$RH = \frac{P_w}{P_{ws}} \quad [22]$$

The condensation potential of each wall was expressed as the hours where the RH at the sheathing was greater than 100%. The relationships in Equations 21 and 22 were also used to determine the vapour pressure drive between the interior and exterior air as well as between the stud cavity and drainage space.

4.4.1 *Condensation hours*

The number of condensation hours represents the time that the temperature of the interior side of the sheathing was below dew point or above 100% RH based on the hourly recorded sensor data. The condensation hours were determined for the middle OSB MC-sensor in-line with the RH/T bundle located mid-depth at the vertical centre of the stud cavity (J'-J in Figure 3-4). The condensation hours were also calculated for the remaining MC-sensor locations using the assumption that the RH-sensor data from the central stud cavity location was representative of the upper and lower reaches of the cavity. The vertical MC-profiles examined in Section 4.3 suggested that this assumption was valid for wall Types 3-7 but was subject to uncertainty in wall Types 1-2. This uncertainty arises from hygroscopic nature of the cellulose and the potential for variable cellulose moisture contents within the stud cavity. In addition, this uncertainty will tend to bias the condensation results lower for the upper OSB and plate locations and higher for the lower OSB and plate locations given the tendency of moisture content to increase with height within the Type 1 and 2 walls.

The baseline period for this assessment began on November 20, 2012 after the installation of the spray foam insulation in S4. The column charts presented in Figure 4-15 show the calculated condensation

hours for each MC/T sensor location. These data were separated into the baseline, air injection and drying periods. The number of condensation hours that occurred in the Type 1 and 2 cellulose-insulated walls were consistently higher than the condensation that occurred in the remaining wall types.

Further, the Type 1 Double Stud wall plates were subjected to the most condensation hours since these framing members were thermally broken by the 57 mm space between the 89 mm and 140 mm frames. The upper framing plates and OSB MC-data of the north-facing wall Types 2-5 had more condensation hours during the air injection test than the lower wall components. The cellulose-insulated walls were also the only walls to experience condensation hours during the drying period.

Figure 4-15 Condensation hours calculated for the baseline (Top), air injection (Middle) and drying (Bottom) periods

4.5 *Mould and decay analysis*

High humidity levels and condensation within wall assemblies promotes the growth of mould on wood-based components. As the moisture content of wood-based materials increases above the fibre saturation point, the potential for wood decay increases. The risk analysis parameters for the growth of mould and onset of decay that were determined from the literature review in Section 2.9.1 are the total number of hours the assembly exceeds the following criteria:

1. The onset of mould growth at 16 % MC and the minimum temperature for mould growth (5°C)
2. The fast growth of mould at 20% MC and 10° C,
3. The onset of decay as MC rises above 28% until the MC falls below 20% MC
 - i. Onset of decay using 99 % RH and 10°C (for comparison)

The analysis period for mould growth and decay began on November 20, 2013 after the spray foam was installed and ended on June 3, 2013. The results for the first risk parameter were determined using the baseline, air injection, and drying periods to better illustrate the origin of mould growth risk. The at-risk hours were calculated at each main cavity MC/T sensor for the OSB and framing.

4.5.1 *Onset of mould – slow growth assessment*

The results of the first risk parameter for the onset of mould growth are presented in Figure 4-16. The data are separated into the baseline, air injection and drying periods within the figure. Figure 4-16 (Top) shows that the top plate of the south facing Double Stud wall S1 was at-risk of mould growth for approximately 460 hours. The remaining south facing walls had little to no risk of mould growth during the baseline period. This figure also indicates that within walls N1 and N2, the top and bottom plates also had a risk of mould growth in the range of 125 to 365 hours. In addition, the upper OSB sensor location in N2 had 264 risk hours, which coincides with the elevated MC-data observed in Figure 4-10 (Top). The moisture content levels within the remaining North-facing walls N3 through N7 were maintained below the 16% MC threshold and no mould growth risk was observed.

The mould risk for the air injection period is shown in Figure 4-16 (Middle). The mould growth risk was most apparent in the test walls S1-3 with the plates being most at-risk. The lower plate of the datum wall S3, was the most at-risk with 626 hours. The upper plate of the exterior insulated wall S5 (polyisocyanurate) had 175 risk hours, while the other two exterior insulated walls S6 and S7 did not have any at-risk hours.

Figure 4-16 Onset of mould growth during the baseline (Top), air injection (Middle) and drying (Bottom) periods (MC>16%, T>5°C)

The effects of the injected air were most noticeable in the north-facing walls. The injected air affected the OSB and plates of both wall Types 1 & 2 as well as the datum wall. The lower framing plate and lower OSB within the datum wall N3 had the highest risk hours of these component in all of the north facing walls with 514 and 401 risk hours, respectively. The risk hours for the Type 1 & 2 walls were evenly distributed throughout these walls, which averaged approximately 200 hours at each MC-sensor location. The most dramatic effect of the air leakage was observed in the upper framing plate of wall N5 with 783 at-risk hours. Wall N6 had 331 risk hours in its upper framing plate while sensor locations within test wall N7 remained below the mould growth criteria.

Figure 4-16 (Bottom) shows the mould growth risks associated with the drying period. This figure indicates that the upper and lower plates of the S1 test wall were the only south facing wall components at-risk during this period. The lower plates of the north-facing walls N1-3 were significantly at-risk of decay with between 1117 and 1204 risk hours in these components. This increase in decay risk is associated with residual moisture from the air leakage test and higher springtime temperatures. The upper plate of N5 was the only component of the north facing exterior insulated walls to have at-risk hours during this period.

4.5.2 Fast mould growth assessment

The second parameter for mould growth assessed the risk of fast growing mould within the wall assemblies. This analysis compiled the number of hours that each MC/T sensor location was exposed to 20% MC or higher with temperatures above 10°C. The assessment results presented in Figure 4-17 represent the combined at-risk hours accumulated during the baseline, air injection test, and drying periods.

The data presented in Figure 4-17 show that only south facing wall components at-risk of faster mould

Figure 4-17 Fast growth mould risk - total hours over study period (MC>20%, T>10°C)

growth were the upper and lower plates of S1 with an average of 290 hours. The lower plate in S3 only registered 90 at-risk hours.

The north-facing test wall components to accumulate the most at-risk with the fast mould growth criteria were the bottom plates of N1 and N2. These components had significantly more risk hours than any other component in the test with an average of 820 risk hours each. By comparison, the lower plate of the datum wall N3 had 178 hours. The lower OSB of walls N1 and N2 both had less than 100 risk hours during the course of the study period.

4.5.3 Decay assessment

The third parameter for fungal growth assessed the level of risk associated with the onset of decay. This analysis compiled the number of hours that each MC/T sensor location was exposed to RH greater than 99% and temperatures above 10°C. The results of this assessment are presented in Figure 4-18. These results indicate the combined at-risk hours above 99% RH accumulated during the baseline, air injection test, and drying periods for each of the test walls.

Figure 4-18 Decay risk assessment in OSB (RH>99%, T>10°C)

The south facing walls were the least at-risk of decay as walls S4 to S7 did not have any hours at 99% RH and walls S1, S2, and S3 had negligible exposure to 99% RH. Since decay remains active until the moisture content returns below 20% – after exceeding the 28% MC threshold (2009 ASHRAE) – the MC data were investigated further for a better estimation of the at-risk time for each wall. This assessment used the cumulative hours between the onset of decay at 28% MC and the suspension of active decay below 20% MC. The results of this further assessment are located in Figure 4-19 and they indicate that the lower OSB was at risk of decay in walls N1, N2, and N3, while the lower plates in S1, N1, and N2 had significant decay risk.

Figure 4-19 Decay risk from MC data (28% drying to 20%)

The worst performing wall plates were the lower framing of N1 and N2. These walls each had over 2200 hours at risk of decay and the moisture content of the N1 lower plate was still well above 20% MC at the end of the drying period. The N1 lower plate was still hovering around 20% MC on July 24th, 2013. In comparison, the lower plate of south facing Double Stud wall (S1) had 1327 at-risk hours. The moisture content of the S1 lower plate had dried below 20% MC by April 30th, 2013.

The moisture content versus time charts for the lower plates of wall Types 1-3 are presented in Figure 4-20 (North) and Figure 4-21 (South). These figures illustrate the relative decay risk before, during and after the air injection test. The highest MC reached by any sensor in the study occurred in the N1 lower plate where it rose to ~50%. The N1 wall had over 2000 hours above the 28% MC threshold. The

Figure 4-20 Lower plate moisture content in walls N1, N2 and N3 (datum) from Jan1 to June 15, 2013

Figure 4-21 Lower plate moisture content in walls S1, S2 and S3 (datum) from Jan1 to June 15, 2013

accuracy of the electric moisture sensors degrades above the FSP, which results in greater uncertainty in the absolute value of measurements above 30% MC point

Figure 4-21 shows that the moisture content of the S1 and S2 lower plates were similar to the lower plate moisture content in the datum wall (S3) prior to the air injection test. In comparison, the lower

plate moisture contents of N1 and N2 were elevated by about 6-8% relative to the datum. The lower plate MC-data of N1 and N2 presented in Figure 4-20 show that these walls were susceptible to mould damage prior to the air injection test. The lower plate in wall N2 finally dried below 20% MC in mid-June (2013) and returned to its pre-test moisture content. The excessive wetting of the lower plates was a direct result of the condensation that drained from the OSB during the air injection test. The risk of decay in the OSB was confined to the lower MC/T sensor location in walls N1, N2, and N3.

A comparison of lower OSB MC for walls N1-3 is presented in Figure 4-22. The lower OSB MC in N3 reached the 28% MC threshold first during the air injection test but was able to quickly dry below 20% MC. Since the cellulose insulation buffered the moisture load of the air injection test, it delayed the moisture content increase of the OSB sheathing (N1 and N2). However, the cellulose also inhibited drying since its adsorbed water supplied moisture to the OSB after the air injection test was concluded, which prolonged the drying time required to lower the N1 and N2 lower OSB MC below 20%. The three wetting cycles visible in the N3 profile are associated with cold weather and warming trends.

Figure 4-22 Comparison of lower OSB MC-responses in north walls N1-3

4.6 *Water vapour drive*

The difference in the partial pressures of water vapour across an assembly determines the wetting and drying potential of a wall. The water vapour gradient across the wall determines the direction and rate of flow while the temperature regime determines whether wetting or drying will occur. The factors that influence the direction and magnitude of vapour drives are the structure's orientation to wind driven rain and direct heating by the sun, the water absorption, water vapour permeability and storage capacity of its components as well as the amount of ventilation available to remove moisture from drainage spaces.

The RH/T sensor data and Equations 21 & 22 were used to calculate the partial water vapour pressures (VP) of the main stud cavity and drainage space. These data determined the vapour pressure differential across the OSB and in the case of wall Types 5-7, the exterior insulation as well. These partial pressure differentials were normalized using the distance between the RH/T sensor bundles, which resulted in a pressure gradient that could be used to gauge performance between the different wall types. The VP gradient was calculated by subtracting the exterior VP from the interior VP, thus a positive VP represents outward moisture flow (drying).

The following two sets of charts presented in Figure 4-23 and Figure 4-24 compare the differences between the north and south vapour drives and its effect on the OSB MC of wall Types 1, 3, and 7 on October 25 & 26, 2012. The selected wall types illustrate the performance differences between a deep cavity cellulose wall, the datum wall, and an exterior insulated wall. Wall Type 7 was chosen for comparison as its vapour control system uses 6-mil polyethylene vapour barrier. Figure 4-23 shows the effect of a sunny day on the vapour drive in walls S1 and N1. The initial inward vapour drive (-ve) was most pronounced on the south facing wall, however, this initial inward vapour drive reversed in the afternoon.

Figure 4-23 Comparison of VP gradient and OSB MC for N1 (Top) and S1 (Bottom)

Figure 4-24 VP Gradient and OSB MC Comparison for N3 and S3 (top set); N7 and S7 (bottom set)

The VP and OSB MC profiles for the datum walls are presented the top two charts of Figure 4-24. The datum walls had steeper VP gradients than their Type 1 counterparts did. The daily solar radiation had an increased effect on the OSB in the datum wall since the OSB MC was not buffered by the hygroscopic cellulose within the stud cavity. This effect was observed as a slight drop in the north OSB MC and a much larger decrease in the south OSB MC. The range of the VP gradient was also much higher in the datum walls than in the double stud walls. The inward VP dissipated quickly in the south-facing datum as the exterior drainage cavity was well ventilated with the exterior air. In addition, the siding did not have significant moisture storage that would have otherwise maintained a higher VP in the exterior cavity.

The lower two plots in Figure 4-24 shows the VP and OSB MC profiles for the north and south facing Type 7 exterior insulated walls. The north facing OSB MC only had a slight decrease because of daytime heating while the changes in the south-facing OSB MC were also quite muted in comparison with the datum wall. The overall range of the south facing VP drive was much less than either the datum or the double stud walls.

4.7 Inter-wall moisture content analysis

The inter-wall moisture content analysis was performed using the middle OSB MC-datasets from each test wall. The following series of MC-data comparisons show the performance of the various high RSI value walls with respect to the datum wall based on the construction type (deep cavity or exterior insulated) and orientation. The baseline analysis period for these plots was from Nov 20, 2012 to Feb 19, 2013. This time interval spans from when the S4 insulation was installed to the day that the air injection test started. The exterior temperature for each analysis period was added to the charts with an inverted scale to demonstrate the inverse relationship between temperature and moisture content.

4.7.1 Baseline period

Figure 4-25 compares the OSB MC-data of the deep cavity walls with the datum wall on both orientations. The top chart illustrates the performance of the north facing Double Stud (N1) and I-Joist (N2) stud walls with the north-facing datum (N3). The lower plot shows the performance of the south-facing deep cavity walls with the south datum.

The south facing walls had better moisture performance with the exception of the S1. While S2, S3 and S4 had low OSB MC-values in the 7-8% range and responded in unison to climatic loading, the OSB MC of the south Double Stud wall ranged between 12 and 13% MC over the latter half of the analysis period.

Figure 4-25 Baseline comparison of deep-cavity OSB MC-data – {N1-3 (Top) and S1-4 (Bottom)}

This variability in OSB moisture content as a function of cellulose moisture storage was discussed previously in Section 4.3).

The north facing deep cavity walls, N1 and N2 performed similarly, as the average OSB MC-values increased to between 13 and 17 % towards the end of the baseline period. The north-facing walls N1 and N2 were already at risk of mold growth prior to the air injection test with MC values approaching or exceeding the lower 16% MC threshold for mould growth (as discussed in Section 4.5).

Figure 4-26 compares the OSB MC-data from the north and south exterior-insulated walls with their respective datum walls. These performed well on both orientations but the MC-data were less distributed in the south walls than in the north facing walls. Wall Type 7 performed the best on both orientations as N7 and S7 maintained the lowest OSB MC throughout the baseline period.

The OSB MC-data of the polyisocyanurate and XPS insulated walls showed a minor increase towards the end of the baseline period as the humidifier in the BEG Hut was serviced in mid-January. The interior RH had slowly decreased to the mid-20% RH range over the course of two months. Upon servicing, the interior RH was re-established to ~40% RH prior to the air injection test. Since wall Types 5 and 6 did not

Figure 4-26 Baseline comparison of exterior-insulated OSB MC-data – {N5-7 (Top) and S5-7 (Bottom)}

use the 6-mil polyethylene vapour barrier, these walls responded quickly to changes in the interior relative humidity. The highest MC-data response was observed in the north walls N5 and N6 with data peaks at ~ 11% MC.

4.7.2 Air injection test period

Figure 4-27 compares the OSB MC-data from the deep cavity walls and their respective datum walls during the constant-rate air-injection test. The OSB MC-response to the air injection test was larger in the north walls than the south walls. The north datum wall (N3) clearly shows three distinct cooling trends that elevated the N3 OSB MC-data that were less apparent in the OSB MC-data of the south datum wall (S3).

The OSB MC-data of the north-facing cellulose-insulated walls (N1-2) continually increased throughout the air injection test, while the datum wall N3 had three well-defined drying intervals during the same period that were directly related to exterior temperature. This performance difference resulted from the increased moisture storage capacity of the cellulose insulation and its buffering effect on the OSB. The moisture storage of the N3 stud cavity was composed of fibreglass insulation, air and the moisture

Figure 4-27 Air-injection comparison of deep-cavity OSB MC-data – {N1-3 (Top) and S1-4 (Bottom)}

storage of the framing. In contrast, the moisture storage within deep stud cavities of walls N1 and N2 was composed of the cellulose insulation and its adsorbed moisture, air, and the moisture buffering of the framing. In addition, the cavity volumes were significantly greater in walls N1 and N2 because of wall thickness.

The OSB MC of N1 and N2 averaged 20% MC at the end of the test while the OSB MC of the datum wall was less than 15% MC. The OSB MC-values of S1 and S2 were lower overall than the north walls and as expected, the lowest and most consistent OSB MC values were located in S4, which was excluded from the air injection test. The highest measurements of the OSB MC in walls S3 and S1 were between 12% and 13% MC. The south datum wall was also faster to dry than S1 and finished the test interval with 9% OSB MC compared to 13% MC in wall S1. The lower initial cellulose moisture content in the I Joist test wall S2 led to better moisture performance for this wall. The S2 OSB MC peaked at ~11% and finished the test period with roughly 9% OSB MC.

The OSB MC data for the exterior insulated walls are presented in Figure 4-28. These data indicated that all three exterior insulated walls (Types 5-7) outperformed the datum wall (on both orientations). The

Figure 4-28 Air injection comparison of exterior-insulated OSB MC-data – {N5-7 (Top) and S5-7 (Bottom)}

north-facing XPS wall (N6) had the highest OSB MC with peaks in the 15% MC range. The peak OSB MC in walls N5 and N7 was generally less than 13%. Walls N5 and N6 ended the test interval with OSB MCs of 10% while wall N7 had the lowest OSB MC at less than 8 %.

Each of the south-facing test walls S5, S6 and S7 also outperformed their associated datum wall during the air injection test. Additionally, the data indicated that the exterior insulated wall S7 was essentially unaffected by the air-injection test at the middle OSB sensor location. The S7 OSB MC-data fluctuated within a narrow 0.5% MC range as shown in the bottom chart of Figure 4-28. The OSB MC-data of S5 and S6 fluctuated between 8 and 12% throughout the test.

4.7.3 Drying period

The drying curves shown in Figure 4-29 illustrate the performance of the deep cavity walls on both the north and south orientations. These drying trends were closely related to the rising exterior temperature during the drying period. The performance of the north-facing Double stud wall N1 was comparable to the datum wall N3 as both walls dried below 9% by the end of the drying period. The north-facing I Joist wall N2 only dried as low as 11% because of the large amount of moisture stored in

Figure 4-29 Drying comparison of deep-cavity OSB MC-data – {N1-3 (Top) and S1-4 (Bottom)}

the cellulose-insulation within its stud cavity. The lower sections of the N1 and N2 test walls performed much more poorly than the middle and upper sections during the air injection test and this intra-wall variability was discussed previously in Section 4.3.

The south-facing deep cavity walls started drying from a lower OSB MC than the north deep cavity walls so the south walls were able to dry below 9% relatively quickly. The lower chart in Figure 4-29 shows that the S4 OSB MC remained below 8% for the duration of the drying period. Since the S2, S3 and S4 walls performed similarly during the baseline period (Figure 4-25) and S4 was excluded from the air injection test, the S4 OSB MC-data serves as a performance target for these two walls. The OSB MC-data show that both S2 and S3 dried as low as S4 after 4-5 weeks of drying with the S2 OSB MC-data slightly elevated with respect to S4 (as it was during the baseline period).

The OSB MC-data for the exterior insulated walls are presented in Figure 4-30. These data indicate that the north walls N5-7 outperformed the north datum wall while the only south wall to outperform the datum S3 was the test wall insulated with exterior mineral wool – S7. The Type 7 walls consistently had

Figure 4-30 OSB MC Comparison of north and south exterior insulation walls (Types 5-7) – Drying period

the lowest moisture contents of the walls throughout the study period and had the least variation between orientations. Test walls S5 and S6 dried at approximately the same rate as the south datum.

4.8 Thermal analysis and heat flux sensor data

The centre-of-cavity (C-o-C) and centre-of-stud (C-o-S) thermal resistances of each wall assembly were calculated using the material properties shown in Table 4-8. These RSI-values were compared with the heat flux data as well as to determine the Clear-wall RSI value for each wall. As defined in Christian and Kosny (1995), the C-o-C RSI-value defines a line through the centre of an assembly's stud cavity of an assembly and Clear-wall RSI contains the minimum amount of framing and does not account for windows, wall and floor intersections, corners or other thermal bridging details that reduce the overall RSI-value of the assembly. For the comparison purposes confined to this thesis, the Clear-wall RSI-value was sufficient for a rough comparison between wall types. However, it should be noted that more detailed (and realistic) analyses exist (Straube and Smegal, 2009) to determine the True RSI-value of building assemblies that account for specific framing issues associated with each wall assembly.

Table 4-7 Material properties for thermal resistance calculations

Material	Thermal Conductivity W /m ² · K	Source
Cellulose	0.042	ASHRAE, 2009
Oriented Strand Board	0.11	ASHRAE, 2009
Spruce	0.09	ASHRAE, 2009
Spray foam (ccSPF)	0.024	Straube, 2012
Fibreglass	0.036	Owens Corning Datasheet
Mineral wool	0.0361	Roxul Product Datasheet
Polyisocyanurate	0.0231	Enerfoil IKO Datasheet
Extruded polystyrene (XPS)	0.0288	Owens Corning Datasheet
Interior air film	8.33	(Hutcheon and Handegord, 1983)
Exterior air film	34.0	(Hutcheon and Handegord, 1983)
20 mm air layer	0.13	(WUFI®, 2012)

Table 4-8 contains a summary of the calculated C-o-C and C-o-S thermal resistances and their corresponding U-values for each wall assembly. The Installed RSI-values are also listed in the table along with the wall thickness in metric and imperial. (*THERM was used to determine the Centre of Stud U-value and RSI-value for the I-Joist stud because of the stud's geometry.)

Table 4-8 Thermal resistance data with U-Values (cavity and stud) for Clear Wall RSI calculation

Wall Type	Wall Thickness		Installed RSI	C-o-C Cavity RSI	C-o-S Stud RSI	U-Value Cavity	U-Value Stud
	(m)	(Inch)	m ² · K / W	m ² · K / W		W / m ² · K	
Type 1 - Double Stud	0.34	13.38	6.8	7.5	4.6	0.134	0.216
Type 2 - I-Joist	0.29	11.63	5.8	6.4	4.7*	0.156	0.213
Type 3 - Datum	0.19	7.63	3.9	4.4	2.2	0.227	0.464
Type 4 - ccSPF	0.24	9.38	6.4	7.0	2.7	0.142	0.377
Type 5 -Polyiso	0.24	9.63	6.1	6.6	4.3	0.152	0.230
Type 6 - XPS	0.26	10.13	6.1	6.6	4.4	0.151	0.229
Type 7 -Min. Wool	0.27	10.63	6.0	6.5	4.3	0.154	0.234

The additional wall components (OSB, air films, air layers, siding and drywall) increased the RSI value of each assembly by 0.5 to 0.7 RSI. The RSI for the cavity and the stud sections include the interior and exterior surface coefficients as well as the air layer in the drainage space. The interior strapping air layer was also included for wall Types 1 and 2 as a weighted areal average of the air layer and the strapping.

The Clear-wall RSI-values for each test assembly were determined to illustrate the effect of framing factor (FF). Residential housing have varied FFs due to construction practices and can have average FFs of 25% in non-seismic areas with the FFs multi-storey buildings trending higher because of additional framing support (Carpenter and Schumacher, 2003). An additional study by Qasass et al. (In-press) of

detached, semi-detached and townhouses under construction in the Greater Toronto Area indicated the average FFs could be as high as 31 to 39%. Comparatively, the FF recommended by ASHRAE (2013) is 25% and 19% by the National Energy Code of Canada (NECB, 2011). Clear-wall RSI values were calculated for the High RSI test assemblies using FFs of 19%, 25% and 30%. These data are presented in Table 4-9.

Table 4-9 Test wall RSI and U Values using 19%, 25% and 30% framing factors

Wall Type	RSI 19% FF	RSI 25% FF	RSI 30% FF	U-Value 19% FF	U-Value 25% FF	U-Value 30% FF
	m ² · K / W			W / m ² · K		
Type 1 - Double Stud	6.7	6.5	6.3	0.150	0.155	0.159
Type 2 - I-Joist	6.0	5.9	5.8	0.167	0.170	0.173
Type 3 - Datum	3.7	3.5	3.4	0.272	0.287	0.298
Type 4 - ccSPF	5.4	5.0	4.7	0.187	0.201	0.213
Type 5 - Polyiso	6.0	5.8	5.7	0.167	0.172	0.176
Type 6 - XPS	6.0	5.9	5.7	0.166	0.171	0.175
Type 7 - Min. Wool	5.9	5.8	5.6	0.169	0.174	0.178

All of these calculated RSI-values would be reduced by analysis that is more detailed. Some walls may be disproportionately affected as building features like window openings and floor connections are considered. The externally insulated walls have the added benefit of providing a more uniform insulation layer across floor and wall connections, which will help these walls to maintain higher True RSI-values in comparison with the deep cavity walls.

4.8.1 Heat flux data analysis

The cavity and stud HF sensors were installed in the inboard side of the drywall in walls S2, S3, S4 and S5. These cavity HF sensor was installed mid-height and along the vertical centreline to minimize the thermal influence of the framing members. The stud HF sensors were placed in a shallow 3mm notch to allow them to lie flush with the face of the stud. The stud HF sensors were selected by size for the framing member to minimize the thermal influences of the cavity. Since the thermal conductivity of the stud section was higher than the cavity section, a separate temperature sensor was also installed on the interior surface of S2, S3, S4 and S5 in-line with the stud HF sensor to provide more accurate temperature data for the U-value calculations.

The HF sensor data were used to calculate the cavity and stud U Factors for test panels S2, S3, S4 and S5 using the following equation for steady state conditions (Hutcheon and Handegord, 1983):

$$U_{\text{cavity}} = \frac{Q_{\text{cavity}}}{T_i - T_o} \quad [22]$$

$$U_{\text{framing}} = \frac{Q_{\text{framing}}}{T_i - T_o} \quad [23]$$

U_{cavity} = the U Factor of the test panel through the wall cavity, W/m²K

U_{framing} = the U Factor of the test panel through the wall stud, W/m²K

Q_{cavity} = the heat flux through the test panel cavity, W/m²

Q_{framing} = the heat flux through the test panel stud member, W/m²

T_i = the indoor surface temperature, K

T_o = the outdoor surface temperature, K

The HF sensors were installed on the south facing walls and were considerably affected by solar radiation. The HF-data collected during cloudy periods with lower solar radiation and similar daytime / nighttime temperatures were used to determine the U-value of each wall as the heat flux was most steady during these conditions. Visual inspection of the HF-data was used to determine the intervals that provided these steady conditions for U-value calculations.

Four time intervals were selected when the temperatures across the test assemblies were the most stable. Three of these time intervals occurred during the baseline period in October, December, and January. One interval occurred during the drying period in mid-April.

The data collected during the air injection test was not reliable for the U-value calculations as the heat flux was influenced by the heat of the injected air. The periods selected for the heat flux analysis and their average ambient temperatures are as follows:

- Oct 26 to Nov 8, 2012 (Ambient Temperature: 3.9°C)
- Dec 20 to 27, 2012 (Ambient Temperature: -1.8°C)
- Jan 21 to 25, 2013 (Ambient Temperature: -14.2°C)
- Apr 9 to 14, 2013 (Ambient Temperature: 0.8°C)

The heat flux data collected during the Apr 8 to 16, 2013 are presented in Figure 4-31. These data illustrate the differences between the heat flux through the cavity (Top) and the stud (Bottom). The daily solar radiation was included to demonstrate the influence of the sun on the heat flux through these walls. The heat flux data between April 10th and 14th were used to calculate the U-values presented in Table 4-10 since these data were relatively steady over this period because of the low solar

radiation. Although the cavity data were stable, the stud data were much less steady because of the higher thermal conductivity through the stud section. As expected, the heat flux data from the datum wall S3 was the most variable.

Figure 4-31 Apr 8-16, 2013 HF-data for walls S2, S3, S4 and S5 – cavity data (Top) and stud data (Bottom)

Table 4-10 compares the U-values determined from the material properties with the HF sensor data collected from test walls S2, S3, S4 and S5 during the four analysis periods. The material property U-value for the S2 (*) stud was determined using a THERM simulation to account for the geometry of the I-Joist and size of the HF sensor. The HF sensor data collected during the April 9th to 14th period were used for the calculated stud U-values because data from the additional stud T sensors were available for this period.

The percentage difference between the two U-value estimations indicates that the poorest agreement occurred with test panel S4. The extremely low U-value in the earliest data suggested that there was a problem with the location of the sensor – this led to the re-installation of the sensor on the back of the drywall to ensure good contact. The subsequent data however, still indicate that the heat flux was substantially lower than expected. This deviation from the predicted value may be a result of convection

within the air space between the foam and the drywall since the spray foam did not completely fill the stud cavity.

Table 4-10 U-Value comparison - Material properties and HF Sensor data for walls S2, S3, S4 and S5

Wall ID	U-Value (Material properties) (W / m ² · K)		U-Value (HF Sensor data) (W / m ² · K)		Percentage Difference	
	Cavity	Stud	Cavity	Stud	Cavity	Stud
S2	0.156	0.213	0.138	0.257	10.5%	-20.8 %
S3	0.227	0.464	0.212	0.439	6.8%	5.3 %
S4	0.142	0.377	0.093	0.257	34.5 %	31.9 %
S5	0.152	0.230	0.134	0.267	11.8 %	-15.9 %

The U-values calculated using the sensor data in S2 may also have been influenced by convection within the air layer created by the interior strapping that was used to hold the air permeable membrane in place (Figure 3-6). Any convection within the interior S2 air layer however, would have been limited by the horizontal strapping placed at 0.4 m vertical intervals as opposed the vertical air space in S4 that spanned the height of the cavity. This restricted convection within the interior air layer may have

Figure 4-32 Comparison of calculated U-values for walls S2 and S3 - cavity (Top) and stud (Bottom)

Figure 4-33 Comparison of calculated U-values for walls S4 and S3 – cavity (Top) and stud (Bottom)

contributed to the lower error for the S2 U-value calculations.

The calculated stud and cavity U-values for S2, S4 and S5 are presented in Figure 4-32, Figure 4-33, and Figure 4-34. The S3 HF data is included in each figure for comparison. These U-values were determined from data averages calculated from a time subset within each analysis interval as shown by the vertical lines in Figure 4-31 (Apr 10th to 14th). This smaller subset interval was used to filter the extreme highs and lows of the calculated U-values. The data averages for each wall (stud and cavity) were calculated using the same time subset and these subset averages are included with the U-value curves as straight-dashed lines to indicate the degree of fit with the calculated U-values as well as visually represent the error associated with this type of analysis. The continuous U-value data are represented by the solid-line curves.

The U-value data shown in Figure 4-32 compare the thermal performance of the S2 I-Joist wall and the S3 datum wall from April 10th to 14th, 2013 during near steady state conditions. The S2 cavity data shows that while the calculated S2 cavity U-value was lower than the calculated U-value for S3, the S2 cavity U-

Figure 4-34 Comparison of calculated U-values for walls S5 and S3 – cavity (Top) and stud (Bottom)

value was slightly more variable on April 12th and 13th. This increased variability possibly arose from the higher moisture content of the cellulose insulation in S2 relative to the cavity insulation of S3. The higher outward heat flux between April 14th and 15th coincided with condensation at the middle OSB MC-sensor location in S2. The data do not indicate any condensation in the datum wall S3 during this analysis period. The heat flux through the S2 cavity implies a thermal conductivity of the dense pack cellulose of approximately 0.039 W/ m K as opposed to the value of 0.042 W/m K used in the material property calculations. Further, this suggests that the I-Joist wall cavity had a thermal resistance of 6.8 RSI rather than the 6.4 RSI calculated using for the higher thermal conductivity. A thermal conductivity of 0.039 W/ m K for the cellulose insulation falls at the bottom end of the range cited in ASHRAE (2009) of 0.039 to 0.045 W/ m K for cellulose packed between 35 and 50 kg/m³. The thermal conductivity of cellulose also varies with temperature, which may have affected these results.

The calculated U-values shown in Figure 4-33 compare the thermal performance of the S4 ccSPF wall with the S3 datum from April 9th to 14th, 2013. The S4 cavity heat flux was very stable during this period, which allowed for a relatively precise estimation of the U-value. However, this extremely low U-value

indicated that the data were most likely compromised by the air layer between the foam insulation and the drywall. This calculated U-value implied a thermal conductivity of approximately 0.015 W/ m·K as opposed to the 0.024 W/m K used in the material property calculations. This value is too low to be valid.

The calculated U-value data shown in Figure 4-34 compare the thermal performance of the S5 polyisocyanurate wall with the S3 datum during the April 9th to 14th, 2013 time interval. The S5 cavity and stud heat flux were both relatively stable during this period, which allowed for a reasonable estimation of the S5 U-values. As shown in Table 4-10, the S5 cavity U-value had an error only 7% while the stud U-value had a 16% error.

The errors associated with the stud U-values were larger because of the higher heat flux through the framing portions of the test panels and the influence of the adjoining cavity insulation. Placing the sensors on the north facing exposures would minimize the higher heat fluxes arising from solar gains and would produce more stable heat flux data.

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5 HYGROTHERMAL MODELING

Hygrothermal simulations of the High RSI test walls were created to examine the interactions between climatic conditions, material properties, electrical sensor measurement, and the impact of simulated air leakage. The computer program WUFI® Pro 5.2 was used to create simulation models for the exterior insulated and deep-cavity cellulose insulation High RSI walls as well as the datum walls. The simulation models were calibrated using the measured data recorded between October 4, 2012 and June 3, 2013. During the calibration process, seasonal variations of the surface heat-transfer coefficients were investigated and their effects on the temperature and relative humidity regimes within the assembly were examined. The simulation models used in this study were configured with multiple layers within the OSB sheathing, cavity insulation and the exterior drainage space to facilitate the investigation.

The aim of this study was to explore the key parameters that influenced the moisture transport through the High RSI wall assemblies and create reliable simulation models that could be used to study the performance of these walls using a variety of climatic conditions. The calibration process was primarily concerned with the surface transfer coefficients that control the interactions between the simulation model and the boundary conditions. These surface transfer coefficients are:

- Short wave absorptivity – α
- Ground short-wave reflectivity or albedo (GSWR)
- Cloud index (CI)
- Surface film heat resistances (convective and radiative heat exchange)
 - Wind effects

The heat and moisture transport through the wall assemblies was also determined by the material properties of the various wall components. The thermal conductivity and water vapour permeability had significant influences on the rates that heat and moisture flowed through the assembly; however, the sorption isotherms (moisture storage functions) of the hygroscopic wood-based materials had a more profound effect on the amount of water vapour retained within the assembly.

The boundary conditions (interior and exterior climates) were also important factors determining the calibration of the simulation models since these data represented the heat and moisture loads present throughout the study period. A precise representation of the environmental loading was necessary in order to minimize compounding errors in the surface transfer coefficients. As an example, the heating

effects related to the short wave absorptivity coefficient were determined by the amount of direct radiation as well as the reflected radiation arising from the albedo of the ground surface.

The configuration of the hygrothermal model was designed to facilitate these investigations as well as provide solutions to the inaccuracies caused by rigid coefficients that were used to define variables such as cloud index and albedo as well as cavity ventilation. The two-layer exterior cavity was developed to minimize the effects of excessive ventilation on model fidelity. Once the temperature and relative humidity of the wall cavities and sheathing were calibrated with measured data, the material properties of the OSB sheathing were examined.

The deep cavity cellulose-insulated walls were investigated in detail since these walls had the largest number of moisture related issues. The exaggerated vertical MC profiles of N1, S1, and N2 in contrast to the uniform moisture distribution of S2 required explanation. Although these walls were similar in concept and materials, the Type 2 wall had a central cavity wall-area similar to the datum and exterior insulated walls, while the wall-area of the central cavity in the Type 1 (double –stud) walls was connected to its side cavities through the 57 mm space between the inner and outer framing. The influence of the wall geometry was considered as well as the material properties.

The investigation process began with the calibration the datum walls. The datum walls were calibrated first based on siding and OSB temperature as well as relative humidity at the mid-height sensor locations, because of the similarities between the datum walls and the High RSI walls. The mid-height sensor locations were the most hygrothermally isolated from the temperature and hygroscopic effects of the upper and lower plates. In addition, the temperatures of the mid-height sensors were not noticeably affected by the air leakage test.

5.1 Approach

The north and south facing datum wall models were first calibrated with the measured temperature data of the exterior cladding and OSB sheathing. Once the correlations between these measured and simulated temperatures were optimized, the relative humidity of the exterior cavity was calibrated using the Air Change Rate (ACR). Changes to the exterior cavity ACR had a greater influence on the relative humidity of the cavity than the temperature of the cavity. The relative humidity of the exterior cavity subsequently influenced the moisture content of the OSB sheathing because the sheathing's

hygroscopic (RH dependent) properties. The moisture storage function (MSF) and water vapour diffusion resistance (WVDR) of the OSB were both dependent on the RH of the adjoining air space(s).

The interior cavity RH was more difficult to calibrate as the RH within the cavity was influenced by the hygroscopic materials that enclosed the cavity. The studs and plates bounding the cavity influenced the measured RH data by acting as either sources or sinks depending on the boundary conditions. The WUFI® models could not fully represent these interactions, which resulted in lower correlations between the model and measured data. The main objective for the interior cavity RH of the model data was to achieve an average daily RH that was similar to the measured data rather than try to replicate the daily fluctuations.

Once the calibrations of temperature and humidity were optimized, further correction of the model data was achieved through modifying the material parameters of the OSB sheathing. The OSB material properties of moisture storage function (MSF) and water vapour diffusion resistance (WVDR) factor were obtained from the National Research Council of Canada report NRCC-46090 (Kumaran et al, 2003). These sorption and desorption EMC data were reported as averages along with their standard deviations. The water vapour resistance factors for OSB were also reported as minimum and maximum data values. These ranges of OSB material properties were used to define several OSB material definitions within the WUFI® material database to examine the effect of these properties on OSB moisture content. Separate material definitions were created to encompass the data range using low, average, and high values from the MSF and the WVDR factor datasets reported by NRCC-46090 (Kumaran et al, 2003).

Through successive model simulations, the most appropriate material values were selected. The average density of 650 kg/m^3 was used for each of the material property definitions as the effect of density on temperature, MC and RH did not appear to be significant at an hourly time-step resolution. The MSF, however, had a substantial impact on the calculated OSB MC within the models because it governed the amount of water vapour adsorbed by the OSB at specific RH levels. This fact further emphasized the importance of calibrating the RH levels within the interior and exterior cavities.

5.1.1 Cellulose moisture content

The High RSI test walls were categorized as either deep cavity or conventional construction with exterior insulation. The two cellulose-insulated deep-cavity wall types were investigated in this simulation study to determine the cause of the wide-ranges of OSB and plate moisture content responses recorded

during the study period. The performance of the south-facing I-Joist wall, S2, far exceeded that of the other three cellulose-insulated walls. The S2 wall was the only cellulose-insulated wall that had a uniform vertical OSB MC profile. The remaining cellulose-insulated walls had widely varying vertical MC profiles. To assess these four walls, calibrated WUFI® models were created to investigate the role of the initial moisture content of the cellulose on the performance of these deep cavity walls.

Prior analyses of the measured data indicated that the non-uniform vertical OSB MC profiles in wall types 1 and 2 were linked to the initial moisture content of the cellulose. Using the surface transfer coefficients and model design developed through calibration with the datum walls, the moisture content profiles in wall types 1 and 2 were examined using WUFI® to determine the initial cellulose moisture content.

Further model studies should include an assessment of initial moisture content based on orientation, geographic location and building application.

5.1.2 *Material properties*

The WUFI® model calibrations began with research into the material properties of each wall component. The most significant wall components in each wall were the insulation materials and the OSB. The hygroscopic properties (moisture storage function and water vapour diffusion resistance factor (WVDR)) of each material were of particular importance because these parameters controlled the amount of moisture that was stored in each assembly as well as the moisture transport rate. The material properties of the wall assembly components were obtained from the following sources:

Table 5-1 Data sources for material properties

Source	Material properties
NRCC-46090 (Kumaran et al, 2003)	OSB material properties including MSF and WVDR factor Thermal conductivity
NRCC-50287 (Mukhopadhyaya, P., et al.,2007)	Cellulose properties - MSF and WVDR factor Fibre cement board- MSF and WVDR factor
NRCC-46885 (Kumaran et al, 2006)	WVDR factors of SBPO, paint and primer
2009 ASHRAE Fundamentals (ASHRAE, 2009)	Thermal conductivity spruce lumber, water vapour permeability of OSB
WUFI® material database (WUFI, 2012)	Moisture storage function for Gypsum and Roxul insulation
Owens corning technical data	Thermal conductivity for R22 Fiberglass Thermal conductivity and water vapour permeance for XPS foam insulation
CCMC 13188-L (NRCC, 2012)	Enerfoil IKO polyisocyanurate foam insulation Thermal conductivity and water vapour permeability

The material properties obtained from the NRCC 50287 report for the cladding were not specifically related to the siding product used in the wall assemblies. Rather, the material properties reported in NRCC-50287 were derived from fibre cement sheathing board and although these two components were made from the same material, qualitative observations indicated that because of the finishing treatments on the siding, it was less absorptive and tended to shed water better than the sheathing product. The baked-on finish of the siding probably lowered the sorption potential of the exterior face by affecting the capillary suction characteristics, which in turn would lower the moisture storage function. This uncertainty was investigated and discussed in Section 5.3.5.

In addition, the lapped nature of the siding diminished the reliability of the water vapour permeance since airflow between the siding boards was unrestricted. For this reason, the water vapour calibration of the exterior cavity occurred primarily through the air change rate used for ventilation. The hygroscopic properties and water vapour permeability of this type of siding product should be determined in order to remove these uncertainties from future analyses.

5.2 WUFI® model configuration

The hygrothermal models were configured to enable the investigation of the various wall components and their interactions with environmental and induced moisture loads. The model configuration for the Type 3 Datum wall is presented in Figure 5-1 to illustrate how the wall assembly was modeled in WUFI®. The left edge of the figure represents the exterior of the model with the fibre-cement siding, air space and water resistive barrier (WRB) comprising the drained-screened exterior.

The 18.5 mm air layer was divided into two 9.25 mm layers with the outermost layer ventilated with the exterior air of the climate file at a constant rate of 210 ACH. This layer was separated to minimize the overcooling / overheating that occurred with the single air-layer and a constant ventilation rate. Since the exterior-cavity ventilation rate was defined in the model using a constant-value instead of a variable – determined by solar radiation, wind, and/or air pressure – the double air-layer minimized the temperature effects that occurred when the ventilation rate was either too high or too low. The detrimental effects of the single air-layer were most noticeable on clear days and nights.

By splitting the exterior drainage space air-layer into two components and applying all of the cavity ventilation to the outmost layer, the cavity air was allowed to exchange with the outside air and balance moisture across the cladding. The innermost layer of the exterior cavity provided a relative humidity and

Figure 5-1 Typical WUFI® model configuration

temperature buffer for the OSB during periods when the defined ACR rate was too high. The calibration of the exterior cavity relative humidity was important because the water vapour permeance (WVDR factor) and moisture storage function (MSF) of the sheathing changed with the relative humidity of the cavity air.

The base hygrothermal WUFI® model was designed to investigate the variations in MC within the OSB throughout the High RSI study period. The OSB sheathing layer was initially divided into three sections of 3.0, 5.1, and 3.0 mm to observe the moisture content profile through the OSB. This layered OSB approach also allowed the sensing depth of the OSB MC pins to be investigated. To further the investigation of the MC sensors, the inner 3.0 mm layer was sub-divided into two sections of 1.9 mm and 1.1 mm. The innermost 1.1 mm layer was added as an aid to determine the changes (if any) in the sensing depth of the MC sensors under varying moisture loads. The moisture sensor-pins were installed to a total depth of 5 mm as described in Section 3.6.4.

5.2.1 *Simulation of air leakage*

During the air leakage test, the airflow distribution within the stud cavity was determined by the cross-sectional area and the air-permeability of the insulation in the cavity. The moisture load of the air column depended on the initial moisture load of the interior air, the temperature / moisture profile across the wall as well as along the vertical path within the stud cavity. In order to facilitate the simulation of this hygrothermal system, the insulation cavity was divided into four layers that allowed the 1 mm Air Change Layer (ACL) to be placed at different locations within the stud cavity. This accommodation was provided to observe the effect that the placement of the 1 mm ACL had on the OSB moisture content. The ACL placement had the most significant effects in the deep-cavity cellulose insulated walls because the moisture storage of the cellulose delayed the transport of moisture across the assembly. The segmented stud cavity shown in Figure 5-1 also permitted the use of multiple ACL layers to simulate dispersed paths through the stud cavity with variable ACRs. The air leakage simulations are presented in Section 5.7.

5.3 *Model calibration*

The data collected from the mid-height sensors (Figure 3-4) were used to calibrate the hygrothermal models to the boundary conditions and determine the appropriate material parameters for the OSB sheathing. The datum walls were chosen for the calibration study because these walls contained the same exterior control layers as each of the High RSI test walls. The datum walls also had the same basic framing and sheathing configuration as the exterior insulated wall types. Once the surface transfer coefficients and common material properties were determined, then the cellulose and exterior insulation components were examined individually for each of the High RSI walls (Types 1, 2, 5-7). The measured data used to calibrate the WUFI® models were:

- Exterior temperature,
- Exterior cavity RH,
- OSB temperature, and
- Stud cavity RH

These datasets were compared with corresponding WUFI® output to determine the best-fit settings for the surface transfer coefficients and model configuration. The surface transfer coefficients defined for the WUFI® simulation models determined the heat transfer rate between model and the climate data (boundary conditions).

The principal external coefficients used to calibrate the models were:

- Wind-dependent heat resistance
- Short-wave radiation absorptivity, (α_{sw})
- Explicit radiation balance
 - Cloud index
- Ground short-wave reflectivity

These heat transfer coefficients are discussed in more detail in the following sections. The adhering fraction of rain was also investigated to determine its effect on OSB MC via the exterior cavity RH levels (Section 5.3.5).

5.3.1 *Wind dependent heat resistance*

Heat transfer at exterior surfaces is determined by the convective and radiative heat transfer coefficients that represent the rates at which heat is exchanged through convection and long-wave (thermal) radiation. The combined effects of these coefficients are often referred to as surface film coefficients (Straube et al, 2005). Factors like the direction and magnitude of wind can alter the heat transfer rate between the assembly and its surroundings. WUFI® compensates for these wind-related effects by including a wind dependent heat transfer coefficient that adjusts the value of the surface film based on the orientation of the exterior surface relative to the wind direction – leeward or windward. The values used by WUFI® to determine the exterior surface heat resistance are (WUFI®, 2012):

- Convective heat transfer coefficient = $4.50 \text{ W/m}^2\cdot\text{K}$ (wind velocity = 0 m/s)
- Radiation heat transfer coefficient = $6.5 \text{ W/m}^2\cdot\text{K}$

For wind dependence, WUFI® weights the wind speed based on its direction relative to the building face using:

- $0.33 * \text{Wind velocity}$ (leeward conditions)
- $1.6 * \text{Wind velocity}$ (windward conditions)

The variability of these surface coefficients is shown in Figure 5-2 below for both the north and south facing walls during the period of November 13th to 24th, 2012. This figure shows the variation in the value of the convective component of the surface heat-transfer coefficient as the north and south orientations alternate between leeward to windward conditions. The higher thermal conductance of the

Figure 5-2 The influence of wind direction on the convective component of the surface heat transfer coefficient for north and south facing test walls – S3 and N3 data shown (Nov. 13-24/12)

south facing walls figure indicates that the south facing wall experienced windward conditions for the majority of the time, which resulted in a higher thermal conductance.

Comparative model simulations indicated that the peak (daytime high) cladding temperatures were consistently lower with the wind dependence option disabled. Peak temperature differences of up to 10°C were observed between the model and measured data on sunny days throughout the study period. Figure 5-3 presents a data comparison between the measure S3 siding temperature data and simulation data that was calculated with and without the wind-dependent heat resistance option enabled.

Figure 5-3 indicates that using the wind-dependent heat transfer improved the correlation between the simulated and measured data the most during clear, sunny days. The wind-dependent heat resistance option did not have an observable effect on the nighttime siding temperature and only a slight effect on siding temperature during cloudy days (see Nov 19 data in Figure 5-3).

With the wind dependence option disabled, the calculated cladding temperatures were much lower because WUFI® used the full wind velocity during these time-steps. When the wind-dependent option was enabled, the simulated cladding temperatures were determined using leeward wind velocities that resulted in a better correlation between the measured and simulated siding temperatures. The effect of wind direction had very little effect on the correlation between the measured and simulated siding temperatures of the north-facing walls.

Figure 5-3 Data comparison of measured S3 siding temperature with simulated WUFI® data to show the effect of the wind-dependent heat resistance option

5.3.2 Short-wave radiation absorptivity

The solar absorption coefficient (α_{sw}) had the largest influence on cladding temperature and its value is a function of the cladding's colour. The manufacturer's colour designation for the fibre-cement siding was Antique White, which resembled a very light tan (buff) colour more than white. Typical absorptivity

Figure 5-4 Test wall cladding colour

coefficients for white to light cream surfaces range from 0.3 to 0.5 while yellow to buff building materials range from 0.5 to 0.7 (Hutcheon and Handegord, 1995). The α_{sw} -value of 0.60 was determined using the south-facing datum wall and incremental changes to the α_{sw} -value until the peak daytime cladding temperatures of the simulations were consistently within 1-2°C of the measured data. The α_{sw} -value of 0.60 was used for each of the High RSI test walls on

both the north and south-facing simulations. The cladding colour is shown in Figure 5-4 relative to the dark red siding of the BEG Hut and the bright aluminum flashing covering the top of the test panels. For comparison, the absorptivity of highly polished aluminum, chrome, nickel and tine range from 0.1 to 0.4 and from 0.65 to 0.8 for dark red brick and dark paints (Hutcheon and Handegord, 1995).

The cladding's solar absorptivity value was determined using several trial simulations and varying α_{sw} values. The α_{sw} values were varied between 0.4 and 0.7 to determine the α_{sw} value that most closely

Figure 5-5 Comparative ΔT analysis to determine the short-wave absorptivity coefficient of the cladding using the datum walls ($\Delta T = T_{\text{measured}} - T_{\text{simulated}}$)

simulated the cladding temperature during the day. The differences between the measured and simulated daytime cladding temperatures (for each time-step) were averaged to determine a single, representative ΔT performance-value for the analysis periods from October 4th to January 1st, January 1st to April 1st, and April 1st to August 2nd. These performance values are presented in Figure 5-5 for the south and north-facing walls.

The short-wave absorptivity value was determined from the south facing wall analysis since it was most affected by direct solar radiation. This analysis indicates that the α_{sw} value = 0.60 approximated the measured data the best throughout the study period. Weighted-average ΔT -values for each α_{sw} increment were also calculated by time weighting the average ΔT -values from each of the analysis intervals. These values are also included in Figure 5-5.

The cladding temperatures of wall Types 2, 3, and 6 (I-Joist, Datum, and XPS) are compared with their corresponding measured cladding temperatures in Figure 5-6 and Figure 5-7. The time intervals November 7th to 16th and June 17th to 24th were selected as they represent data collected during periods of low and high peak-solar angles respectively. The simulated temperatures were calculated using $\alpha_{sw}=0.60$.

As these figures show, the simulations performed using $\alpha_s= 0.60$ closely approximated the daytime and peak cladding temperatures for each of these three wall types. The simulated and measured temperatures were generally well correlated for each day with some minor error resulting from the

Figure 5-6 Cladding temperature correlation for $\alpha_{sw}=0.60$ for wall Types 2, 3, and 6 (Nov 7-16/2013)

hourly averaging of the data. Other sources of error arose from the calculation of diffuse and direct radiation, variations in wind speed and direction, as well as the seasonal variability in ground albedo (reflectivity) and cloud cover (cloud index). The cladding α_{sw} value was considered constant throughout the data acquisition period, which ignored the negligible changes due to dust and fading from UV radiation.

Unlike the α_{sw} value, cloud cover varied daily and the ground albedo changed seasonally. Both of these parameters were defined using constant values that were approximated to minimize errors and “best-fit” the climatic conditions at the BEG Hut during the study period. Subsequently, nighttime

Figure 5-7 Cladding temperature comparisons of wall Types 2, 3, and 6 using $\alpha_{sw}=0.60$ (June 17-24/2013)

temperatures and the daily temperature profiles were slightly varied between the two datasets. The cloud index and ground short-wave reflectivity coefficients are discussed in the following sections, while the influence of wind speed and direction were discussed in the preceding section.

The north-facing temperature comparisons for the Datum wall N3 using $\alpha_{sw} = 0.60$ are shown in Figure 5-8. The measured and simulated temperature datasets were well correlated throughout the study period with the most deviation occurring during the winter (as shown in Figure 5-5). These deviations were most likely related to the change in the ground's albedo resulting from snow cover. Snow cover at

Figure 5-8 Cladding temperature comparison of the north Datum wall N3 using $\alpha_{sw} = 0.60$

the BEG Hut location was only consistent between mid-January and mid-March. The north-facing cladding temperatures were also as well correlated as the south-facing wall data.

The calculated and measured OSB temperatures were also well correlated for both of the north and south-facing walls. Further analysis of the exterior insulated wall models indicated that these calculated sheathing temperature data also closely approximated the measured OSB sheathing temperatures in wall Types 5-7.

5.3.3 Explicit radiation balance

The explicit radiation balance option was used to simulate the daily long-wave radiation exchange between the test wall and its surroundings so that nighttime radiant losses could be accurately determined. Radiant energy loss to the night sky occurs because the gasses in the atmosphere only reradiate long wave radiation in certain wavelengths coincident with their energy states rather than across the spectrum like opaque materials (Hutcheon and Handegord, 1995). In the absence of cloud cover, radiant energy is lost from building surfaces which results in cladding temperatures that fall below the ambient air temperature. This overcooling occurs only at night when it is not counter-balanced by incoming solar radiation.

The amount of radiant energy loss that occurs on any given day is determined by the location's cloud cover. A cloud index (CI) represents this cloud cover and if recorded, a continuous cloud index can be included in the boundary conditions via the exterior climate file. In the absence of a continuous cloud cover index, a typical CI-value must be estimated to represent the average amount of nighttime cooling expected at the study location. This constant CI-value was optimized using the nighttime data when the effects of cloud cover could be isolated from incoming solar radiation – direct, diffuse, and reflected. The optimization was achieved by calculating the difference between the nighttime cladding temperatures (measured – simulated) using a series of cloud index values from 0.4 to 0.9. These cloud index values were repeated for three α_{sw} values from 0.55, 0.58 and 0.60. The averages of these data were calculated and plotted to reveal the linear relationship, shown in Figure 5-9.

Comparative modeling analysis determined that the optimized cloud index coefficients were 0.58 for the south-facing walls and 0.65 for the north-facing walls. The differences between these two CI-values resulted from variations in areal exposure to the night-sky as well as orientation to the wind.

Figure 5-9 Cladding night-temperature difference [Measured – Simulated] for cloud index values (0.4 to 0.9) and α_{sw} values = 0.55, 0.58 and 0.60

Additionally, variations in the ground long-wave (thermal) emissivity and reflectivity may have contributed to the difference between the CI-values. The default values of 0.9 and 0.1 were used for these thermal coefficients, respectively. The difference between the daily temperature profiles of the simulated and measured data occasionally varied by 3-4°C for several hours during very clear nights when the actual cloud cover was substantially below that predicted by the 0.58 or 0.65 CI-values. Generally, however, the differences between the measured and simulated overnight cladding temperatures were less than 2°C.

5.3.4 *Ground short-wave reflectivity*

The ground short-wave reflectivity (GSRW) coefficient was used to define the amount of solar radiation reflected from the ground to the exterior surface of the wall. The ground reflectivity is otherwise known as albedo and its value changed seasonally at the BEG Hut depending on the grass colour (brown or green) and snow cover.

WUFI® has several predefined coefficient values and the value of 0.26 (green grass) proved to provide satisfactory year round cladding temperatures for the south-facing simulations. However, the cladding temperatures of the north-facing simulations were often over-heated during periods of high-angle and high intensity radiation. The combination of more intense radiation and an over-estimation of the backscatter associated with high angle sunlight caused disproportionately high cladding temperatures in the north facing simulations during the April to August period.

Comparative models were created to determine the seasonal variation and optimal value for the ground's short-wave reflectivity. North and south orientations of these models were simulated using reflectivity values ranging from 0.0 to 0.40. The results were analysed using the differences between the daytime cladding temperatures [Measured – Simulated]. Averages for these datasets were determined on a seasonal basis and the plotted to illustrate the effect of the varying albedos. The magnitude of these values was affected by the short-wave absorptivity, cloud index, and wind-dependent heat resistance. For this reason, the primary focus of this section was to determine suitable ranges for the GSRW values and to observe the seasonal influence of albedo. Negative values indicated that the simulated temperatures were higher than the measured data.

The averages calculated from the north-facing temperature differences are shown in Figure 5-10. These data illustrate the exaggerated effect of higher albedo values on the cladding temperatures during April to August. While higher reflectivity values better approximated the measured data during fall and

Figure 5-10 Effect of different ground reflectivity values on cladding temperature (North exposure)

winter, its effect during the April to August period was disproportionately higher. Although these average temperature changes were minor, the cumulative effect on moisture content was significant and led to over-estimations of drying potential in the simulations of the High RSI wall during the April to August period.

The data presented in Figure 5-10 indicate that for the north-facing simulations, a GSWR between 0 and 0.1 was best since GSWR values above 0.1 disproportionately affect the spring and summer cladding temperatures. The value of the GSWR coefficient varied with application but in general, the 0.26 value was used for the air injection test and baseline model calibration. For data analysis after April, 0 or 0.1 was used where appropriate.

The average cladding ΔT -data calculated from the south-facing simulations are presented in Figure 5-11. These data indicate that reflectivity values between 0.20 and 0.26 provided the best seasonal

Figure 5-11 Effect of different ground reflectivity values on cladding temperature (South exposure)

approximations of the measured data. The simulated cladding temperatures were least affected by changes to the reflectivity coefficient during the fall period and most affected during the spring and summer. The wintertime albedo was very well approximated with 0.30. The GSWR value used in the south facing simulations was 0.26.

5.3.5 Adhering fraction of rain

The adhering fraction of rain (AFR) option, previously known as the rain reduction factor or rainwater absorption factor, was used to define the amount of water that adhered to the exterior surface of the cladding. This adhered rainwater was available for capillary suction during and after rainfall events. In light of the uncertainties with respect to the material properties of the fibre cement siding, the AFR setting was investigated by observing the results of two simulations that were performed with the AFR enabled and then disabled. All other surface transfer coefficients were held constant between these two simulations and the default AFR setting of 0.70 was used when the setting was enabled. The cavity ventilation was set for 200 ACH.

The effects of the AFR function were investigated because the absorption of water into the cladding can increase the vapour pressure within the exterior cavity. Changes to the vapour pressure profile affect the wall's drying potential directly through the magnitude of the vapour drive and indirectly through the WVDR and MSF of the OSB sheathing. Since the OSB sheathing is hygroscopic, its moisture content and water vapour permeability depend on the relative humidity in the adjoining air cavities. Figure 5-12 shows the impact of the AFR option on the RH of the exterior cavity in the south-facing datum wall S3. The WUFI® simulated RH data for the exterior cavity are compared with the measured data. The rainfall events are shown at the top of the figure with its inverted scale on the right-hand side of the chart. Prior to the first precipitation event, the two sets of WUFI® RH data were identical and approximated the

Figure 5-12 Effect of the AFR option on exterior cavity RH in the south datum wall S3 (Nov 30 to Dec 16/2012)

measured RH data relatively well. However, immediately following the rainfall on Dec 2, 2012, the WUFI® RH data calculated with the AFR enabled was elevated by several percent, while the non-AFR data continued to track the measured RH more closely. This pattern repeated itself during and after most rainfall events. The AFR option was disabled for all subsequent modeling.

The accuracy of the AFR setting depended on the cladding's material properties. Material properties specific to the fibre-cement siding product used in the High RSI wall study were not available and were substituted with the material specifications for fibre-cement sheathing board. This product had the same density and thickness; however, the surface treatments of these products varied based on their intended applications. The properties for the fibre-cement sheathing board were updated with MSF data from the NRCC-50287 report (Mukhopadhyaya, et al., 2007) to create a custom material property for the siding. The properties for capillary suction were the same the sheathing board, which may also be a source of error for this material. While the fibre-cement sheathing and siding are the same basic material, their surface treatments are different. It is suspected that the siding's exposed face has lower capillary suction than the sheathing because of the paint and embossed design applied to this side for durability and aesthetics. The siding's glossier finish probably limits the adherence and absorption of rain, which precluded the need for the AFR option to account for rain adherence.

5.3.6 Exterior cavity ventilation

The exterior drained-screened wall system and its 18.5 mm air space were common to each of the test panels in the High RSI wall study. This exterior wall system was assembled using 8 mm fibre cement siding fastened to 18.5 mm (600 mm OC) strapping that provided the air layer (drainage space). The lap joints between the individual siding boards supplied the air layer with ventilation. This ventilation was simulated in WUFI® using an Air Change Source and a constant rate air exchange with the exterior boundary conditions. Since the actual air-change rate varied throughout the study period, comparative models were used to optimize the air-change rate of the cavity in order to minimize error. The air-change rate (ACR) was varied between 0 and 400 ACH (0 to 7.4 m³/ hour per m²) for both the north and south-facing wall models. The WUFI® models were constructed using the datum wall configuration, which also included separate single and double air layer models to observe their relative performances. The 2-Layer air cavity exchanged air in the outermost layer only, which provided an inner layer temperature buffer for the sheathing during periods when the constant air change rate was too high. From a modeling perspective, excessive and insufficient air change of the exterior cavity is inevitable when the ACR is defined by a constant value. This investigation attempted to minimize these errors.

Figure 5-13 Exterior cavity ACR optimization for days (Top) and nights (Bottom) using 1 and 2-Layer exterior air layers in S3 and N3 ($\Delta RH = RH_{\text{measured}} - RH_{\text{simulated}}$)

The model results were divided into daytime and nighttime intervals for analysis. These datasets were analysed by determining the differences between the measured and simulated RH data ($\Delta RH = RH_{\text{measured}} - RH_{\text{simulated}}$) for each model time-step. Median values of these data were calculated for each ACR during the three analysis periods from October to January, January to March, and April to August. A time-weighted average of these three median ΔRH -values produced a single ΔRH -value for each ACR (from 0 to 400). These single ΔRH -values were used to observe the effect of varying the exterior cavity ACR by plotting a ΔRH versus ACH plots as shown in Figure 5-13. The daytime ΔRH data are shown in the upper plot of Figure 5-13, while the nighttime data are presented in the lower plot. It is important to note that the air change rate is denoted in air changes per hour (ACH) of the single layer cavity volume – the ACH for the double layer was increased to maintain comparative volumes since only the air in the outermost layer was ventilated with the outdoor air. All other surface transfer coefficients were held constant and only the ACR of the exterior cavity was changed. The simulation RH data was collected from an RH-monitor that was positioned close ($\sim 2\text{mm}$) to the centre of the exterior cavity within the innermost exterior air layer. Detailed ΔRH data are presented in Appendix L.

In general, the data presented in Figure 5-13 show that the different air change rates influence the exterior cavity RH differently based on orientation and time of day. The measured daytime RH data for Datum wall N3 (blue) were best approximated by 50 ACH for the 1-Layer and 100 ACH for the 2-Layer air-layer. At night, the measured north wall data were best represented by no ventilation (0 ACH) for both the 1-Layer and 2-Layer models. Since the model results for 0 ACH rapidly diverged from the daytime data (for both air layers), this ACR was not suitable. The RH data from the 400 ACH simulation of the 1-Layer model also closely approximated the nighttime measured RH data from N3; however, this flow rate also diverged from the daytime measured RH data. These data indicated that an exterior cavity ACR between 100 and 210 ACH best approximated the measured data for the north-facing walls and the sensitivity to changes in exterior cavity ACR generally decreases below 50 ACH.

The measured daytime RH data for Datum wall S3 were well approximated by simulations that used both the single and double air layer models between 100 and 400 ACH. The 2-Layer simulation data calculated with a 200 ACH air change rate gave the closest approximation by a narrow margin. The nighttime data were best approximated with the 2-Layer model and an ACR of 50 ACH. Overall, an ACR of either 100 ACH or 210 ACH approximated these measured RH data fairly well.

The data curves in Figure 5-13 show that the 2 layer air cavity model had a moderating effect on RH when higher ACRs were used in the simulations. For air change rates between 210 and 400 ACH, the differences between the measured and simulated RH data were uniform in the 2-Layer dataset, while the results diverged in the 1-Layer dataset. The two-layer air space was implemented to compensate for the over-mixing of air that occurred at extremes during the day (peak heating) or at night (peak cooling). The effect of the two layer air cavity is shown in Figure 5-14 using a comparison of measured N3 RH data with model RH data that was simulated using an ACR = 210 ACH in both the single and double air layer

Figure 5-14 Relative humidity comparison showing the effect of the 2-Layer exterior air cavity

models. These data show that during some days, the single air layer over predicted the measured RH while the two-layer model minimized this overshoot.

The modeling results of this exterior cavity investigation indicated that an option for a variable or two-stage air change rate would be beneficial in modeling the exterior cavities of drain-screened wall assemblies. A two-stage air change rate could specify separate nighttime and daytime ACRs that would likely improve the accuracy of modeling results. By reducing the air change rate at night to reflect actual conditions, the cavity RH could be kept at a more realistic level as shown in Figure 5-15. This figure compares simulated RH data using two different ACRs. The S3 data were recorded from November 14-22, 2013 during a period of clear sunny weather that caused well-defined RH lows in the exterior cavity during the day. The measured RH data indicated the air change rate was very low during these nights since the cavity RH remained suppressed relative to the ambient RH.

Close examination of Figure 5-15 shows that the simulated RH data calculated using an ACR = 210 ACH more closely approximated the *ambient RH* rather than the *measured RH*-data during the nighttime hours as the cavity RH increased towards 80% (on par with ambient). The measured RH-data were generally in the range of 40 to 50% RH during the overnight periods from Nov 15 -21. In addition, since the nighttime RH was about 30-40% higher, the simulated daily lows during this period were also elevated by about 20%. The simulated RH-data calculated using an ACR = 100 ACH provided a better approximation of the nighttime measured data but these data poorly estimated the RH low during the daytime. These data support the need for a variable or two-stage ACR in the exterior cavity.

The rate of air exchange between the exterior cavity and the outside air can be coarsely divided into daytime and nighttime categories. The data analysed in this section indicated that the ACR and ambient

Figure 5-15 Relative humidity comparison of measured and ambient with simulated rates 100 and 210 ACH

temperature were well correlated and further analysis could determine the relationship between exterior cavity ACRs and solar driven convection or wind speed and wind direction. At the very least, the ability to set a nighttime and a daytime ACR could improve the model results for south-facing exterior air cavities.

5.3.6.1 Air change rate and cladding temperature

The exterior cavity ACR was determined to have very little effect on the cladding temperature. The cladding temperature data extracted from the comparative ACR models were analysed and are presented in Figure 5-16. These data show that negligible temperature effects were associated with the varying ACRs. The exterior cavity ACRs of 0, 25, 100 and 210 ACH (0, 0.46, 1.85, 3.89 m³/hr) were assessed using a standard deviation test across each measured data point and corresponding model time-step.

The data shown in Figure 5-16 illustrate that the primary source of temperature deviation occurred during the peak solar radiation hours on the south-facing walls. These temperature profiles show that there was generally less than a 2°C difference in the simulated cladding temperatures during the peak solar (direct) radiation hours. The standard deviations between the daytime cladding temperatures were 0.07°C in the south data and 0.02°C in the north data for simulations that used a 2-layer exterior air cavity. The standard deviation between the different ACRs of the south facing walls with a single layer air space was 0.29°C.

Figure 5-16 Cladding temperature comparison for air change rates (ACR) of 0, 25, 100, and 210 ACH (2-Layer)

5.4 *Solar data processing*

The measured solar radiation data were collected using a horizontally positioned pyranometer located at the BEG Hut test facility (Figure 3-1). These data required processing to separate the total radiation into its diffuse and direct components for integration with the exterior climate file used in the hygrothermal modeling. Quantification of the direct solar radiation component was necessary for the accurate simulation of the heating that occurred during each of the simulation's time-steps. These detailed solar data also enabled WUFI® to simulate a variety of orientations and inclinations for each assembly under investigation.

The separation of the diffuse and direct radiation components was accomplished using a methodology presented in the reference "Solar Engineering of Thermal Processes" (Duffie and Beckman, 2006). In addition to this resource, a thorough description of the methodology was also located that included how-to instructions on the creation of an Excel spreadsheet to perform this calculation (Finch, 2007). Both resources proved instrumental in accomplishing this task.

Once the solar data was processed, a summation analysis was performed to ensure that the calculated solar components were similar in magnitude to the measured data. This error analysis was completed by calculating the difference between the total measured radiation and the sum of its calculated components (diffuse and direct). Summation errors occurred in 22% of the solar file's time steps and occurred with an average error of 4.9% or 4.50 W/m^2 . Errors greater than the average occurred in 8.2% of the total time steps and the maximum error observed was 15.8 W/m^2 or 11% of the total measured radiation. The errors were most often associated with cloudy or hazy days when the magnitude of the direct component was very low (or close to zero) and the diffuse component calculated slightly higher than the total measured solar radiation. Since the excess solar radiation was diffuse radiation, the influence of these errors on cladding temperature was minimal. The nature of these errors indicated that the diffuse and direct radiation components were suitable for use in the hygrothermal modeling. A sample of the calculated and measured solar data is presented in Figure 5-17 to illustrate the results of the solar data conversion process. These data were measured between May 5th and 13th in 2013.

The solar data from May 5th to 7th represent relatively clear days while the remaining five days show the effect of cloud cover on the diffuse and direct components. The data collected using the horizontal pyranometer recorded non-quantifiable counter-radiation during the night. These negative data were

Figure 5-17 Comparison of total solar radiation (I) with the calculated direct and diffuse components

filtered out of the measured horizontal data file prior to processing. The effects of nighttime cooling were represented in the model using the explicit radiation balance and the cloud index coefficient.

The final solar radiation data file was also used to create a logical operator (1 or 0) for each time-step. These operators were used in the calibration of the surface transfer coefficient by classifying the relative humidity and temperature data as day or night based on solar radiation.

5.5 OSB material properties

Once the basic WUFI® model was calibrated with the BEG Hut test data, the next task was to ensure that relevant material properties for the OSB were obtained. The WUFI® database was updated several OSB definitions using the OSB material properties located in the NRCC-46090 report (Kumaran et al, 2003). These material definitions were determined through investigations of six different OSB products. The OSB density was found to range from 575 to 725 kg/m³. The average value of this range (650 kg/m³) was used as the bulk density for each new database entry and the thickness was defined as 11.1 mm.

The NRCC report tabled the average sorption and desorption ECM data along with the standard deviations associated with each data point. The sorption data for 50%, 69.3%, and 91.5% RH were combined with the 88.9%, and 93% desorption data. The standard deviation data were used to define low, average, and high moisture storage functions (MSF) for three OSB material property definitions. These moisture storage functions are shown in Figure 5-18. The additional curves for OSB 1, and OSB 2 denote the sorption curves that were calibrated to the measured OSB MC data in some of the High RSI

Figure 5-18 OSB sorption curves defined in the WUFI® database using NRCC-46090 data

test walls. All of the sorption curves used in the High-RSI hygrothermal simulations are presented in Appendix M.

The upper and lower ranges of the WVDR factor were also used to define two OSB materials in the WUFI® database. The average-MSF was used in both of the high and low-WVDR OSB definitions. Comparative models were created for each of these new definitions and their simulation results for the baseline period from October to January are shown in Figure 5-19. The light grey line defines the measured OSB MC data from the mid-height MC-sensor in datum wall S3. These data are compared with the inner 3 mm OSB MC data (stud-cavity side) from the WUFI® simulations.

The WUFI® simulation data calculated using the high-MSF and low-MSF OSB definitions showed a wide variation in simulated moisture content. The OSB MC-data calculated using the high-MSF OSB were 2.4% MC higher on average than the OSB MC-data calculated using the low-MSF. This separation in OSB MC continued throughout the study period with minimum and maximum differences of 1.3 and 3.2% MC.

Figure 5-19 OSB MC values calculated using the upper and lower ranges of MSF and WVDR in comparison with measured S3 data

The OSB MC-data that were calculated using the high and low-WVDR factors showed that variations in this parameter had a negligible effect on the OSB MC throughout the study period from October 2012 to June 2013. These data are shown in Figure 5-19 (red lines) and both sets of model data are essentially superimposed on the model data calculated using the average-MSF value. The difference in OSB MC between the high and low-WVDR datasets was 0.02% on average with a maximum difference of only 0.3% MC.

Additionally, the liquid transport functions for the OSB were generated by WUFI® from the following data:

- Reference Water Content 80 kg/m³
- Free Water Saturation 377 kg/m³ (58% MC @ 100% RH)
- Water Absorption Coefficient 0.0011 kg/m²·s^{-½}

The values listed the NRCC-46090 report for the water absorption coefficient ranged from 0.0011 to 0.0033 kg/m²·s^{-½}. The low end of this range was used in the OSB material property definitions.

5.5.1 OSB moisture storage calibration

The measured and simulated MC-data shown in Figure 5-19 illustrates how the measured data varies within the range of expected OSB MC. Initially, the measured data appeared to be well approximated by the high-MSF OSB simulation. In contrast, during the latter part of the baseline period, the measured data were better represented by the low-MSF OSB. This variation between the measured and simulated data was minimized by changing the moisture storage function to reflect the OSB 1 sorption curve shown in Figure 5-18.

Figure 5-20 Comparison of measured S3 OSB MC-data with simulation results using the MSF curves OSB 1, Low-MSF, and High-MSF

Figure 5-21 Comparison of measured S3 OSB MC-data with the simulated MC-data from the interior 1.1 mm and 3 mm OSB layers

This modification of the sorption curve was based on seasonal changes in the measured relative humidity of the wall cavities. The measured S3 MC-data were compared with simulation data calculated using the OSB 1 sorption curve. These data are presented in context with the Low-MSF and High MSF (blue) results in Figure 5-20. As these data show, the measured MC-data were better approximated by the OSB 1 sorption curve.

The simulated OSB MC data represented in the preceding two figures were derived from the inner 3 mm layer of OSB. A detailed comparison of measured and simulated MC-data is presented in Figure 5-21. These data show that the response of the interior 1.1 mm OSB layer (see Figure 5-1 for model configuration) closely approximated the rapid daily fluctuations in the OSB MC while the 3 mm appeared to represent a longer period average of the measured MC-data. The 1.1 mm OSB model data were used to calibrate the air change rates and initial moisture RH levels for the cellulose insulation.

5.6 High RSI calibrations

This section contains the calibration results of the High RSI wall assemblies. Once the datum models were calibrated, the surface transfer coefficients and the exterior cavity ACRs were used to create hygrothermal models for the remaining High RSI wall types. The datum models were expanded to include the extra insulation components of the High RSI wall designs. Since the surface transfer coefficients were assumed consistent between each test panel, only the additional insulating materials required calibration for each of the remaining wall types. In the case of wall Types 5 and 6, the interior 6-mil vapour barrier was removed from the model.

5.6.1 Deep cavity cellulose wall Types 1 and 2

The deep cavity cellulose walls were shown in Chapter 4 to have a performance issue related to excess moisture in the OSB sheathing. The investigation documented in this section used the calibrated WUFI® models to illustrate that the source of the elevated OSB MC readings resulted from the entrained moisture content of the cellulose at the time of installation. The effectiveness of the moisture pin isolators was also examined.

The material properties for cellulose fibre were obtained from the NRCC-50287 report (Mukhopadhyaya et al., 2007). The sorption and desorption data were merged to create a single sorption curve and adjusted to reflect the difference between the installed density $\sim 68 \text{ kg/m}^3$ and the NRCC reported

Figure 5-22 Sorption isotherm for cellulose insulation – data adjusted for density from NRCC-50287 (Mukhopadhyaya et al., 2007)

density of 26 kg/m^3 . The sorption isotherm determined the moisture storage function for the cellulose and its hygrothermal performance by defining the amount of moisture retained by the cellulose as the relative humidity of the air fluctuated. These data were used to define the material properties of cellulose insulation in the WUFI® materials database. The sorption curve of the cellulose insulation

is shown in Figure 5-22. These data were assumed representative of the cellulose insulation installed in wall Types 1 and 2 since detailed analyses were not performed on samples of the installed cellulose.

5.6.1.1 Baseline simulation results

The two types of deep cavity walls that contained cellulose insulation were the Double stud and the I-Joist stud wall. The insulation cavities of these walls were 286 mm and 241 mm respectively. Both wall types experienced serious moisture problems arising from interstitial condensation during the test period. Moisture content analysis indicated that the vertical profile of the OSB MC was not uniform in three of the four test panels. The south-facing I-Joist wall (S2) was the only deep cavity cellulose wall that had little to no variation in the vertical OSB MC profile. The lower, middle and upper OSB MC-data

Table 5-2 Summary of initial cellulose RH

Initial RH across Cellulose				
	S1	N1	S2	N2
Upper	65%	55%	38%	78%
Middle	54%	60%	38%	72%
Lower	36%	55%	38%	53%

collected from S2 were as uniform as the data collected from the datum walls and the exterior insulated walls. Since at least one of the Type 1 and 2 walls was not subject to serious condensation problems, this suggested that the probable cause of the OSB

MC variability was the initial distribution of moisture within the cellulose.

A series of WUFI® simulations were performed to determine the effect that the initial cellulose moisture content had on the OSB performance. Results of these simulations were compared with the measure OSB MC-data to determine the probable initial moisture content of the cellulose. The initial RH values for the cellulose are summarized in Table 5-2. The OSB moisture content results are presented in Figure 5-24 to Figure 5-27 using the simulated 11.1 mm, 3 mm, and 1.1 mm OSB MC-data in comparison with the measured OSB MC-data. The 11.1 mm simulated OSB data were omitted from Figure 5-24 for clarity since the 3 mm and 1.1 mm data effectively overlay the measured data.

There were two distinct OSB moisture storage functions used in the WUFI® simulations for wall Types 1 and 2, which were designated OSB 2 and OSB 3. The OSB 2 sorption isotherm was used in the S1, N1, and S2 simulations, while the OSB 3 sorption isotherm was used in the N2 simulations. These OSB sorption isotherms were selected as they improved each model's approximation of the measured OSB MC-data for the lower, middle and upper MC-sensors. The OSB 2 and OSB 3 sorption isotherms are shown in Figure 5-23 relative to the upper and lower sorption boundaries defined by the NRCC-46090 data (Kumaran et al, 2003).

Figure 5-23 OSB sorption isotherms for the cellulose-insulated walls

The WUFI® simulations used the established surface transfer coefficients and the two-layer exterior cavity with an ACR of 210 ACH on the exterior air layer (equivalent to 105 ACH using a single air layer). The initial cellulose moisture content was then varied to determine the initial moisture content of the cellulose insulation by visually comparing the simulated and measured OSB MC-datasets.

The S2 I-Joist WUFI® model simulations indicated that the initial moisture content of the cellulose insulation was 2.85 kg/m³ (4.2% MC), which corresponded to the EMC at 38% RH (23°C). The moisture content distribution within the stud cavity was determined to be uniform since the measured datasets of the lower, middle, and upper OSB MC-sensors could be modeled using the same initial moisture conditions. The WUFI® simulation data for wall S2 is presented in Figure 5-24. The circled area in this figure denotes the change in OSB MC that resulted from the installation of the MC-sensor isolators.

Figure 5-24 Comparison of measured and simulated S2 OSB MC-data for the baseline period from Oct to Feb (Initial RH 38% across the cellulose)

The remaining cellulose-insulated walls required a range of initial moisture contents to simulate their measured OSB MC-datasets because of the wide range in OSB MC within these walls.

The north-facing I-Joist wall, N2, had the widest distribution of OSB MC in the vertical profile. Figure 5-25 shows the lower, middle and upper OSB MC-data curves of the N2 wall during the baseline period in comparison with the WUFI® model data. The simulated OSB MC-data approximated the measured data well for the lower and middle MC-sensor locations. However, the upper MC-sensor data were more difficult to approximate because of the higher initial moisture content of the cellulose. The initial concentrations used at the L, M, and U sensor locations for the N2 WUFI® simulations were 53%, 72%, and 78% respectively.

Figure 5-25 Vertical OSB MC profile of the N2 test wall comparing WUFI® model results with the measured data for L, M, and U horizontal model planes (Initial RH – 53%, 72%, 78%)

The circled data in Figure 5-24 and Figure 5-25 show the effect of the moisture sensor isolators that were installed to eliminate the bypass current that passed through the cellulose insulation. These insulators were most effective with in walls where the initial RH across the stud cavity was below ~55% RH and the OSB MC was below 10%.

The relationship between the electrical sensor responses and the moisture contents of the OSB and cellulose should be analysed in detail to determine the effects of electrical polarization within the cellulose insulation and its overall effect on the electric field and measured resistance values

Figure 5-26 Vertical OSB MC profile of the N1 test wall comparing WUFI® model results with the measured data in the L, M, and U horizontal model planes (Initial RH - 55%, 60%, 55%)

The OSB L MC-data shown in Figure 5-25 also indicated that the electrical isolators applied to the MC-sensors were most effective at lower moisture contents since the simulated data closely approximated the measured data prior to the isolator installation in the middle and upper OSB MC-datasets. The middle and upper MC-data indicated that when the OSB MC was above 10-12% MC, the electrical resistance of the cellulose insulation was similar to the resistance of the OSB. The middle and upper data from this figure also show that the cellulose was rearranged during the installation of the isolators. This cellulose rearrangement suppressed the measured OSB MC until the moisture content of the cellulose re-equilibrated within the immediate vicinity of the MC-sensors. This effect was not seen in the

comparisons of the lower MC-sensor data because the cellulose MC was uniform across the depth of the wall cavity.

The simulated MC-data for the 11.1 mm, interior 3 mm, and the innermost 1.1 mm thicknesses how the electrical moisture sensor's depth of investigation changed based on the moisture flux. Under the more stable natural exposure conditions, the 11.1 mm WUFI® OSB MC-data was more representative of the measured data; however, during short-duration changes in the vapour drive, the 1.1 mm OSB thickness represented the MC-response more accurately. For this reason, the moisture content of the innermost 1.1 mm layer of the simulated OSB data was used as to compare with the measured datasets during the air leakage analysis.

The north-facing Type 1 wall performed marginally better than its south-facing counterpart did; however, both of these walls significantly underperformed the moisture performance of S2. The initial relative humidity values applied to the cellulose insulation were 55%, 60% and 55% through the N1 L, M, and U modelling planes, respectively. These data are presented with the N1 measured data in Figure 5-26 and they indicate that the isolators worked well when the initial relative humidity across the cellulose insulation was about 55% RH. The simulated data also indicated MC-sensor isolators had the largest effect on the measured data at the lower OSB MC-sensor location while the isolators only had a slight effect on the measured middle and upper OSB MC-sensor data.

The increased effect of the isolators on the OSB L MC-data shown in in Figure 5-26 may be a result of the cellulose density where better compaction at the lower MC-pins that improved the contact between the insulation and the MC-sensors.

The comparisons of the S1 OSB MC-data are presented in Figure 5-27. The measured S1 L MC-data were well correlated with the WUFI® data throughout the entire baseline analysis period while the measured data from the middle and upper MC-sensors were not as well approximated by the simulated data. The higher OSB MC-data (relative to the hygrothermal model) recorded at the middle and upper MC-sensor locations were probably caused by three-dimensional effects –like convective air movement – that could not be properly represented in a one-dimensional model.

The initial relative humidity values used for the cellulose insulation were 55%, 54% and 60% through the N1 L, M, and U modelling, respectively. The comparison of these measured and simulated MC-data also illustrated the diminishing effectiveness of the moisture sensor isolators at higher moisture contents or elevated RH-levels.

Figure 5-27 Vertical OSB MC profile of the S1 test wall comparing WUFI® model results with the measured data in the L, M, and U horizontal model planes (Initial RH – 36%, 54%, 65%)

5.6.1.2 Initial cellulose moisture content simulations for N2 I Joist wall

The differences between the OSB MC of the north and south facing I-Joist walls were investigated using the calibrated hygrothermal models. Since the south facing I-Joist wall, S2 performed much better than its north-facing counterpart did; multiple simulations were performed using the calibrated N2 wall model. These simulations used several different initial cellulose moisture contents to determine how the north facing I-Joist wall would have performed by varying the initial moisture content of the cellulose insulation. The initial cellulose moisture content was defined in the model by the setting the initial RH across the cellulose insulation. These initial RH-values were 30%, 40%, 50%, 72%, and 80%. The MC-

Initial RH (23°)*	Initial MC% Cellulose	Simulated OSB MC (Feb 19,2013)
30%	3.3%	9.2%
40%	4.4%	10.3%
50%	5.5%	11.6%
72%	10.7%	15.4%
80%	12.1%	21.6%

Table 5-3 Initial cellulose MC-values corresponding to initial RH condition

values of the cellulose that correspond to the initial RH-values used in the simulations are summarized in Table 5-3. This table also contains the calculated OSB MC-values at the end of the baseline period for each simulation (Feb 19, 2013). The cellulose moisture content values were determined from the moisture storage function created from the NRCC-50287 report data (Mukhopadhyaya et al., 2007).

The initial RH-value of 72% corresponded to the best-fit simulation value for the middle OSB MC-sensor data of wall N2 as shown in Figure 5-25 (middle). As a performance reference, the initial RH across the cellulose insulation in the best-fit model for the south facing I-joist wall, S2, was determined to be 38%, which corresponded to a cellulose moisture content of approximately 4.2% by weight.

The results of the N2 simulations are presented in Figure 5-28 using the OSB MC-data for the innermost (stud cavity side) 3 mm layer of OSB. These data indicate that the OSB MC was affected by the initial moisture content of the cellulose insulation and that the simulation data calculated using initial cellulose RH-values of 30% less yielded the lowest OSB MC-values. These data also indicated that the OSB MC responded sooner to higher initial cellulose MCs.

The measured stud cavity RH-data from each of the cellulose-insulated walls are presented in Appendix N. These data show that the S2 stud cavity RH was consistently lower than the RH measured in the N2 stud cavity during the baseline period, which resulted in the significant difference in OSB MC between these N2 and S2 walls. The RH data from the Type 1 walls were closely correlated between the north and south walls.

Figure 5-28 Simulated N2 OSB MC using a range of initial cellulose RH-values (30% to 80%)

5.6.2 Exterior insulated wall Types 5, 6, and 7

The three wall types that were insulated with rigid exterior insulation were also simulated using hygrothermal models created with the WUFI® software. These models used the same established surface transfer coefficients and exterior cavity ventilation rates as the previous simulations for the cellulose insulated walls. The OSB sorption curves were also adjusted to match the seasonal performance of the sheathing.

The measured OSB MC-data indicated that wall Types 5, 6, and 7 did not exhibit the same moisture

Figure 5-29 Baseline comparisons of measured and model MC-data for walls S 5, 6, and 7

related problems as indicated by the data collected from the deep cavity cellulose-insulated walls. Wall Types 5-7 had more uniform vertical moisture content profiles within the OSB sheathing as well as between upper and lower plates. For this reason, the measured and simulated MC-data comparisons for these three wall types are presented in Figure 5-29 (South) and Figure 5-30 (North) using only the middle OSB sensor datasets.

The simulated MC-data closely approximated the OSB moisture content of these three walls during the baseline period with the 1.1 mm OSB layer data yielding the closest approximation of the measured

Figure 5-30 Baseline comparisons of measured and model MC-data for walls N 5, 6, and 7

data. The model data for the Type 5 wall (polyisocyanurate insulation) tended to overestimate the amount of interior moisture relative to the other two wall types. The simulated cladding and OSB temperatures were well correlated with the measured data so the cause of this discrepancy was more likely related to the vapour permeability of the polyisocyanurate insulation or the interior drywall. Air leakage may also have been a factor since the Type 5 wall had a higher leakage rate than either the Type 6 or Type 7 walls (see Section 3.8.2 -Air tightness test data).

5.7 Air leakage simulations

The method used to simulate the air leakage (Künzel, 2012) involved the placement of a thin 1 mm air layer within the stud cavity (Figure 5-1) to simulate the air leakage. The air within this 1 mm layer was exchanged with the interior climate air using an Air Change Source. The maximum air exchange rate was determined by the converting the air injection rate to an air leakage rate based on the cavity wall area

Table 5-4 Air leakage rate for model simulations

Cavity Width	Cavity Height	Cavity Wall Area	Air Injection Rate	Cavity ALR
<i>(m)</i>	<i>(m)</i>	<i>(m²)</i>	<i>CFH (L/hr)</i>	<i>(L/hr·m²)</i>
0.570	2.30	1.311	40 (1133)	864

as shown in Table 5-4. Since the equivalent volume of the 1 mm air-change layer was one litre (0.001 m³), the calculated ACR for the cavity was 864 ACH for wall Types 2, 3, and 5-7. The ACR for wall Type 1 was 432 ACH because

of the interconnection between each stud cavity within the test panel. Modeling indicated that the actual ACR required to approximate the OSB MC data was higher than the theoretical 432 ACH.

The thin air-layer method of air leakage modelling was used with the middle and upper OSB MC-sensor data, since it did not simulate the enthalpy of the air leak. Rather, this method simulates low-flow air leakage with long, tortuous paths, and convective moisture sources (Künzel, 2012). Analysis of the vertical temperature profiles indicated that the middle and upper OSB temperatures were not appreciably affected by the injected air. Therefore, this method was more suitable for use with the middle and upper OSB sensor data rather than the lower OSB sensors. In order to model the lower OSB MC-sensor data, an additional heat source with a transient file would be required for the proper simulation of the heat associated with the injected air.

Figure 5-31 shows the temperature differences between the lower and middle S3 OSB sensors in comparison with their corresponding WUFI® output from February 17th to 23rd, 2013. The air injection

Figure 5-31 OSB temperatures during air injection test show the difference between the measured lower and middle OSB data and the WUFI® data.

test started on February 19th at 16:30 hours and, as the figure shows, the temperature response recorded by the lower OSB T sensor was immediate. In comparison, the S3 WUFI® simulation more closely approximated the measured OSB temperature data at the middle sensor location. The WUFI® model used an 864 ACH air change rate in the 1 mm air change layer (the upper OSB temperature data were omitted from Figure 5-31 for clarity.)

5.7.1 Air leakage modeling methodology

The air leakage modeling exercise examined the variability of the injected air flow-path by calibrating the ACR of the 1 mm air change layer with the measured data from the high RSI and datum walls. The idealized flow-path for the air injection experiment is shown in Figure 5-32 along with the minimum expected vertical air-velocities. The flow-path and air velocity within the stud cavity, however, were influenced by the cavity geometry as well as insulation type and density. The flow-paths within the south-facing walls may also have been enhanced by convective air currents arising from solar heating.

The WUFI® simulations were calibrated by varying the leakage rate via the ACR of the 1mm air change layer and its placement along the horizontal plane of the OSB MC-sensors shown at M and U in Figure 5-32. The airflow rate for each simulation was calibrated with the corresponding OSB MC-data to establish an effective or equivalent flow rate based on the moisture load of the interior air and the RH of the stud cavity.

The location of the 1 mm air-layer along the horizontal model plane influenced the OSB MC primarily through the through arrival time of the OSB moisture response and to a lesser degree the magnitude of the MC response. Placement of the 1 mm air-layer at the inner surface of the OSB generally had the closest approximation of the OSB MC curve for the fiberglass-insulated stud cavities of the datum walls.

Figure 5-32 Idealized flow path of the injected air and the modeling planes L, M, and U (Lower, Middle and Upper)

For the cellulose-insulated walls, the arrival time of the moisture flux was greatly affected by the moisture storage of the cellulose and the placement of the 1 mm air layer relative to the OSB. The walls with exterior insulation were generally modeled with the 1 mm air layer in the centre of the stud cavity.

5.7.2 Air leakage model calibration

The air leakage modeling used a segmented stud cavity (quartered) so that the 1mm air layer could be

Figure 5-33 Stud cavity configuration for air leakage modeling

repositioned within the cavity. Figure 5-33 illustrates the configuration of the stud cavity and the location of the 1 mm air layer for the calibration. The air layer position was designated as a percentage of cavity depth starting from the interior face of the OSB sheathing (0%) to the exterior side of the 6-mil polyethylene (100%). During comparative modeling

analysis, the 1 mm air layer was initially placed at the 100% position and moved towards the OSB with changes to the air change rate depending on the model results. This process determined the air change rate and position of the 1 mm air layer that best approximated the moisture content response of the OSB to the air leakage test.

Table 5-5 Summary of 1 mm air layer position and air change rate

	South						North					
	1	2	3	5	6	7	1	2	3	5	6	7
Position	50%	50%	0%	50%	50%	50%	25%	50%	0%	25%	50%	25%
ACH	864	778	300	100	300	100	864	864	300	864	864	864

A sample of some comparative results for the south-facing walls S1, S2, and S3 are presented Figure 5-34. These data show the close correlation between the measured and simulated data during the air leakage test. The two datasets diverge, however, at the end of the test (April 8th) through the drying

period. The model data predicted lower OSB MC values during this time because the one-dimensional model did not account for the entire volume of moisture stored within the wall as well as additional moisture loads arising from convective moisture movement. At the end of the drying period (June 3), both the measured and modeled datasets had converged to within 1%.

The hygrothermal models of the remaining High RSI test walls were also calibrated in this manner. The purpose of this calibration to the measured data was to improve the predictive capacity of the models. The middle OSB MC-sensor data were used to determine the effective flow rate and position of the 1

Figure 5-34 Moisture content comparison of measured and simulated data for S1-3 during air leakage test

mm air layer. The results of this model exercise are summarized in Table 5-5 with the position and air change rate for the 1 mm air layer that most closely approximated the OSB M MC-data during the air injection test. These tabled data show that the north-facing walls generally required higher air change rates in the 1 mm layer as well as placement closer to the OSB. This difference is likely a result of solar heating in the south facing test walls that reduces the impact of air leakage on the OSB moisture content.

The lower OSB MC-data could not be modeled as precisely because of the temperature and air current effects caused by the air injected air and the drainage of condensation from the upper sections of the wall. The temperature effects of the air leak were the lowest in the deepest cavity wall – Type 1, with negligible temperature effects in the north-facing wall and only nighttime temperature differences in the south-facing wall, S1. The measured and simulated MC-data are presented in Figure 5-35 to illustrate the effects of condensation, temperature and air circulation at the lower horizontal model plane 'L'. The OSB sheathing of S1 experienced greater drying because of its southern exposure and subsequently less condensation, which the WUFI® model was able to simulated relatively well. The simulations did not replicate the sheathing moisture content in the north-facing wall since the

Figure 5-35 Air leakage comparisons of the measured and simulated MC-data at the Lower model plane of S1 & N1

Figure 5-36 Air leakage comparisons of the measured and simulated MC-data at the upper model plane of S1 & N1

condensation accumulated in the lower portion of the wall without the drying influence of the sun and convective airflow.

The measured S1 OSB L MC-data (shown in Figure 5-35) were modeled with the 1 mm air layer located at the OSB (0% cavity position) and an 864 ACH air change rate. The measured data for N1 OSB L were modeled using three 1 mm air layers that distributed the moisture load throughout the air injection period; otherwise, the shape of the OSB MC resembled the response observed in the S1 MC-data. The three air layers were placed at 0%, 25% and 50% with corresponding air change rates of 216, 216, and 432 ACH. By distributing the total air change rate within the stud cavity, the effect of the cellulose insulation's moisture storage capacity was more effectively simulated. The effect of condensation, however, would require an additional moisture source and a transient file defining the amount of liquid water present.

During the modeling process, it was also observed that the placement of the 1 mm air layer at (or too close to) the OSB sheathing resulted in a drying effect that reduced the OSB MC by drying the cellulose. This effect occurred because the moisture load of the interior air was less than that of the cellulose insulation. This drying effect only occurred where the cellulose moisture content was initially elevated.

5.8 *Model discussion*

The surface transfer coefficients were the primary target of optimization as these constants controlled how the model interacted with the boundary conditions, which ultimately determined the temperature regime of the hygrothermal model. The temperature regime was also determined by the thermal conductivity of the wall components and to a lesser extent the cavity ventilation of the drained-screened cladding system. The ventilation of the exterior cavity primarily influenced the flow of water vapour through the assembly in conjunction with the water vapour permeance values of the assembly components (M-values). The optimization of the surface transfer coefficients was also an iterative process as some of the coefficients were interdependent. Some of these coefficients were defined with constants although they varied seasonally like albedo and to a certain degree cloud index. When combined with certain three-dimensional effects like the moisture storage in framing, some inter-seasonal analyses can become difficult to perform accurately. These issues were most apparent in the divergences between the measured data and the simulated data during the drying period after the air injection test.

The sequence in which model calibrations were performed minimized some of the compounding effects of physical property errors by first optimizing the factors that governed the temperature regime within the model. As some of the surface transfer coefficients represented variables but were defined with constant values, these constants inherently led to seasonal inaccuracies. These errors were minimized by calibrating the surface transfer coefficients separately through isolation. Accurate climate data were essential to establish representative boundary conditions for the model.

Once the temperature and humidity profiles of the interior and exterior wall cavities were established in the model, the hygroscopic properties of the sheathing and insulation materials were then investigated and optimized. The temperature and humidity of the wall cavities adjacent to the sheathing governed the moisture content and vapour permeability of this component because of the sheathing's hygroscopic properties. The interconnected nature of the surface transfer coefficients, boundary conditions, and material properties necessitated this sequencing in order to obtain optimized-values for the coefficients and minimize compounding errors.

6 CONCLUSIONS

The following conclusions are based on observations between October 2012 and June 2013 and do not include summertime moisture responses or the water injection test. These results are applicable to southern Ontario in an urban setting with simulated air leakage during the 49-day test from February to April 2013 and do not constitute the final results of the High RSI wall study.

6.1 *High RSI wall performance*

The datum walls, wall Type 4, and the exterior insulated test wall Types 5-7 had uniform moisture distribution throughout their wood-based components during the baseline period. The standard deviation of the MC-data in these walls was less than 0.5% in the OSB sheathing and less than 1% between the upper and lower plates. Moisture distribution within the deep cavity cellulose-insulated walls was more complex and the data indicated that the moisture stratification occurred with an overall tendency of higher MC-data in the upper portions of the cavity and framing. This effect was most exaggerated in the north facing walls.

The air injection test illustrated that the warmer OSB sheathing of the exterior insulated walls reduced the risk of moisture related problems especially near the location of the air leak. The sheathing in wall Types 5-7 performed very well during the air injection test as the OSB MC-data were consistently below 16%. The upper section of the stud cavity and the upper framing members had very slight risks of mould growth in the walls with low vapour permeability exterior insulation (Types 5 and 6). The upper plate in wall Type 5 was the highest of the exterior insulated group with the moisture content of the N5 upper plate exceeding 20% for two weeks in March 2013.

The exterior insulated walls performed better than the deep cavity walls during the wintertime air leakage test primarily because the sheathing and framing materials were kept well above the condensation point. Wall Type 7 outperformed the other two exterior insulated wall types because of the high vapour permeability of its exterior insulation, which allowed the sheathing and framing to dry to the exterior. The MCs within the Type 7 walls did not exceed 12% MC at any time during the analysis period.

The deep cavity cellulose-insulated walls and the datum walls had the largest overall increase in OSB and plate MC during the study period. The condensation in these walls began in early fall and continued into late spring. The very high MC in the lower plates of the deep cavity walls remained long after the other

wall types had dried below the lower decay and mould risk thresholds. The condensation arising from the cold sheathing may have been trapped on the plates by the OSB and WRB. In the south orientation, solar heating assisted drying by evaporating the condensed water, which allowed the water vapour to escape through the sheathing and WRB. The north facing walls did not benefit from direct solar radiation so the drying process was much slower. The slower drying potential of the north facing walls also indicated that the thermally isolated exterior plates in the double stud walls could be especially problematic when coupled with cold, uninsulated sheathing that promoted condensation and increased the potential for rundown and the pooling of liquid water on the plate.

The south facing I-Joist (S2) wall showed some promise for the deep cavity cellulose approach as its OSB sheathing moisture performance was better than that of the south datum wall. Model analysis suggested that the lower OSB MC-values within S2 arose from a low initial cellulose MC in the ~4% MC range. However, even though the OSB sheathing in S2 wall performed well, the framing plates still experienced elevated MC-levels in the 20% range. While reducing the initial moisture content of the cellulose lowers the built-in moisture load of the wall and can reduce moisture related problems by increasing its moisture buffering capacity, the fundamental issue with this wall type remains the presence of a cold, uninsulated sheathing that provided a condensation plane in cold weather.

Obtaining reliable moisture content data from walls insulated with cellulose was challenging since the electrical properties of the cellulose insulation also changed with moisture content. The electrical field produced during the moisture content measurements was affected by both the conduction of electricity through the cellulose as well as the polarization of the cellulose (specifically the adsorbed water). The largest source of uncertainty associated with the cellulose insulation was determined to be the direct conduction of electricity through the exposed wire connections on the moisture sensor pins. This uncertainty was minimized by the installation of the silicon-filled caps overtop of the moisture sensor pins. These caps or similar electrical insulation should be installed over the MC-sensors prior to the placement of the cellulose in future research.

In future studies with unconventional framing materials like I-Joist wall studs, moisture content sensors should be installed near the base of the I-Joist web to monitor the impact of interstitial condensation and determine risks to the structural integrity of these types of framing members.

6.2 *Hygrothermal modeling*

The OSB sorption data were used to improve the calibration between the simulated and measured MC-data by adjusting the values within the OSB MSF. These changes were based on the prevalent RH-values within the stud and exterior cavities during periods when significant divergences occurred between the measured and simulated datasets. These RH-values proved to be effective in removing the uncertainty associated with the OSB MSF. Upon completion of the High RSI wall study, sorption isotherms could be determined for the OSB at the MC-sensor locations in order to compare the measured with predicted OSB MSFs.

The upper and lower bounds of the OSB sorption curves suggested that an average 2-3% MC performance range could be expected in the simulation results within a model calibrated for temperature and humidity. The range of values in the OSB MSF had the greatest effect on the difference between the measured and simulated MC-values while the range of uncertainty in the OSB WVDR factor had a negligible effect on the model performance.

Adjustments to the moisture storage function (once isolated through the calibration of the temperature and humidity regimes) resulted in significant improvements between the measure and simulated results. These improvements varied by wall type and orientation; however, they were typically in the 2-4% MC range. At 50% RH (and below), the uncertainty in the OSB MSF could result in a 3.3% MC difference, while above 93% RH the uncertainty climbed to 6%. Between 50% and 93% RH, the uncertainties in the OSB MSF were in the range of 1-2% based on the range of values in the sorption/desorption data.

The four sections of the OSB layer provided useful insight into the MC-profile across the thickness of the OSB both seasonally and during active moisture loading. The measured MC-data were most closely approximated by the MC-data simulated using the innermost 1.1 mm OSB layer. The multi-layered OSB could also be used to investigate the effect of RH differentials across the sheathing on its water vapour permeability. Multiple OSB model layers may also assist in the development of a damage function for OSB sheathing by providing an estimation of the degree of wetting present through moisture content distribution.

The two-layer exterior cavity improved the correlation between the measured RH and simulated RH of the exterior cavity by buffering the effects of excessive ventilation that occurred as a result of the constant air change rate. While the two-layer exterior cavity provided some insight into the air

movement within the cavity, the daily fluctuations in the exterior air layer could have been simulated using a transient file. The transient file may also be easier to relate the magnitude of the ACR to solar radiation or wind, however these ACRs would be specific to a given weather file.

The air leakage modeling indicated that the 1 mm air change layer was effective for simulating the OSB MC that was not affected by temperature. The simulations showed that a separate transient file would be necessary to account for the heat associated with the air leak in order to simulate the lower OSB MC-sensor data.

The location of the 1 mm air change layer within the stud cavity was found to be most representative in the middle or at 50% of the cavity depth for the south facing walls. The north walls were best represented by either the 50% or 25% cavity depth position as measured from the OSB. Since the location of the 1 mm layer within the cavity affected the 1 mm ACR that best fit the data, there exists uncertainty with respect to the absolute values of the simulated flow rates or 1 mm air layer position.

The simulations required lower ACRs in the 1 mm air change layer in order to simulate the measured MC-data of the south facing exterior insulated walls relative to their north facing counterparts. The ACRs used in the north facing simulations were the same for each High RSI wall type. Both Type 1 walls used the calculated ACR value of 864 ACH while the other wall types varied from north to south – this may have been a function of cavity depth.

The location of the 1 mm air change layer within the stud cavity affected the OSB MC-response time most significantly in the Type 1 & 2 deep cavity walls because of the moisture storage within the insulation that buffered the introduced moisture and retarded the OSB MC-response.

7 FUTURE WORK

A model study should extend the performance evaluations of the High RSI walls to include geographical locations with a wide range of climates in order to determine the limits of performance. An expanded model study could also be pursued to investigate wall modifications like different materials or framing configurations. The models created in this project could also be used to determine the effects / limits of higher RSI levels on moisture performance.

The investigation of deep-cavity cellulose-insulated walls would benefit from more detailed material property data that examined the sorption and desorption curves at typical high, low, and average service temperatures. Enhanced knowledge regarding the electrical properties of cellulose and its susceptibility to polarization at varying relative humidities or moisture contents would also be beneficial for data acquisition. Future work should also include a greater number of RH/T sensors within deep cavity cellulose-insulated walls in order to determine how entrained moisture migrates on a seasonal basis.

The mould and decay analysis should be extended to include a time-component that reflects the length of time required to initiate mould growth on OSB and spruce-pine-fir lumber. This was not included in this study but it would be beneficial asset in the determination of wood framed wall durability.

Appendix A. CONSTRUCTION AND INSTALLATION DETAILS

In July and August of 2012, the 1.2mx2.4m test wall panels were constructed and installed at the University Of Waterloo Building Engineering Group (BEG Hut) test facility. The top and bottom of the test hut wall openings were divided into bays to accept the test panels. These bays were hygrothermally isolated with 38mm extruded polystyrene (XPS) insulation and finished with spruce plywood (12.5 mm) that provided a nailing surface. Vertical separators were then installed to isolate each assembly. The separators consisted of 241mm I Joists with 12.5mm XPS insulation adhered to either side of the web and flush with the flange edges. The wall openings of the test facility were subsequently flashed with Blueskin membrane to ensure against the ingress of rainwater. The rough installation is illustrated shown below in Figure 7-1 Installation of rough framed test panels prior to instrumentation and sealing. SW corner of BEG Hut shown.

The wall assemblies were placed into the rough openings with a 12.5 mm (approximate) space around

Figure 7-1 Installation of rough framed test panels prior to instrumentation and sealing. SW corner of BEG Hut shown.

the panel edge to allow access for external sensors and supply tubing. These spaces were sealed with spray foam and silicone to eliminate the possibility of air leakage around the edges of the test panels.

The structural framing of each wall type was completed according to the technical drawings located in Detailed Construction Drawings. The rough framing of each assembly consisted of two main central stud members, top and bottom plates, two 9.5 mm plywood edge studs as well as the OSB sheathing. The OSB sheathing was installed in two pieces (610 x 1220 mm, 1829 x 1220 mm) to ensure that one sheathing joint was identically located in each test assembly. The joint was placed 610 mm up from the bottom of the wall.

Once the roughed in wall assemblies were fastened into position, the monitoring sensors, wetting sheet and supply tubing were installed. The final placement of the exterior temperature and air cavity space RH/T sensors was completed with the installation of the siding.

The exterior wetting sheet was stapled into position with the 6 mm poly tubes as shown in Figure 7-2. The feeder tubes were routed inside between the assembly and the dividers. The wetting sheet wrapped around the perforated end of the tubing across the width of the sheet to ensure the even distribution of injected water and stapled to the OSB. The tubing was perforated using with a 3mm drill bit create four holes (top, bottom and sides) at 50 mm intervals across the width of the wetting sheet. The wetting sheet was placed on the vertical centre line of the panel about 90mm above the bottom

Figure 7-2 Location of exterior wetting apparatus on the exterior OSB surface (left photo) – close -up photo (right)

edge of the OSB. The top edge of the wetting sheet (and the tubing) was placed 90mm below the OSB joint.

Once the wetting sheets and tubing were installed, the Tyvek air barrier / water resistive barrier (WRB) was placed on the OSB and sealed to the Blueskin using the red construction tape shown in Figure 7-3. The space around the panel was sealed from the inside using spray foam (window and door foam sealant). The exterior was then finished with insulation (as required) and spruce strapping to provide a nailing surface for the siding and an air space for the rain screen.

Figure 7-3 Air and water barrier of the drainage cavity

The siding was installed in the latter half of August 2012. The siding was installed continuously over the entire length of the adjoining test panels. The siding joint locations were carefully selected to ensure that each test panel had the same number of joints. At this time, the installation of the exterior temperature and RH/T sensors was completed. Figure 7-4 show the north and south facing walls (respectively) of the BEG Hut prior to siding installation.

After the siding was installed, a continuous flashing was placed at the top of the test walls to shed rainwater. Once the exterior of the building was completed, the instrumentation was finished on the interior. The interior fibreglass insulation was installed as well as the 6-mil poly where required. Each sheet of gypsum wallboard was cut and fit with an air injection port then sealed.

Figure 7-4 North BEG Hut test walls N1 to N7 (left photo); South test walls S1 to S7 (right photo)

The sensor wiring and datalogger programming followed throughout the month of September. Data collection began on October 4, 2012.

Appendix B. DETAILED CONSTRUCTION DRAWINGS

S2, N2 – 241 mm I Joist Framed Wall

Plan View

S3, N3 – Standard 38 x 140 mm Framed Wall

Plan View

S4 – 38 x 184 mm Framed Wall with Closed Cell Spray Foam

Plan View

S5, N5 – 38 x 140 mm Framed Wall with 50 mm Exterior Polyisocyanurate Insulation

Plan View

S6, N6 – 38 x 140 mm Framed Wall with 64 mm Exterior XPS Insulation

Plan View

S7, N7 – 38 x 140 mm Framed Wall with 76 mm Exterior Mineral Wool Insulation

Plan View

MUX #1 Temperature – South Walls

Power out from Vx1 to South Power Bar (2.5 V)
Res wired to C1 and Clk wired to C2 – MUX 1 run
simultaneously with MUX 2

MUX #2 Temperature – North Walls

Power out from Vx2 to North Power Bar (2.5 V)
Res wired to C1 and Clk wired to C2 – MUX 1 run simultaneously with MUX 2

MUX #3 Moisture Content – Top 3 pin sets

7 – SW12 Power wires out to S Power Bar – CH 1–13 (ODD H) Blue {Bundled or individual as necessary}
 6 – SW12 Power wires out to N Power Bar – CH 15–25 (ODD H) Blue {Bundled or individual as necessary}

MUX #4 Moisture Content – Bottom 2 pin sets

- 5 – SW12 Power wires out to S Power Bar – CH 1–9 (ODD H) Blue {Bundled or individual as necessary}
- 4 – SW12 Power wires out to N Power Bar – CH 10–17 (ODD H) Blue {Bundled or individual as necessary}

Orange Tape (All)

MUX #5 Relative Humidity and Heat Flux

RH Power out from 5 V on Datalogger, RH Ground returns to Datalogger power strip

RH signals Single-ended voltage 2x32 CH 1-13, (Odd, Even) H-G, L-G

HF signals Differential Voltage 2x32 CH 15-22, Odd H-L, Even H-L

HF Wires bundled yellow for S2, S3 and white for S4, S5

Appendix D. SENSOR CODE AND TERMINAL STRIP PLAN

Position	Panel ID -			
		Sensor Code	Wire color	
1	MC Pwr		White/Blue	
2	MC Pwr		White/Blue	
3	MC1	MDET		Plate T
4	MC2	MEIU		OSB T
5	MC3	MEIM		OSB M
6	MC4	MEIL		OSB B
7	MC5	MDEL		Plate B
8	MC_T Pwr		White/Orange	
9	MC_T Pwr		White/Orange	
10	MC_T1	TDET		Plate T
11	MC_T2	TEIU		OSB T
12	MC_T3	TEIM		OSB M
13	MC_T4	TEIL		OSB B
14	MC_T5	TDEL		Plate B
15	RH Pwr		White/Green	
16	RH Ground			
17	RH1	RINM		Fur Cavity
18	RH2	RCNM		Ins Cavity
19	RH_T Pwr		White/Orange	
20	RH T1	TINM		Fur Cavity
21	RH T2	TCNM		Ins Cavity
22	TPwr		White/Orange	
23	T1	TJEM		Ext Temp
24	T2	TAIM		Int Temp
25	HF1-in	HCIM		Cavity
26	HF1-out			
27	HF2-in	HDIM		Stud
28	HF2-out			
29				
30				
31				
32				

Appendix E. CAMPBELL SCIENTIFIC DATALOGGER PROGRAM

```

Program: Final DAQ Program (Nov19).CR1
'CR1000 Series Datalogger
'To create a different opening program template, type in new
'instructions and select Template | Save as Default Template
'date: NOV 19,2012
'program author:MF
'Wall Assemblies -
'N1 OR S1 = 2x4 / 2x6 Double Stud Construction with cellulose insulation
'N2 OR S2 = 9.5" I Joist Construction with cellulose insulation
'N3 OR S3 = 2x6 Standard Construction
'S4 = 2x8 Construction with ccSPF
'N5 OR S5 = 2x6 Construction with exterior polyisocyanurate
'N6 OR S6 = 2x6 Construction with exterior XPS
'N7 OR S7 = 2x6 Construction with exterior Roxul

Public PTemp, batt_volt
Public SensorRes(6)

Public TempS(64)      'Reads directly from Multiplexer
Public TempN(64)      'Reads directly from Multiplexer

Public MCTemp(65)
Public AirTempS(1)
Public AirTempN(1)

Public MDET(13)      'Reads directly from Multiplexer
Public MEIU(13)      'Reads directly from Multiplexer
Public MEIM(13)      'Reads directly from Multiplexer
Public MEIL(13)
Public MDEL(13)
Public Btm2MC(27)    'Reads directly from Multiplexer

Public MDETperc(13)
Public MEIUp(13)
Public MEIMperc(13)
Public MEILperc(13)
Public MDELperc(13)

Public RH(28)        'Reads directly from Multiplexer
Public RHAirS(1)
Public RHAirN(1)

Public HF(9)          'Reads directly from Multiplexer
Public HFFinal(9)

'Define the units for each variable'
Units TempS = degC
Units TempN = degC

Units MDET= MOhms
Units MEIU= MOhms
Units MEIM= MOhms
Units MEIL= MOhms
Units MDEL= MOhms

Units Btm2MC= MOhms
Units RH= %
Units HF = W_m2
Units HFFinal= W_m2
Units PTemp = degC
Units batt_volt = Volts

'The number of samples for each MC sensor'
Const MCsamples = 10

'Heat flux sensors are wired and read as - S2-cavity, S2-framing, S3-cavity, S3-framing, etc...

```

Program: Final DAQ Program (Nov19).CR1

```

Const HFMulti1 = 5.84 'Sensor #4386
Const HFMulti2 = 5.9 'Sensor #4385
Const HFMulti3 = 11.11 'Sensor #3134
Const HFMulti4 = 5.99 'Sensor #4387
Const HFMulti5 = 11.01 'Sensor #3132
Const HFMulti6 = 26.31 'Sensor #815
Const HFMulti7 = 11.36 'Sensor #3133
Const HFMulti8 = 26.94 'Sensor #816
Const HFMulti9 = 11.05 'Sensor #3131

'Constants for a and b in MC calculation
Const a = 0.702 ' offsets for Eastern White / Norway Spruce
Const b = 0.818
Const aOSB = 1.1114 'offsets for OSB
Const bOSB = 0.366

'Variables defined for use in CJS subroutines'
Dim ThermVolt(2), ThermRes(2), LnThermRes(2), ThermTemp(2) 'These arrays store the measured variables from SE 1,2
Dim ThermVoltN(2), ThermResN(2), LnThermResN(2), ThermTempN(2) 'These arrays store the measured variables from SE 3,4
Dim OutputFlag
Dim HycalRH(2) 'For RH subroutine to store measured variables from SE 11,12'
Dim ChannelNum
Dim MCNum
Dim Count, CountS, CountN,
Dim SampleNum, Vsup, ChNum
Dim Meas, MeasSum, MeasCnt, MeasAvg, WoodRes, SensRes
Dim HFTemp
Dim MDETunc(13), MEIUunc(13), MEIMunc(13), MEILunc(13), MDELunc(13)
Dim TDET(13), TEIU(13), TEIM(13), TEIL(13), TDEL(13)
Dim SCount, NCount

'*****Read
'Define Data Tables

'Data table for Air Injection RH and Temp sensors
DataTable(AirInj, true, -1)
DataInterval(0, 60, min, -1)
Average(1, AirTempS, IEEE4, 0)
Average(1, RHAirS, IEEE4, 0)
Average(1, AirTempN, IEEE4, 0)
Average(1, RHAirN, IEEE4, 0)
EndTable

'Data table For Battery,
DataTable(General, True, -1)
DataInterval(0, 60, min, -1)
Minimum(1, batt_volt, IEEE4, 0, 0)
Average(1, PTemp, IEEE4, 0)
Sample(6, SensorRes, IEEE4)
EndTable

'*****
'*****
DataTable(MDET, true, -1)
DataInterval(0, 60, min, -1)
Average(13, MDET, IEEE4, 0)
EndTable

DataTable(MEIU, true, -1)
DataInterval(0, 60, min, -1)
Average(13, MEIU, IEEE4, 0)
EndTable

DataTable(MEIM, true, -1)
DataInterval(0, 60, min, -1)
Average(13, MEIM, IEEE4, 0)

```

Program: Final DAQ Program (Nov19).CR1

```
EndTable

DataTable (MEIL,true,-1)
    DataInterval (0,60,min,-1)
    Average (13,MEIL,IEEE4,0)
EndTable

DataTable (MDEL,true,-1)
    DataInterval (0,60,min,-1)
    Average (13,MDEL,IEEE4,0)
EndTable

DataTable (HF,true,-1)
    DataInterval (0,60,min,-1)
    Average (9,HFFinal,IEEE4,0)
EndTable

DataTable (TempS,true,-1)
    DataInterval (0,60,min,-1)
    Average (64,TempS,IEEE4,0)
EndTable

DataTable (TempN,true,-1)
    DataInterval (0,60,min,-1)
    Average (64,TempN,IEEE4,0)
EndTable

DataTable (Btm2MC,true,-1)
    DataInterval (0,60,min,-1)
    Average (27,Btm2MC,IEEE4,0)
EndTable

DataTable (RH,true,-1)
    DataInterval (0,60,min,-1)
    Average (28,RH,IEEE4,0)
EndTable

DataTable (MCperc,true,-1)
    DataInterval (0,60,min,-1)
    Average (13,MDETperc,IEEE4,0)
    Average (13,MEIUpert,IEEE4,0)
    Average (13,MEIMperc,IEEE4,0)
    Average (13,MEILperc,IEEE4,0)
    Average (13,MDELperc,IEEE4,0)
EndTable

DataTable (T_RH_HF_15min,true,-1)
    DataInterval (0,15,min,-1)
    Sample (64,TempS,IEEE4)
    Sample (64,TempN,IEEE4)
    Sample (28,RH,IEEE4)
    Sample (9,HFFinal,IEEE4)
EndTable

DataTable (MCperc_15min,true,-1)
    DataInterval (0,15,min,-1)
    Sample (13,MDETperc,IEEE4)
    Sample (13,MEIUpert,IEEE4)
    Sample (13,MEIMperc,IEEE4)
    Sample (13,MEILperc,IEEE4)
    Sample (13,MDELperc,IEEE4)
EndTable
'*****
'Define Subroutines
Sub Tsub ()
```

Program: Final DAQ Program (Nov19).CR1

```

'----FENWALL UNICURVE(R) 10K THERMISTOR Subroutine CJS
'Read V across 1000 Ohm fixed resistor in 1/2 bridge with 10K thermistor
'South Readings
ExciteV (Vx1,2500,0) 'Turn on Excitation E1 @ 2500 mV
Delay (0,10,msec)
'Make Measurements
VoltSe (ThermVolt(),2,autorange,1,0,0,_60Hz,1.0,0)
ExciteV (Vx1,0,0) 'Turn off Excitation E1

For Counts = 1 To 2
'Calc thermistor resistance in Ohms
ThermRes(Counts)=1.00E3*(2500-ThermVolt(Counts))/ThermVolt(Counts)
'Calc Ln(ThermRes)
LnThermRes(Counts) = LN(ThermRes(Counts))
'Calc temperature in degC
ThermTemp(Counts) = -0.101*(LnThermRes(Counts))^3 + 4.346*(LnThermRes(Counts))^2 - 77.18*(LnThermRes(Counts)) + 446.05
'Filter ThermTemp values
If ThermTemp(Counts) = 446.05 Then
ThermTemp(Counts) = NaN
ElseIf ThermTemp(Counts) < -100 Then
ThermTemp(Counts) = NaN
EndIf
Next
'North Readings
ExciteV (Vx2,2500,0) 'Turn on Excitation E2 @ 2500 mV
Delay(0,10,msec)
VoltSe (ThermVoltN(),2,autorange,3,0,0,_60Hz,1.0,0)
ExciteV (Vx2,0,0) 'Turn off Excitation E2

For CountN = 1 To 2
'Calc thermistor resistance in Ohms
ThermResN(CountN)=1.00E3*(2500-ThermVoltN(CountN))/ThermVoltN(CountN)
'Calc Ln(ThermRes)
LnThermResN(CountN) = LN(ThermResN(CountN))
'Calc temperature in degC
ThermTempN(CountN) = -0.101*(LnThermResN(CountN))^3 + 4.346*(LnThermResN(CountN))^2 - 77.18*(LnThermResN(CountN)) + 446.05
'Filter ThermTemp values
If ThermTempN(CountN) = 446.05 Then
ThermTempN(CountN) = NaN
ElseIf ThermTempN(CountN) < -100 Then
ThermTempN(CountN) = NaN
EndIf
Next
EndSub

'*****
Sub MFASub (ChannelNum)
'----MEASUREMENT, FILTER & AVERAGE Subroutine CJS
'Begin Reset Loop
MeasSum = 0
MeasCnt = 0
'End Reset Loop
'Begin Measurement & Filter Loop - Measure voltages X times & filter out -ves
'Read V across fixed resistor in 1/2 bridge with resistance based sensor
'Check PassNum & Make Measurement

If ChannelNum = 5
For SampleNum = 1 To MCsamples
VoltSe (Meas,1,autorange,5,0,20000,_60Hz,1.0,0)
'Begin Filter Loop
If Meas>0 Then
'Add current measurment to sum & add 1 to count
MeasSum = MeasSum + Meas
MeasCnt = MeasCnt + 1
SensRes = 10000

```

Program: Final DAQ Program (Nov19).CR1

```

EndIf
'End Filter Loop
Next 'End Measurement & Filter Loop
ElseIf ChannelNum = 6
For SampleNum = 1 To MCSamples
VoltSe (Meas,1,autorange,6,0,20000,_60Hz,1.0,0)
'Begin Filter Loop
If Meas>0 Then
'Add current measurment to sum & add 1 to count
MeasSum = MeasSum + Meas
MeasCnt = MeasCnt + 1
SensRes = 10000
EndIf
Next 'End Measurement & Filter Loop
ElseIf ChannelNum = 7
For SampleNum = 1 To MCSamples
VoltSe (Meas,1,autorange,7,0,20000,_60Hz,1.0,0)
'Begin Filter Loop
If Meas>0 Then
'Add current measurment to sum & add 1 to count
MeasSum = MeasSum + Meas
MeasCnt = MeasCnt + 1
SensRes = 10000
EndIf
'End Filter Loop
Next 'End Measurement & Filter Loop
ElseIf ChannelNum = 8
For SampleNum = 1 To MCSamples
VoltSe (Meas,1,autorange,8,0,20000,_60Hz,1.0,0)
'Begin Filter Loop
If Meas>0 Then
'Add current measurment to sum & add 1 to count
MeasSum = MeasSum + Meas
MeasCnt = MeasCnt + 1
SensRes = 9850
EndIf
'End Filter Loop
Next 'End Measurement & Filter Loop
ElseIf ChannelNum = 9
For SampleNum = 1 To MCSamples
VoltSe (Meas,1,autorange,9,0,20000,_60Hz,1.0,0)
'Begin Filter Loop
If Meas>0 Then
'Add current measurment to sum & add 1 to count
MeasSum = MeasSum + Meas
MeasCnt = MeasCnt + 1
SensRes = 9900
EndIf
'End Filter Loop
Next 'End Measurement & Filter Loop
ElseIf ChannelNum = 10
For SampleNum = 1 To MCSamples
VoltSe (Meas,1,autorange,10,0,20000,_60Hz,1.0,0)
'Begin Filter Loop
If Meas>0 Then
'Add current measurment to sum & add 1 to count
MeasSum = MeasSum + Meas
MeasCnt = MeasCnt + 1
SensRes = 9870
EndIf
'End Filter Loop
Next 'End Measurement & Filter Loop
EndIf
'Calculate average of +ve voltage measurements
MeasAvg = MeasSum/MeasCnt 'in mV (?)

```

Program: Final DAQ Program (Nov19).CR1

```
EndSub
'*****
Sub MCRSub (ChannelNum)
'----MOISTURE CONTENT BY RESISTANCE Subroutine CJS
'Read V across 10000 Ohm fixed resistor in 1/2 bridge with wood MC pins
'Turn on Switched 12V
SW12 (1)
'Delay to ensure 12V on
Delay (0,1000,mSec)
'Measure Battery Voltage
Battery (Vsup)

'Call Measurement, Filter & Average Subroutine
Call MFASub (ChannelNum)
'Turn off Switched 12V
SW12(0)
'Delay to ensure 12V off
Delay (0,5,msec)
'Calculate wood resistance (in MOhms) <MJF> ADD in actual resistor voltages ch8=9850,ch9=9900,ch10=9870,ch5,6,7=10000
WoodRes = (SensRes*(Vsup/(MeasAvg/1000)))-SensRes 'Voltage divider formula (in Ohms) Rt=(Vt/Vs)*Rs, Rt=Rw+Rs, Rs=10kOhms. mV/mV
WoodRes = WoodRes*10^(-6) 'convert to MOhms
SensorRes(ChannelNum-4) = SensRes

EndSub

'*****
Sub RHSub ()
'----HYCAL HIH 4000 RELATIVE HUMIDITY Subroutine CJS
'NOTE: Calculating RH for Hycals
'Mult and Offset are calculated for each RH sensor using the
' NIST calibration coefficients specific to that sensor
'Example using the Generic RH Equation
' RH = (Vout - 0.826)/0.0315 with Vout measured directly
'Mult = (1/1000)/(0.0315) = 0.031746
'Offset = (-0.826)/(0.0315) = -26.22222

'Read Hycal No ___ using SE Volts measurment (in %RH)
'RH = (Vout - 0.826)/0.0315
'Check PassNum & Make Measurement

VoltSe (HycalRH(),2,autoRange,11,0,20000,_60Hz,0.031746,-26.22222)

'Filter HycalRH values
If HycalRH < 0 Then
HycalRH = NaN
ElseIf HycalRH >100 Then
HycalRH = 100
EndIf
EndSub
'*****

'Main Program
BeginProg
Scan (15,min,40,0)
PanelTemp (PTemp,250)
Battery (batt_volt)
'Turn on MUX1 and MUX2 for Temperature measurements,2x32
PortSet(1,1)
Count = 0
SubScan(0,usec,32)
'Switch to next channel
PulsePort(2,2000)
Count = Count+1
'Measure Thermistors on SE 1,2,3,4
TSub()
```


Program: Final DAQ Program (Nov19).CR1

```

TempS(count+(Count-1))=ThermTemp(1)
TempS(Count+Count)=ThermTemp(2)
TempN(count+(Count-1))=ThermTempN(1)
TempN(Count+Count)=ThermTempN(2)
NextSubScan
'Turn off MUX1 and MUX2
PortSet(1,0)
'Turn on MUX3 for Moisture Content measurements, 4x16, read SE 5,6,7
PortSet(3,1)
Count = 0
SubScan(0,usec,13)
'Switch to next channel
PulsePort(4,2000)
Count = Count + 1
'measure resistance
MCRSub(5)
MDET(Count) = WoodRes

MCRSub(6)
MEIU(Count) = WoodRes

MCRSub(7)
MEIM(Count) = WoodRes

NextSubScan
For Count = 14 To 16
    PulsePort(4,2000)
    Count = Count+1
Next
'Turn off MUX3
PortSet(3,0)

'Turn on MUX4 for Moisture Content measurements, 4x16, read SE 8,9,10
PortSet(5,1)
Count = 0
SubScan(0,usec,9)
'Switch to next channel
PulsePort(6,2000)
Count = Count +1
MCRSub(8)
Btm2MC(count+((Count-1)*2))= WoodRes

MCRSub(9)
Btm2MC((count+1)+((Count-1)*2))= WoodRes

MCRSub(10)
Btm2MC((count+2)+((Count-1)*2))= WoodRes

NextSubScan

For Count = 10 To 16 'Clock MUX4 to end
    PulsePort(6,2000)
    Count = Count+1
Next

'Turn off MUX4
PortSet(5,0)

'Turn on MUX5 for RH sensors on SE 11,12; 2x32, measure Volt Diff for Heat Flux on 6H 6L
PortSet(7,1)
Count = 0
SubScan(0,usec,14)
'Switch to next channel
PulsePort(8,2000)
Count = Count +1

```

Program: Final DAQ Program (Nov19).CR1

```
RHSub()
  RH(count+(Count-1)) = HycalRH(1)
  RH(Count+Count) = HycalRH(2)
NextSubScan
Count = 0

'Heat Flux - read Volt Difference on MUX channels 15 to 23 H&L through datalogger CH 6H 6L
SubScan(0,usec,9)
PulsePort(8,2000)
Count = Count +1

VoltDiff(HFTemp,1,mV2_5,6,true,0,_60Hz,1.0,0)
HF(Count)=HFTemp
NextSubScan
PortSet(7,0)

'Apply the calibration constants to the HF sensors
HFFinal(1)=HF(1)*HFMulti1
HFFinal(2)=HF(2)*HFMulti2
HFFinal(3)=HF(3)*HFMulti3
HFFinal(4)=HF(4)*HFMulti4
HFFinal(5)=HF(5)*HFMulti5
HFFinal(6)=HF(6)*HFMulti6
HFFinal(7)=HF(7)*HFMulti7
HFFinal(8)=HF(8)*HFMulti8
HFFinal(9)=HF(9)*HFMulti9

'*****Translation Tables*****
'Extract the Injection Air parameters
RHAirS(1)=RH(27)
RHAirN(1)=RH(28)
AirTempS(1)=TempS(55)
AirTempN(1)=TempS(56)

'Translate the MEIL and MDEL variables from Btm2MC
MEIL(1)=Btm2MC(1)
MEIL(2)=Btm2MC(3)
MEIL(3)=Btm2MC(5)
MEIL(4)=Btm2MC(7)
MEIL(5)=Btm2MC(9)
MEIL(6)=Btm2MC(11)
MEIL(7)=Btm2MC(13)
MEIL(8)=Btm2MC(16)
MEIL(9)=Btm2MC(18)
MEIL(10)=Btm2MC(20)
MEIL(11)=Btm2MC(22)
MEIL(12)=Btm2MC(24)
MEIL(13)=Btm2MC(26)

MDEL(1)=Btm2MC(2)
MDEL(2)=Btm2MC(4)
MDEL(3)=Btm2MC(6)
MDEL(4)=Btm2MC(8)
MDEL(5)=Btm2MC(10)
MDEL(6)=Btm2MC(12)
MDEL(7)=Btm2MC(14)
MDEL(8)=Btm2MC(17)
MDEL(9)=Btm2MC(19)
MDEL(10)=Btm2MC(21)
MDEL(11)=Btm2MC(23)
MDEL(12)=Btm2MC(25)
MDEL(13)=Btm2MC(27)

'Extract temp data for moisture content % output
```


Program: Final DAQ Program (Nov19).CR1

```
'TDET
TDET(1)=TempS(29)
TDET(2)=TempS(30)
TDET(3)=TempS(31)
TDET(4)=TempS(32)
TDET(5)=TempS(33)
TDET(6)=TempS(34)
TDET(7)=TempS(35)
TDET(8)=TempN(25)
TDET(9)=TempN(26)
TDET(10)=TempN(27)
TDET(11)=TempN(28)
TDET(12)=TempN(29)
TDET(13)=TempN(30)

'TEIU
TEIU(1)=TempS(36)
TEIU(2)=TempS(37)
TEIU(3)=TempS(38)
TEIU(4)=TempS(39)
TEIU(5)=TempS(40)
TEIU(6)=TempS(41)
TEIU(7)=TempS(42)
TEIU(8)=TempN(31)
TEIU(9)=TempN(32)
TEIU(10)=TempN(33)
TEIU(11)=TempN(34)
TEIU(12)=TempN(35)
TEIU(13)=TempN(36)

'TEIM
TEIM(1)=TempS(43)
TEIM(2)=TempS(44)
TEIM(3)=TempS(45)
TEIM(4)=TempS(46)
TEIM(5)=TempS(47)
TEIM(6)=TempS(48)
TEIM(7)=TempS(49)
TEIM(8)=TempN(37)
TEIM(9)=TempN(38)
TEIM(10)=TempN(39)
TEIM(11)=TempN(40)
TEIM(12)=TempN(41)
TEIM(13)=TempN(42)

'TEIL
TEIL(1)=TempS(50)
TEIL(2)=TempS(51)
TEIL(3)=TempS(52)
TEIL(4)=TempS(53)
TEIL(5)=TempS(54)
TEIL(6)=TempS(55)
TEIL(7)=TempS(56)
TEIL(8)=TempN(43)
TEIL(9)=TempN(44)
TEIL(10)=TempN(45)
TEIL(11)=TempN(46)
TEIL(12)=TempN(47)
TEIL(13)=TempN(48)

'TDEL
TDEL(1)=TempS(57)
TDEL(2)=TempS(58)
```

Program: Final DAQ Program (Nov19).CR1

```

TDEL(3)=TempS(59)
TDEL(4)=TempS(60)
TDEL(5)=TempS(61)
TDEL(6)=TempS(62)
TDEL(7)=TempS(63)
TDEL(8)=TempN(49)
TDEL(9)=TempN(50)
TDEL(10)=TempN(51)
TDEL(11)=TempN(52)
TDEL(12)=TempN(53)
TDEL(13)=TempN(54)
TDET(1)=TempS(29)
TDET(2)=TempS(30)
TDET(3)=TempS(31)
TDET(4)=TempS(32)
TDET(5)=TempS(33)
TDET(6)=TempS(34)
TDET(7)=TempS(35)
TDET(8)=TempN(25)
TDET(9)=TempN(26)
TDET(10)=TempN(27)
TDET(11)=TempN(28)
TDET(12)=TempN(29)
TDET(13)=TempN(30)

'Calculate Moisture Content - uncorrected
Count=1
For Count=1 To 7 Step +1
MDETunc(Count)=(10^(2.99-2.113*(LOG10(LOG10((MDET(Count)*10^6))))))
MEIUunc(Count)=(10^(2.99-2.113*(LOG10(LOG10((MEIU(Count)*10^6))))))
MEIMunc(Count)=(10^(2.99-2.113*(LOG10(LOG10((MEIM(Count)*10^6))))))
MEILunc(Count)=(10^(2.99-2.113*(LOG10(LOG10((MEIL(Count)*10^6))))))
MDELunc(Count)=(10^(2.99-2.113*(LOG10(LOG10((MDEL(Count)*10^6))))))
Next Count

Count = 8
For Count=8 To 13 Step +1
MDETunc(Count)=(10^(2.99-2.113*(LOG10(LOG10((MDET(Count)*10^6))))))
MEIUunc(Count)=(10^(2.99-2.113*(LOG10(LOG10((MEIU(Count)*10^6))))))
MEIMunc(Count)=(10^(2.99-2.113*(LOG10(LOG10((MEIM(Count)*10^6))))))
MEILunc(Count)=(10^(2.99-2.113*(LOG10(LOG10((MEIL(Count)*10^6))))))
MDELunc(Count)=(10^(2.99-2.113*(LOG10(LOG10((MDEL(Count)*10^6))))))
Next Count

'Calculate Moisture Content - corrected
Count=1
For Count=1 To 7 Step +1
MDETPerc(Count)=(((MDETunc(Count)+(0.567-0.026*TDET(Count)))+(0.000051*(TDET(Count))^2))/(0.881*(1.0056^(TDET(Count)))))- b)/a
MEIUPerc(Count)=(((MEIUunc(Count)+(0.567-0.026*TEIU(Count)))+(0.000051*(TEIU(Count))^2))/(0.881*(1.0056^(TEIU(Count)))))- b)/a
MEIMperc(Count)=(((MEIMunc(Count)+(0.567-0.026*TEIM(Count)))+(0.000051*(TEIM(Count))^2))/(0.881*(1.0056^(TEIM(Count)))))- b)/a
MEILperc(Count)=(((MEILunc(Count)+(0.567-0.026*TEIL(Count)))+(0.000051*(TEIL(Count))^2))/(0.881*(1.0056^(TEIL(Count)))))- b)/a
MDELperc(Count)=(((MDELunc(Count)+(0.567-0.026*TDEL(Count)))+(0.000051*(TDEL(Count))^2))/(0.881*(1.0056^(TDEL(Count)))))- b)/a
Next Count
Count=8
For Count=8 To 13 Step +1
MDETPerc(Count)=(((MDETunc(Count)+(0.567-0.026*TDET(Count)))+(0.000051*(TDET(Count))^2))/(0.881*(1.0056^(TDET(Count)))))- b)/a
MEIUPerc(Count)=(((MEIUunc(Count)+(0.567-0.026*TEIU(Count)))+(0.000051*(TEIU(Count))^2))/(0.881*(1.0056^(TEIU(Count)))))- b)/a
MEIMperc(Count)=(((MEIMunc(Count)+(0.567-0.026*TEIM(Count)))+(0.000051*(TEIM(Count))^2))/(0.881*(1.0056^(TEIM(Count)))))- b)/a
MEILperc(Count)=(((MEILunc(Count)+(0.567-0.026*TEIL(Count)))+(0.000051*(TEIL(Count))^2))/(0.881*(1.0056^(TEIL(Count)))))- b)/a
MDELperc(Count)=(((MDELunc(Count)+(0.567-0.026*TDEL(Count)))+(0.000051*(TDEL(Count))^2))/(0.881*(1.0056^(TDEL(Count)))))- b)/a
Next Count

'Call Output Tables
CallTable(General)
CallTable(AirInj)

```

Program: Final DAQ Program (Nov19).CR1

```
CallTable (TempS)  
CallTable (TempN)
```

```
CallTable (MDET)  
CallTable (MEIU)  
CallTable (MEIM)  
CallTable (MEIL)  
CallTable (MDEL)  
CallTable (RH)  
CallTable (HF)  
CallTable (Btm2MC)  
CallTable (MCperc)  
CallTable (T_RH_HF_15min)  
CallTable (MCPerC_15min)
```

```
NextScan  
EndProg
```

Appendix F. THERMISTOR RESISTANCE CALCULATION

Measuring the resistance of a thermistor using only voltage requires that the thermistor be wired in series with a 1000-Ω measurement resistor so the voltage divider can be used to determine the resistance of the RTD. The resistance of the thermistor is calculated using Ohm's law, the series resistance formula, and Kirchoff's voltage law. The relationship between voltage, current and resistance is shown by Ohm's law (Floyd, 2010):

$$I = V/R, \text{ where;}$$

$$I = \text{Current (Amps)}, V = \text{Voltage (Volts)} \text{ and } R = \text{Resistance } (\Omega)$$

The thermistor measurement circuit is shown in Figure 7-5. The current and voltage applied to the circuit are shown by I_{sup} and V_{sup} , while the resistance of the thermistor and its voltage potential are

Figure 7-5 Thermistor measurement circuit

shown by R_{therm} and V_{therm} . Finally, the resistance of the sensor resistor and its voltage potential are represented by R_{sensor} and V_{sensor} .

Since the measurement circuit is a series circuit with only one path for the current to flow; the current remains constant at all points in the circuit. It also follows that the total circuit resistance,

$$R_{\text{total}} = R_{\text{therm}} + R_{\text{sensor}}$$

Further, using Kirchoff's voltage law, which indicates that the sum of the voltage drops through a series circuit, equals the total voltage applied across the circuit (Floyd, 2010).

The current, voltage and resistance relationships can now be re-stated as follows:

$$I_{\text{supply}} = V_{\text{supply}} / R_{\text{total}}$$

$$I_{\text{therm}} = V_{\text{therm}} / R_{\text{therm}}$$

$$I_{\text{sensor}} = V_{\text{sensor}} / R_{\text{sensor}}$$

Since, $I_{\text{supply}} = I_{\text{therm}} = I_{\text{sensor}}$, it follows that, $V_{\text{therm}} / R_{\text{therm}} = V_{\text{sensor}} / R_{\text{sensor}}$. The relationship can be rewritten as $(V_{\text{therm}} / V_{\text{sensor}}) \cdot R_{\text{sensor}} = R_{\text{therm}}$ and then by substituting $(V_{\text{supply}} - V_{\text{sensor}})$ for V_{therm} , the final equation to calculate the thermistor resistivity is:

$$R_{\text{therm}} = R_{\text{sensor}} \cdot (V_{\text{total}} - V_{\text{sensor}}) / V_{\text{sensor}}$$

Using this equation the value for R_{therm} can then be used in Equation 22 (Section 3.6.3) to determine the temperature of the thermistor in degrees Celsius.

Appendix G. MOISTURE PIN ISOLATORS

Installation of Silicone Insulators in the I-Joist and Double Stud Wall Assemblies

Moisture content (MC) pins were installed in the OSB sheathing (3 sets) and spruce plates (2 sets) on all of the test walls. The moisture contents measurements indicated that the sheathing and plates of the 2x6 framed walls were closely correlated between each of the different walls – by location in the wall and wall orientation. The calculated MC was also within the expected range indicated by both the hand held meter as well as the calculated equilibrium moisture content (EMC). For example, the EMC for wood at 20°C and 50% RH is 9.3%. With slightly lower temperature within the wall cavities, moisture contents 1-2% higher can be expected.

The moisture contents calculated for the sheathing and plates of the deep cavity walls, however, were higher than expected. The two deep cavity walls, I Joist and Double Stud, were filled with dense-pack cellulose insulation. The cellulose insulation had a higher electrical conductivity compared to the fiberglass insulation. Since the cellulose is hygroscopic, the adsorption of water molecules in the pores of the cellulose affects its electrical conductivity and dielectric strength. The insulation and the bare wire connectors on the MC sensors created a bypass circuit that resulted in lower measured resistances and increased the calculated MC values.

Figure 7-6 Silicone insulator caps used to isolate moisture pins from cellulose insulation

The remedy, shown in Figure 7-6, was to install 20 mm long pieces of silicone filled 12.5 mm diameter polyethylene tubing over the top of the sensor pins to insulate the bare wire connections on the pins from the cellulose insulation. The polyethylene tubing allowed the silicone to be placed over top of the bare connections with minimal disruption to the insulation. The risk of contaminating the silicone with cellulose was reduced as well. Subsequent measurements revealed

that the silicone caps reduced the electrical ‘leakage’ around the moisture pins and resulted in more representative moisture content measurements.

Results

The moisture content data from the affected walls is presented below along with the MC data from the datum wall (Type 3) for comparison in Figure 7-7 to Figure 7-11. The silicone insulators were installed around midday on October 22, 2012.

Top Plates

Figure 7-7 Top Plate MC (%) - South Walls (Left), North Walls (Right)

South facing top plates (Figure 7-7) – **S1-MDET** has the highest average moisture content - 12.1% compared with 10% moisture content of the remaining south facing top plates. The top plate moisture content in S2 closely matches the datum, S3.

The calculated EMC for the S1 top plate is 11.2% when the plate temperature and cavity RH is used (60% and 12°C). Since the exterior plate of the double stud wall does not bridge to the interior, it can be expected to be at a lower average temperature during this time of year and is more likely to be influenced by exterior conditions.

North facing top plates (Figure 7-7) – **N2-MDET** has the highest average moisture content - 13.2% (reduced from 15.8%). The calculated EMC using the average cavity RH and plate temperature is 11.4 %. The isolators had less of an impact on **N1-MDET** similar to **S2-MDET**.

OSB – Upper, middle and lower MC-sensors

The silicone insulators were most effective in reducing the current loss in the OSB moisture pins

Upper OSB – The measurements for the upper OSB MC in the south facing walls (Figure 7-8 - Left) occur within a 1% range (6.1% to 7.1%) after the installation of the insulators. The average MC values for **S1-MEIU** were reduced from 10.1% to 7.1%. The MC of the upper OSB in the north facing walls (Figure 7-8 - Right) occurs within a 2% range (6.3% to 8.3%). The highest MC values were recorded at the **N2-MEIU** sensor – these measurements were reduced from 14.6% to 8.3%.

Figure 7-8 Upper OSB MC (%) – South walls (Left), North walls (Right)

Middle and Lower OSB – The south facing measurements fall within a 1% range while the north facing measurements fall within a 2% range (Figure 7-9).

Figure 7-9 Middle OSB MC (%) – South walls (Left), North walls (Right)

Figure 7-10 Lower OSB MC (%) – South walls (Left), North walls (Right)

The replacement of T-sensor **S1-TEIL** is also visible in Figure 7-10 (Left) on October 22.

Lower Plates

South facing lower plates (Figure 7-11) – The moisture content of the south facing lower plates averages 10.1% overall and plot within an approximate 2% MC range of each other – there is no significant difference in the calculated MC as a result of the cellulose isolators.

North facing lower plates (Figure 7-11) – The highest moisture content measurements occur in N1 and N2. The average MC of **N1-MDEL** is 12.5% (reduced from 14.1%) and **N2-MDEL** is 11.1% (reduced from 13.2%). The moisture content of the remaining north facing lower plates is 10.4% on average. The lower plates in the north walls are still slightly elevated with respect to the other test panels. The lower plate MC in N1 returned to its previous MC (~14%) within a week.

Figure 7-11 Lower Plate MC (%) - South Walls (Left), North Walls (Right)

Appendix H. WEATHER DATA

Figure 7-12 Baseline weather data - RH and T (Top), Solar Radiation and precipitation (Middle), Wind direction and speed (Bottom)

Figure 7-13 Air-Injection test weather data - RH and T (Top), Solar Radiation and precipitation (Middle), Wind direction and speed (Bottom)

Figure 7-14 Drying period weather data - RH and T (Top), Solar Radiation and precipitation (Middle), Wind direction and speed (Bottom)

Appendix I. OSB TEMPERATURE PROFILES FOR FEB 9-11, 2013

Figure 7-15 Weather data for Feb 9-11, 2013 – Wind Data (Left), Temp and Radiation (Right)

Figure 7-16 Vertical temperature profiles for S1 (top) and S2 (bottom)

Figure 7-17 Vertical temperature profiles for S3 (top), S4 (middle) and S5 (bottom)

Figure 7-18 Vertical temperature profiles for S6 (top) and S7 (bottom)

Figure 7-19 Vertical temperature profiles for N1 (top), N2 (middle) and N3 (bottom)

Figure 7-20 Vertical temperature profiles for N5 (top), N6 (middle) and N7 (bottom)

Appendix J. VERTICAL ΔT -DATA COMPARISONS

Figure 7-21 OSB vertical ΔT comparisons

Figure 7-22 Plate vertical ΔT comparisons

Appendix K. VERTICAL MC PROFILES

Figure 7-23 Vertical OSB MC-profiles for deep cavity walls S1, S2, and S4 with datum S3

Figure 7-24 Vertical OSB MC-profiles for exterior insulated walls S5-7 with datum S3

Figure 7-25 Vertical framing plate MC-profiles for deep cavity walls S1, S2, and S4 with datum S3

Figure 7-26 Vertical framing plate MC-profiles for exterior insulated walls S5-7 with datum S3

Figure 7-27 Vertical OSB MC-profiles for walls N1-7

Figure 7-28 Vertical framing plate MC-profiles for walls N1-7

Appendix L. EXTERIOR CAVITY AIR CHANGE RATE OPTIMIZATION

Figure 7-29 ΔRH (Measured – Simulated) versus ACR for north facing datum wall – comparisons between single and double exterior cavity as well as day and night

Figure 7-30 ΔRH (Measured – Simulated) versus ACR for north facing datum wall – comparisons between single and double exterior cavity as well as day and night

Appendix M. OSB MOISTURE STORAGE FUNCTION DETAILS

Figure 7-31 Sorption isotherms developed for the High-RSI walls

The OSB MSFs are compared in the graph presented in Figure 7-31 to illustrate the differences between each of the MSFs. The predominant OSB MSF type used in the hygrothermal simulation was OSB 2. The most common deviation from the OSB 2 MSF occurred in the 50% RH range with OSB 3 and OSB 4 varying at the 70% RH data point. For higher RH-values, the OSB 2 and OSB 3 MSF definitions used the

Table 7-1 Wall types with the OSB MSF used in simulations

OSB 1	OSB 2	OSB 3	OSB 4	OSB 6
S3	S1,S2,S6		S7	S5
N3	N1,N6	N2	N7	N5

upper bounding data point of the high-MSF curve, while OSB 1, OSB 4, and OSB 6 MSF definitions used values from the lower bounding data of the low-MSF curve.

The OSB moisture storage functions that were used in the hygrothermal simulations are listed in Table 7-1 for each wall type. The moisture storage values for each modified OSB MSF-curve are listed in Table

7-2

Table 7-2 Water content values for the modified OSB MSFs

RH	OSB 1	OSB 2	OSB 3	OSB 4	OSB 6
0	0	0	0	0	0
50	32	43.6	21.5	37	40
69.3	48.1	48.1	63.7	63.7	48.1
88.9	89	95.6	95.6	95	89
91.5	100.8	111.2	111.2	100.8	100.8
93	113.8	152.8	152.8	113.8	113.8
100	377	377	377	377	377

Appendix N. STUD CAVITY RH FOR THE CELLULOSE-INSULATED WALLS

Figure 7-32 Stud cavity RH-data for wall Types 1 and 2 during the baseline analysis period

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