Vapour Diffusion Control in Framed Wall Systems Insulated with Spray Polyurethane Foam

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

The Intergovernmental Panel on Climate Change (IPCC) estimates that buildings account for 40% of the global energy use. The IPCC believes substantial improvements to building efficiency can be implemented easily by improving building enclosures through increased levels of insulation, optimizing glazing areas and minimizing infiltration of outside air.

Building enclosure design encompasses a wide range of parameters but the transport of heat, air and moisture through the enclosure is of primary importance. In predominantly cold Canadian climates, adequate thermal insulation, effective air barriers, and proper moisture control are crucial for energy savings and durability of the structure.

For decades, standard construction practice in Canada dictated a polyethylene sheet behind the interior drywall layer to serve as a vapour barrier for assemblies with traditional fibre-based cavity insulation. If the polyethylene sheet was sealed carefully enough it had the added benefit of reducing air leakage. Unfortunately, vapour barriers place the emphasis on the wrong moisture transport mechanism; air leakage can have 10 times or greater the wetting potential than vapour diffusion. Regardless, code enforcement personnel continued (and continue in some areas) to require vapour barriers in all climates, all assemblies, and all occupancies. To do so, they overrule the provision in Part 5 of The National Building Code of Canada that states vapour barriers are not required if it can be shown that the uncontrolled vapour diffusion will not affect the operation of the building and systems, or the health and safety of the occupants.

Foam plastic insulations perform better than fibre-based insulation in terms of the combined resistance to transmission of heat, air and vapour. This research investigated several types of open cell and closed cell spray polyurethane foam insulation in a variety of assembly configurations both in lab tests and hygrothermal simulations. The simulations were extrapolated to seven Canadian climate categories and three levels of interior relative humidity. The goal was to determine which spray polyurethane foam applications required the addition of a dedicated vapour barrier layer beyond what the foam itself could provide.

The moisture content of the oriented strand board sheathing layer (OSB) in the tested and modelled assemblies was used as the performance evaluation point because during wintertime vapour drives, the wood sheathing is the most likely condensing surface. Prolonged high moisture content (greater than 20%) in wood and wood products in wall assemblies leads to mould growth and decay. By this measure, if the wood sheathing moisture contents stay within the safe range (less than 19%) a vapour barrier is not necessary. The results are presented in Table 7-4.

The performance of assemblies containing closed cell spray foam was excellent for all climates and humidity levels. Their performance was equivalent to traditional wall assemblies incorporating a polyethylene sheet vapour barrier. The performance of assemblies with open cell spray foam was equivalent to traditional wall assemblies containing no vapour barrier. Open cell spray foam and fibreglass batt both require additional vapour control layers with all but the mildest Canadian climates with the lowest interior humidities. However, in those mild climates with low interior humidities, the only vapour control layer required was a medium permeance latex paint with primer.

Acknowledgements

Many thanks to Dr. John Straube for giving me the opportunity to join the Building Engineering Group at Waterloo. His knowledge and guidance were invaluable. I wanted to be part of the building science field since 1993 and he helped me achieve that reality.

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For Jim and Toots

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Chapter 1
Introduction

1.1 Background

In the past few years, public concern about rising energy costs, greenhouse gas emissions, and energy security have focused attention on buildings, one of the largest sectors of energy consumption. The Intergovernmental Panel on Climate Change estimates energy consumption by buildings is 40% of all global energy use (IPCC 2007). The IPCC report titled *Mitigation of Climate Change* concluded that the building sector could generate 29% reductions in its energy consumption by the year 2020 without large cost. This is the highest potential reduction of all sectors including transport, industry, energy generation, agriculture and forestry.

The IPCC indicates the most cost-effective energy reductions come from reducing heating and cooling loads. The report states, “A simple strategy for reducing heating and cooling loads is to isolate the building from the environment by using high levels of insulation, optimizing the glazing area and minimizing the infiltration of outside air.”

This statement from the IPCC report, whether intentional or not, is a succinct description of the main principles of energy-efficient building enclosure design. The aim of building science is to properly control the flow of heat, air and moisture through the building enclosure. This is achieved through the design and construction of four distinct functional elements of the enclosure:

- Heat control layer – provided by thermal insulation.
- Air control layer – in the form of a continuous air barrier to minimize uncontrolled air infiltration and exfiltration.
- Rain control layer – a water resistant barrier (also called a rain drainage plane) to control liquid water penetration.
- Vapour diffusion control layer – a wall could also include a vapour diffusion barrier, if warranted by assembly materials, local climate, and interior humidity conditions.

This thesis investigates which Canadian climate conditions warrant a vapour barrier for several standard construction assemblies incorporating specific types of spray polyurethane foam insulation.

There are many well-established techniques to maximize performance of each of the control layers in the building enclosure. The Canada Mortgage and Housing Corporation initiative *Building for Energy Efficient Housing* recommends some specific techniques (CMHC 2008). They are listed here with the relevant control layer indicated in brackets.

- Increase the amount of insulation in the walls and roofs [heat control layer]
- Seal all openings through which air could leak in or out [air control layer]
- Eliminate thermal bridging, where non-insulating materials such as steel or concrete pass through the insulation and conduct heat from the building [heat control layer]

- Provide a vapour barrier to limit vapour diffusion condensation in the wall - condensation reduces the effectiveness of the insulation and causes deterioration of the wall [vapour diffusion control layer]
- Use double glazed windows, glazed with low-emissivity glass, fill the air space with inert gas, such as argon [heat, air and rain control layers]

CMHC estimates these technologies will increase costs by 10% and lead to energy savings of 60% compared to standard construction. They calculated the simple payback as 5 to 8 years at 2008 energy costs.

It is well understood in the construction industry that increasing insulation is a means of reducing energy consumption over the life of the structure. Not so well understood, however, is that the amount of energy savings depends on the choice of insulation, how is it installed and where it is located in the building enclosure assembly. Poor design and workmanship can reduce the effectiveness of the insulation and produce an enclosure that transfers much more heat than the theoretical value of the insulation would indicate. In addition, if enclosure weaknesses such as thermal bridging are not properly addressed, the heat transfer will short circuit around the insulation, making the heat control layer less effective overall.

Three categories of insulation are common: mineral fibre, organic fibre and foamed plastic. Mineral fibre insulation is non-combustible and air and vapour permeable. Examples of mineral fibre are fibreglass and rock wool. Organic fibre insulation is combustible but can be treated inexpensively to provide excellent performance. Like mineral fibre insulation it is air and vapour permeable. Examples of organic fibre insulations are cellulose and recycled cotton. Foamed plastic insulation products are combustible and have a range of air and vapour permeances. Examples of foam plastic insulation are expanded polystyrene, extruded polystyrene, polyurethane and polyisocyanurate. Some insulation materials provide higher resistance to heat flow than others for the same thickness of material (Figure 1-1).

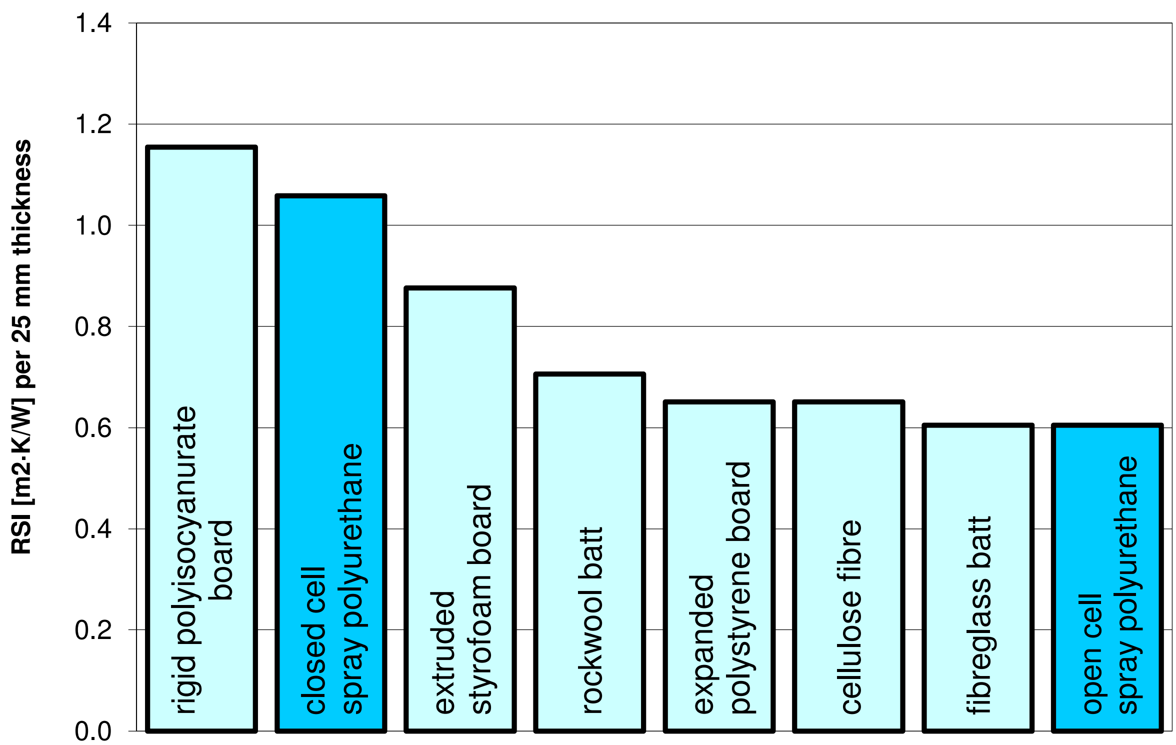

Figure 1-1: Average RSI values of Common Insulation Types (Straube and Burnett 2005)

Some insulation materials have the added benefit of providing significant resistance to air leakage, rain penetration, vapour diffusion or any combination of the three. For example, some types of foam plastic have a high resistance to flow of heat, air, and water (both liquid and vapour) and therefore have the potential to function as the heat, air and moisture control layers. At the other end of the spectrum, a material like fibreglass batt performs well as a heat control layer only. In an enclosure using fibreglass as the heat control layer, the air and moisture control layers must be designed and provided separately by other materials.

1.2 Spray Polyurethane Foam (SPF) Insulation

Spray polyurethane foam (SPF) is one type of foam plastic that is of great interest in building enclosure design because it can perform very well as multiple control layers. SPF provides one the highest heat resistances of any commonly available insulation products

SPF is created and applied on-site from two liquid components that are combined and mixed as they are being sprayed from a pressurized gun. The two liquids react chemically, bubbles form, the product expands, and the liquid is transformed into a cellular plastic. The advantage of the on-site application process is that the liquid foam enters cracks, gaps and irregular cavities and fills them up as it expands. The foam cures within seconds and creates a seamless, semi-rigid thermal and air barrier layer. It also adheres tenaciously to most surfaces.

There are two broad classes of SPF based on cellular structure – open cell and closed cell. Open cell foam is low density; closed cell foam is medium density to super high density. Open cell foam is classified as semi-flexible. It has relatively low values for compressive strength and density and is used in wall and joist cavities. Closed cell foam is more rigid and can withstand substantial compressive load without deforming and can be applied as a continuous layer to almost any solid substrate. Medium density foam is used in wall and floor cavities and outboard of exterior walls if it will be covered by cladding. High density and super high density closed cell foams are used in roofing applications because they are strong enough to support environmental loads and live loads from workers and maintenance. The foam surface will degrade when subjected to long-term UV exposure; therefore, exterior applications require a UV-blocking membrane. This project was limited to studying open cell foams and medium and high density closed cell foams.

Medium and high density spray polyurethane foams also provide considerably more moisture resistance than traditional insulation materials. As a result, there may be some cases where medium and high density SPF can serve as the water and vapour control layers depending on where they are located within the assembly (Figure 1-2).

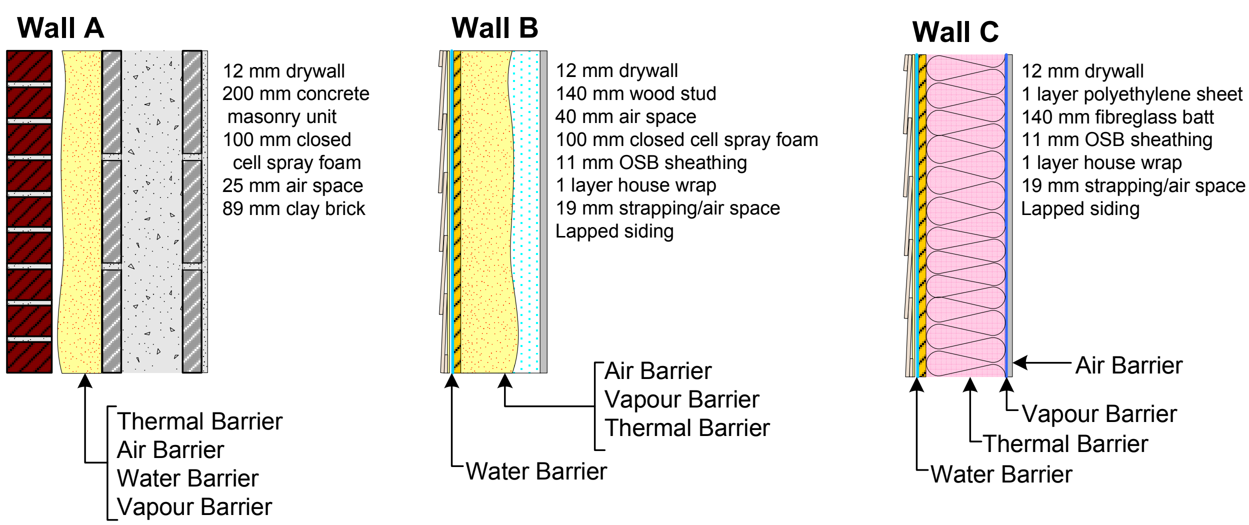

Figure 1-2: Location of Control Layers in Three Example Walls

Unfortunately, there is often confusion on the part of designers, builders and code enforcement officials about if and when spray polyurethane foam acts as a vapour barrier. If the cases could be identified and codified, the construction industry could benefit from eliminating the time consuming and unnecessary construction step of installing a separate vapour diffusion control layer. There is also a risk of trapping construction moisture if an interior vapour barrier is unnecessarily applied.

1.3 Objectives

The objective of the research was to investigate how different types of spray polyurethane foam insulation products perform as a vapour diffusion control layer in framed wall systems subject to a variety of Canadian climates and interior conditions. This thesis reviews the background science and previous research and documents the research results and findings.

1.4 Scope

The scope of the project included vapour diffusion tests of a series of open and closed cell foams with and without polyethylene vapour barriers. The foam samples were subjected to constant temperature and relative humidity conditions in a lab setting. The results from the lab experiment and previous field experiments were then compared and validated with a well-established hygrothermal computer modelling program. The computer model was then used to predict performance of other types of wall assemblies subject to a wide range of climates in representative Canadian cities with various interior humidity loads.

1.5 Approach

The thesis begins with an overview of how building science defines heat, air and moisture transport mechanisms. The discussion continues with how the mechanisms are affected by the material properties of assembly materials such as spray foam insulation, vapour diffusion control products and wood. Some previous work on vapour diffusion performance of spray foam is discussed. The experimental plan and set-up is covered in detail. The experimental results are presented and discussed in Chapter 5. The analysis and discussion of the test results are presented in Chapter 6. Computer and mathematical models are developed and presented in Chapter 7. Conclusions and recommendations for industry are presented in Chapter 8

Chapter 2

Building Science and Material Properties

Building science often focuses on the flow of heat, air and moisture through a building enclosure. The enclosure acts as an environmental separator which helps to provide controlled interior conditions regardless of the variability of the outdoor climate. The enclosure materials must be able to perform well under the changing loads from heat, air, moisture, solar radiation, impact, fire, sound, etc. If the materials are not suitably chosen, the building could experience problems such as excessively high operating costs, low occupant comfort, poor air quality, water leaks, material damage, decay and corrosion which could lead to premature failure of construction assemblies and systems.

2.1 Heat

Heat energy moves in the direction of warm to cold in three possible ways: conduction, radiation, and convection. Conduction occurs when heat energy is transferred from molecule to molecule in materials; the transfer cannot occur unless there is direct contact. Convection occurs when a fluid, such as water or air, moves away from a heat source taking the heat energy with it. Radiation occurs when a heat source emits electromagnetic energy to colder materials in its direct line of sight. Building enclosures can experience any of these modes of heat transport separately or simultaneously.

2.1.1 Heat Control Layer

Thermal insulation works because, by definition, it is a very poor conductor of heat. The conductivity of a material, k or λ, is a measure of how much heat flows across a unit area through a unit thickness for a temperature gradient of 1°C. It is measured in terms of Watt per metre Kelvin [W/m·K]. A low k-value means the material is a poor conductor and thereby a good insulator. Still air is a very poor conductor of heat; therefore, any material that incorporates a high amount of still air in its structure, (i.e., a low density material) is also a good insulator. In general, low density materials have low k-values (Straube and Burnett 2005). Standard material tests combine all three modes of heat transport into the measurement of k-values.

Spray polyurethane foams (SPF) are some of the lowest density insulation materials available due to their high air content. Even though spray foams are categorized as low, medium and high density foams, they all still contain a very large percentage of air (99% porosity) compared to other solid materials.

The conductance of a material, C, is the conductivity of a specific thickness of material, Equation 2-1. For example, closed cell spray foam has a conductivity of 0.024 W/m·K; while 100 mm (4 in.) of closed cell spray foam has a conductance of 0.24 $W/m^2 \cdot K$.

$$C = \frac{k}{t}$$ **Equation 2-1**

C	[W/m²·K]	Conductance, thermal
k	[W/m·K]	Conductivity, thermal
t	[m]	Thickness of material layer

Good insulators tend to be materials that can reduce conduction to the 0.05 to 0.07 W/m·K range or lower (Straube 2005). The heat flow characteristics of some building products, such as windows and hollow concrete blocks are specified in terms conductance. If the reported value includes the resistance of the surface films, it is called the U-value. Insulation materials and enclosure assemblies use the inverse of conductance – the resistance or RSI.

$$RSI = \frac{1}{C}$$ **Equation 2-2**

RSI	[m²·K/W]	Resistance, thermal
C	[W/m²·K]	Conductance, thermal

The average homeowner typically refers to the RSI by the better known imperial version of R-value. For example, average values in new residential construction are R-40 for attic insulation or R-20 for exterior walls. The R-value can be calculated by multiplying the RSI value by 5.678 which converts the units to hr·ft^2·°F/Btu.

2.2 Air

Air can leak into or out of buildings through cracks, gaps and discontinuities in the enclosure. Some builders and homeowners say they prefer their buildings to "breathe" that way. Adequate ventilation is crucial in any occupied building, but uncontrolled air leakage is the cause of many building problems. For example, heating and cooling energy is wasted when air leaks in or out making the building expensive to operate. The humidity of the indoor air is difficult to control leading to occupant comfort problems. Moisture in the air can condense along the air leakage path putting the durability of the structure at risk. Uncontrolled air flows through the assembly can lead to air quality problems as the source and path of the air is random.

A well designed and installed air barrier may be the most important aspect of building an energy-efficient, comfortable, healthy, long-lasting building. Note that mechanical ventilation systems go hand-in-hand with air barrier systems. The mechanical ventilation provides fresh air, expels stale air, dilutes indoor pollutants, and helps keep the interior humidity under control. The absence of mechanical ventilation in an "air tight" building can lead to excessively high humidity, indoor air quality problems, condensation build-up on cold surfaces and mould growth which could lead to structural damage if left unchecked.

Air leakage is driven by air pressure differences between the inside and outside of a building. Three distinct mechanisms can create air pressure differences:

Wind forces on a building create pressure on the enclosure. Windward surfaces experience infiltration of air. Leeward surfaces experience exfiltration. The amount of pressure at a particular point on the building enclosure depends on the magnitude and direction of the wind and the location of the point on the structure. Pressures on windward sides tend to be greater at the centres of walls and roofs. Suction forces on leeward roofs and walls tend to be greater at edges and corners. A wind speed of 15 km/h is equivalent to a 10 Pa air pressure difference.

Stack Effect occurs when warmer air in a building rises naturally thereby increasing the pressure in the upper section of the building and decreasing the air pressure in the lower section. Over the top half of the building, there will be exfiltration of air; over the bottom half there will be infiltration of air. The taller the building, the more pronounced the effect. Wintertime stack pressures on a two-storey house can be 5 to 10 Pa.

Mechanical Ventilation to bring in fresh air will pressurize the building. If fans are expelling stale air the building will be depressurized. A balanced ventilation system seeks to supply and exhaust the same volume of air. Some buildings are intentionally pressurized in order to control interior humidity conditions more easily, by preventing outdoor humidity from intruding. Some buildings are temporarily depressurized when exhaust fans are operating on equipment such as furnaces, fireplaces, cooking appliances, clothes dryers, and bathroom fans. Mechanically-induced pressures can range from less than 5 Pa to more than 100 Pa.

The intensity of the pressure difference determines the intensity of the air leakage. Air leakage rates are given in terms of $L/s \cdot m^2$ at standard pressure of 50 or 75 Pa.

2.2.1 Air Control Layer

In order for the air control layer to prevent air leakage it must satisfy five requirements:

Continuity - even small holes and discontinuities can permit a considerable amount of air leakage. Add up all the air leakage holes in an enclosure and the result is what is termed the normalized leakage area. A 1997 National Resources Canada survey found that the national average normalized leakage area was 1.44 cm^2/m^2 for new conventionally-built (non-R2000) houses constructed after 1991 (CANMET 1997).

Strength – the air barrier layer must be able to withstand the pressure difference between the interior and the exterior of the enclosure. It is preventing the pressure from equalizing therefore it must transfer those forces into the structure. If it cannot, it will deform, loosen or puncture.

Durability– the location of the air barrier may be in the interstitial space of the enclosure and therefore repairs or maintenance to the air barrier is impractical.

Stiffness – the barrier must be stiff enough to transfer the forces from the pressure difference.

Air impermeability – if it is not impermeable, air leakage will occur.

Heat loss from air leakage can account for 25-40% of energy loss in a building (CMHC 1999). Building codes recognize this heat loss mechanism and have created building air tightness recommendations. For example, the air permeance of the enclosure is specified as 2.0 $L/s \cdot m^2$ at 75 Pa. The National Building Code of Canada (NBCC 2006) specifies maximum air permeances for materials (0.02 $L/s \cdot m^2$ at 75 Pa) with some exceptions. Air leakage through the enclosure can also lead to moisture build-up within wall cavities when water vapour condenses along the air leakage path. A general requirement to limit condensation is that a building component (i.e. wall, window, roof) should not have an air permeance of more than 0.2 $L/s \cdot m^2$ at 75 Pa.

2.3 Moisture

Water in liquid or vapour form can enter and exit building enclosures in a number of ways. The physics of moisture transport is a large, complex topic and in building science the main types of moisture transport are simplified to the following mechanisms:

Liquid flow –The flow of liquid water can be driven by gravity forces as is the case with rain. Typically this is bulk water that creates leaks around windows, in roofs or in basements. Liquid flow can also be driven by capillary action as is the case with groundwater wicking up through concrete foundations. Capillary flow depends on the pore size of a material or gap size between materials. Capillary flow moves liquid water through spaces if they are sufficiently small. In larger spaces capillary flow is not an issue because it is small and hence overcome by gravity forces.

Air movement – also called convective water vapour transport. This is the mechanism by which water vapour is moved along with air convection. As mentioned in the previous section on air transport, if air is leaking out of or into a building, water vapour is transported along with it and can condense if the air leakage path is cold enough. Once the water vapour condenses, liquid flow transport takes over.

Vapour diffusion – water vapour will diffuse from areas of high water vapour concentration to areas of low water vapour concentration without any help from the above transport mechanisms. The vapour can diffuse through most materials as long as a difference in vapour concentration (measured by the partial vapour pressure of water vapour) exists. The amount that will diffuse through the material depends on the permeability of the material and the magnitude of the pressure difference.

2.3.1 Moisture Control Layer

Moisture intrusion into an assembly becomes a problem when the enclosure has very little moisture storage capacity and does not have the ability to dry out in a reasonable amount of time. Rain penetration and air movement can create significant moisture problems if the storage capacity and drying of the enclosure is limited.

Moisture damage is rarely controlled by a single layer in an enclosure, but rather a combination of elements that perform different tasks to manage the different types of moisture migration through an enclosure.

Every enclosure requires some type of water resistant barrier (WRB) to minimize rainwater intrusion into the assembly. Water resistant barriers in above-grade walls often work in concert with the exterior cladding. The effectiveness of the cladding at shedding water and the rain exposure of the wall determine how resistant the WRB should be. Products such as self-adhesive rubberized asphalt membrane (“peel & stick”), spun-bonded polyolefin membrane (Tyvek), asphalt impregnated building paper, and closed-cell spray foam are some examples of water resistant barriers.

Every enclosure also requires an air barrier to prevent convective water vapour transport, and air leakage, for reasons already outlined in Section 2.2. Examples of air barriers are metal cladding, pre-cast concrete, gypsum board, and structural wood panels, as long as all edges and joints are air sealed.

Vapour diffusion can also lead to water accumulation in the wall but it is often misunderstood or blamed for problems caused by the other transport mechanisms, particularly air movement. It can be difficult to identify vapour diffusion because it depends on a complicated relationship between exterior climate, interior climate, solar absorptance, rainwater absorption, the vapour and thermal resistance and safe storage capacity of all layers in the construction assembly, not just the presence or absence of a vapour barrier (Straube 2002).

2.3.2 Vapour Diffusion

As discussed in 2.3, vapour diffusion is driven by the difference in vapour pressures between two adjacent spaces (Figure 2-1). If there is a material layer separating the two air volumes, the rate of vapour movement that passes through depends on the pressure difference and the permeability of the material layer.

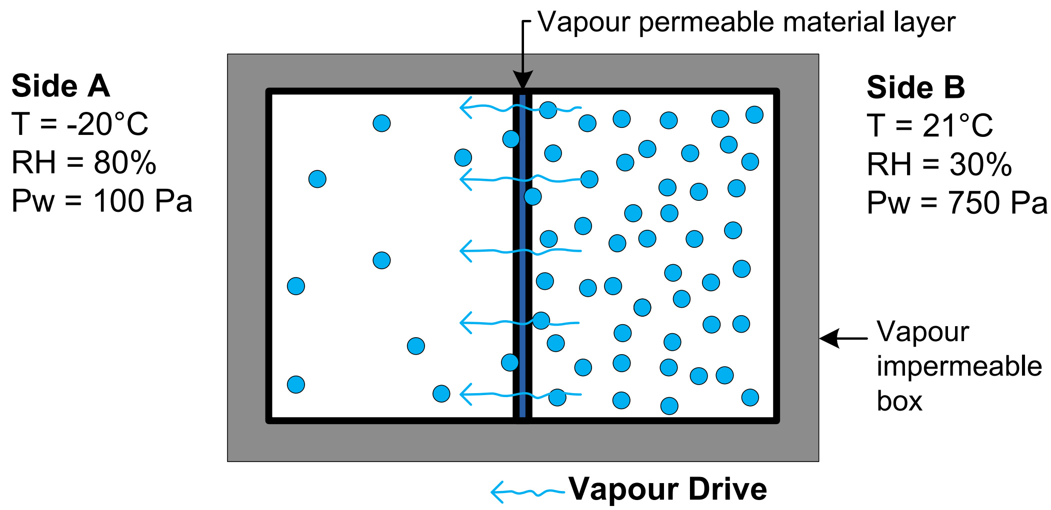

Figure 2-1: Vapour Diffusion from High to Low Vapour Pressure

Water vapour diffusion through a single material can be estimated from one-dimensional steady-state simplification of Fick’s Law:

$$Q_V = \frac{\mu}{l} \cdot A \cdot \Delta P_V$$ **Equation 2-3**

Q_V	[g/s]	Rate of vapour diffusion
μ	[ng/Pa·s·m]	Vapour permeability
A	[m^2]	Area
l	[m]	Thickness
ΔP_v	[Pa]	Difference in water vapour partial pressure across the material layer

Vapour permeability, μ, is a property inherent in the material structure and is measured in ng/Pa·s·m. The water vapour permeance of a material, M, is its permeability for a specific thickness and is measured in ng/Pa·s·m^2. The permeability is often assumed to be constant but actually varies with moisture content. The permeance of a material is determined by testing, usually *ASTM E-96 Standard Test Methods for Water Vapour Transmission of Materials* (ASTM 2000). One common way the test may be performed is according to "Procedure A" or the "dry-cup test" where a sample is affixed to the top of an open container into which desiccant has been placed. Once the sample has been sealed to the container it provides an interior humidity of 0% RH. Tests performed according to "Procedure B" or the "wet-cup test" are identical except the container holds water instead of desiccant in order to create an interior RH of 100%. In both procedures the entire container is placed in a 23°C /50% RH space and the subsequent mass gain or loss of the container is measured regularly over a period of a few days or weeks, depending on the nature of the sample, until the mass change has reached steady state. The vapour permeance is calculated by dividing the rate of mass loss (or gain) by the vapour pressure difference and the area of the sample (Figure 2-2).

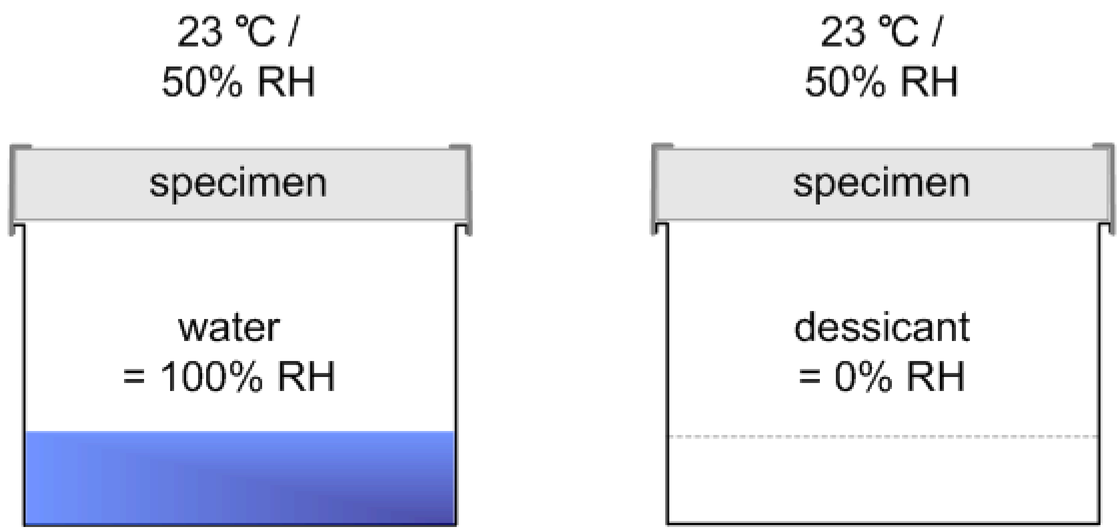

Figure 2-2: Wet Cup and Dry Cup Vapour Permeance Tests (Straube and Burnett 2005)

The tests may be performed for other temperatures or humidities, which will alter the vapour drives and calculations accordingly. The permeance of a material can change depending on its water content, which in turn depends on the relative humidity surrounding the material, therefore the dry-cup and wet-cup tests can yield quite different permeance values. A comparison of these values will help identify a material's sensitivity to changing RH in situ.

2.3.3 Water Vapour in Air

Water vapour pressure in air is a function of temperature. At a given temperature, air can hold a maximum amount of water vapour before the air becomes saturated and water begins to condense. The maximum amount of vapour pressure at that point is called the saturation pressure and can be calculated using a simplified equation, Equation 2-4.

$$P_{WS} = 1000 \cdot e(52.28 - \frac{6790.5}{T} - 5.028 \ln T) \qquad \textbf{Equation 2-4}$$

P_{WS}	[Pa]	Water vapour saturation pressure
T	[K]	Temperature

If the values of P_{WS} are plotted for a series of temperatures, the result is the saturation curve shown in Figure 2-3.

Relative humidity is defined as the ratio between the partial pressure of the water vapour in a sample of air and the saturation vapour pressure at the same temperature. The saturation pressure corresponds to a relative humidity of 100%.

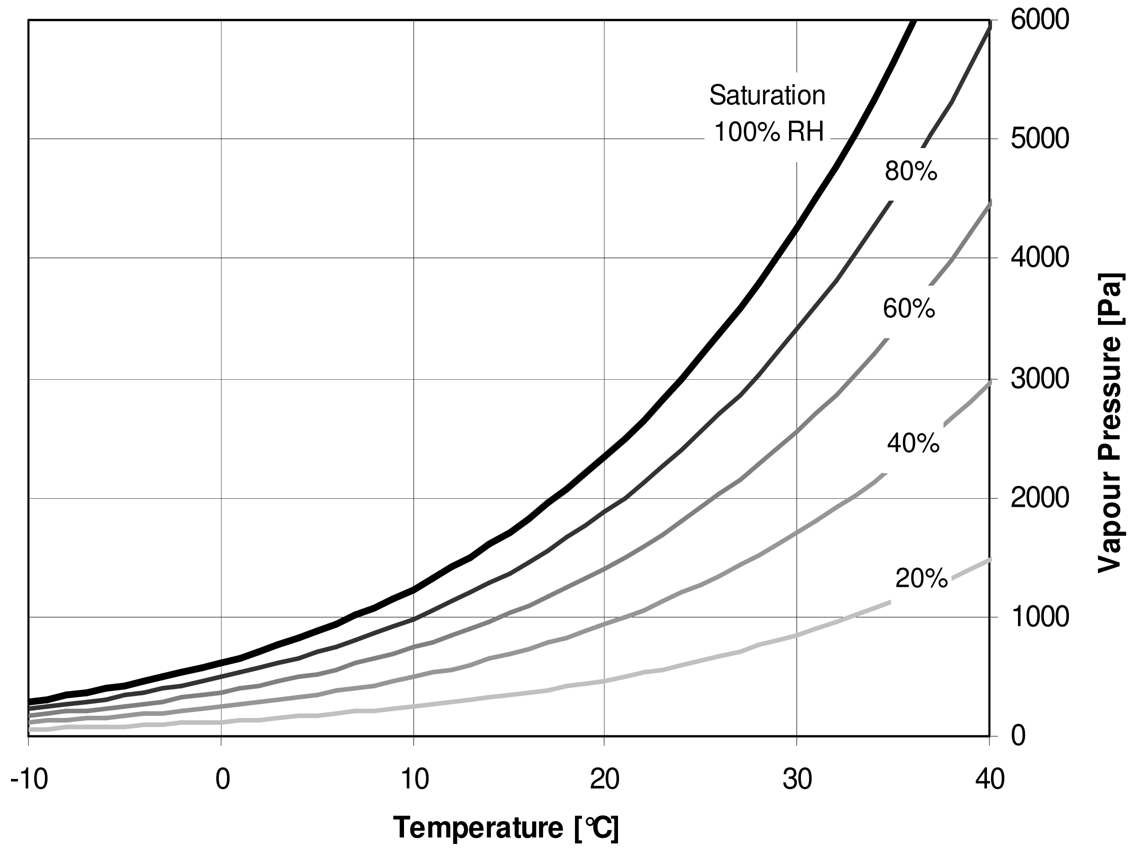

Figure 2-3: The Psychrometric Chart

For any other RH value at the same temperature the vapour pressure, P_w, can be calculated using the following equation:

$$\phi(RH\%) = \frac{P_W}{P_{WS}}$$ **Equation 2-5**

Φ	[%]	Relative humidity
P_W	[Pa]	Water vapour partial pressure
P_{WS}	[Pa]	Water vapour saturation pressure

If the temperature of a given sample of air drops, the relative humidity of the sample increases. The amount of water vapour does not change, but the capacity of that air to hold water is reduced. If the temperature drops low enough, the relative humidity will increase to 100% and the water vapour will condense out of the air. The temperature at which this occurs is termed the dew-point of the air sample. The dew-point temperature can be calculated by rearranging Equation 2-4, which results in Equation 2-6.

$$t_d = \frac{4030}{18.689 - \ln \frac{P_W}{133}} - 235$$ **Equation 2-6**

t_d	[°C]	Dew-point temperature
P_W	[Pa]	Water vapour partial pressure

2.3.4 Moisture Storage

Most building materials are hygroscopic, that is, they have the ability to attract water in liquid and vapour forms. Non-porous materials such as steel, glass and some plastics have hygroscopic surfaces and can store a small amount of water as droplets, a layer of ice or frost or as an adsorbed layer on their surface. Adsorption occurs when there is molecular attraction between a water molecule (which is slightly polarized) and a surface. Adsorption layers tend to be only a few layers thick because the molecular attraction to the material surface is weakened by the increased distance of each successive layer of adsorbed water. Porous materials such as wood, concrete, and clay brick have the ability to store a much larger amount of adsorbed water because water vapour can diffuse into tiny pores and form layers of adsorbed molecules on the pore walls. The adsorbed layers may be only a few molecules thick, but the resulting amount of water storage is significant because there is such a large amount of internal surface area, often measured in terms of m^2 per gram of dry material.

If a dry, porous material is placed in a humid space, it will adsorb water until the material reaches equilibrium with the relative humidity of the space. The material will have an equilibrium moisture content quantifying how much moisture has been gained. The moisture content [%] is a ratio of the mass of water in the material to the mass of the material if it were completely dry. If the same material is removed to a lower humidity space it will emit water vapour until it is in equilibrium with the humidity of the new space which will result in a lower equilibrium moisture content of the material. This is termed desorption. Hence the moisture content of a material is closely related to the relative humidity of the air surrounding the material. This relationship is described in Figure 2-4 for a typical hygroscopic material.

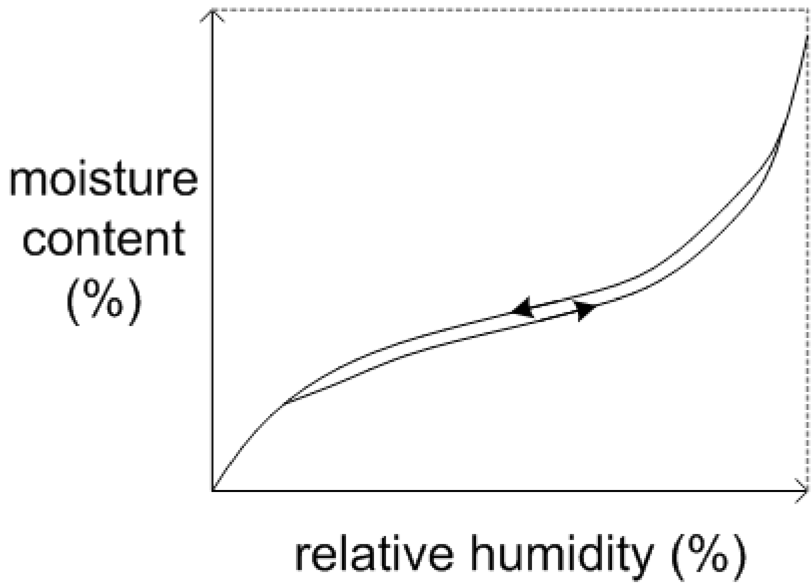

Figure 2-4: Typical Sorption Isotherm of Hygroscopic Material (Straube and Burnett 2005)

The sorption isotherm curve describes the adsorption (wetting) and desorption (drying) based on the moisture content and relative humidity. The sorption-desorption curves do not necessarily follow the same path for reasons that are not completely understood. One hypothesis is that hysteresis is occurring where capillary pressures (and RH) are the same but the pore may be empty in one case and full in the other, resulting in a difference in moisture content. In any event, the difference is usually small enough that collapsing the isotherm into a single curve provides adequate results.

Likewise, sorption behaviour is slightly different at different temperatures, but not enough to make an appreciable difference for most building science problems, hence the temperature is removed from the relationship and the isotherm is the result.

Once a porous material has taken on as much moisture as it can by adsorption (regimes A, B and C in Figure 2-5), it will begin to absorb water through capillary suction. At this point, moisture content increases dramatically for very small changes in RH (regime D). Materials generally do not reach super-saturation (regime E) unless there is some external force acting on the material to force water into every available pore space.

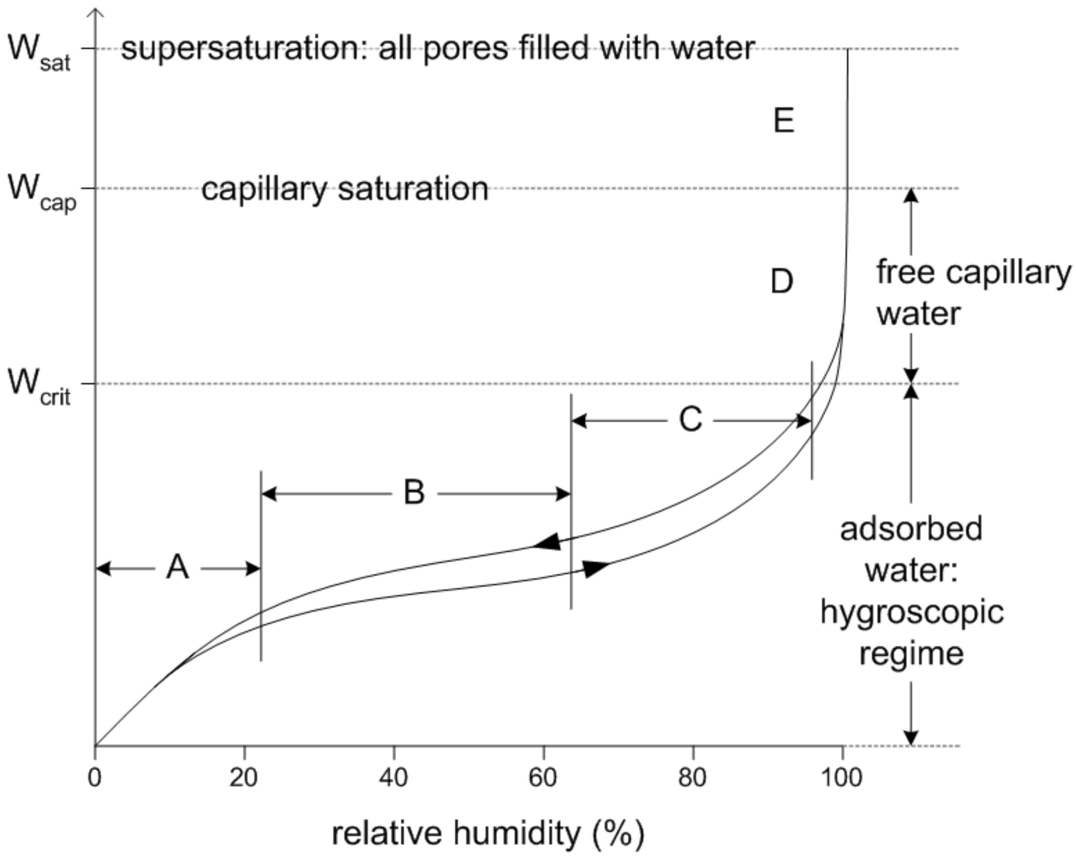

Figure 2-5: Regimes of Moisture Storage in Hygroscopic Porous Material (Straube and Burnett 2005)

Sorption isotherms are very useful for predicting the moisture storage potential of materials, but developing accurate sorption isotherms has proven difficult. The low RH or hygroscopic regimes of A through C can be measured and also predicted effectively through the use of some advanced theories that are beyond the scope of this thesis. The high RH (>95%) regimes D and E are more difficult to measure, but again, some advanced theories help in defining behavior in this regime.

Figure 2-6 shows the sorption isotherms of several building materials as reported by Kumaran et al (2002) at NRC's Institute for Research in Construction. The data is a result of the Moisture management by Exterior Wall Systems (MEWS) project where one of the tasks was to develop values for hygrothermal properties of several common generic building materials.

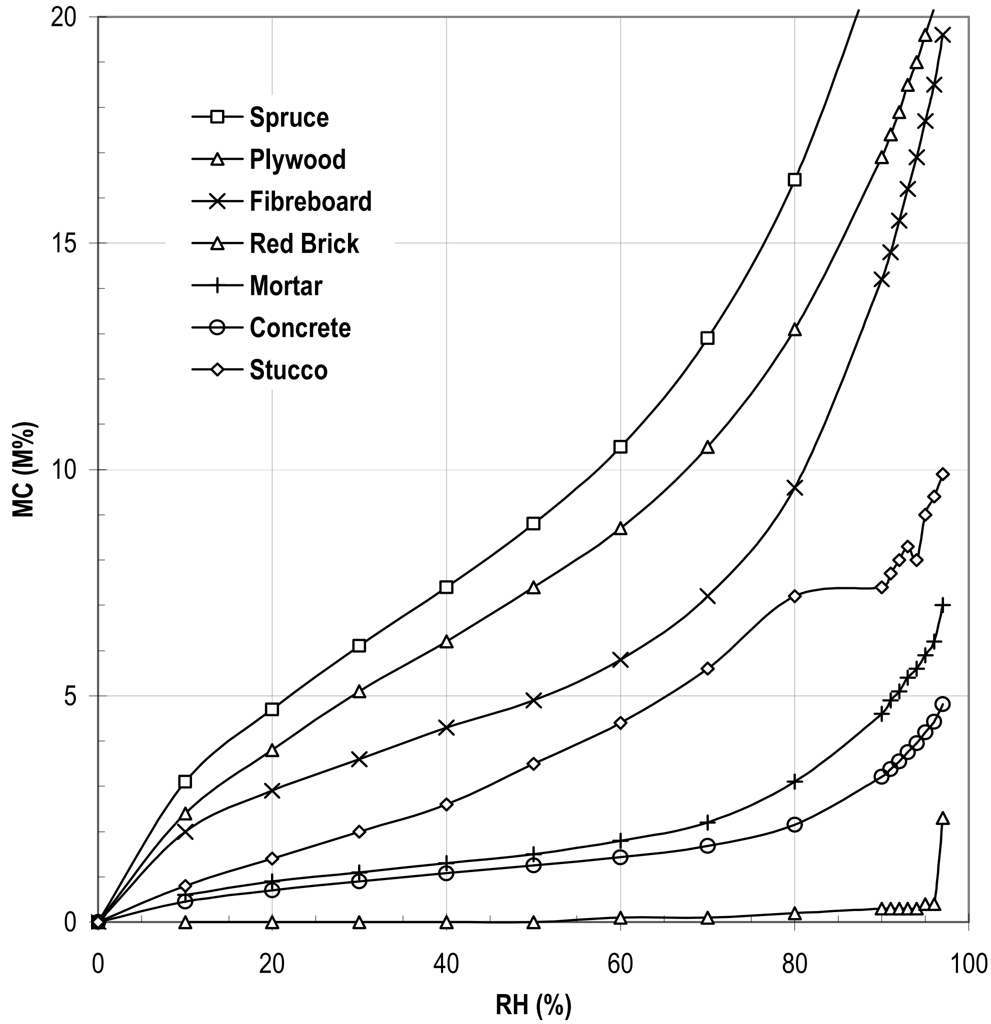

Figure 2-6: Sorption Isotherms of Several Building Materials (Straube and Burnett 2005)

Reliable material property information is crucial for hygrothermal modelling software. Inaccurate material properties are considered one of the biggest obstacles to producing meaningful hygrothermal computer simulations. Building science researchers go to considerable trouble and expense to develop accurate material property information. The Fraunhofer Institute for Building Physics in Germany maintains an extensive database of material properties (for European as well as North American building materials) to use with their hygrothermal modelling software WUFI.

2.4 Vapour Barriers

Most building materials are vapour permeable to some degree, with the exception of glass and metal which are vapour impermeable. Technically speaking the term *vapour barrier* is not quite accurate in many cases because vapour barriers may permit small amounts of vapour diffusion. For example, a 6 mil polyethylene sheet (a commonly specified vapour barrier) has a permeance of around 5 $ng/Pa{\cdot}s{\cdot}m^2$. To address this reality the term *vapour diffusion retarder* has come into use. However, this thesis follows uses the terms *vapour barrier* and *vapour diffusion retarder* interchangeably.

As mentioned earlier, one of the problems with the emphasis on vapour barriers in construction is that vapour diffusion is often blamed for moisture problems caused by other transport mechanisms. To put the wetting potential of diffusion in perspective, the National Research Council published *Building Practice Note No. 54* (Quirrouette 1985). Quirrouette calculated the wetting potential of a 1 m^2 wood-frame wall assembly with fibreglass insulation and wood sheathing under two scenarios. Wall 1 in Figure 2-7 was subjected to vapour diffusion only and contained a polyethylene sheet as a vapour barrier. Wall 3 was the same construction assembly, but contained a 625 mm^2 (1 in^2) hole in the air barrier. The two assemblies were subject to the same interior and exterior winter conditions. Quirrouette calculated the amount of potential vapour diffusion into Wall 1 to be 6 g for a one month period. He calculated the amount of convective water vapour transport (i.e. water movement from air leakage) in Wall 3 was equal to 14 kg for a one month period. Not all the water vapour would condense along the leakage path in Wall 3, therefore he assumed the amount of liquid water accumulation would be only 10% of the total amount, or 1.4 kg. Even so, the water accumulation due to vapour diffusion through Wall 1 was only 0.4% of the accumulation for air leakage in Wall 3. The vapour diffusion in Wall 1 of 6 g represents a trivial amount and could easily be stored and evaporated later without damaging the assembly. Keep in mind that the temperature conditions for both calculations were kept constant for an entire month. In reality, daily fluctuations of temperature and humidity would decrease both wetting potentials considerably.

For the sake of comparison, Wall 2 has been added to Figure 2-7 to demonstrate the wetting potential of vapour diffusion of the same wall without a polyethylene sheet vapour barrier but with a coating of paint with a permeance of 275 $ng/Pa{\cdot}s{\cdot}m^2$. The calculated amount (96 grams) is still less than 7% of the air leakage wetting potential and may be tolerable if the assembly had the ability to dry adequately over the next season.

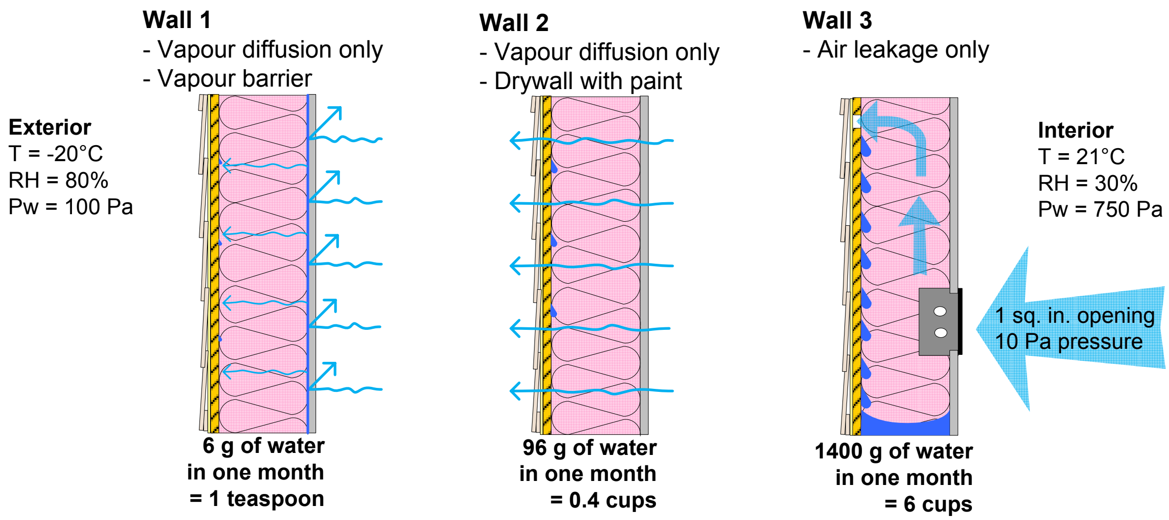

Figure 2-7: Wetting Potential of Vapour Diffusion vs. Air Leakage per m^2 of wall

The previous example emphasizes the importance of an effective air barrier. If a polyethylene sheet is used as a combination air/vapour barrier it is imperative that all holes and gaps are sealed for the sake of air control, not for vapour diffusion control. If an air barrier is provided by a means other than the polyethylene sheet, then gaps and tears in the vapour barrier have little potential to damage the wall.

Vapour diffusion is not always harmless and there are cases where the wetting potential is high enough to be of concern. Buildings with high humidities, or moderate humidities in very cold climates, have much larger vapour drives and significant wetting potential. Swimming pools, hospitals, and museums tend to have intentionally high humidities and will almost certainly require a vapour barrier layer if a high permeance fibrous insulation layer is used.

The rule-of-thumb for placement of a vapour barrier in an assembly is "install on the warm side of the insulation". This prevents the moisture from diffusing into the wall and condensing, and potentially freezing, at the lowest permeance layer. In the case of Wall 2 in Figure 2-8, the frost build-up occurs on the wood sheathing layer.

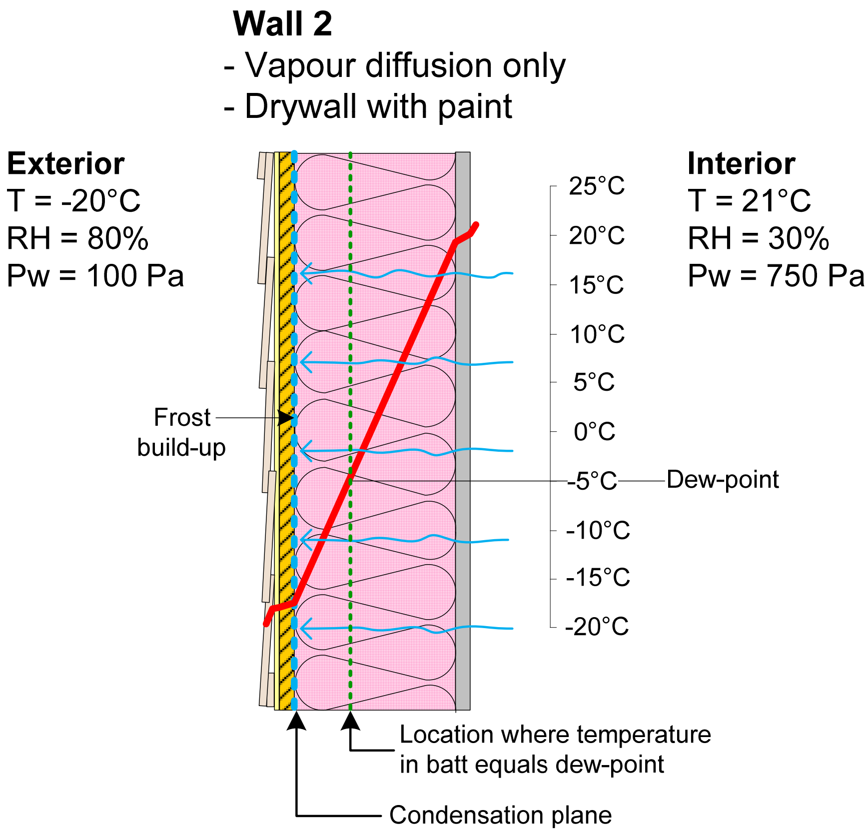

Figure 2-8: Wall 2 with Thermal Gradient and Frost Accumulation

In warm weather or in very low temperature buildings such as cold storage facilities, the vapour drive is reversed and flows from exterior to interior. The water vapour can condense on a layer close to the air conditioned interior if the layer reaches dew-point. In these conditions, the vapour barrier layer should be placed outboard of the insulation, i.e. the warm side. Vinyl wall coverings can be very low permeance and may unintentionally impede inward vapour diffusion and cause problems with moisture build-up and mold growth between the wall and wall paper. Hotels often use vinyl wall paper in guest rooms because it is inexpensive and easy to clean, but hotels in warm climates are notorious for developing mold problems behind vapour impermeable wall coverings. Canada has a climate with cold winters and warm summers; this means that the "warm side of the insulation" changes sides between seasons.

2.4.1 Requirements for Vapour Barriers

Part 5 of the National Building Code of Canada (NBCC) 2006 pertains to commercial or professionally-designed construction. Section 5.5 specifies vapour barriers are required "where a building component or assembly will be subjected to a temperature differential and a differential in water vapour pressure" except in cases "where it can be shown that uncontrolled vapour diffusion will not adversely affect any of, (a) health or safety of building users, (b) the intended use of the building, or (c) the operation of the building services." This is a performance-based code requirement that gives the building designer the flexibility to determine if, where, and how a vapour barrier should be installed.

Part 9 of NBCC is a prescriptive code that applies to smaller buildings (<600 m^2). It requires vapour barriers in any "thermally insulated wall, ceiling and floor assemblies" and that vapour barrier materials must have a permeance of 60 ng/Pa·s·m^2 or less. In wall assemblies that have low permeance exterior sheathing the vapour barrier must be 15 ng/Pa·s·m^2 or less. This provision (which, with a ratio of 4:1, harkens back to the "obscure 5:1 ratio" discussed earlier) permits outward drying if moisture enters the interstitial space between the vapour barrier and the low permeance cladding/sheathing.

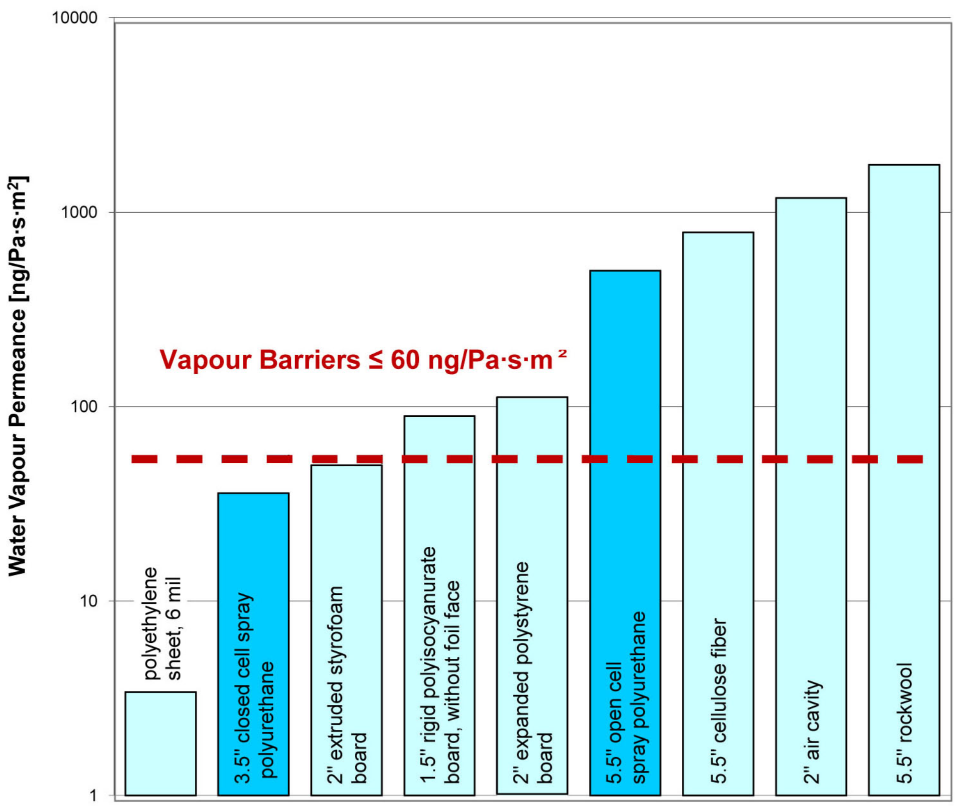

Figure 2-9: Permeance of Common Assembly Layers

The chart in Figure 2-9 shows the relative permeance values for polyethylene sheet and for several types of insulation already discussed. The standard CAN/CGSB-51.33-M89, "Vapour Barrier Sheet, Excluding Polyethylene, for Use in Building Construction." classifies vapour barriers into two types and provides performance and physical requirements for each. The vapour permeance values are listed in Table 2-1.

Table 2-1: Permeance of Type 1 and Type 2 Vapour Barriers

Vapour Barrier	Vapour Permeance [ng/Pa·s·m^2]
Type 1 (low permeance)	15 (before and after aging)
Type 2 (standard permeance)	45 (before aging)
	60 (after aging)

From this information it is clear that some types of insulation products such as 3.5 inches of closed cell SPF and 2 inches of XPS fulfill the code requirements of vapour barriers. In fact, 2 inches of closed cell foam still meets the prescriptive permeance requirements of the code.

In the U.S., the requirements are the same but the vapour barrier definition of "1 perm" converts to about 60 ng/Pa·s·m^2 (Figure 2-10). The information in this figure is slightly dated; the definition of Vapor Retarder < 1 perm has now been adopted into the International Residential Code as well as the International Energy Conservation Code (IECC).

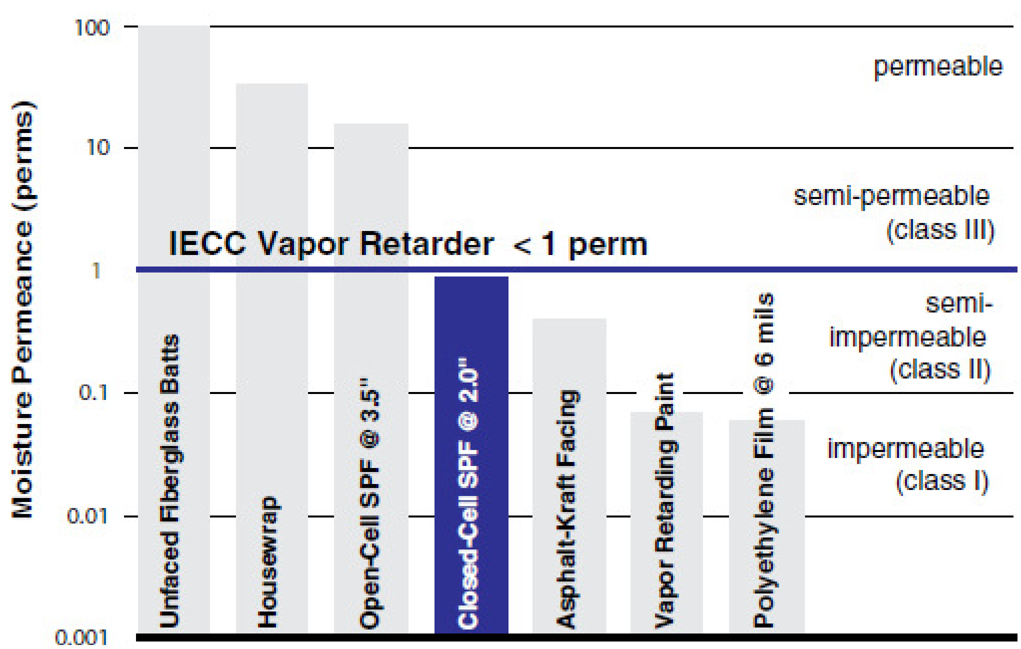

Figure 2-10: U.S. Vapour Barrier Classifications (Honeywell)

2.5 Spray Polyurethane Foam Insulation

The development of the first polyurethane foam was reported in Germany by Otto Bayer in 1947 (Woods 1982). Rigid foams were developed by 1957 and used as insulation in building cavities since the 1960s. Spray polyurethane foam (SPF) comprises two liquid components - a polyisocyanate compound (often called the A component) and a polyhydroxyl compound (the B component). Component B contains additives such as blowing agents, catalysts, stabilizers and fire retardants.

Most rigid foam plastic insulations (except expanded polystyrene) used chlorofluorocarbons (CFCs), such as Freon R, as a blowing agent until it became clear in the early 1990s that CFCs had high ozone depletion potential (ODP). Foam manufacturers switched to some form of hydrochlorofluorocarbon (HCFC) which breaks down faster and is much less damaging to the ozone layer. The trade-off was that RSI values of urethane type foams may be slightly lower and their global warming potential (GWP) may be higher. HCFCs are being phased out (by 2020) by using a chlorine-free hydrofluorocarbon (HFC) blowing agent with both low ODP and GWP values.

2.5.1 Properties of SPF

Two broad classes of SPF are used as cavity insulation – open cell (0.5 pcf) foam and closed cell (2 pcf) foam. High-density rigid SPF is commonly used in roofing and can support the substantial compressive loads generated by environmental, material and maintenance loads. Other applications for SPF are in industrial process equipment and in pipe and duct insulation.

Widespread acceptance of foam as insulation in residential construction has been rather limited due its high cost which is in the range of 3-5 times that of traditional fibrous insulation such as fibreglass or cellulose (Bomberg and Kumaran 1999).

When open cell SPF is sprayed in wall cavities, it often expands beyond the wall framing and is trimmed flush with the face of the wall after it has cured. A skin may form on the surface of this type of foam but it is often trimmed off therefore can not be relied upon for any extra vapour control. Open and closed cell foams have different values in heat conductance and vapour permeance, with higher values corresponding to lower densities.

The chemical reaction that creates the expansion of closed cell foam produces a considerable amount of heat. The foam installer applies the foam in lifts of up to two inches in order to avoid substantial heat buildup that could lead to combustion of building materials. The cavity of a 2x6 wood framed wall is rarely filled to full depth because thinner (and less costly) layers will provide sufficient heat resistance for most projects and the labour to cut back the foam is costly. The total thickness of closed cell foam layers should be close to 50 mm (two inches) in order for the foam layer to provide sufficient vapour control (Bomberg and Kumaran 1999). A smooth skin may form on the topmost surface of the foam; it cannot be relied upon to provide extra vapour diffusion resistance due to the fact that its formation is unpredictable and no design values have been published for this characteristic. Even so, the vapour resistance of the foam itself is often high enough that accounting for the increased resistance from the skin is unnecessary.

SPF must be applied to a dry, clean, rigid substrate in order to adhere well. In addition, the liquid components of the foam must be mixed in the correct ratios at the correct temperatures in order for the foam to react and cure properly. Failure to achieve proper mixing conditions can lead to foam shrinkage or uncured foam that does not reach published RSI values. Typically, if foam shrinkage occurs it is apparent within a day and can be remedied by filling gaps with one-component canned foam. If foam is sprayed on an excessively cold substrate, the exothermic reaction of the foam dissipates quickly reducing the effectiveness of the reaction leading to underdeveloped foam properties. This can be prevented by heating cold surfaces or covering them with a thin “flash coat” of foam which warms up the surface in preparation for a full thickness lift. If the foam is sprayed on a wet surface, the A component tends to react with the water which throws off the balance of the mixing ratio. One of the by-products of the reaction is carbon dioxide, essentially more blowing agent, which leads to larger cells, lower densities and less adhesion. Foam also will not adhere properly to dusty or oily surfaces. Foam chemical suppliers cite the rule of thumb that foam can be applied to any surface that can be painted safely.

Many of these performance issues can be addressed through proper training of SPF installers. In Canada, only trained, certified and licensed installers can install medium density spray polyurethane foam building insulation. All work must meet the requirements of the CAN/ULC S705.2 Installation Standard and must be supervised by a licensed contractor. There is no mandatory certification required for installers or contractors in the United States.

All densities of SPF permit negligible amounts of air leakage (in the range of 0.0001 $L/s{\cdot}m^2$ at 75 Pa) and thereby fulfill the NBCC requirements for maximum air leakage rates for materials of 0.02 $L/s{\cdot}m^2$ at 75 Pa. Air leakage can reduce the effective RSI value of insulation materials. Denser materials reduce heat loss through convection, but increase heat loss through conduction. Figure 2-11 shows various types of insulation and their relative amounts of “apparent thermal conductivity” a value which accounts for heat flow due to conduction, convection and radiation. Polyurethane foam outperforms the other materials by a significant amount.

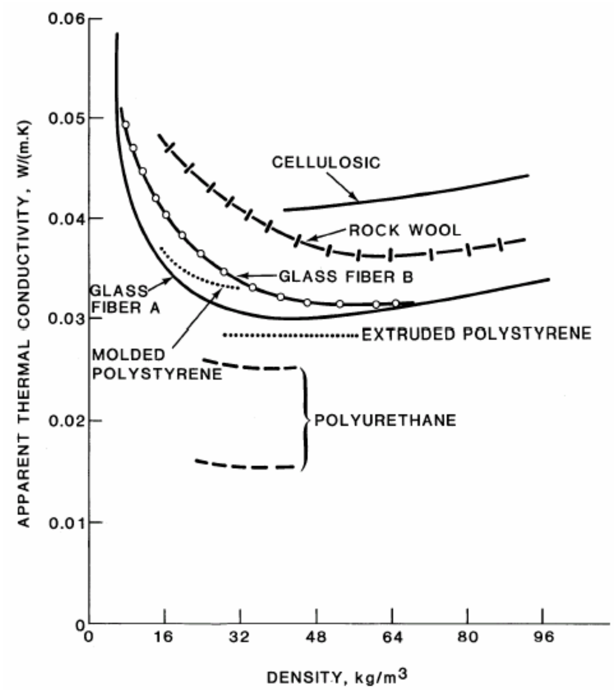

Figure 2-11: Apparent Conductivity of Several Types of Insulation (ASHRAE 2001)

The generic material properties for both open cell SPF and medium-density closed cell SPF are listed below in Table 2-2.

Table 2-2: Material Properties for 25 mm of Generic SPF

Property	Open Cell SPF	Closed Cell SPF
Density	8 kg/m^3 (0.5 pcf)	32 kg/m^3 (2 pcf)
Compressive Strength	4.8 kPa (0.7 psi)	185 kPa (27 psi)
Thermal Resistance	RSI = 0.6 m^2·K/W (R-value = 3.4 hr·ft^2·°F/Btu)	RSI = 1.05 m^2·K/W (R-value = 6 hr·ft^2·°F/Btu)
Air Permeance	<0.002 L/s·m^2 at 75 Pa	<0.0001 L/s·m^2 at 75 Pa
Vapour Permeance	1200 ng/Pa·s·m^2	90 ng/Pa·s·m^2

2.6 Wood Properties

Solid wood, plywood and oriented strand board (OSB) have very similar thermal resistance properties but their vapour transmission properties are quite different. The vapour permeance of plywood and OSB are plotted in Figure 2-12.

Most people have encountered real-life examples of the effects of moisture on wood and wood products. Excess moisture often results in swelling and possibly mold or decay of the wood. If one were to visualize the microscopic structure of wood material, one could imagine the structure swelling and closing off pathways for further vapour diffusion, reducing the vapour permeance. In fact, the opposite is true. Figure 2-12 plots the vapour permeance of plywood and shows the vapour permeability increases with increasing humidity, and therefore, moisture content. A publication from the British Columbia Homeowner Protection Office describes this property as an advantage in a wall assembly because "the assembly is self-correcting" (HPO 2006). Meaning that the higher its moisture content, the greater its diffusion and subsequent drying ability.

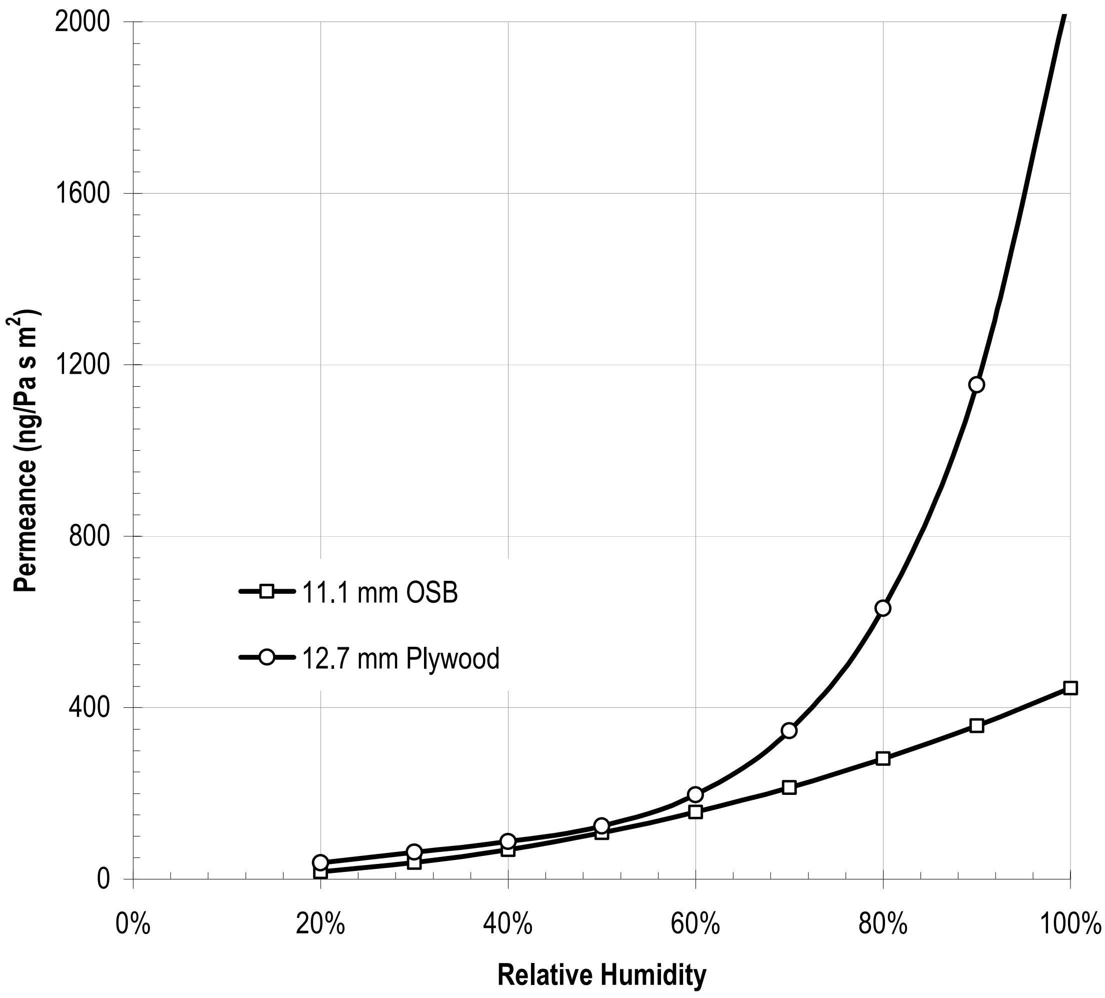

Figure 2-12: Vapour Permeance vs. RH of OSB and Plywood (Straube and Burnett 2005)

There are several theories as to why the permeance increases with RH in wood-based products, but all of them acknowledge that vapour diffusion is not the only transport mechanism at play.

2.6.1 Wood Decay

Wood-rotting basidiomycetes (WRB) are the main decay fungi for untreated wood and wood-based products (Morris 1998). WRB thrives in high humidity environments where high-MC wood can be found. Decay fungi require food, water, oxygen and warmth to sustain and grow. The wood itself supplies the food source and of the other three items, the water or moisture content of the wood is the only thing left under our control. Morris states, “Moisture control is key to durability of wood systems.”

Some moulds can survive at moisture contents between below 20% but they achieve little growth. Moisture content above 20% can sustain growth, but in order for spore to infect outlying areas, moisture contents need to be at 29% or above. This would require a relative humidity of close to 96%. If moisture contents above 29% have established the WRB, the ongoing MC needs only to be in the 22 - 24% range to proceed (Morris 1998). For this reason, safe MC levels are capped at 20%.

A separate Building Engineering Group project researched mould growth on wood and wood products and found that the industry’s commonly quoted critical relative humidity threshold of 80% was very conservative (Black 2006). The project results indicated that wood sheathing with a moisture content of well over 30% and 25°C did not exhibit any mould growth and decay at 16-19 weeks. It did find that mould growth accelerated rapidly once liquid water was present.

Chapter 3
Past Research

3.1 History of Vapour Barriers

Prior to 1920, traditional residential construction disregarded vapour diffusion as a serious concern because it had little effect on building performance (Rose 1997). Materials like plaster and wood were generally vapour impermeable enough that any water vapour transport was safely stored in the material and evaporated later or diffused through each layer of the assembly until it evaporated to the interior or exterior depending on the conditions.

Diffusion only started raising concerns when enclosures began to incorporate materials that were of much lower permeance, lower water storage capacity, higher thermal resistance or some combination thereof. These factors led to a buildup of water in the building enclosure which in turn led to problems with moisture damage, decay, corrosion and failure (Hutcheon and Handegord 1983).

As researchers grew to understand the physics of water vapour transmission, they developed methods for permeance testing and formulating permeance values for building materials. By the building boom of the 1940s, Canadian construction was incorporating thermal insulation, water resistant barriers on the exterior, and some type of vapour barrier on the interior (Bomberg and Onysko 2002). In 1950, by reference in the National Building Code of Canada, vapour barriers became mandatory in construction. Under the imperial unit system of the time, vapour barriers were required to have a permeance of less than 0.75 perm (45 ng/Pa·s·m^2). A perm, it was agreed in Canada and the U.S, was an acceptable amount of vapour diffusion in an enclosure. Bomberg and Onysko (2002) point out, "One must remember that 1 perm was a unit of water vapour permeance introduced to characterise a well performing but leaky wood-frame house built in 1930s." Condensation from air leakage was not being addressed at all.

In 1958, Glaser introduced a simple method for calculating the potential for condensation from vapour diffusion within construction assemblies (Glaser 1958) based on the earlier, individual work of Dr. Frank Rowley of the University of Minnesota (Rowley 1939) and J.D. Babbitt of the Canadian Scientific Liaison Office (Babbitt 1939). This led to somewhat of a fixation on vapour control in buildings. Bomberg and Onysko (2002) state that for Canada, "the emphasis on vapour control has received a disproportionate amount of attention." If calculations predicted any condensation in an assembly, it was deemed unacceptable and vapour barriers were promoted as the solution. The treatment was unwarranted because it was clear from actual building performance that a certain amount of moisture storage in hygroscopic materials was harmless. Bomberg and Onysko (2002) speculate that diffusion control became the focus because, of all moisture transport mechanisms, water vapour transmission is the easiest to calculate. It is interesting to note that J.D. Babbit, one of the earliest researchers in this area, took exception to the amount of influence granted to vapour diffusion in total moisture transport. He stated in the early 1950s, "I think it worthwhile, therefore, to take a little of your time to point out what is predicted by the traditional theory of diffusion and to show you how the migration of moisture departs from these predictions" (Rose 1997).

3.2 Vapor Barrier/Air Barrier Confusion

According to Bomberg and Onysko (2002) condensation from air leakage was relatively ignored until the early 1960s when researchers were investigating condensation rates on windows (Wilson 1960, 1961). It was not until the early 1970s when researchers were able to tie some pertinent research to practical problems occurring in the field with condensation problems in houses with electric baseboards. These houses were presumably equipped with the mandatory vapour barriers, but moisture from air leakage was accumulating in attic spaces causing considerable damage in some climates. Air leakage was finally being given some consideration in moisture transport. By 1980, construction was tightening up enough that the National Building Code had to start specifying mechanical ventilation rates.

It was a relatively short jump from there to the concept of a combination air/vapour barrier, which led to further confusion about the intended functions of air and vapour barriers. Not to mention the most commonly specified and used air/vapour barrier – polyethylene sheet, cannot properly perform as an air barrier in all cases because it can’t transfer significant wind load and is difficult to air seal in the field. The National Building Code does not require polyethylene sheet as a vapour or air barrier but provides performance thresholds for the enclosure to meet in both these areas. There are several other methods that could achieve these purposes as was discussed in Section 2.4.

3.3 Is a Vapour Barrier Necessary?

The Moisture Control Handbook (Lstiburek and Carmody 1993) refers to an “obscure recommendation” from F.A. Joy in 1957 of a 5:1 for a difference in permeability of exterior versus interior assembly layers. This recommendation meant that in cold climates the exterior elements of the enclosure should be five times more vapour permeable than the interior elements. This would allow outward drying of the enclosure should any moisture enter the enclosure from diffusion or leakage. The risk is that if low permeance layers are located on both the inside and outside they slow drying of any interstitial water, which could lead to water accumulation and subsequent decay. A recent Finnish research project using climate chamber testing confirmed that wall assemblies incorporating either mineral or organic fiber insulations should follow the 5:1 ratio for outside to inside vapour permeance (Vinha and Käkelä 1999) in cold climates.

Straube (2001) argued that vapour barriers are rarely needed in most climates and in fact can add to problems by preventing inward drying during warmer months. Incidentally, Lstiburek published an errata for the Moisture Control Handbook in 2002 stating that vapour diffusion retarders (of any type) should be avoided in all below grade insulated wall assemblies as well as any above grade assemblies located in climates less than 8000 heating degree days °F (approximately 4430 heating degree days °C). He had determined diffusion was not problematic enough in these climates to warrant a dedicated vapour barrier layer and finishes like standard latex paint on gypsum board were adequate for slowing diffusion. Furthermore, the addition of the vapour barrier layer was causing more problems (i.e. with inward summer drives) than it was solving.

Some building envelope practitioners (Lawton and Brown 2003) disputed the assertion of vapour barriers creating moisture problems in summer months and pointed to simulations and field evidence of walls in Lower Mainland B.C. as proof that eliminating the polyethylene vapour barrier "did not significantly improve the wall's ability to dry when there was rain penetration into the wall." They believed that "Furthermore, both the analysis and field observations indicate that removing the polyethylene will increase the risk of mold growth on paper-faced gypsum board used as interior sheathing."

Straube et al (2007) responded to the dispute with data and simulations from a Canada Mortgage and Housing study conducted at the University of Waterloo's Building Engineering Group test hut (BEGhut). They found that in three south facing walls – one with poly, one without, and one with XPS sheathing, the wall with the highest summertime condensation risk was the wall with poly. It was at risk 41% of hours over a 91 day period. The No Poly wall was at risk 1% of the hours and the XPS wall had no risk of condensation.

3.4 Spray Foam Insulation as Vapour Barrier

A study conducted with the Canadian Urethane Foam Contractors Association (CUFCA) investigated the performance of full-scale cavity walls containing either open or closed cell foam exposed to the environment of Southwest Ontario (Finch at al 2007). The walls did not contain any vapour control other than the spray foam and medium permeance paint (300 ng/Pa·s·m^2). The exterior of the walls were finished with a ventilated brick cavity and the walls were exposed to real climate conditions for a number of months (Figure 3-1).

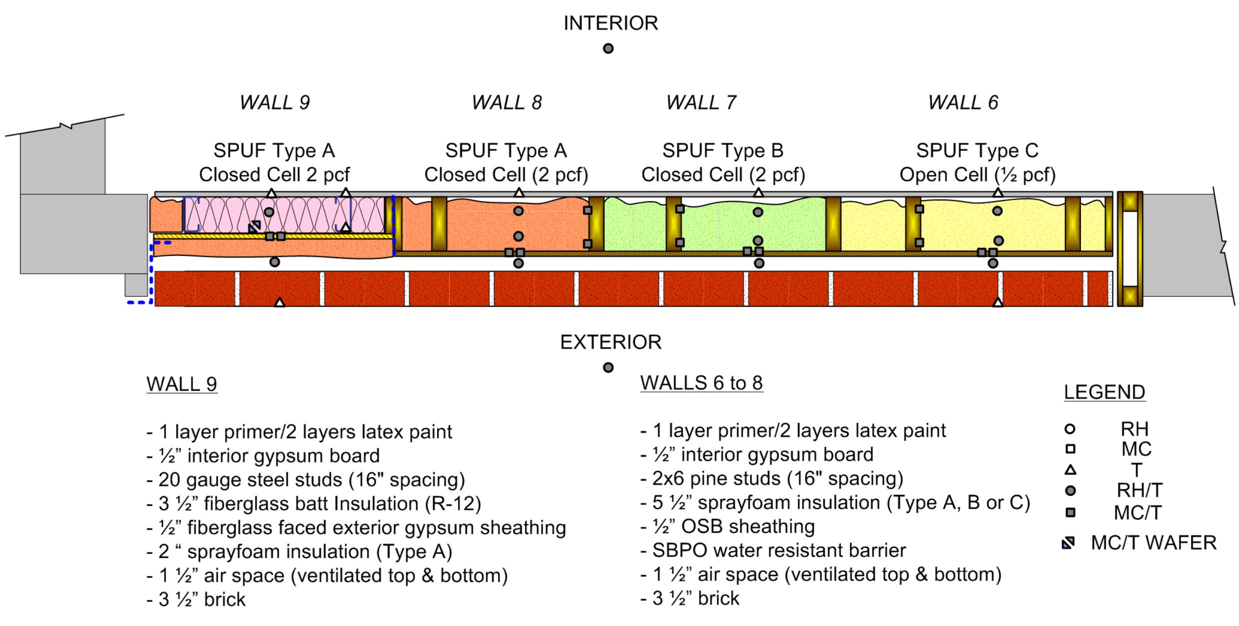

Figure 3-1: BEGhut Full Scale Wall Tests (Finch et al 2007)

The BEGhut maintained interior conditions of 20°C and 50% relative humidity which is higher than most occupancies, except for hospitals, museums and pools. Finch did not recommend these interior conditions in cold climates and specified relative humidities should be kept to 40% or lower in practice. He found Wall 6 with open cell foam resulted in “dangerously high moisture contents of the sheathing as a result of vapour diffusion.” He recommended additional vapour control in climates of more than 4000 heating degree days °C (comparable to Toronto’s climate and colder (more on heating degree days in Chapter 7)) in the form of a vapour retarding paint (in the order of 300 $ng/Pa \cdot s \cdot m^2$), smart retarder, or polyethylene sheet.

Finch found the walls filled with closed cell foam, Walls 7 and 8, performed well and were barely affected by the high humidity. His computer modelling showed that the closed cell foam performed at 50% RH in climates as cold 6500 HDD ºC (Edmonton and colder).

Incidentally, Finch mentioned a potential moisture issue for sheathing materials inboard of cladding with large water storage capacity, such as brick. During inward vapour drives in the summer months his measurements and modelling showed that the sheathing panels were experiencing a significant increase in moisture content. To control this he recommended an exterior vapour control layer on the exterior of the sheathing similar to the layer of closed cell SPF shown in Wall 9 of Figure 3-1.

Chapter 4
Research Plan and Experimental Setup

4.1 Research Plan

The plan for this research was to investigate several types of open cell and closed cell spray polyurethane foam insulation in a variety of assembly configurations both in lab tests and hygrothermal simulations. The lab tests were conducted under steady state conditions. The hygrothermal simulations were conducted for seven wall assemblies, seven Canadian climate categories and three levels of interior relative humidity. The goal was to determine which spray polyurethane foam applications required the addition of a dedicated vapour barrier layer beyond what the foam itself could provide.

4.2 Experimental Objective

The objective of the lab experiment was to determine how much resistance to water vapour diffusion was offered by various spray polyurethane foam (SPF) insulation products installed in representative wall assemblies subjected to large-gradient temperature and humidity conditions.

4.3 Experimental Scope

The scope of the experiment was to test the most common types of open and closed cell spray polyurethane foam insulation used in Canadian residential and commercial construction. Fibreglass batt insulation was included in the test as a reference case.

4.4 Experimental Approach

The experiment was conducted by installing the test boxes into an air-tight wall assembly built into a climate chamber (Figure 4-1). One side of the climate chamber was conditioned to simulate room temperature with a high humidity load; the other side was conditioned to simulate cold outdoor conditions. The test boxes were subjected to large, steady gradients for temperature and relative humidity over a period of 57 days. Water accumulation was observed through periodic mass gain measurements and moisture content readings in the exterior oriented strand board (OSB) sheathing of each test box.

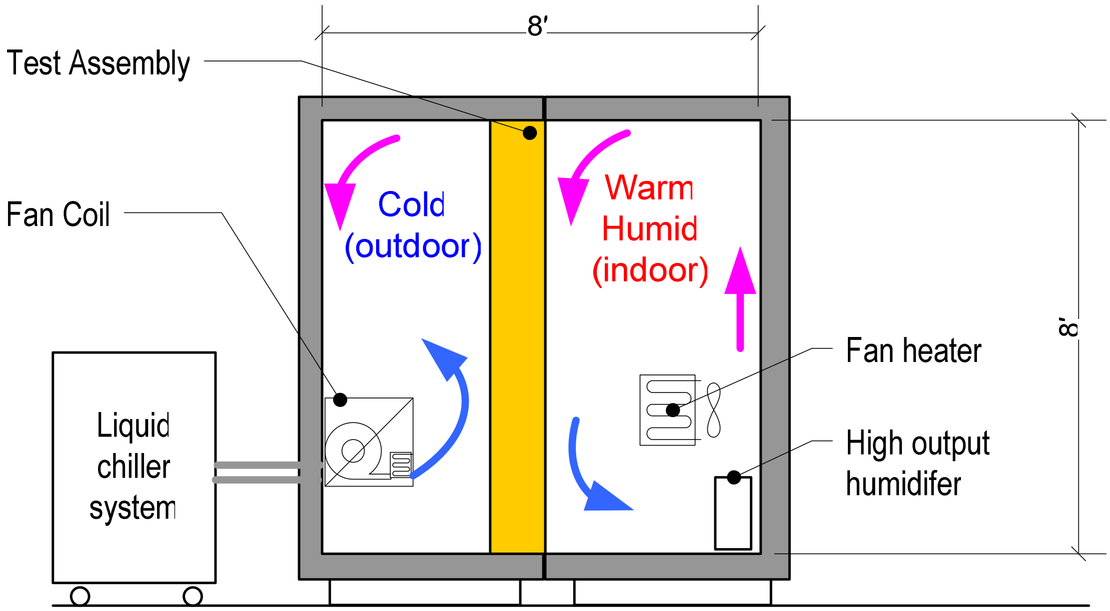

Figure 4-1: Section of the BEG Climate Chamber

4.5 Test Samples

The test boxes contained representative samples of SPF from different manufacturers and in different configurations based on common field applications. Eight different foam type/thickness combinations were tested, with each combination having a test box with a polyethylene vapour barrier (the A-series) and a test box without a polyethylene vapour barrier (the B-series). A ninth combination of A and B test boxes included fibreglass batt insulation. The fibreglass acted as a reference case for standard wood frame wall construction. Two more test boxes were built, one to investigate the performance of high density foam and the other to investigate flame retardant treated foam on exterior gypsum and steel studs. Table 4-1 lists the details of each combination and its test purpose.

Table 4-1: Test Box Variables

Test Boxes				Test Purpose(s)	
Insulation Type-Thickness	Cell	Poly VB	No Poly		
BASF Walltite - 3.5"	closed	**1A**	**1B**	+/- poly	+/- manufacturer
DOW Styrofoam™ 3.5"	closed	**2A**	**2B**	+/- poly	
Polar Foam PF7300 3.5"	closed	**3A**	**3B**	+/- poly	+/- thickness
Polar Foam PF7300 4.5"	closed	**4A**	**4B**	+/- poly	
Demilec HeatLok Soya 3.5"	closed	**5A**	**5B**	+/- poly	+/- thickness
Demilec Heatlok Soya 4.5"	closed	**6A**	**6B**	+/- poly	
Demilec Sealection 5.5"	open	**7A**	**7B**	+/- poly	+/- manufacturer
Icynene Gold Seal 5.5"	open	**8A**	**8B**	+/- poly	
Fibreglass 5.5"	n/a	**9A**	**9B**	+/- poly	reference case
Polar Foam, Class One, 2" min.	closed	**-**	**10**	commercial demo	
Polar Foam, High Density, 2" +/-	closed	**-**	**11**	role of density	

4.6 Boundary Conditions

The climate chamber was bisected by the air-tight wall assembly that contained the test boxes. One half of the chamber was conditioned to warm, "room side", or interior conditions of 25°C and 50% relative humidity. The other half of the chamber was conditioned to cold, "climate side", or exterior conditions of -10°C with an unregulated relative humidity of approximately 60%.

A higher than normal interior temperature of 25°C was chosen to increase the vapour pressure drive across the assemblies to 1417 Pa. It would have been difficult to reduce the vapour pressure on the cold side without large decreases in temperature, whereas a small increase from 21 to 25°C at 50% RH results in a 30% overall increase in the vapor pressure drive. The small difference in temperature should have no other effect on the material properties or behaviour.

4.7 Experimental Setup and Apparatus

4.7.1 Climate Chamber

The Building Engineering Group (BEG) climate chamber is a large box constructed from 2x4 in. wood studs sheathed with plywood on the exterior and plastic-coated fibre board panels on the interior. The wall and roof cavities are filled with 3.5 in. of fibreglass batt insulation and covered with two layers of 1 in. aluminum foil-faced polyisocyanurate board insulation. The floor cavity is filled with 5.5 in. of fibreglass batt insulation and two layers of 1 in. polyisocyanurate board insulation (Black 2006).

The interior dimensions of the chamber are 8 x 8 x 8 ft. The chamber can be separated completely into two halves in order to insert an 8 x 8 ft. wide test assembly into the opening. The chamber is reassembled by forcing the two halves together using a system of ratchet buckles and nylon webbing. The joint between the halves are sealed with sill gasket and construction tape. Each half of the chamber can be accessed by a door built into the end walls (Figure 4-2).

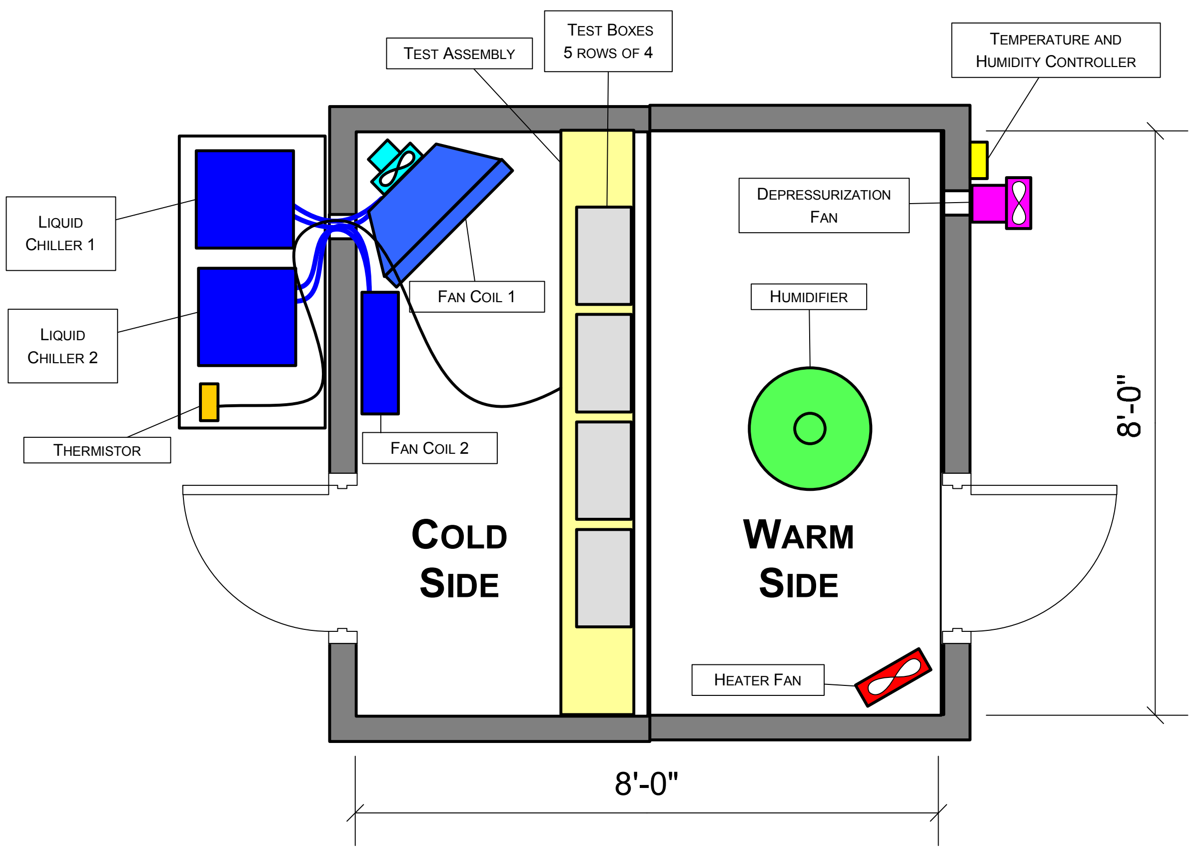

Figure 4-2: Plan View of Climate Chamber Set-up

The chamber walls and roof provide an effective thermal resistance of approximately RSI 4.7 (R-25), while the floor provides RSI 5.9 (R-30). The interior finish of the plastic-coated panels provides a very low permeance coating. The result is a closed chamber interior that is well isolated from ambient thermal and moisture effects of the Fluid Hydraulics Lab where the chamber is located in the University of Waterloo Engineering 3 building.

Figure 4-3: BEG Climate Chamber

4.7.2 Design of Test Assembly and Test Boxes

For this particular experiment, the cold side of the chamber contained the test assembly. The test assembly consisted of a plywood shelving unit that fit into the 8 x 8 ft. opening with a small amount of clearance between the assembly and the chamber walls (Figure 4-4). The assembly provided compartments for the test boxes in a 4x5 grid.

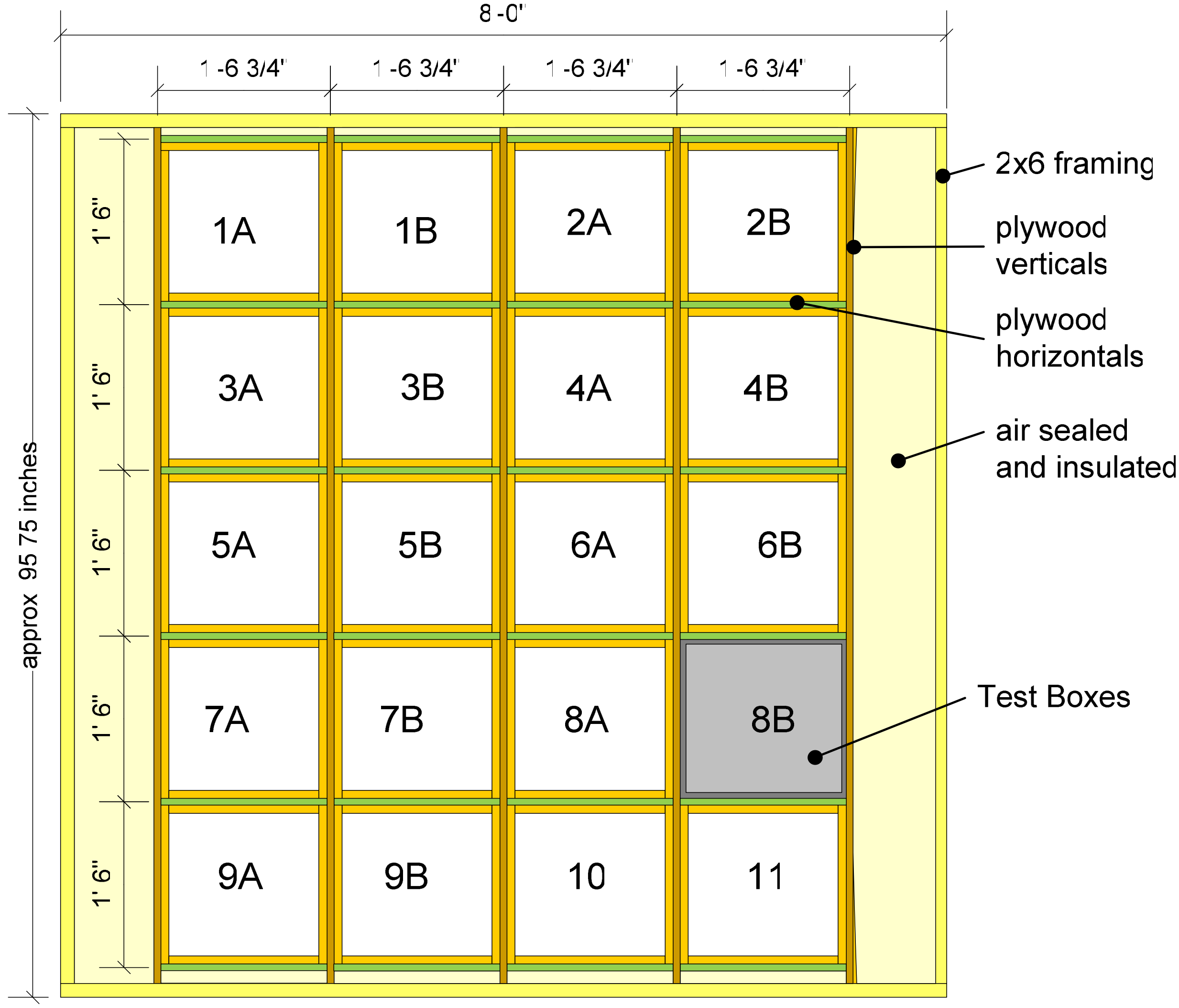

Figure 4-4: Elevation View of Test Assembly

The test boxes had to be large enough to eliminate possible edge effects but still mimic real life assemblies. This requirement determined the sample dimensions were each made with an interior width of approximately 16 x 16 in. to simulate full-size standard wood framing at 16 in. on-center. The height of the case was slightly less than 16 in. in order to accommodate all 20 boxes within the chamber opening.

The standard construction for each test box was a melamine case with a panel of Oriented Strand Board (OSB) covered with Tyvek house wrap on the exterior face, and ½ in. gypsum board coated with primer and latex paint on the interior face. The panels were fastened at each side by a 1 x 6 in. board of Eastern White Pine to simulate a stud wall cavity at 16 in. on centre. The "stud" created a 5.5 in. deep cavity between the faces of these two panels (Figure 4-5).

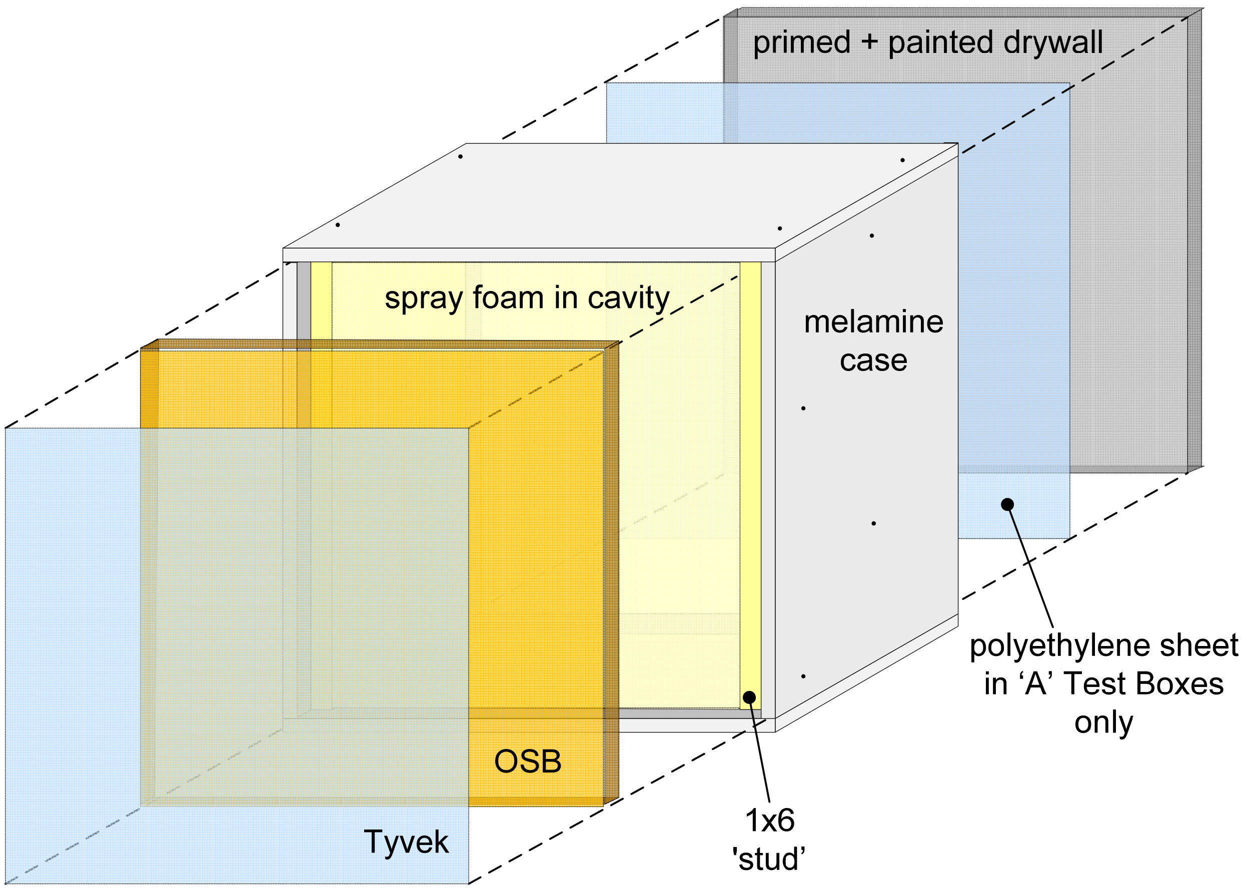

Figure 4-5: Axonometric View of Test Box Construction

In order to produce meaningful results, it was important that the test samples were applied using the same process and thicknesses that they would be out in the field. For this reason, the test boxes were delivered to various insulation providers in order to have the insulation applied by certified installers on existing jobsites.

4.7.3 Preventing Air Leakage in the Test Assembly

As mentioned previously, the test assembly was inserted into the cold side chamber. The 8 x 8 ft. opening in the cold chamber was first outfitted with 2 x 6 in. wood stud frame with a top plate, bottom plate and one column on each side. The shelf assembly fit snugly into the frame opening and was fastened in place. Any non-intentional openings were sheathed in plywood and all joints were caulked with silicone. The test shelf did not fill up the entire 8 x 8 ft. chamber opening; therefore the 9 in. cavity around the perimeter was sheathed in ¼ in. plywood, insulated and all gaps were covered with foam, sealant or tape to prevent air leakage between the two chambers.

The joint between the two chambers was filled with 1 in. foam backer rod to suppress convection and taped with construction tape as an air seal. Any air leakage from this joint would be from the ambient conditions of the lab to the warm side of the chamber. Since conditions on the warm side chamber were relatively easy to regulate, the air leakage from this joint was not of as great concern as air leakage from the cold side chamber to the warm side chamber.

4.7.4 Preventing Air Leakage in the Test Boxes

The melamine case constructed for each test box was taped with aluminum tape at all cut edges before construction. Once each box was assembled, each exposed edge was taped again with another layer of aluminum tape and a one of construction tape (Figure 4-6). On the exterior face of the test box, the Tyvek layer was installed between the aluminum and construction tape layers (Figure 4-7). The gypsum board was fastened to the Eastern White Pine "studs" and all edges were caulked with silicone sealant to prevent any air leakage. If it was an A-series test box (one with a polyethylene vapour barrier) the polyethylene was attached to the backside of the gypsum board with construction tape on all edges. This created a test box that would only be subject to vapour diffusion and no convective (i.e., air leakage) moisture transport.

The 20 test boxes were inserted into the test assembly shelf from the cold side (Figure 4-8). The empty assembly resembled a shelving unit of twenty equally sized compartments with an open back except for a short lip around the back perimeter of each compartment. The lip edge provided a means of minimizing air leakage between the two chambers when the test box was forced up against a strip of weather-stripping (3/4 in. wide closed-cell neoprene) installed on the lip (Figure 4-9). The lip edge necessitated that the test boxes be inserted or removed from the cold side only. Once the test boxes were inserted, a manual screw-down block provided enough compression to keep them tight against the interior compartment weather-stripping (Figure 4-10). As a further precaution, a flexible flap of closed-cell polyethylene sill gasket was installed on the front edge of each compartment to minimize convective currents in the space between the test box and shelf walls. Another strip of closed-cell neoprene weather-stripping was installed along the top of each test box for the same reason.

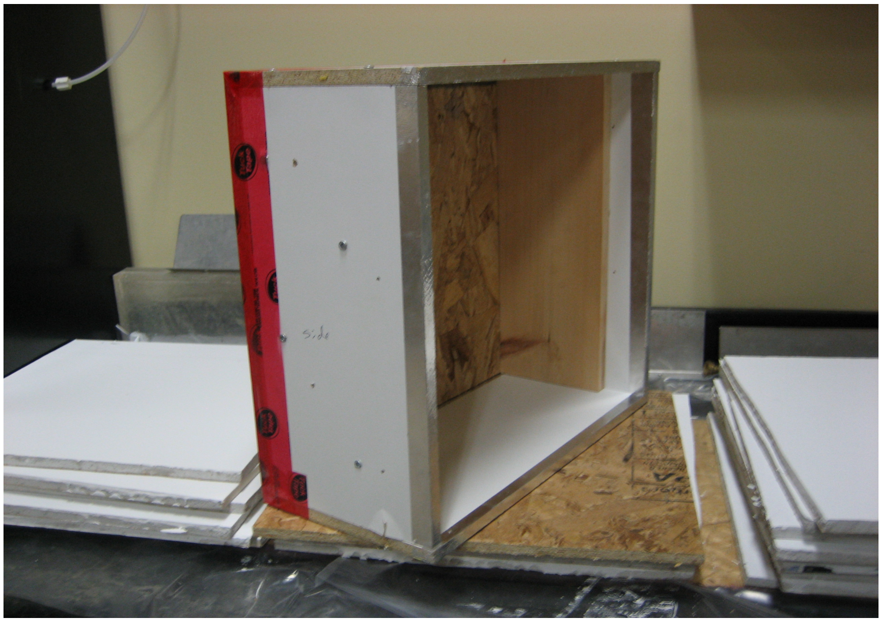

Figure 4-6: Test Box, Prior to Insulation and Gypsum Board on Interior Face

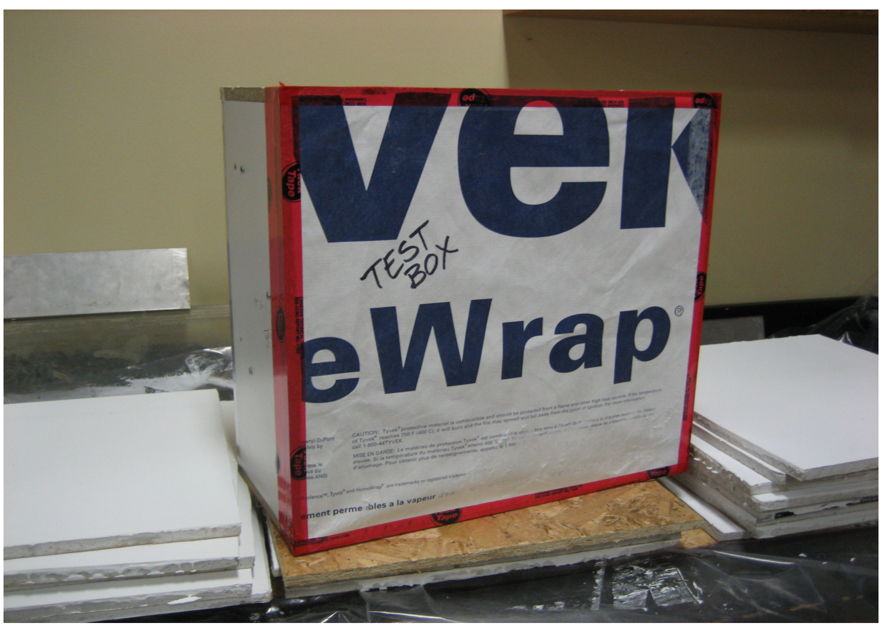

Figure 4-7: Test Box, After Tyvek Installed on Exterior Face

Figure 4-8: Test Boxes facing Cold Side in Test Assembly

Figure 4-9: Weather-stripping Around Test Box Opening, View from Cold Side

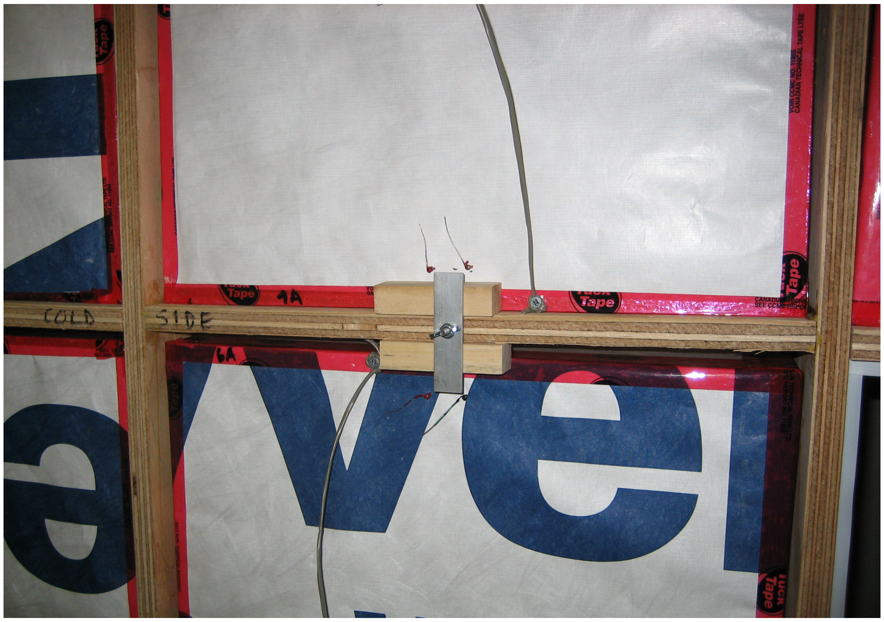

Figure 4-10: Manual Screw-Down Block to Force Test Box into Weather-stripping

Figure 4-11: Test Boxes from Warm Side

Figure 4-12: Test Box Weather-stripping Detail, View from Warm Side

4.8 Instrumentation and Controls

4.8.1 Warm Side Controls

Heat for the warm chamber temperature was generated using a 1500 Watt electric fan heater. The humidity was generated from a 1000 Watt high-output humidifier. Both the fan heater and the humidifier were regulated through relay switches of a Dwyer Series THC Temperature/Humidity Switch fastened to the exterior of the chamber. The controller monitored conditions in the chamber using a Campbell Scientific HMP50 humidity and temperature probe manufactured by Vaisala. Conditions in the chamber were measured and recorded with an Onset Computer Corp HOBO HO8-003-02 temperature and relative humidity data logger. See Appendix B for details of the instrumentation.

4.8.2 Cold Side Controls

Cooling for the cold chamber was generated from two VWR model 1197P chillers. The chillers circulated a 50/50 water-glycol mix that was piped to the chamber through insulated three-quarter inch plastic tubing. Two fan-coil units were installed inside the cold side chamber, one per chiller. The first unit was constructed by the BEG group using an automotive radiator, plywood shroud, and Fantech in-line duct fan model FR140. The second unit was a manufactured fan coil unit model MU-235 by Blanchard-Ness.

The temperature in the chamber was measured by a Fenwal 10 kΩ precision thermistor (with +/-0.2°C NIST traceable.) installed on the surface of the frame of the test assembly at mid-height and mid-width. The thermistor had a lead extending out of the chamber in order to take manual readings without disturbing the conditions inside the chamber. Thermistor readings were taken with a digital multi-meter. The thermistor readings were converted from ohms to degrees Celsius using the conversion chart in Appendix A. Conditions in the chamber were also recorded with the same type of HOBO temperature and relative humidity data logger used on the warm side.

4.8.3 Defrost Cycle

To reach a target temperature of -10℃, chilled heat-transfer fluid of -20℃ was supplied to the fan coils. All refrigerators and freezer cooling coils are prone to condensation if they drop to dew point temperatures or lower. If the coil temperatures drop to below freezing, frost build up occurs on the coils. Frost buildup adversely affects heat transfer from the chamber to the coil and slows down cooling which results in higher chamber temperatures. In order to handle frost buildup a manual defrost cycle was built-in to the testing regime. Every week to ten days, depending on the severity of frost buildup the chillers were reset to +10°C for approximately one hour. This gave the coil enough time to melt the frost into a drip tray, and partially dry. The liquid condensate was drained from the drip trays by plastic tubing connected to an otherwise closed plastic bucket. The collected liquid was then removed from the chamber. Once the frost was fully melted and drained, the chiller temperatures were set to just above freezing for approximately a two hour period to promote further condensation and drainage without frosting. After that time, the temperature was gradually dropped at about the rate 5°C per hour until it was back at the experiment set point of -20°C.

4.8.4 Moisture Content and Mass Measurements

In order for mass measurements to be taken at regular intervals throughout the testing period the test boxes had to be sturdy and relatively easy to insert and remove without damage to the test box. The test box could not exceed the 12 kilogram capacity of the Sartorius model FBC6CCE-H mass scale. The chambers had to provide a separation between the warm and cold side when the test boxes were removed otherwise, warm, humid air would flow into the cold side making it that much more difficult to maintain constant below-freezing conditions. The test boxes themselves could not be taken out of the cold chamber for weighing because ambient air conditions in the lab would immediately lead to condensation forming on all cold surfaces of the test box, affecting the accuracy of the mass measurements.

The solution to these constraints was to install wire handles on the exterior of the test boxes so that they could easily be pulled out from test assembly. Before any box was pulled from the assembly, the whole face of the warm side of the assembly was covered with a curtain fashioned from a polyethylene sheet, over which a layer of foil-faced polyisocyanurate board was clamped. This measure served to minimize air and heat transfer from the warm side to the cold when a test box was removed from the assembly. The test box was weighed inside the cold chamber using a scale sitting on the roof of the chamber. A small hole was drilled through the ceiling roof. A chain was attached to the under-scale hook of the scale. The chain extended directly down through the hole to about one meter below ceiling level. A hook at the end of the chain could support a test box by its wire handle

(Figure 4-13). The chain was removed and the hole covered over whenever mass measurements were completed.

Figure 4-13: Photo of Under-scale Mass Reading of Test Box

Once mass measurements were complete all test boxes were measured for moisture content. Each box had three pairs of moisture content pins installed on the face (Figure 4-14). The pins were created from insulated brass nails that were driven from the outside so that the uninsulated tips were on the inside face of the OSB panel, the surface where moisture content was predicted to be highest (Figure 4-15). The pins were installed as pairs separated by 1 inch. A Delmhorst J-4 wood moisture meter was attached to the wire leads soldered to the exposed side of the pins.

Figure 4-14: Three Pairs of Moisture Pins Installed in Tyvek covered OSB

The Delmhorst wood moisture meter passes a small electrical current through the wood and measures the electrical resistance of the wood between the two pins. Water has a lower resistance than dry wood and the electrical current follows the path of least resistance, therefore the measurement occurs at the wettest part of the OSB (Figure 4-15). In this case, the OSB is wettest at the interior face which happens to be the location that is of most interest in the experiment. The coating on the pins tends to further isolate the reading to the interior face in case there were any anomalies in the deposition of water or in the structure of the OSB.

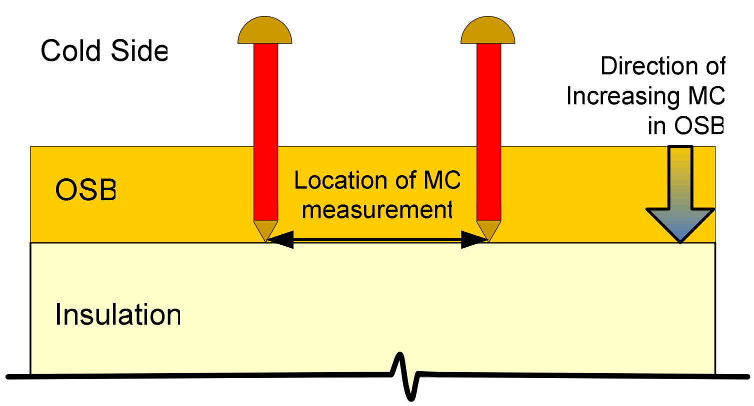

Figure 4-15: Schematic of Moisture Pins in OSB

The Delmhorst meter is calibrated to base all moisture content readings in terms of Douglas-fir at 70°F. Each MC reading was corrected for species and temperature given that the material was OSB and the temperature was typically -10°C when measurements were taken. Equation 4-1 from Garrahan (1988) calculates the corrected temperature from the uncorrected MC measurement, the temperature when the MC was taken, and two species-dependant regression factors. Engineered wood products such as plywood and OSB may be of no easily identifiable species, therefore generic coefficients for these products have been developed. Straube, Onysko and Schumacher (2002) published values for the regression coefficients as a = 1.1114 and b = 0.366 for OSB.

$$MC_c = \frac{\left(\frac{MC_u + 0.567 - 0.0260t + 0.000051t^2}{0.881(1.0056^t)}\right) - b}{a}$$

Equation 4-1

MC_c	[%]	Corrected moisture content
MC_u	[%]	Uncorrected moisture content reading
t	[°C]	Temperature of the wood
a, b	[-]	Species-dependent regression coefficients: a = 1.1114, b = 0.366

4.9 Experimental Procedure

In order to monitor the amount of water accumulation over time in each of the test boxes, the moisture content of the OSB sheathing and mass readings of the boxes were measured and recorded approximately every ten days. The mass measurements were taken before the start of the test and at six other intervals up to and including the final day 57. Every test box was weighed at the start and on day 57, and on at least four of the six intervening measurement periods. Generally, the boxes predicted to have a relatively large mass change over time were weighed more often.

Chapter 5
Experimental Results

5.1 Actual Climate Chamber Performance

The experiment started on March 10, 2008 with the intention of running for a 60-day period. The chillers performed well and kept the cold side chamber to an average of -9.8°C with a low of -12.9°C throughout the first 47 days of the test (Figure 5-1).

According to the HOBO data, the temperature of the cold side chamber started rising near midnight on day 47. It continued to rise until day 49 when it was discovered that Chiller 1 was no longer operating; this was represented by the +30°C spike in Figure 5-1. It appeared that the digital controller was electrically damaged. The fact that there was a partial blackout in the city of Waterloo on day 47 at the same hour the temperature started rising seems to indicate a power surge was the most likely culprit for the controller damage.

The cold side chamber continued to run with reduced cooling power for the next eight days at an average temperature of 0.4°C. The experiment was shut down on day 57, three days short of the originally planned 60 day period; however the measurements taken up to that point were sufficient to fulfill the requirements of the experiment.

The periodic temperature spikes that occurred before day 47 represent the defrost cycles and instances where the chamber door was opened to perform measurements.

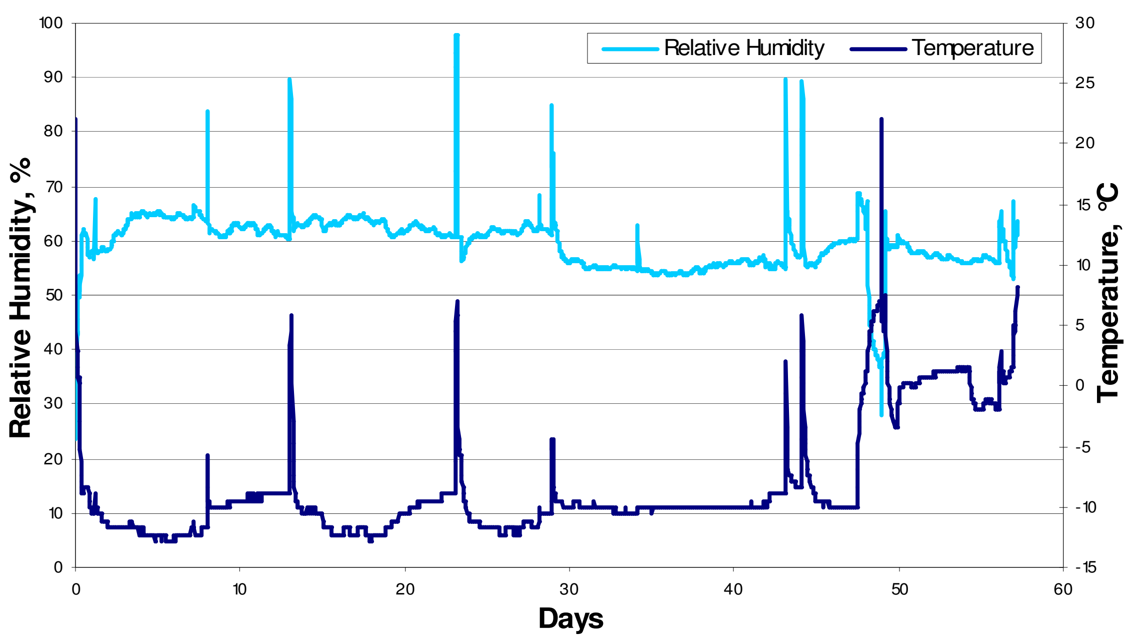

Figure 5-1: Conditions in Cold-Side Chamber

The warm side chamber ran steadily at 25°C and 50% RH humidity according to the Dwyer THC switch. A HOBO data logger was placed in the warm side chamber as secondary measurement verification. At the end of the test, the data download showed that the HOBO logger was faulty and the recorded measurements were incorrect. This was not problematic as the Dwyer THC switch provided a sufficient measurement system.

5.2 Gravimetric Measurements

The first chart, Figure 5-2, shows the mass of water accumulation in the A-series of test boxes that contained a full polyethylene vapour barrier between the gypsum board and the insulation. Mass gains in the test boxes averaged in the 100 g range over the 57 day test period.

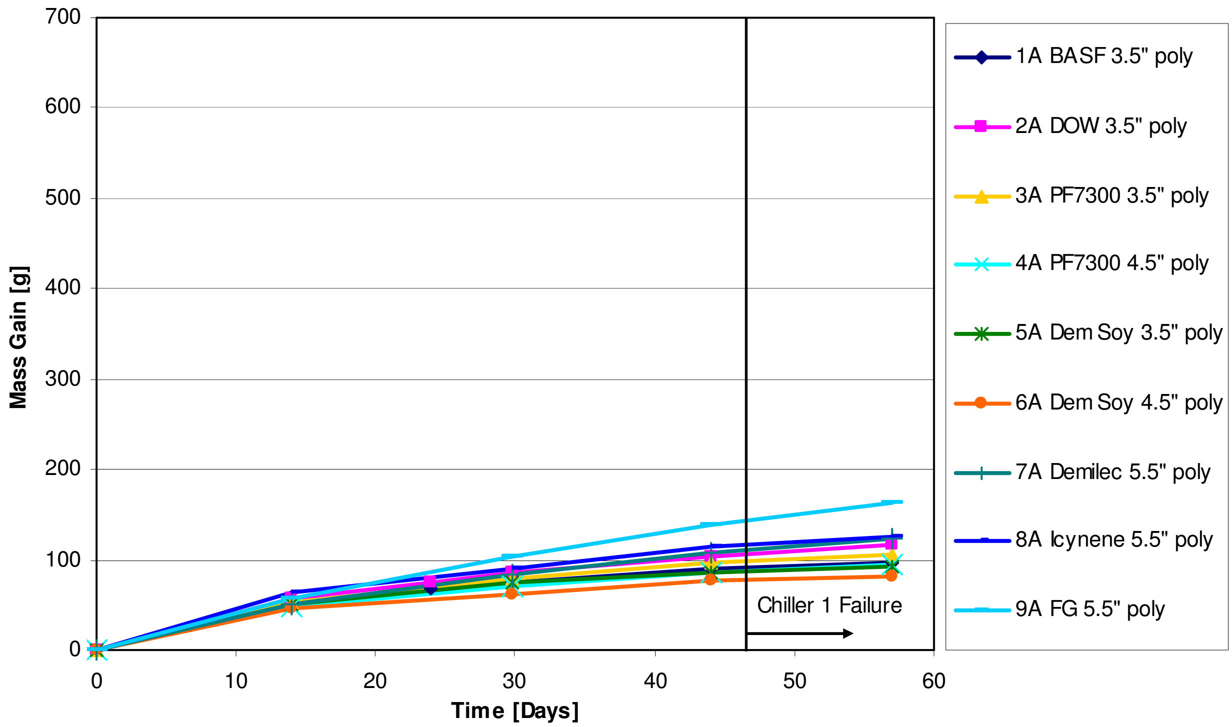

Figure 5-2: Mass Gain Rate of A-series Test Boxes with Polyethylene Vapour Barrier

The second chart, Figure 5-3, shows the results for the B-series test boxes which had no polyethylene vapour barrier. The fibreglass (9B) and open cell SPF (7B and 8B) samples have the highest vapour permeance values and the largest mass gains over the test period. Average mass gains for the lower permeance test boxes were in the 200 g range, almost twice the gains seen in the A-series boxes.

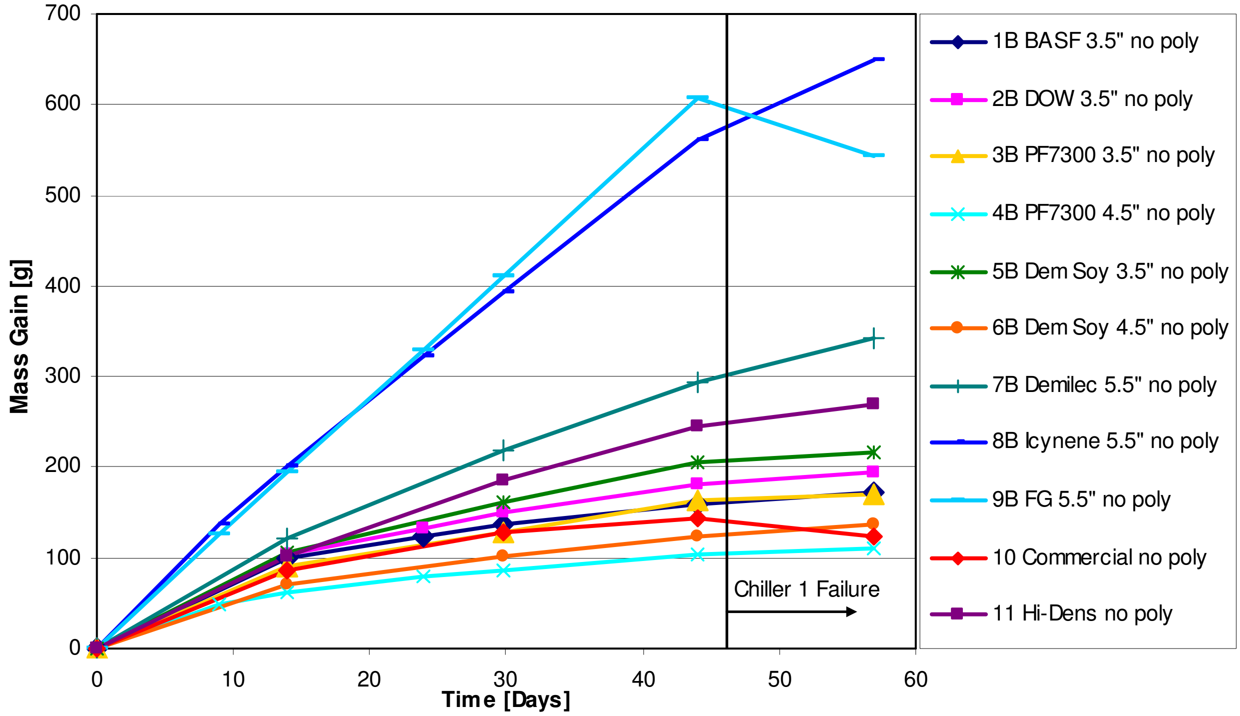

Figure 5-3: Mass Gain Rate of B-series Test Boxes with No Polyethylene Vapour Barrier

The corrected average MC measurements of the OSB in each test box are presented in Figure 5-4 and Figure 5-5.

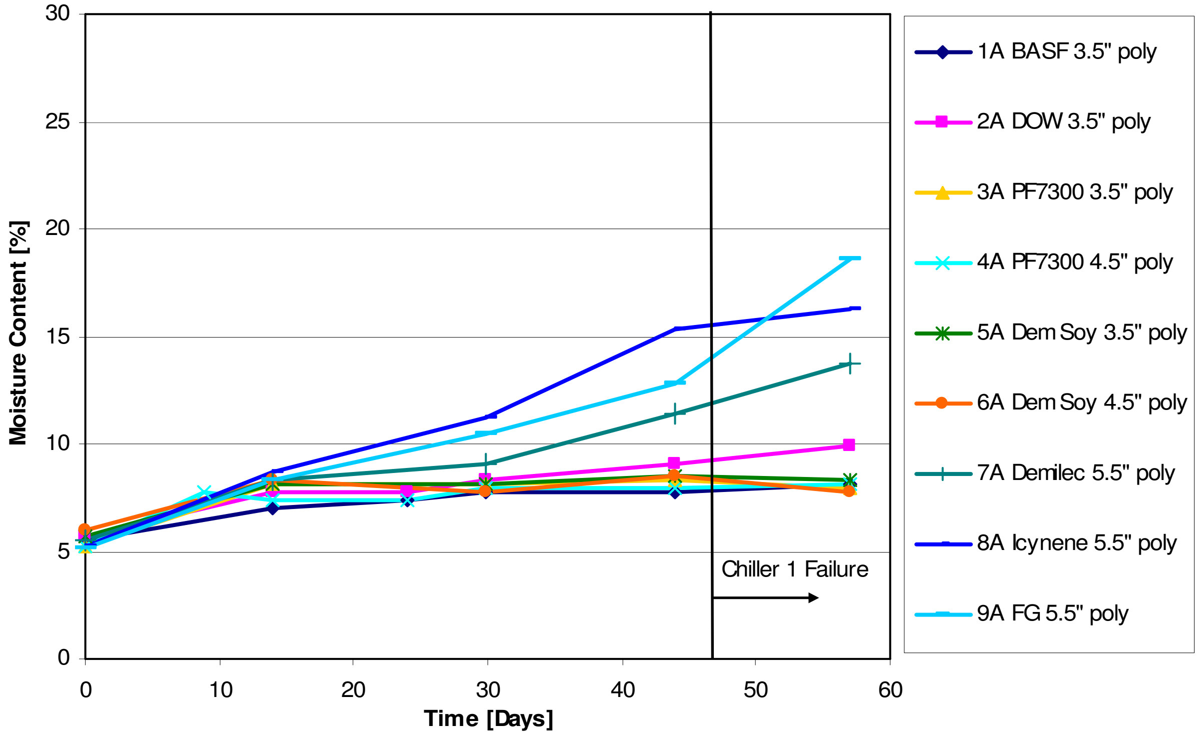

Figure 5-4: Corrected MC of OSB in A-series Test Boxes with Polyethylene Vapour Barrier

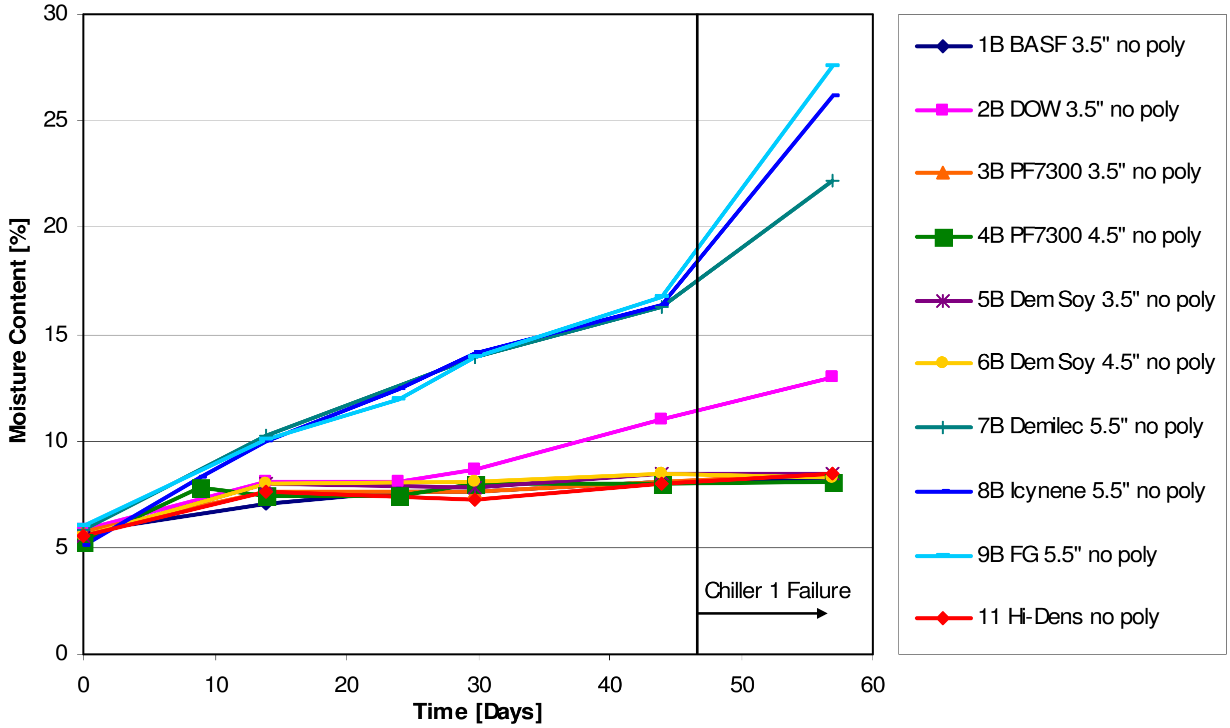

Figure 5-5: Corrected MC of OSB in B-series Test Boxes with No Polyethylene Vapour Barrier

Chapter 6

Analysis and Discussion

6.1 Gravimetric Measurements

The high humidity, warm side chamber (1590 Pa at 25°C and 50 % relative humidity) created a vapour pressure drive to the cold side chamber (173 Pa at -10°C and 60% relative humidity). Essentially, the test boxes were acting as large scale wet-cup permeance tests. The predicted results were that the A-series test boxes would experience a small amount of moisture gain through vapour diffusion governed by the low permeability of the polyethylene sheet layer. The B-series test boxes were predicted to take on a low, moderate or high amount of moisture through vapour diffusion governed by the permeability and thickness of their respective insulation materials.

The predicted amount of water vapour diffusion through a sample is given by Fick's law, written as Equation 6-1.

$$Q_v = \frac{M \cdot A \cdot \Delta P_w \cdot 3600 \cdot 24}{1 \times 10^9}$$ **Equation 6-1**

Q_v	[g/day]	Vapour Flow
M	[ng/Pa·s·m^2]	Permeance of layer
A	[m^2]	Area of layer
ΔP_w	[Pa]	Change in water vapour pressure across layer
$\frac{3600 \cdot 24}{1 \times 10^9}$	[(s/day)/(ng/g)]	Conversion factor for ng/s to g/day

6.1.1 Glaser Method Calculations

The Glaser method predicts the vapour pressure at the upstream and downstream side of each layer under static boundary conditions and whether there is a risk of vapour diffusion condensation at the layer. The first step is to calculate the vapour pressure change across each material interface in a building assembly (Table 6-1). If the resulting vapour pressure is higher than saturation pressure for the temperature and relative humidity at that interface (i.e., if the relative humidity exceeds 100%) condensation may be a risk. The example shown below shows low risk of condensation as the highest

RH is 73% at the spray foam-OSB interface. Thus, no condensation is predicted in this wall. However, if the polyethylene vapor barrier is removed (B-series), the RH at the inside face of the OSB is predicted to reach 100%RH for the open-cell SPF and batt samples. When condensation is predicted, further calculations can determine the amount of evaporative potential for the condensed water. The remaining water accumulation must be considered for its potential to create damage in the assembly.

Table 6-1: Glaser Calculations for Condensation Potential in Sample Test Box

Sample 1A	thickness	permeance	resistance	ΔPv·Rvi/ΣRv	vapour pressure	rel. humidity = Pw/Pws
BASF 3.5" With Poly	**t**	**M=μ/t**	**Rvi**	**ΔPw**	**Pw**	**RH**
Material	[m]	[ng/Pa·s·m2]	[Pa·s·m2/ng]	[Pa]	[Pa]	[%]
interior					1590	50%
Interior film	n/a	15000	6.7E-05	0.4		
					1590	53%
paint, latex + primer	n/a	275	3.6E-03	20		
					1570	52%
gypsum board	0.0127	1969	5.1E-04	2.8		
					1567	55%
polyethylene sheet	0.0001	4.74	2.1E-01	1172		
					395	14%
air space	0.0508	3445	2.9E-04	1.6		
					393	14%
spray foam - BASF	0.0889	36	2.8E-02	156		
					238	73%
OSB	0.011	91	1.1E-02	61		
					177	58%
Tyvek	n/a	1500	6.7E-04	3.7		
					173	57%
Exterior film	n/a	75000	1.3E-05	0.1		
exterior					173	60%
		ΣR_V = 0.255		ΣΔPw = 1417		

The method is simplified because it does not account for several factors - initial water contents of materials, the water storage capability of materials, material properties that change with water content, the presence of liquid transport, and fluctuations in boundary conditions. It cannot provide a realistic simulation of heat and moisture transport, but rather it is used as an initial check to see which aspects of an assembly may require further study. For a more complete picture of the assembly behavior computer simulation tools are required.

It is important to note, however that the RH across the OSB layer drops from 74% to 58%. This change drives adsorption in the OSB from the cold side to the warm side. This mechanism will prove to be of importance later in this section.

For the A-series test boxes, the diffusion flow through the polyethylene sheet layer was of most interest because it was the lowest permeability of all the layers and would therefore determine how much water vapour reached the OSB from the warm side. Given that the permeance of the 6 mil polyethylene sheet is 3.4 ng/Pa·s·m^2, Equation 6-1 above was solved for each of the A-series test boxes, Table 6-2. This calculation is even simpler and more limited than the Glaser analysis above.

Table 6-2: Calculated Mass Gain due to Water Vapour Diffusion in A-series Test Boxes

Test Box – Foam Type	Vapour Flow Qv_1 [g/day]	Vapour Flow Qv_{57} [g/57 day test]
1A – 3.5 in. closed cell	0.06	3.2
2A – 3.5 in. closed cell	0.06	3.2
3A – 3.5 in. closed cell	0.05	3.1
4A – 4.5 in. closed cell	0.05	2.9
5A – 3.5 in. closed cell	0.05	2.9
6A – 4.5 in. closed cell	0.05	2.8
7A – 5.5 in. open cell	0.06	3.6
8A – 5.5 in. open cell	0.05	2.7
9A – 5.5 in. fibreglass	0.06	3.5

The average calculated mass gain due to vapour diffusion through the polyethylene into the A-series test boxes was 3.1 g for the 57 day test period. This amount of liquid water is equivalent to 3 g or slightly more than one-half teaspoon; an insignificant amount in terms of moisture wetting of the wall assembly. The values listed in Table 6-2 would be even lower if the calculation had not been simplified to assume all vapour flow terminated and collected within the assembly, when in reality, and even in the Glaser analysis of Table 6-1, some or all will continue to diffuse completely through the OSB and out to the cold side chamber. It is an unrealistic simplification but it emphasizes that vapour barriers are not true barriers, even though they significantly reduce vapour diffusion.

6.1.2 Calculated versus Measured Mass Gains

The average calculated mass gain was 3.1 g and the results from Figure 5-2 showed the average measured mass gain for the A-series test boxes to be in the 100 g range at the end of the 57 day test. This discrepancy was further investigated in Figure 6-1 which plots the mass gains in terms of calculated values from Table 6-2 and measured values from Figure 5-2. The values for three test boxes are shown— values from 3A are representative of closed cell foam; test box 7A represents open cell foam; and test box 9A for the fibreglass batt sample.

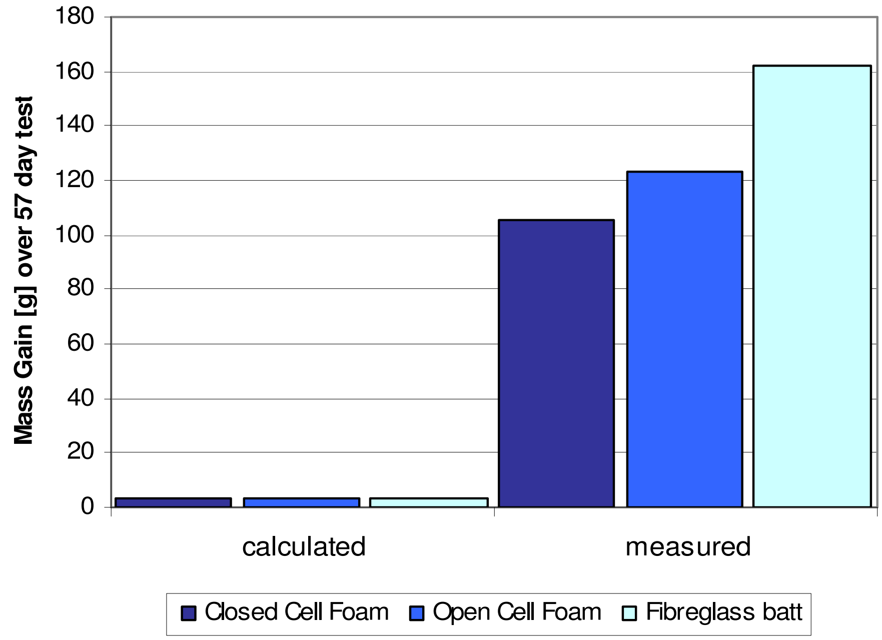

Figure 6-1: Mass Gain Behaviour of Representative Test Boxes with Poly Vapour Barrier

Similarly, the mass gains for the B-series test boxes were each calculated for their respective permeance values and vapour pressures, Table 6-3 using the full Glaser method (which accounts for the vapour flow into and out of the assembly). The difference in vapour flow represents the amount of possible moisture gain in the OSB sheathing.

Table 6-3: Calculated Mass Gain due to Water Vapour Diffusion in B-series Test Boxes

Test Box – Foam Type	Vapour Flow Qv_1 [g/day]	Vapour Flow Qv_{57} [g/57 day test]
1B – 3.5 in. closed cell	0.46	26
2B – 3.5 in. closed cell	0.46	26
3B – 3.5 in. closed cell	0.46	26
4B – 4.5 in. closed cell	0.36	21
5B – 3.5 in. closed cell	0.46	26
6B – 4.5 in. closed cell	0.36	21
7B – 5.5 in. open cell	1.8	103
8B – 5.5 in. open cell	1.3	74
9B – 5.5 in. fibreglass	3.5	200

Figure 6-2 compares the calculated values from Table 6-3, and the measured values for the three representative test boxes.

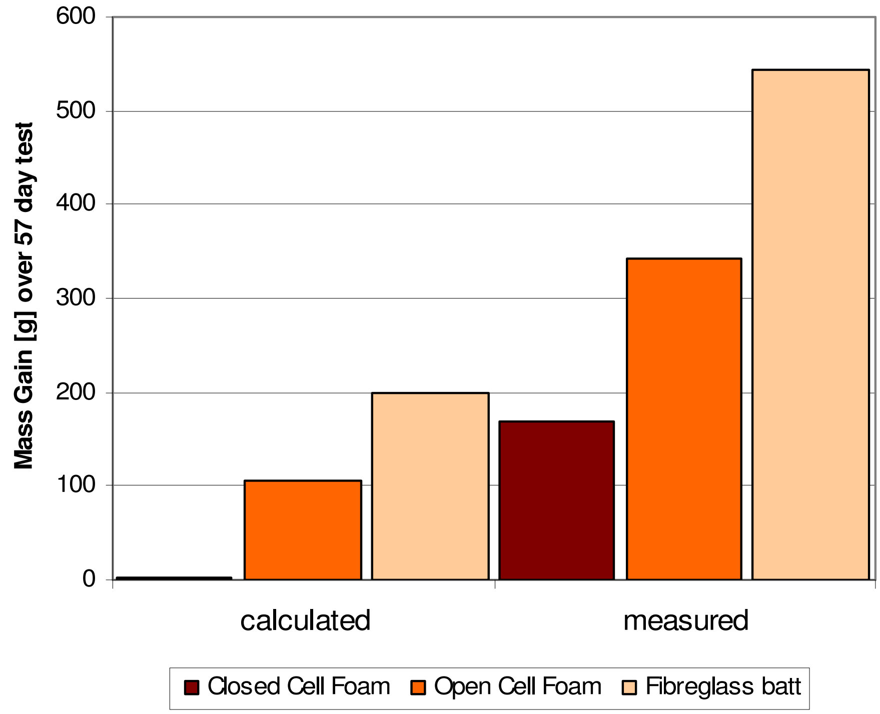

Figure 6-2: Mass Gain Behaviour of Representative Test Boxes without Poly Vapour Barrier

Both Figure 6-1 and Figure 6-2 clearly show the large discrepancy between the measured values and calculated values. Initially, it was assumed the gravimetric measurements would be straightforward and conform to predictable vapour diffusion behaviour from warm side to cold side. By day 14 of the test, it was clear the mass gains were much higher than anticipated. From the outset, the calculated values from the Glaser method were expected to be lower overall since it does not account for initial moisture contents or moisture storage capabilities within the materials themselves. However, the measured values were three times the calculated values. This warranted further investigation.

6.1.3 Interpretation of Measurements

One possible explanation for the high gravimetric measurements was that moisture transport due to convection was occurring. Convective moisture transport is caused by air leaking through holes in the assembly. The water vapour in the air can condense along the leakage path if the temperature along the path is sufficiently low. The problem with this explanation was that the test boxes were air sealed at all edges and foam insulation products, which meet the requirements of air barriers, completely filled the test box cavities. There were no leakage paths; it was unlikely convective moisture transport was occurring.

Another possible explanation was that the melamine cases used to construct test boxes were taking on significant amounts of moisture, which indeed happened initially. An early experimental setup in November 2007 resulted in measurements that were much higher compared to the gains predicted in the Glaser calculations and computer simulations. In fact, after fewer than 20 days observed mass gains were much higher than predictions for the planned eight-week test period.

On day 31 of the Nov 2007 test there were visual observations of frost, ice and liquid water forming in the spaces between the test boxes and the test assembly shelves. Furthermore, the edges of the melamine cases were showing signs of swelling during the second set of measurements. Aluminum tape had been installed to waterproof the cut edges of the melamine and the tape adhesive appeared to have failed. The test boxes themselves were taking on extra moisture thereby rendering the gravimetric measurements meaningless. At that point, the experiment was shut off and the experiment was considered a failure (but an excellent demonstration of building assembly weaknesses). The test boxes were removed from the assembly, and left to dry in the fully heated and ventilated chamber. The dry-down process took almost a full month before the test boxes returned to their pre-experiment weight.

While the test boxes were drying out, the test setup was improved in several ways:

- **Test boxes**: all exposed edge tape was removed from the melamine cases. After the boxes had dried completely, all exposed edges and surface screw holes were treated with two layers of epoxy resin.
- **Melamine testing:** a water absorption test was performed on melamine samples to determine if the melamine coating was faulty and not impermeable to water. The tests showed that the coating was indeed impermeable.
- **Test assembly shelving**: The shelving was treated with a layer of impervious shellac primer. All cut butt joints on the lip edge strapping were caulked with silicone sealant. All weather-stripping inside the test box compartments was replaced with wider and deeper weather stripping. Great care was taken to ensure it was continuous around the perimeter and aligned with the front face of the test box when inserted into the compartment. The perimeter cavities that contained fibreglass covered with edge-taped polyethylene sheet were emptied. The cavities were re-filled with single component expanding spray foam. All caulked joints on the remaining cavities were resealed.
- **Chamber pressure:** An in-line duct fan with a manual variable-speed controller was installed on the exterior of the warm side chamber. This enabled the warm side to be negatively pressurized so that any air leakage between the two chambers would be from the cold to side to the warm side. This would prevent subsequent ice build-up from forming in the spaces around the test boxes. The chamber was depressurized to 5 Pa, slightly more than the stack effect pressure expected for a chamber 8 ft. high.

The modifications to the set-up succeeded in that there was no frost, ice or liquid water build-up in the test assembly and there was no swelling of melamine edges on the test boxes. However, the second run of the experiment still resulted in high mass gains as displayed in Figure 5-2 and Figure 5-3. The permeability of the melamine cases did not provide a plausible explanation for the high gravimetric measurements.

6.2 Moisture Content Readings

The moisture content readings taken in the OSB were originally planned to be a secondary measurement to confirm the gravimetric measurements. They turned out to be a crucial part of the collected data and were quite important in investigating the results for the test boxes.

The initial pre-test equilibrium moisture content readings of the OSB averaged about 6% for all test boxes, which corresponds to an ambient relative humidity of about 30 to 40%. This seems high for a late winter interior relative humidity, but the experiment and samples were located in the University of Waterloo's Fluids Lab which has several large sources of open water nearby. The accuracy of the Delmhorst meter in the range of 6% MC is in the order of +/-2% MC.

Several hygrothermal simulations were run on assemblies for the A-series and B-series boxes. The cases run were 3.5 in. of closed cell SPF, 4.5 in. of closed SPF, 5.5 in. of open cell SPF and 5.5 in. of fibreglass batt; all used generic values supplied by WUFI, the hygrothermal modelling software. WUFI is discussed in more detail in Section 7.2.

Recall the corrected OSB moisture content readings were shown in Figure 5-4 and Figure 5-5. The final average value across the three MC pins is tabulated and compared to results from WUFI hygrothermal simulations performed on the test boxes for the same conditions.

The A-series test boxes (Table 6-4) containing closed cell foam (excluding the outlier 2A) had OSB with an average moisture content of 8.0% at the end of the test. This corresponded very well with hygrothermal simulations of the experiment that predicted the average OSB moisture content of these test boxes to be 8.3%. These results did not correspond to the gravimetric measurements, which if the water gain was completely contained in the OSB, the moisture content readings would have read 5-6% higher.

The insulations with higher permeance values, open cell foam and fibreglass, had considerably higher measured MC values than their modelled counterparts. The dry density of the OSB is 650 kg/m^3; an 11 g water gain in the OSB layer resulted in a 1% increase in the moisture content. Test boxes 7A, 8A, and 9A increased their measured MC values by 7.7%, 10.2%, and 12.6% respectively. The MC increases correspond to water weights of 85 g, 112 g, and 139 g. In reality they gained, 123 g, 126 g, and 161 g each. In that sense, the gravimetric and MC measured values corresponded well to each other but not well to the modelled values which were in the 8% MC range. Keep in mind the test boxes had polyethylene vapour barriers with no air leakage so the considerable moisture gain was a surprise.

Table 6-4: OSB Moisture Content Results for Test Boxes with Poly Vapour Barrier

Test Box – Foam Type	OSB - Measured MC	OSB - Modelled MC
1A – 3.5 in. closed cell	8.1	8.3
2A – 3.5 in. closed cell	9.9	8.3
3A – 3.5 in. closed cell	7.9	8.3
4A – 4.5 in. closed cell	7.9	8.5
5A – 3.5 in. closed cell	8.3	8.3
6A – 4.5 in. closed cell	7.8	8.5
7A – 5.5 in. open cell	13.7	8.1
8A – 5.5 in. open cell	16.2	8.1
9A – 5.5 in. fibreglass	18.6	7.7

The corresponding B-series test boxes (Table 6-5) with closed cell foam did not have significantly higher MC values compared to the A-series and they averaged 8.3% at the end of the test (again, not including the outlier of 2B). These are very modest MC increases and are on average 1% lower than what was predicted by the WUFI hygrothermal simulations.

The 7B, 8B and 9B test boxes were predicted to have high MC values almost into the fibre saturation zone (MC>30%) for the OSB. However, the modelled values of MC were relatively close to the measurements. For example, 7B measured 22% and modelled 17%. Discrepancies between the actual and modelled material properties would be enough to produce the variation. Unlike the A-series test boxes, these boxes did not correspond well to the gravimetric measurements. The measured MC values converted to mass gains were 176 g, 220 g, and 238 g. The gravimetric measurements were 341 g, 650 g, and 544 g. Clearly all of the water was not entirely residing in the OSB as it would have corresponded to a MC value of 65% in test box 8B. Some of the moisture in these samples must have been stored in the foam and the wood “studs” along the side of the sample.

Table 6-5: OSB Moisture Content Results for Test Boxes without Poly Vapour Barrier

Test Box – Foam Type	OSB - Measured MC	OSB - Modelled MC
1B – 3.5 in. closed cell	8.3	9.5
2B – 3.5 in. closed cell	13.0	9.5
3B – 3.5 in. closed cell	8.5	9.5
4B – 4.5 in. closed cell	8.1	9.1
5B – 3.5 in. closed cell	8.5	9.5
6B – 4.5 in. closed cell	8.3	9.1
7B – 5.5 in. open cell	22.2	17
8B – 5.5 in. open cell	26.1	17
9B – 5.5 in. fibreglass	27.6	19.1

6.3 Adsorption

The most likely explanation for the high gravimetric measurements is adsorption of water vapour into the OSB layer from the cold side of the chamber. Adsorption and wood behaviour were discussed previously in Section 2.6. The sorption isotherm for OSB is shown in Figure 6-3; it was derived from the material properties database of the hygrothermal modelling software. It clearly shows large water content increases once capillary condensation has commenced in the pores at greater than about 90% RH. However, the experiment was run at 50% RH on the warm side and 60% on the cold side. The Glaser analysis shown earlier predicts that the OSB would be exposed to 73%RH on the warm side and 58% on the cold side. Depending on the shape of the assumed sorption isotherm, these conditions correspond to moisture contents in the 8-12% MC range which is one the high side of the MC measurements using the Delmhorst.

Hence, the A-series test results (both gravimetric and Delmhorst) for samples with closed-cell SPF can be explained by the adsorption of vapor from the cold climate side, rather than diffusion of vapor from the warm side.

The B-series tests were influenced by the additive effect of diffusion from the warm inside of the climate chamber and diffusion from the cold side. The results were only slightly higher than predicted, which could be due simply to a higher than assumed paint permeance values.

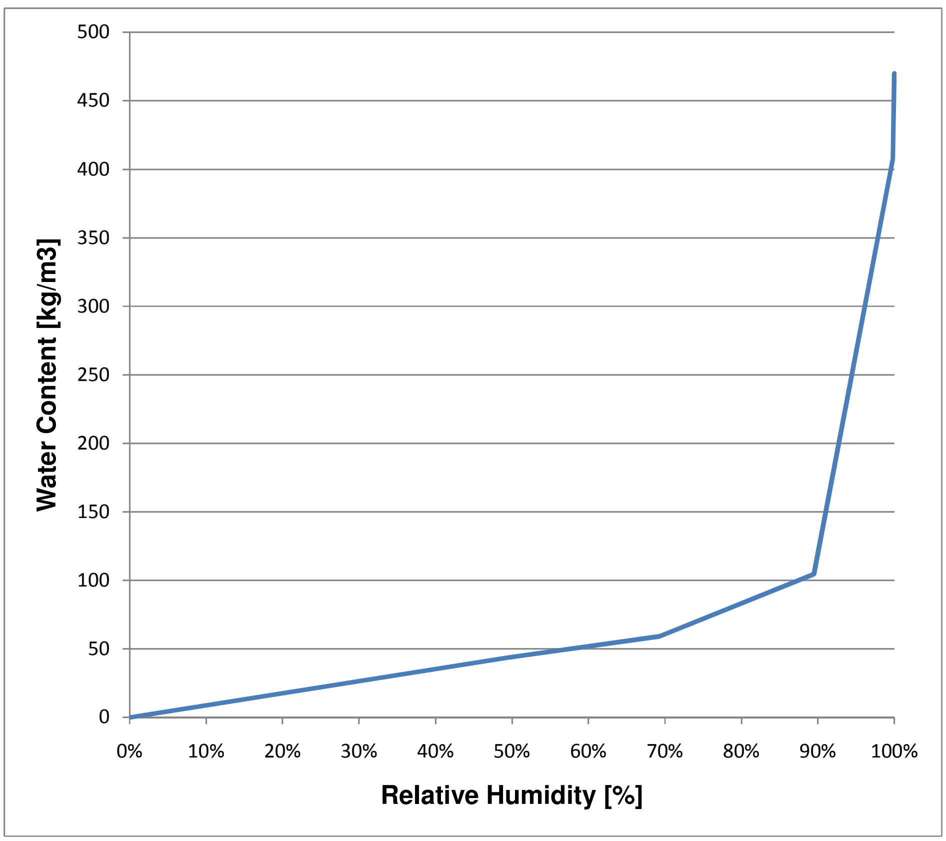

Figure 6-3: The Sorption-Isotherm for OSB from the WUFI Materials Database

The adsorption transport mechanism works by the attraction of a few layers of water vapour molecules to the walls of pores in the material. Materials with large amounts of very small pores, such as cement paste, can accumulate a significant amount of water through adsorption and in some cases reach capillary flow (liquid transport) with mid-range relative humidities (Straube and Burnett 2005).

In the case of the experimental test boxes, vapour diffusion from the warm to cold side occurred from the vapour pressure drive of 1590 Pa inside to 173 Pa to the outside as shown in Figure 6-4. The graphic shows how a test box with a vapour barrier layer can gain water vapour from both sides of the chamber.

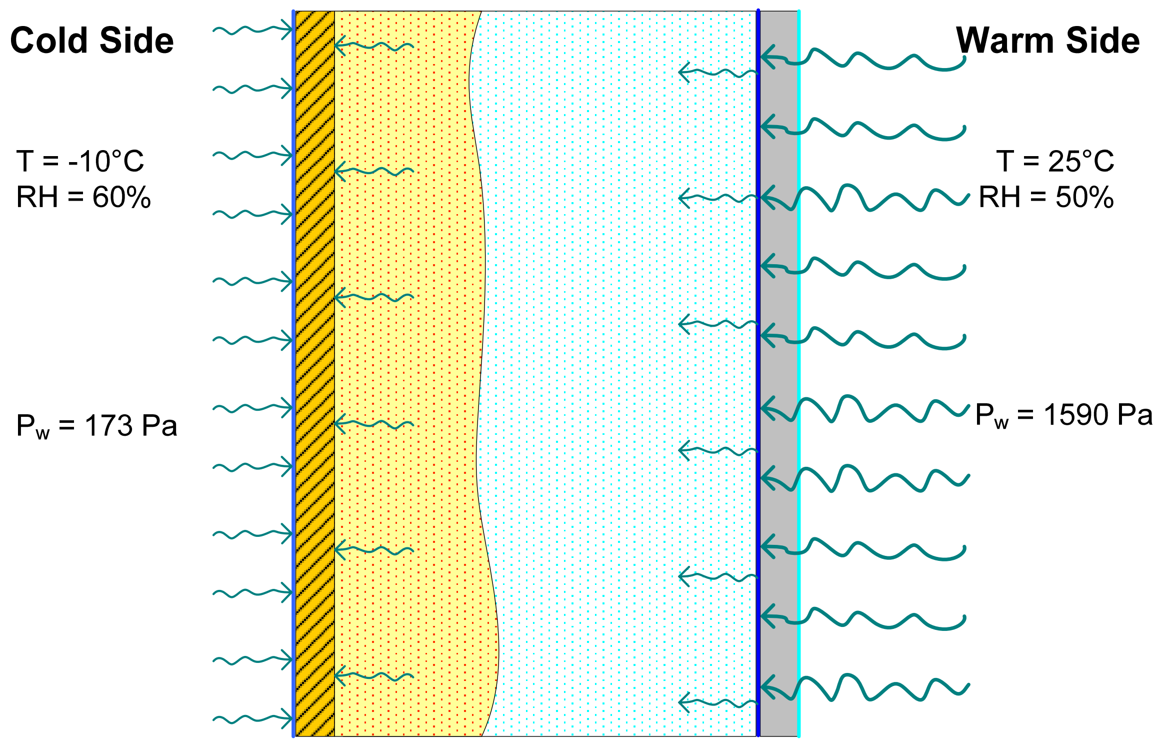

Figure 6-4: Vapour Pressure Drives in A-Series Test Box

However, once the pore walls have been lined with adsorbed layers of water molecules another process occurs – surface diffusion. It occurs when weakly attached molecules in the adsorbed layers move to nearby locations with a stronger attraction, usually thinner adsorbed layers. This mechanism is more dependent on RH than vapour pressure drive therefore it is possible for surface diffusion to occur simultaneously and in the reverse direction of vapour diffusion (Figure 6-5). The importance of this mechanism is that the vapour permeance of the OSB sheathing increases as it is exposed to and reaches equilibrium with high relative humidity. The assumptions in the simple Glaser analysis are that the OSB has a fixed and relatively low permeance (91 metric perms). Because of surface diffusion, the effective vapour permeance actually increases significantly.

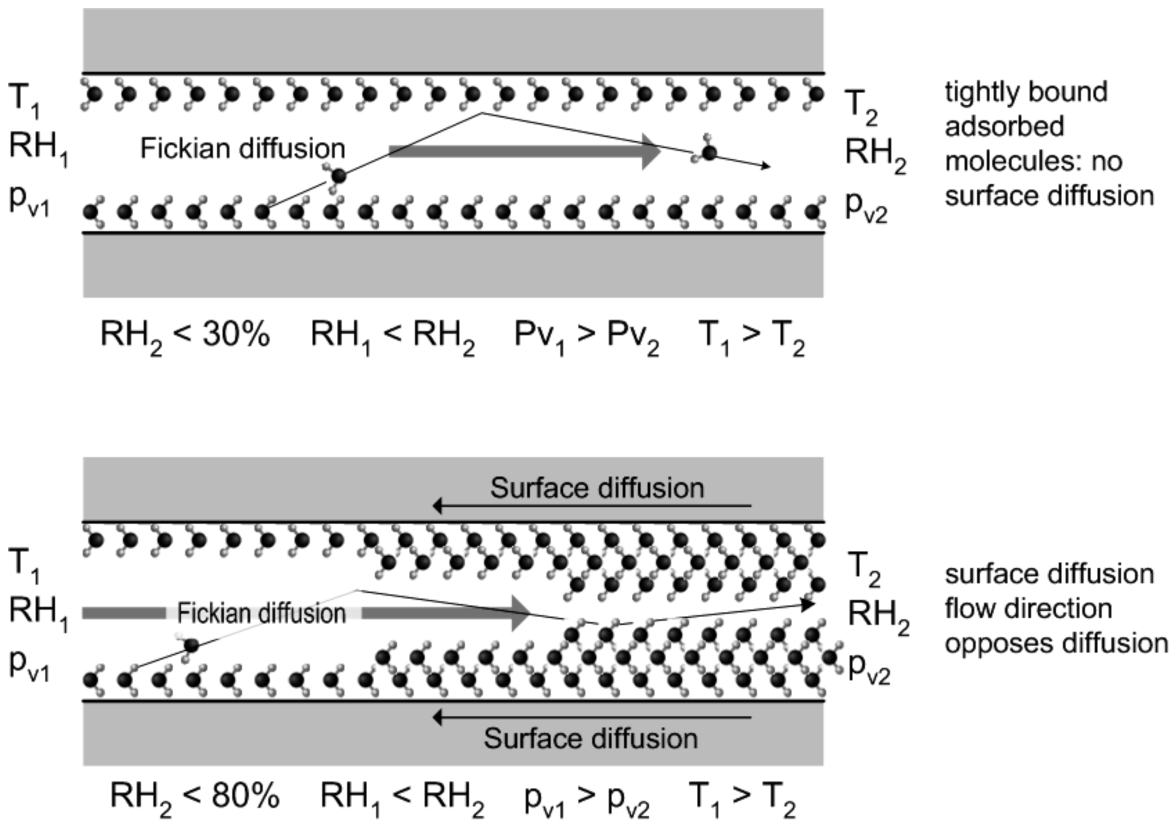

Figure 6-5: Vapour and Surface Diffusion under Opposing T and RH Gradients (Straube & Burnett 2005)

6.4 Conclusions

In summary, the laboratory experiments showed that:

All samples of the closed cell SPF performed well in controlling the MC of OSB with or without a poly vapor barrier. Most of the moisture content rise noted was due to adsorption of water vapor diffusing from the climate side, not diffusion from the interior.

The open cell SPF and fiberglass batt without poly performed very poorly. This was expected given the extreme conditions but the measured OSB moisture contents and sample mass gain were worse than the predictive calculations.

The open cell SPF and fiberglass with polyethylene vapour barrier also performed poorly, and OSB moisture contents of 20-30%MC were recorded. These results were noted despite the exceptional efforts taken to ensure airtight test samples, and control the pressure so that any air leakage would be from the cold side to warm side.

None of the samples, even the very wet ones, showed significant or visible mold growth, likely because the accumulation happened at cold temperatures.

Chapter 7
Hygrothermal Model Extrapolation

7.1 Evaluation of Enclosure Performance

The review presented in Chapters 2 and 3 demonstrate that the amount of vapour diffusion control required in enclosures depends on many factors such as the resistance to heat and vapour of the individual layers of the wall assembly layers, their position in the assembly, the interior conditions, and the exterior climate. It is little wonder that designers, builders and code officials are confused on how to proceed.

This section reports on a series of detailed hourly simulations that explore these variables. It evaluates seven common wall assemblies in terms of expected moisture content in the exterior OSB sheathing in seven Canadian climate categories and three interior humidity levels. A similar approach was used by Karagiozis et al (2007).

7.2 WUFI Computer Model

A more complete picture of building enclosure performance can be developed when the inter-dependency of heat and moisture transmission is coupled using a model that includes realistic boundary conditions that incorporate fluctuations for weather and occupants, moisture sources and sinks, solar radiation, initial water contents and changes to material properties based on water content. Obviously, this is a much more complex calculation than the Glaser calculations mentioned earlier. Several hygrothermal modelling programs have been developed to perform these calculations. The University of Waterloo Building Engineering Group uses a program called WUFI from Fraunhofer Institute for Building Physics in Germany. WUFI is a German acronym for "transient heat and moisture".

The evaluations were performed with the WUFI Pro 4.1 hygrothermal model (WUFI 2006). This model was shown to predict the field performance of walls by Finch (2007). The simulations were repeated for each of seven types of wall assembly (Figure 7-1) in each of seven climate categories and three humidity levels for a total of 147 simulations. The results for the maximum moisture content (MC) of the OSB for all the simulations are presented in Table 7-4.

The performance thresholds for the wood moisture content were chosen based on the level of wood decay expected in the moisture content range as mentioned in Section 2.6.1. The performance threshold are:

- **MC < 20%** - no moisture problems expected
- **20% < MC < 28%** - potential for mould growth
- **MC > 28%** - moisture problems expected, this design is NOT recommended

Wall 7 is a simulation of the stud portion of a 2x4 or 2x6 wood-framed wall. The properties of the cavity fill insulation are irrelevant to this because this simulation considers 1-dimensional hygrothermal behaviour through the stud only. Wall 7 has been included to address concerns that low permeance insulation, such as closed cell foam, promotes increased vapour diffusion through wood framing.

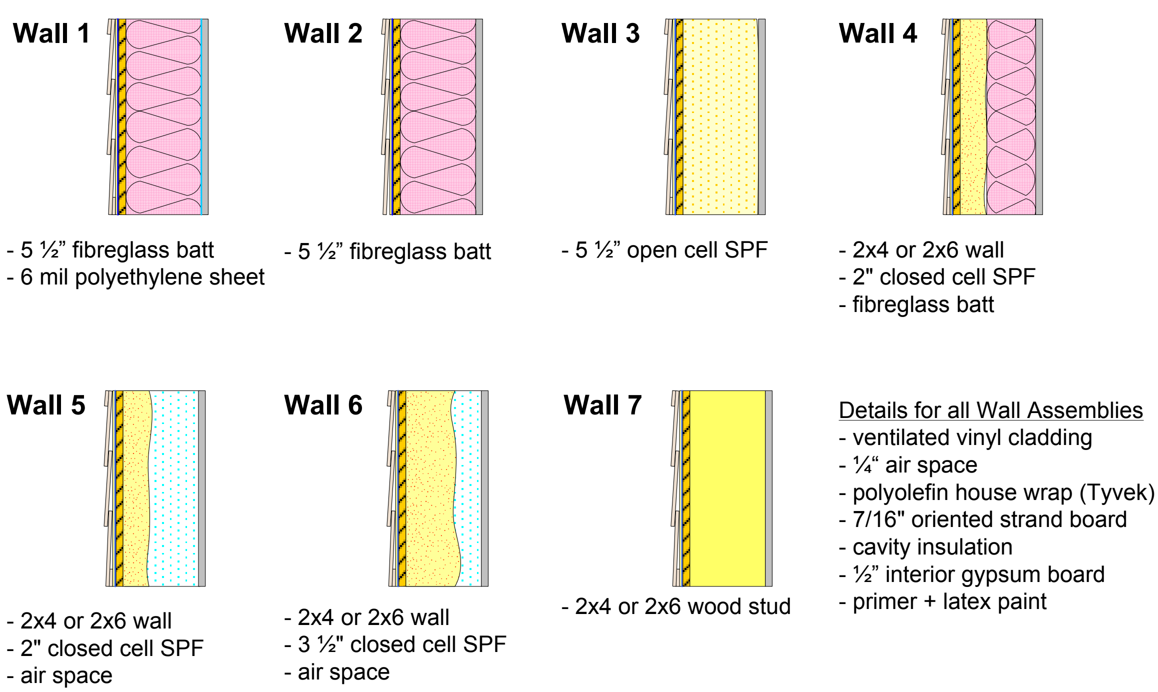

Figure 7-1: Cross-sections of Modelled Wall Assemblies

The remaining variables for the seven climate categories and three levels of interior relative humidity are detailed in separate sections below.

7.3 Parameters for the WUFI 4.1 Model

The following section documents all assumptions, material data, topology, and data inputs. The material data is provided as part of the WUFI materials database which contains Basic Values for a large number of North American building materials extracted from a variety of sources such as NIST publications, ORNL publications and ASHRAE 1018-RP - Thermal and Moisture Transport Property Data Base for Common Building and Insulating Materials (Kumaran et al 2002) (ASHRAE 2002). The Basic Values provided in the database include bulk density, porosity, dry specific heat capacity, dry thermal conductivity, and water vapour diffusion resistance factor. The Basic Values have been modified in some cases to accommodate specific values provided by manufacturers' technical literature. Refer to 0 for complete reports of all WUFI material data used in the simulations.

7.3.1 Assembly Materials

The construction of the wall assemblies modelled in the simulations is identical with the exception of the contents of the insulation cavity and the presence of the polyethylene sheet vapour barrier. Figure 7-2 shows a sample screen shot for an assembly containing open cell SPF and no polyethylene vapour barrier between the open cell foam insulation and the gypsum board.

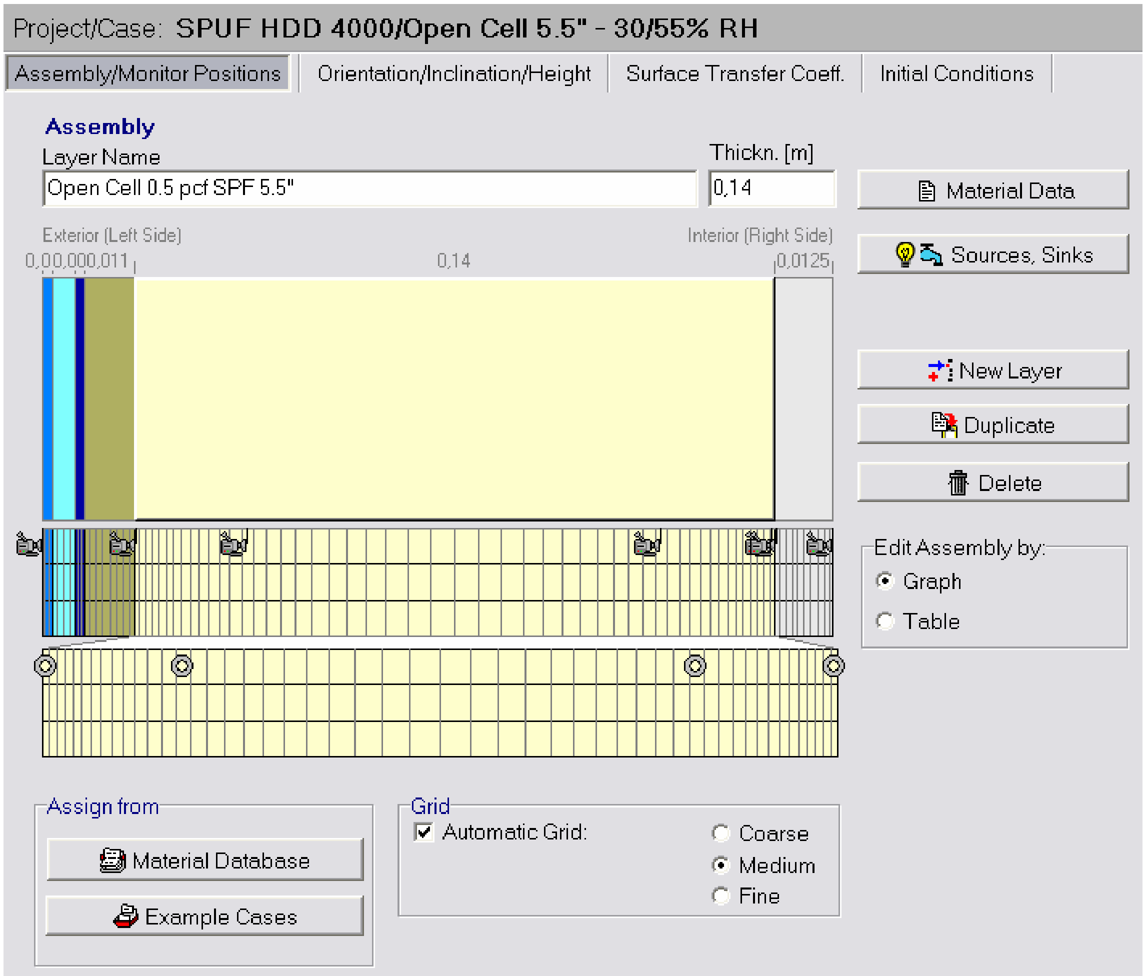

Figure 7-2: Screen shot of WUFI Assembly Input

In order from exterior to interior, every assembly material is listed below. As mentioned previously, complete data for each assembly material is available in 0.

Vinyl Ventilated – is a custom material added to the user-defined material database to simulate a light-colored vinyl cladding. Vinyl material is very impermeable but cladding installations are not airtight and permit a considerable amount of ventilation. The values for this item were modified from the roof membrane item listed in the WUFI Generic Materials database. The Water Vapour Diffusion Resistance Factor was adjusted to a low number (0.05) to account for the vapour permeable nature of the cladding installation.

Air Layer (5 mm) – the material properties were taken directly from Generic Materials database.

Spun Bonded Polyolefin Membrane (Tyvek Housewrap) – the material properties were taken directly from the WUFI Generic North American database.

Oriented Strand Board (11 mm, 7/16 in.) – the material properties for all Basic Values were available in WUFI. The average bulk density was 650 kg/m^3. Typical Built-in Moisture input was modified from 90.0 kg/m^3 (moisture content of 19%) to 55 kg/m^3 to correspond to more realistic closed-in moisture content reading in the 8.5% range.

Low Density Open Cell Insulation – this type has a density in the 8 kg/m^3 range. The experimental samples were supplied from Demilec and Icynene. Basic values in the Generic North America database for open cell Sprayed Polyurethane Foam were used with the exception of two values. Heat conductivity was modified from 0.037 W/m·K to 0.042 W/m·K, which better matches the manufacturers' technical literature. The Water Vapour Resistance Factor was modified from 2.38 to 5.8 – an average of the two manufacturers' literature.

Medium Density Closed Cell Insulation – this type has a density in the 32 kg/m^3 range. The experimental samples were supplied by BASF, Dow, Polar Foam PF7300, Demilec Soya, and Polar Foam PF Class One. Medium density foams are listed in the North America database as Sprayed Polyurethane Foam; closed cell. The Basic Values were used as given.

High Density Closed Cell Insulation – this type has a density of 46 kg/m^3. The test sample for this type is PF 7203 from Polar Foam. Basic Values for closed cell foam were used except for the following properties bulk density = 45 kg/m^3 average, k = 0.022 W/m·K.

Fibreglass Batt Insulation – the material properties were taken directly from the WUFI Generic North American database.

Air Layer – varies with thickness of insulation and the depth of the wall cavity. Possible air layers are 1.5 in., 2 in., and 3.5 in. thick. Basic Values were not changed from standard WUFI values for air layers.

PE Membrane (poly; 0.07 perm) - this was chosen from the Generic Materials database for a 6 mil polyethylene vapour barrier.

Gypsum Board (1/2 in.) – was chosen from the Generic North American database. No Basic Values were modified.

7.3.2 Orientation

The wall constructions were oriented facing north which will produce the lowest exterior surface temperatures of all compass orientations due to the near absence of direct solar radiation. This creates the worst-case scenario for vapour diffusion wetting because the thermal gradient and vapour drive gradient will be greater at the lower exterior temperatures. The wall inclination was assumed to be vertical at 90° and the building height was specified as a short building less than 10 m in height.

7.3.3 Surface Transfer Coefficients

The exterior surface was selected as a light-colored ventilated vinyl cladding for all simulations.

Exterior surface heat resistance - corresponds to the "Outer Wall" selection with a defined input of 0.0588 $m^2 \cdot K/W$. This corresponds to a surface film conductance of 17 $W/m^2 \cdot K$ which is considered average conditions for moving air across an exterior surface (Straube and Burnett 2005).

Vapour diffusion thickness (Sd-value) - for the exterior side was set to zero because the ventilated vinyl cladding has already accounted for this property.

Short-wave radiation absorptivity - was set to 0.4 which accounts for the fact that the cladding is a light color similar to values for aged white plaster and untreated spruce.

Long-wave radiation emissivity - was set to 0.9 as it is with all non-metallic surfaces.

Rain water absorption factor - set to zero, this factor accounts for how much rain water is not available for capillary suction into the wall material because it has been lost when it splashes away upon impact with the wall. Vertical walls have a factor of almost zero, horizontal walls have factors of almost one.

Interior surface heat resistance - was chosen as 0.125 $m^2 \cdot K/W$. This corresponds to an inner wall vertical surface film conductance of 8 $W/m^2 \cdot K$ which is considered average conditions for moving air across an interior surface (Straube and Burnett 2005).

Vapour diffusion thickness (Sd-value) - the room side of the ½ in. gypsum board wall was finished with one coating of latex primer and paint. The paint and primer layer was specified as 0.6 metres. It is calculated by dividing the permeance of air (185 $ng/Pa \cdot s \cdot m^2$) by the permeance of the layer in question. A permeance of 300 $ng/Pa \cdot s \cdot m^2$ chosen for the primer and paint layer as a conservative value based on poor quality primer and paint at 400 $ng/Pa \cdot s \cdot m^2$ and better quality at 150 $ng/Pa \cdot s \cdot m^2$.

7.3.4 Initial Conditions

All of the wall simulations began with a constant temperature of 22°C across all components. The only layers with any appreciable initial moisture content were the OSB layer (at 55 kg/m^3 or 8.5% moisture content by dry mass) and the wood stud (at 30 kg/m^3 or 6% moisture content by dry mass). These settings correspond to the typical range from 4% to 10% moisture content of wood products in post-construction conditions (Morris 1998).

7.3.5 Calculation Period

The modelling period ran for one year from August 1, 2007 to August 1, 2008 in time steps of one hour. August was chosen as the starting month because it typically represents an annual minimum in plots of exterior wood sheathing moisture content values. An August start date also allows the annual winter moisture content peaks to plot in the middle of an annual graph, which is useful since they are of most interest.

7.3.6 Outdoor Climate

Every simulation case was run for seven different Canadian climates. The climates were categorized according to the number of heating degree days below 18°C. Heating degree days (HDD) are calculated by summing the number of degrees each average daily temperature is below 18°C for a full year of historical temperature data. The total number provides a measure of how much annual heating is required in a particular location (Figure 7-3).

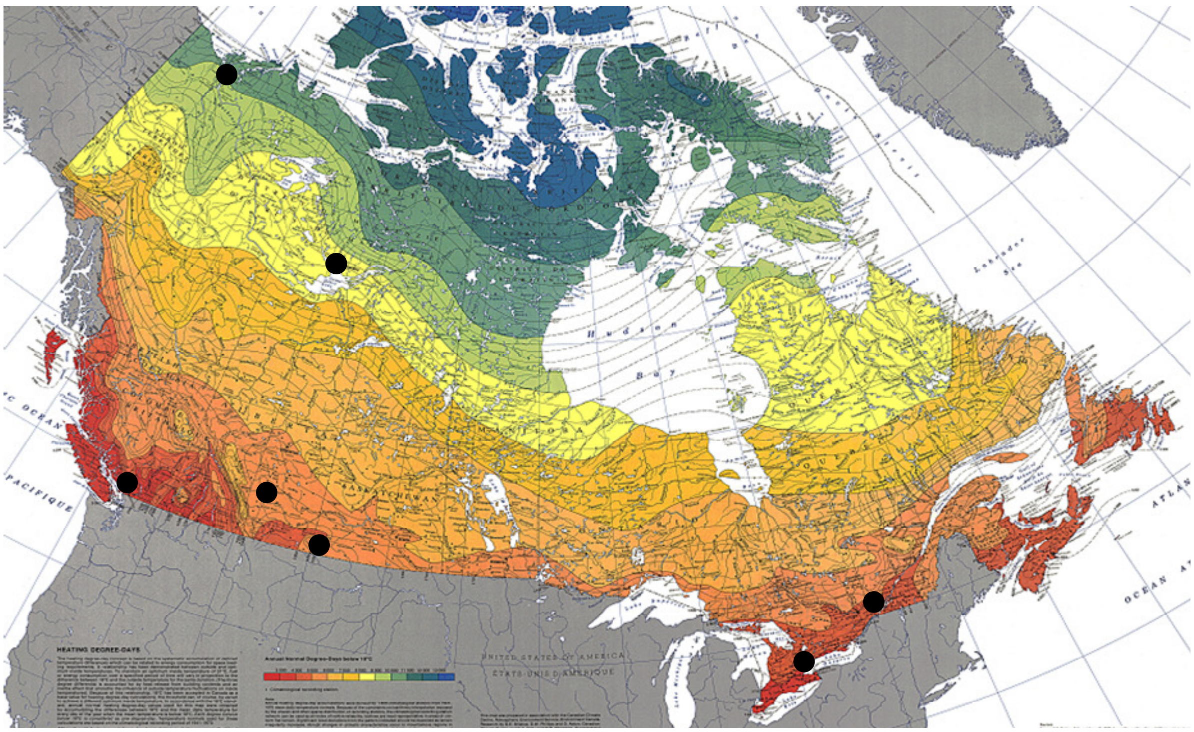

Figure 7-3: Map of Canada Heating Degree Days (National Atlas of Canada, 5th ed.)

For Canada, most populated centres are in the range from 3000 to 6000 HDD, with most northern communities in the 6000 to 10,000 HDD range, Table 7-1. The heating degree data is derived from Environment Canada's online database for *Canadian Climate Normals 1971-2000* (Environment Canada, 2008). The city associated with each climate category is a representative location only (the black circles on the map in Figure 7-3). The results of the simulations in any given category apply to other geographic locations with HDD values in the same range. The urban core populations of the cities listed in Table 7-1 represent more than 60% of the Canadian population based 2006 Statistics Canada census data.

Table 7-1: Canadian Cities by Climate Category

HDD Climate Category (with range)	Representative Location (with HDD)	Some Cities in this Range (with HDD)
HDD 3000 (Up to 3500)	Vancouver (2926)	White Rock (2782) Abbotsford (2981) Victoria (3040)
HDD 4000 (3501 to 4250)	Toronto (4065)	Windsor (3524) Niagara Falls (3661) Kelowna (3869) Oshawa (3917) Hamilton (4012) Halifax (4030) London (4057)
HDD 4500 (4251 to 4750)	Ottawa (4602)	Kitchener-Waterloo (4288) Kingston (4289) Montréal (4518) Moncton (4585) Charlottetown (4715)
HDD 5000 (4751 to 5500)	Calgary (5108)	St. John's (4881) Trois-Rivières (4929) Prince George (5132) Sherbrooke (5151) Québec City (5202) Sudbury (5343)
HDD 6000 (5501 to 7000)	Winnipeg (5777)	Regina (5660) Edmonton (5708) Thunder Bay (5717) Saskatoon (5852) Whitehorse (6811)
HDD 8000 (7001 to 9000)	Yellowknife (8256)	Dawson (8166)
HDD 10,000 (9001+)	Inuvik (9767)	Iqaluit (10117) Resolute (12526)

The seven climate locations used in these simulations are listed in Table 7-2 with a nominal HDD for the category and the actual HDD derived from the climate file used in the WUFI simulation for that particular location. Note the HDD values from the WUFI climate file and from Environment Canada's *Climate Normals* are not the same. The two values were derived from different data sets, however, they fall within the prescribed HDD range for the category. Table 7-2 also lists general conditions for temperature, relative humidity and rainfall to give a sense of how the climates differ from one another.

Table 7-2: General Conditions of Climate Categories Used in WUFI Simulations

Representative Locations	Vancouver	Toronto	Ottawa	Calgary	Winnipeg	Yellowknife	Inuvik
Nominal Heating Degree Days (<18°C)	3000	4000	4500	5000	6000	8000	10,000
HDD<18°C in WUFI Climate File	3056*	4022*	4874*	5384*	6377*	8243**	9935**
Mean Temperature, °C	9.1	6.7	5.2	2.5	1.2	-4.5	-9.2
Max. Temperature, °C	27.2	32.8	36.1	30.6	33.9	27.8	28
Min. Temperature, °C	-11.1	-23.3	-28.3	-36.7	-45.0	-42.8	-47.2
Mean Relative Humidity, %	78	76	67	63	73	66	67
Maximum Relative Humidity, %	100	100	100	100	100	100	100
Minimum Relative Humidity, %	14	21	18	14	19	17	24
Normal Rain Sum, mm/year	1169	606	586	304	309	161	114

*WUFI Climate Files derived from ASHRAE International Weather for Energy Calculations (IWEC). All files are “cold year” versions.
**WUFI Climate Files derived from typical meteorological year (TMY2) data sets from the 1961-1990 National Solar Radiation Data Base.

Each WUFI climate file contains a one-year data set of hourly information for temperature, relative humidity, wind speed, wind direction, rain fall, air pressure, cloud cover, solar radiation, and long wave radiation. It also maps the location according to latitude, longitude and elevation in order to calculate the actual amount of solar radiation the enclosure will experience based on its compass orientation and angle of inclination.

WUFI plots the temperature and relative humidity values to give the user a general idea of how the yearly data varies seasonally. The Toronto “cold year” climate file is shown in Figure 7-4.

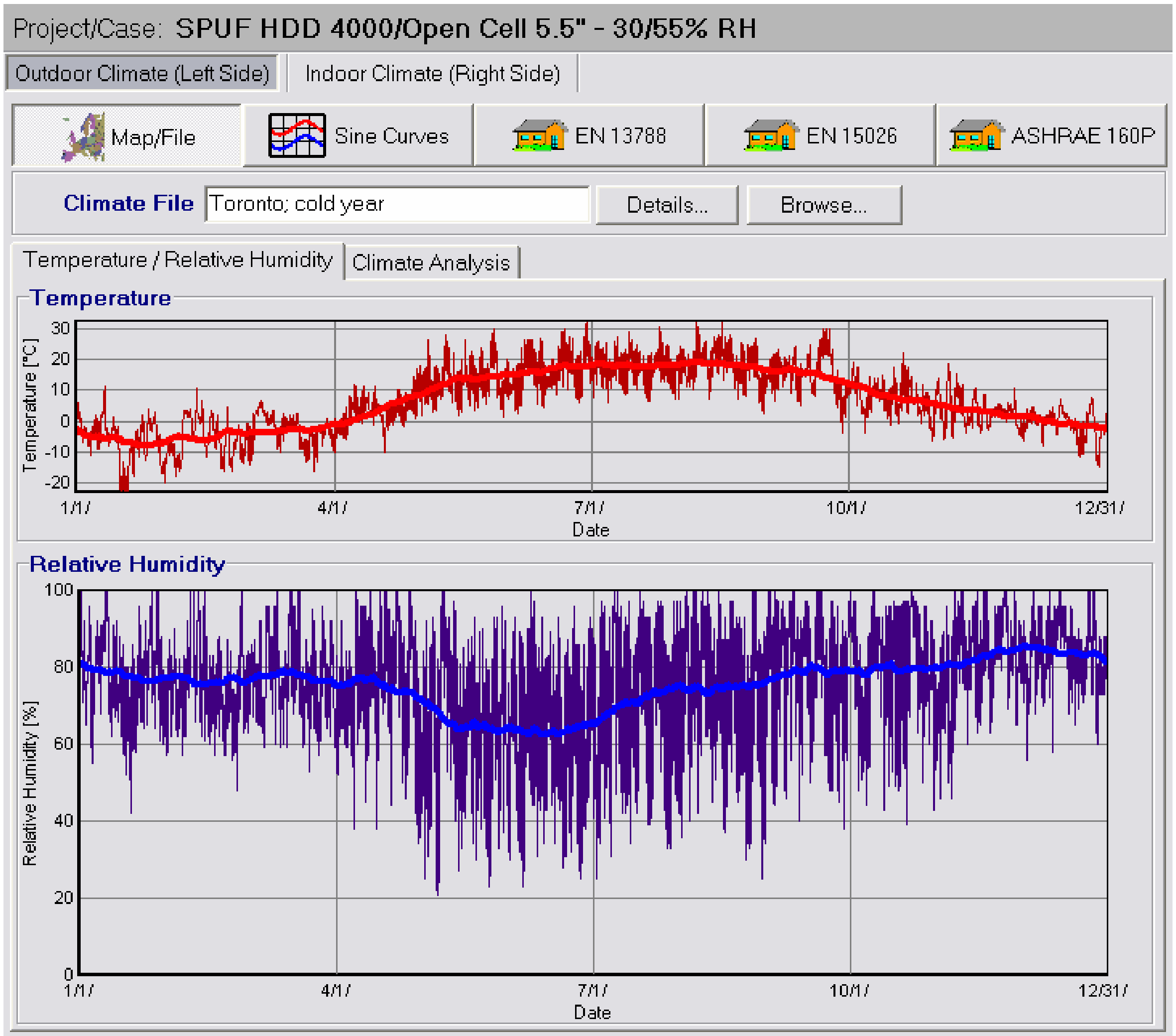

Figure 7-4: Screen shot of WUFI Plot of Outdoor Climate File for Toronto

7.3.7 Indoor Climate

The temperature for interior conditions in all simulations was set at 22°C with an annual variation of 1°C, Figure 7-5. Each climate category was modelled with three interior climate conditions – low, medium and high indoor relative humidities. The actual number used for the indoor climate settings depended on the climate category. For example, a low interior relative humidity (30%) in a warmer, rainier climate like Vancouver is higher than what would be considered a low interior relative humidity (20%) in a cold, northern climate like Yellowknife.

Table 7-3: Categories for Indoor Relative Humidities

Climate Categories	Low RH*	Medium RH*	High RH
HDD 3000 Vancouver HDD 4000 Toronto HDD 4500 Ottawa HDD 5000 Calgary HDD 6000 Winnipeg	30% to 55%	40% to 60%	50%
HDD 8000 Yellowknife HDD 10,000 Inuvik	20% to 50%	30% to 55%	50%
Description of possible conditions in this RH category	- older, air-leaky construction - newer buildings with mechanical ventilation - few occupant activities contributing to humidity load - condensation rarely forms on standard windows during cold snaps	- more air tight construction - operating a mechanical humidifier - high humidity loads from frequent cooking, washing, and firewood storage - condensation often forms on standard windows during cold snaps	- mechanically-generated RH levels are constantly high year round - examples are indoor pools, hospitals, museums - condensation constantly forms on standard windows during cold snaps

*Seasonal variation - low end of range in winter, high end of range in summer

The seasonal variations in the low and medium RH categories follow a sine wave formation which leads to the high end of range occurring on August 1, selected as the high point of the summer season. The low end of the range occurs six months later on February 1, the low point of the winter season. The indoor climate conditions for the Low RH category of 30 to 50% are shown in the screen capture of Figure 7-5.

Figure 7-5: Screenshot of WUFI Plot of Low RH Category 30-50%

7.4 Output from WUFI Model

The WUFI program provides several ways to displays the simulation data. One comprehensive way to view the data is running the "film". This is an animation of the one-dimensional heat and moisture balances changing over successive one hour increments during the one-year simulation period. The final hour of the simulation is shown in the screen capture in Figure 7-6.

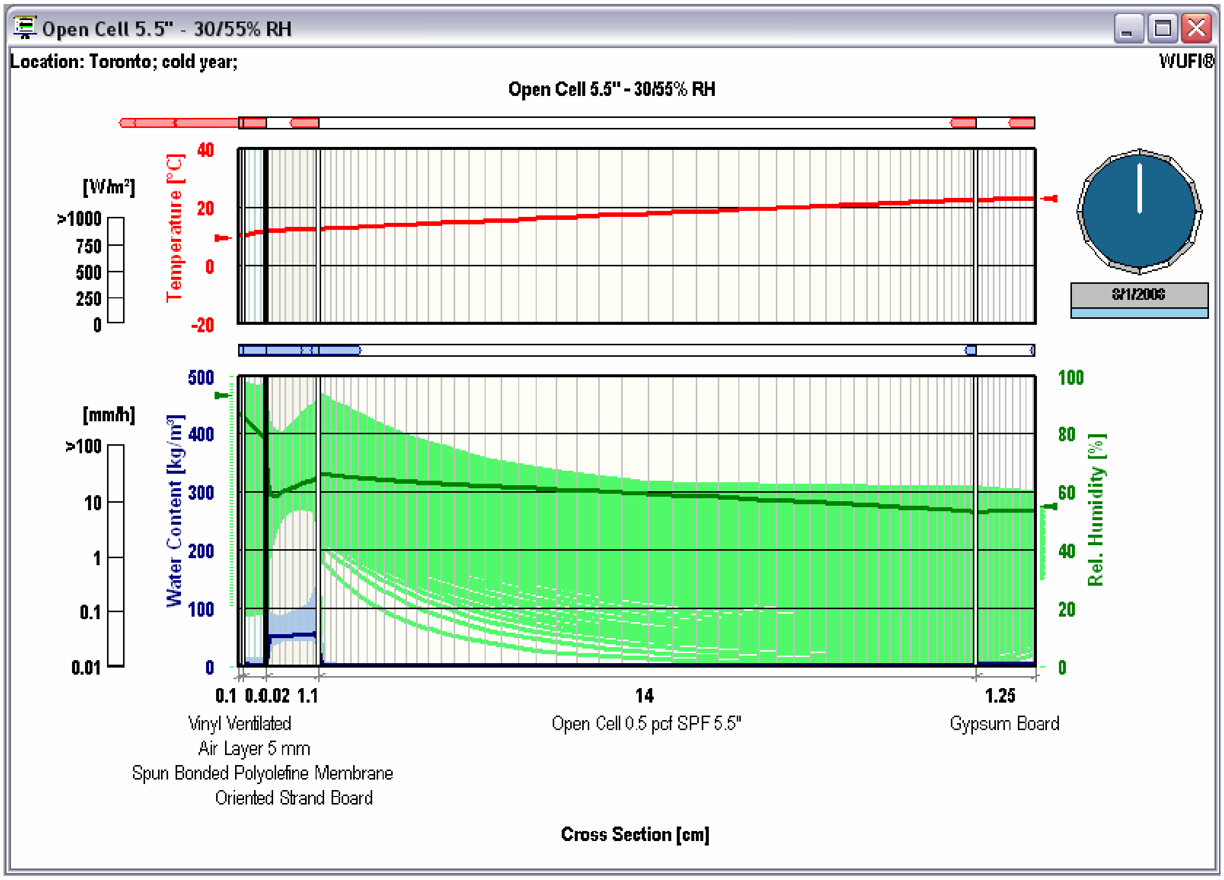

Figure 7-6: Screen Shot of WUFI Film for Open Cell SPF in Toronto at 30/55% RH

In Figure 7-6, the exterior climate is represented on the far left with amounts shown for temperature, rainfall, solar radiation and exterior relative humidity. The interior conditions of temperature and relative humidity are displayed on the far right. The grid in between represents the multi-layer assembly; the labels along the bottom axis specify the location and thickness of each layer. The gradients for temperature, relative humidity and water content are plotted with the heavy red, green and blue lines respectively. The bars at the top of each section show the direction of heat or moisture transfer at a particular moment in time. The lighter green and blue areas are trace lines that indicate what the humidity or water content was over the previous time intervals.

The area at the bottom showing the blue line and trace area represents the water content in the OSB and is of most interest in this exercise (Figure 7-7). Note that the dark blue line is indicating the OSB has a water content of approximately 50 kg/m^3. The density of the OSB according to the WUFI material database is 650 kg/m^3, therefore the moisture content of the OSB is 8% on August 1, at the end of the test period. The trace area shows the water content over the previous year. The peak occurred at the inside face of the OSB as predicted and was approximately 125 kg/m^3 which converts to MC of 19%. The MC at the exterior face of the OSB is noticeably lower.

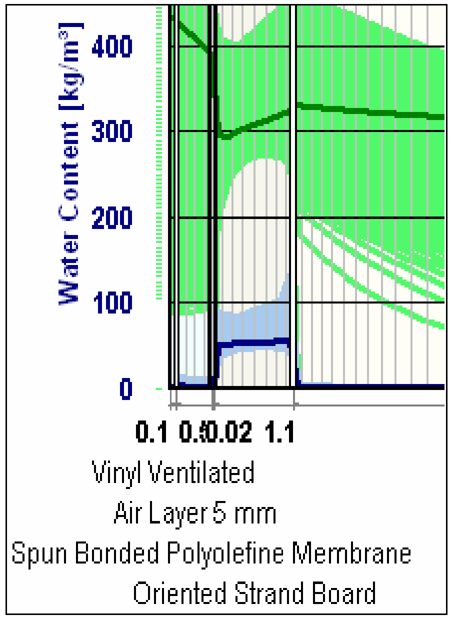

Figure 7-7: Close-up of Water Content in OSB

Rather than read the values for water content from the film, WUFI provides a plot of values over the year long simulation period, Figure 7-8. In this particular case, the peak water content is at approximately 92 kg/m^3, which is quite a bit lower than that shown in the film (125 kg/m^3). As mentioned above, the trace of the MC over time shows the exterior and interior faces of the OSB having quite different peak values. The MC value plotted in Figure 7-8 is an average MC value taken across the full width of the OSB. This is considered acceptable because the peak values by definition cannot be sustained for long time periods, and the MC of the OSB will gradually come to a lower MC equilibrium under those conditions.

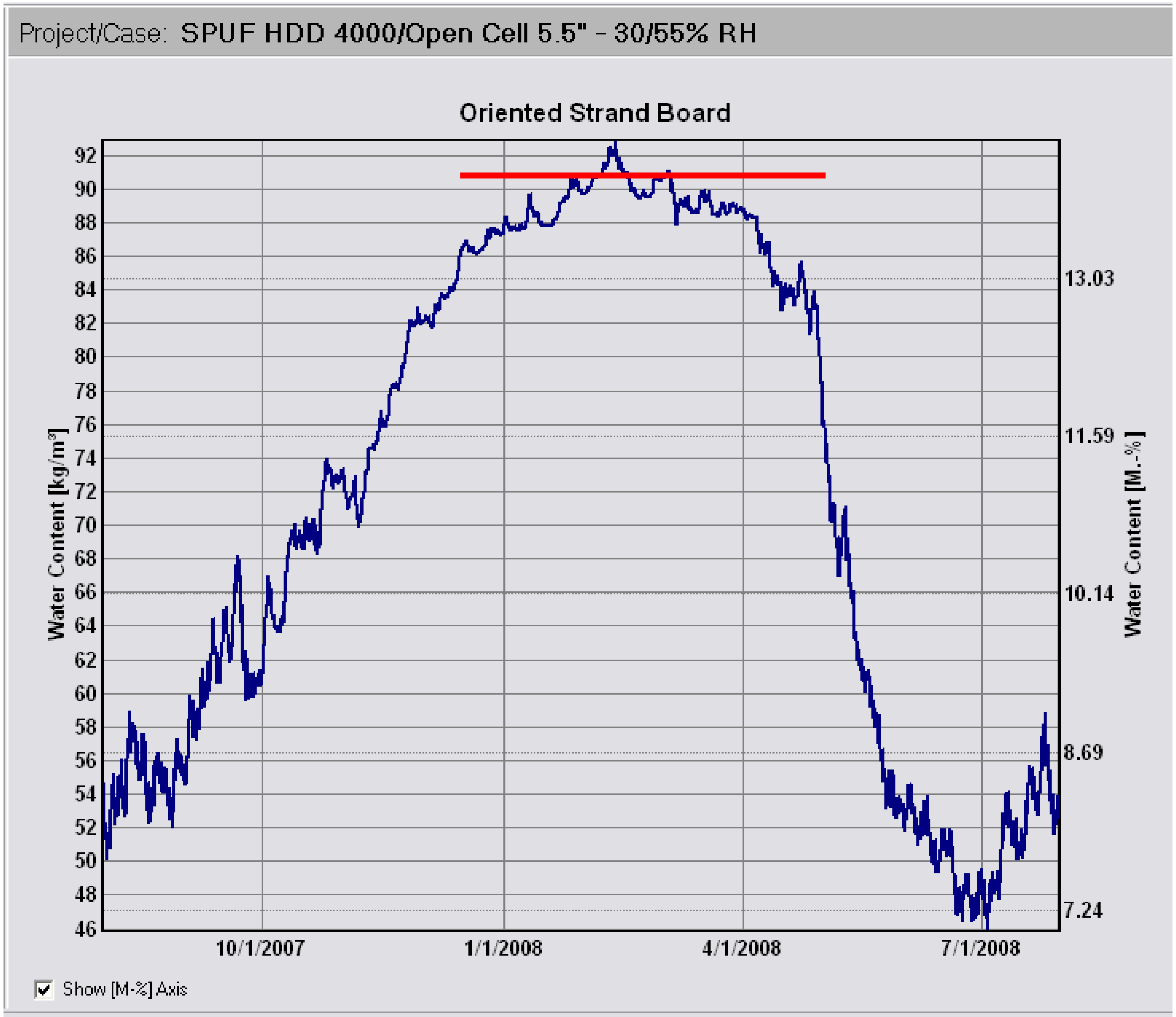

Figure 7-8: Screen Shot of WUFI Water Content Plot for OSB

The plot shows a maximum value of approximately 92 kg/m^3 but for only a brief period, perhaps a few hours. In order to dampen this effect, the maximum MC value was visually estimated by selecting a peak range rather than a peak point. In this case, it was chosen as 91 kg/m^3 and is indicated by the solid red line added to Figure 7-8. The peak range was converted to MC = 14%; all MC values were rounded to the nearest whole number.

7.5 Simulation Results

The same method was executed for all 147 simulations and the results were tabulated in Table 7-4 along with footnotes to help clarify the intention of how the results may be applied.

Table 7-4: Moisture Content Prediction for OSB Layer

Moisture Content (MC) in Wood Exterior Sheathing Subjected to Various Canadian Climates and Interior Relative Humidities
Chart values are %MC by dry mass of wood and represent a predicted maximum annual value

Green = MC < 20%, no mold growth; Yellow = MC is 20 to 28%, potential for mold growth; Red = MC > 28%, moisture problems expected, this design is NOT recommended

Wall Construction				Vancouver HDD 3000			Toronto HDD 4000			Ottawa HDD 4500			Calgary HDD 5000			Winnipeg HDD 6000			Yellowknife HDD 8000			Inuvik HDD 10000		
	Contents of Cavity	Depth of Cavity	Type of Vapour Control	Low RH 30/55%	Med. RH 40/60%	High RH 50%	Low RH 30/55%	Med. RH 40/60%	High RH 50%	Low RH 30/55%	Med. RH 40/60%	High RH 50%	Low RH 30/55%	Med. RH 40/60%	High RH 50%	Low RH 30/55%	Med. RH 40/60%	High RH 50%	Low RH 20/50%	Med. RH 30/55%	High RH 50%	Low RH 20/50%	Med. RH 30/55%	High RH 50%
Fiberglass (FG)		5.5"	Polyethylene sheet	12%	12%	12%	11%	11%	11%	10%	10%	10%	9%	9%	9%	10%	10%	10%	11%	11%	11%	10%	10%	10%
Fiberglass (FG)		5.5"	Latex paint+primer	14%	18%	21%	18%	25%	30%	21%	27%	33%	22%	28%	35%	28%	37%	43%	27%	37%	43%	35%	43%	46%
Spray Polyurethane Foam (SPF)	Open Cell	5.5"	Latex paint+primer	14%	15%	17%	14%	18%	21%	16%	20%	23%	16%	20%	22%	21%	26%	28%	20%	25%	27%	24%	28%	29%
Spray Polyurethane Foam (SPF)	Closed Cell[3]	2"SPF +3.5"FG[1]	Latex paint+primer	13%	14%	14%	12%	13%	13%	11%	12%	12%	10%	11%	11%	13%	13%	13%	13%	13%	14%	12%	12%	12%
Spray Polyurethane Foam (SPF)	Closed Cell[3]	2"SPF in 3.5/5.5"	Latex paint+primer	12%	13%	13%	11%	12%	13%	10%	12%	12%	10%	11%	12%	13%	14%	14%	12%	13%	14%	13%	14%	14%
Spray Polyurethane Foam (SPF)	Closed Cell[3]	3.5" SPF in 3.5/5.5"	Latex paint+primer	12%	13%	13%	12%	12%	12%	10%	11%	11%	9%	10%	10%	12%	12%	12%	12%	12%	12%	11%	12%	12%
Wood Stud[2]		3.5" or 5.5"	Latex paint + primer	7%	7%	7%	7%	7%	7%	5%	6%	6%	5%	5%	5%	6%	7%	7%	7%	7%	7%	5%	5%	6%
Other Applicable Locations (Heating Degree Days below 18°C) *From Environment Canada's Canadian Climate Normals 1971-2000*				White Rock (2782) Vancouver (2926) Abbotsford (2981) Victoria (3040)			Windsor (3524) Niagara Falls (3661) Kelowna (3869) Oshawa (3917) Hamilton (4012) Halifax (4030) London (4057) Toronto (4065)			Kitchener-Waterloo (4288) Kingston (4289) Montréal (4518) Moncton (4585) Ottawa (4602) Charlottetown (4715)			St. John's (4881) Trois-Rivières (4929) Calgary (5108) Prince George (5132) Sherbrooke (5151) Québec City (5202) Sudbury (5343)			Regina (5660) Edmonton (5708) Thunder Bay (5717) Winnipeg (5777) Saskatoon (5852) Whitehorse (6811)			Dawson (8166) Yellowknife (8256)			Inuvik (9767) Iqaluit (10117) Resolute (12526)		

General Notes:

a. Walls are residential wood frame with light-colored, thin cladding facing north: this is a worse-case scenario for cold-weather diffusion wetting.
b. Values are for OSB; plywood sheathing values will be equal or lower. OSB permeance is always over 60 ng/Pa·s·m2 in exterior sheathing applications.
c. Sheathings of DensGlas, FiberBoard, and Gypsum Board are all very vapour permeable and hence will have lower moisture contents.
d. Thicker foam will always result in lower wintertime sheathing moisture contents.
e. Effective Air Barrier is assumed to be installed, as is proper rain control. Interior temperature is 22°C.

Specific Notes:

1. Apply SPF directly onto back of exterior sheathing.
2. MC values are for outer 1/2" of wood stud.
3. Closed Cell SPF should be applied in total thicknesses of more than 2" (50 mm), usually in lifts of no more than 2" (50 mm).

7.6 Conclusions

The hygrothermal simulations validated the OSB test performance for the closed cell SPF. The closed cell SPF simulations performed well for all climates and humidities. The moisture content of the OSB sheathing in walls insulated with closed cell SPF is equivalent to that of the traditional wall assembly with a polyethylene vapour barrier and fibreglass batt.

The hygrothermal model of the wall section at a wood stud shows that it is the least permeable of all modelled cases in all climates and interior humidities. It is difficult to foresee where vapour diffusion through the wood stud would be a problem.

The open cell SPF and fibreglass batt insulation performed similarly, which is to say, they both require additional vapour control layers in all but the mildest Canadian climates with the lowest interior humidities. However, in those mild climates with low interior humidities, the only vapour control layer required was a medium permeance latex paint with primer (with a permeance of 300 ng/Pa·s·m^2 or less).

All simulations were assumed to have an effective air barrier, proper rain control and light-colored, ventilated cladding.

Performance for walls not included in the simulations can be estimated for the following modifications, if all other variables are the same:

- Plywood sheathing will result in lower or equal MC values as plywood is more vapour permeable.
- DensGlas, FiberBoard, and gypsum board sheathing are much more vapour permeable than OSB and hence will have lower moisture contents.
- Thicker foam will reduce wintertime sheathing moisture contents. Closed cell SPF must be at least 2 inches thick in order to provide sufficient vapour resistance for the conditions considered.

Significant modifications to the simulation variables (climate, exposure, materials, humidities) beyond those outlined above require customized modelling to evaluate assembly performance.

Chapter 8
Conclusions and Recommendations

Water vapour diffusion through building assemblies is dependent on factors such as interior relative humidity condition, exterior temperature, and the permeability and location of materials within the assembly. Water vapour diffuses in the direction of high concentration to low concentration. Buildings with high interior relative humidities (50% RH) and low winter temperatures (HDD°C > 4500) have very high vapour diffusion drives. Vapour diffusion through assemblies is only a problem if the vapour condenses within the assembly and cannot dry quickly enough to keep the water content of any water-damage susceptible materials within their safe range.

The objective of the research was to evaluate the performance of wall assemblies containing closed cell or open cell spray polyurethane foam under various vapour diffusion drives and determine which assemblies required a dedicated vapour control layer as described in Part 5 of the National Building Code of Canada. The code specifies that vapour barriers are not required when "it can be shown that uncontrolled vapour diffusion will not adversely affect any of, (a) health or safety of building users, (b) the intended use of the building, or (c) the operation of the building services." By this measure, if the wood sheathing moisture contents stay within the safe range (MC < 19%) a vapour barrier is not necessary.

The wall assemblies considered in this research are typical for Canadian residential construction. The moisture content was used as the performance evaluation point of the wood sheathing layer (OSB) in the tested and modelled assemblies because during wintertime vapour drives, the wood sheathing is the most likely condensing surface. Prolonged high moisture content (MC > 20%) in wood and wood products in wall assemblies leads to mould growth and decay.

Experimental Conclusions

Closed cell foam performed well and predictably for both measured and modelled cases, with and without polyethylene vapour barriers. The experimental gravimetric and moisture readings for the OSB sheathing in the lab test samples containing closed cell spray polyurethane foam showed excellent performance, with moisture contents not exceeding 10% in either the measured or modelled cases.

Open cell foam and fibreglass performed poorly in the extreme climate chamber conditions and exhibited a greater amount of water accumulation than predicted, with and without polyethylene vapour barriers. The OSB sheathing in the laboratory test samples containing a polyethylene vapour barrier and open cell spray polyurethane foam or fibreglass test had much higher readings than anticipated. The results of these tests were surprising given the relatively low permeance of the vapour barrier layer and the care used in airtightening the samples. Adsorption of water vapour from the cold side of the climate chamber to the OSB is certainly one of the mechanisms at work, but is not sufficient to explain the measurements. The moisture gain in the test boxes with no polyethylene vapour barrier also show a much greater amount of water accumulation than predicted. Higher permeance paint than assumed in the calculations or normal inaccuracies in warm side RH measurement could help explain at least some of this discrepancy.

Hygrothermal Simulation Conclusions

The hygrothermal simulations provided reliable results and validated the OSB performance in the lab test results.

The closed cell SPF performed well for all climates and indoor humidity levels considered. The moisture content of the OSB sheathing in walls insulated with closed cell SPF is equivalent to that of the traditional wall assembly with a polyethylene vapour barrier and fibreglass batt.

The wall section at a wood stud shows that it is the least permeable of all modelled cases.

Open cell SPF and fibreglass batt insulation with no polyethylene vapour barrier performed poorly in all but the mildest Canadian climates with the lowest interior humidities where a standard layer of latex paint and primer provided sufficient vapour control.

Recommendations

Future work should extend this study to vented and unvented roof systems, as well as explore vapour diffusion control strategies for open cell SPF in cold climates.

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Appendix A

Material Properties of SPF Products

WALLTITE Series

INSULATION SYSTEM

PRODUCT DESCRIPTION:

WALLTITE is a closed-cell polyurethane system utilizing an EPA approved, zero ozone-depleting blowing agent. It is designed for use in commercial and residential construction applications. WALLTITE is compatible with most common construction materials. The benefits of **WALLTITE include:**

- Superior insulation performance
- Control moisture infiltration
- Controls air infiltration
- Ease of application
- Non-fibrous

APPROVALS AND CREDENTIALS:

ASTM E-84* Listed at SGS US Testing Co., Inc.

Class I

SPF Thickness	4.0 inches
Flame Spread Index	25
Smoke Development Index	350

NFPA 286

8 inch wall
12 inch ceiling
with 15 min. thermal barrier
Tested at Intertek ETL Semko
Test Report Number: 3116019-002d

Attic & Crawl Space

Tested at Intertek ETL Semko
Test Method SwRI 99-02
Test Report Number: 3116311-002d

* - This numerical flame spread rating does not reflect hazards presented by this or any other material under actual fire conditions. Polyurethane foam systems should not be left exposed and must be protected by a minimum 15-minute thermal barrier or other code-compliant material as allowed by applicable building code(s) and Code Officials. Building Codes provide guidelines representing minimum requirements. Further information is available at www.iccsafe.org. Consult all Authorities having jurisdiction over an area for additional or specific requirements prior to beginning a project.

TYPICAL PROPERTIES**:

PROPERTY	VALUE	TEST METHOD
Liquid Resin – As Supplied		
Specific Gravity @ 70°F	1.180	ASTM D 1638
Viscosity @ 70°F (cps)	440	Brookfield
As Cured		
Iso:Resin Mix Ratio (vol:vol)	1:1	
Density, core (pcf @ 2" lift)	Nominal 2.0	ASTM D 1622
Compressive Strength (psi)	22	ASTM D 1621
Tensile Strength (psi)	28	ASTM D 1623 Type C
Closed Cell Content (%)	>90	ASTM D 6226
Initial k-factor (Btu in/ft^2 hr °F)	0.165 (R=6.1/in)***	ASTM C 518
Permeance (perms)	1.82	ASTM E 96
Permeability (perm inch)	1.82 @ 1" SPF 0.91 @ 2" SPF 0.61 @ 3" SPF 0.46 @ 4" SPF	ASTM E 96
Air Permeance (L/s/m^2 @ 75 Pa)	0.000025	ASTM E 2178-01
Air Leakage (L/s/m^2 @ 75 Pa)	0.000025	ASTM E 283-99
Dimensional Stability (%Volume Change)		
Dry Age 28 Days (158°F)	+8 to +12%	ASTM D 2126
Freeze Age 14 Days (-20°F)	+0.07 to –0.21%	ASTM D 2126

*** - These physical property values are typical for this material as applied at our development facility under controlled conditions. SPF performance and actual physical properties will vary with differences in application (i.e. ambient conditions, process equipment and settings, material throughput, etc). As a result, these published properties should be used as guidelines solely for the purpose of evaluation. Physical property specifications should be determined from actual production material.*

The above data was collected from samples prepared using the following equipment configuration:

- *Gusmer® H-20/35 proportioner set at 1:1 volume ratio with 50 ft of heated delivery hose*
- *Gusmer® GX-7 spray-gun configured with a #1 mix module and #70 PCD and/or GAP spray-gun configured with a #1 mix chamber*
- *Process temperature settings: Isocyanate 130°F; Resin 130°F; Hose 130°F*
- *Process pressure: 1000 psig minimum while spraying*

WALLTITE *has shown acceptable on-site performance with temperature settings in the range of 110°F - 130°F for Isocyanate, Resin and Hose. Every job site and set of ambient /substrate conditions are different; therefore, one set of process settings may not work for every situation. It is the responsibility of the applicator to evaluate the on-site conditions and then determine the appropriate SPF reactivity and process settings.*

****The data chart shows the R-value of this insulation. "R" means resistance to heat flow. The higher the R-value, the greater the insulating power. Compare insulation R-values before you buy. There are other factors to consider. The amount of insulation will depend upon the climate, the type and size of your house, and the fuel use patterns and family size. If you buy too much insulation it will cost you more than what you will save on fuel. To achieve proper R-values, it is essential that this insulation be installed properly.*

Technical Data Sheet

Helping Make Buildings Better™

BASF
The Chemical Company

BASF Polyurethane Foam Enterprises LLC

GENERAL INFORMATION:

WALLTITE is a spray polyurethane foam (SPF) system intended for installation by qualified contractors trained in the processing and application of SPF systems, as well as the plural-component polyurethane dispensing equipment required to do so. Contractors and applicators must comply with all applicable and appropriate storage, handling, processing and safety guidelines. BASF Polyurethane Foam Enterprises LLC technical service personnel should be consulted in all cases where application conditions are questionable.

CAUTIONS AND RECOMMENDATIONS:

WALLTITE is designed for an application rate of ½ inch minimum to 2 inches maximum. Once installed material has cooled it is possible to add additional applications in order to increase the overall installed thickness of SPF. Typical installations are limited to a total thickness of 4 inches. This application procedure is in compliance with the Spray Polyurethane Foam Alliance (SPFA).

WALLTITE is **NOT** designed for use as an **EXTERIOR** roofing system. BASF Polyurethane Foam Enterprises LLC offers a separate line of products for exterior roofing applications. For more information please contact your sales representative.

Cold-storage structures such as coolers and freezers demand special design considerations with regard to thermal insulation and moisture-vapor drive. **WALLTITE** should **NOT** be installed in these types of constructions unless the structure was designed by a design professional for specific use as cold storage.

WALLTITE is designed for installation in most standard construction configurations using common materials such as wood and wood products, metal and concrete. **WALLTITE** has performed successfully when sprayed onto wood substrates down to 30°F. For other substrates, please consult your BASF Polyurethane Foam Enterprises LLC sales or technical service representative for specific recommendations.

Foam plastic materials installed in walls or ceilings may present a fire hazard unless protected by an approved, fire-resistant thermal barrier with a finish rating of not less than 15 minutes as required by building codes. Rim joists and / or sill plates, in accordance with the IRC, IBC and approval by the local Code Authority, may not require additional protection. Foam plastic must also be protected against ignition by code-approved materials in attics and crawl spaces. See relevant Building Codes and **www.iccsafe.org** for more information.

This product is neither tested nor represented as suitable for medical or pharmaceutical uses.

In addition to reading and understanding the MSDS, all contractors and applicators must use appropriate respiratory, skin and eye Personal Protective Equipment (PPE) when handling and processing polyurethane chemical systems. Personnel should review the following document published by Spray Polyurethane Foam Alliance (SPFA):

AX-171 *Course 101-R Chapter 1: Health, Safety and Environmental Aspects of Spray Polyurethane Foam and Coverings*

and the following document available from the Center for the Polyurethanes Industries (CPI):

Model Respiratory Protection Program for Compliance with the Occupational Safety and Health Administration's Respiratory Protection Program Standard 29 C.F.R. §1910.134

As with all SPF systems, improper application techniques such as: excessive thickness of SPF, off-ratio material and spraying into or under rising SPF. Potential results of improperly installed SPF include: dangerously high reaction temperatures that may result in fire and offensive odors that may or may not dissipate. Improperly installed SPF must be removed and replaced with properly installed materials.

LARGE MASSES of SPF should be removed to an outside safe area, cut into smaller pieces and allowed to cool before discarding into any trash receptacle.

SPF insulation is combustible. High-intensity heat sources such as welding or cutting torches must not be used in contact with or in close proximity to WALLTITE or any polyurethane foam.

SHELF LIFE AND STORAGE CONDITIONS:

WALLTITE Series has a shelf life of approximately three months from the date of manufacture when stored in original, unopened containers at 50-80°F. As with all industrial chemicals this material should be stored in a covered, secure location and never in direct sunlight. Storage temperatures above the recommended range will shorten shelf life. Storage temperatures above the recommended range may also result in elevated headspace pressure within packages.

LIMITED WARRANTY INFORMATION – PLEASE READ CAREFULLY:

The information herein is to assist customers in determining whether our products are suitable for their applications. Our products are only intended for sale to industrial and commercial customers. Customer assumes full responsibility for quality control, testing and determination of suitability of products for its intended application or use. We warrant that our products will meet our written liquid component specifications. We make no other warranty of any kind, either express or implied, by fact or law, including any warranty of merchantability or fitness for a particular purpose. Our total liability and customers' exclusive remedy for all proven claims is replacement of nonconforming product and in no event shall we be liable for any other damages.

Revised 06.04.07

STYROFOAM™ Spray Polyurethane Foam Insulation

1 PRODUCT NAME

STYROFOAM™ 2.0 pcf Spray Polyurethane Foam Insulation

2 Manufacturer

The Dow Chemical Company
Building & Construction
200 Larkin
Midland, MI 48674
1-866-583-BLUE (2583)
Fax 1-989-832-1465
www.dowstyrofoam.com/architect
www.insulateyourhome.com

3 Product Description

STYROFOAM™ Spray Polyurethane Foam (SPF) Insulation is a two-component spray-applied polyurethane foam insulation that creates a seamless, monolithic barrier for protection against water and air. The SPF blend successfully incorporates the Enovate 3000 blowing agent from Honeywell.

BASIC USE

STYROFOAM™ SPF Insulation is created from a unique polyol technology, which offers improved foam yield and wide processing latitude. Offered in two formulations for both new and retrofit applications, STYROFOAM SPF Insulation expands during installation to fill cavities, cracks and crevices, preventing uncontrolled air leakage and maintaining consistent, comfortable indoor temperatures. The closed-cell, 2.0 pcf foam serves as both an insulation and air sealant for a wide range of applications throughout the building envelope. In addition, STYROFOAM SPF Insulation resists moisture and provides structural reinforcement for improved racking strength.*

SIZES

STYROFOAM™ SPF Insulation is sold in 55 gal drum sets (one A isocyanate and one B polyol blend; total 950 lb). Contact your Dow sales representative with questions.

4 Technical Data

APPLICABLE STANDARDS

Applicable test methods include:

- ASTM C1029 – Standard Specification for Spray-Applied Rigid Cellular Polyurethane Thermal Insulation
- ASTM C518 – Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus
- ASTM D1621 – Standard Test Method for Compressive Properties of Rigid Cellular Plastics
- ASTM D1622 – Standard Test Method for Apparent Density of Rigid Cellular Plastics
- ASTM D6226 – Standard Test Method for Open Cell Content of Rigid Cellular Plastics

CODE COMPLIANCES

STYROFOAM™ SPF Insulation complies with the following codes:

- Conforms to IRC requirements for foam plastic insulation; see ASTM C1029
- Underwriters Laboratories, Inc. and Intertek Research Report (UL) Classified Class I at 4 inches; see UL 723
- ABAA standards for air leakage per ASTM E283

Contact your Dow sales representative or local authorities for state and local building code requirements and related acceptances.

*STYROFOAM SPF Insulation provides structural enhancement only. Use in conjunction with approved structural components and framing members consistent with following local building code requirements.

PHYSICAL/CHEMICAL PROPERTIES

STYROFOAM™ SPF Insulation exhibits typical physical properties as indicated in Table 1 when tested as represented.

ENVIRONMENTAL DATA

STYROFOAM™ SPF Insulation is chlorofluorocarbon (CFC) free and uses the Enovate 3000 blowing agent from Honeywell, which is a zero ozone-depleting product.

FIRE PROTECTION

STYROFOAM™ SPF Insulation is organic and combustible and may constitute a fire hazard. Do not expose foam to flame or temperatures above 240°F.

TABLE 1

Typical Physical Properties[1] of STYROFOAM™ SPF Insulation

Property and Test Method	Value	
	STYROFOAM™ SPF Insulation 3062 *35°F-80°F (35°F-100°F) Ambient (Substrate) Processing*	**STYROFOAM™ SPF Insulation 3049** *60°F-100°F (60°F-120°F) Ambient (Substrate) Processing*
Core Density, ASTM D1622, lb/ft^3	>2	>2
Compressive Strength, ASTM D1621, lb/in^2, parallel	26	26.4
Tensile Strength, ASTM D1623, lb/in^2, parallel	55	53.3
Closed-cell Content, ASTM D6226	94	96
Thermal Conductivity, ASTM C518, k-factor[2]	0.154	0.154
Thermal Resistance, ASTM C518, R-value per inch[3]	6.5	6.5
Water Vapor Permeability, ASTM E96, perm-inch	1.1	1.4
Water Absorption, ASTM D2842, % by volume	3.2	3.2
Dimensional Stability, ASTM D2126, % volume change		
At -20°F, 14 days	<1.0	<1.0
At 200°F, 14 days	<1.0	<1.0
At 158°F, >98% R.H.	<4.0	<3.3
Surface Burning Characteristics[4], ASTM E84, 4" thickness (Intertek UL 723)		
Flame spread	<25	20
Smoke developed	400	<350

(1) Not to be considered sales specifications.
Properties determined by processing foam with Gusmer H2O/35 primary heater at 120°F (A,B), hose temperature of 120°F with GX7 gun; .028 drilled module with 70 PCD; dynamic pressures at 600 psi-1,000 psi.
(2) Initial value. Aged k-factor: 0.185 at 180 days, 50% R.H. per FTC requirements.
(3) Initial value. Aged R-value: 5.4 at 180 days, 50% R.H. per FTC requirements.
(4) Calculated flammability values for this or any other material are not intended to represent hazards that may be present under actual fire conditions.

5 Installation

Only personnel trained in spray polyurethane foam application should install STYROFOAM™ SPF Insulation.

STYROFOAM SPF Insulation contains isocyanate, hydrofluorocarbon blowing agent and polyol. Read the Material Safety Data Sheet carefully before use. Wear protective clothing, gloves, goggles and proper respiratory protection. Supplied air or an approved air-purifying respirator equipped with an organic vapor sorbent and a particle filter is required to maintain exposure levels below applicable ACGIH, OSHA or WEEL limits. Provide adequate ventilation.

Spray equipment must be capable of delivering the proper ratio (1:1 by volume) of polymeric isocyanate and polyol blend at adequate temperatures and spray pressures. Substrate must be at least 5 degrees above dew point, with best processing results when ambient temperature humidity is below 80 percent. Substrate must also be free of moisture (dew or frost), grease, oil, solvents and other materials that would adversely affect the adhesion of the polyurethane foam. Substrate temperatures should not exceed 120°F for STYROFOAM SPF 3049 (commonly referred to as “Summer” formula) and 100°F for STYROFOAM SPF 3062 (commonly referred to as “Fall/Spring” formula).

Due to the exothermic reaction of the isocyanate and polyol blend, mixed components should be applied in layers (maximum 2-1/2" thickness per layer). Allow foam to cool completely before applying successive layers.

Contact a local Dow representative or access the literature library at www.dowstyrofoam.com/architect or www.insulateyourhome.com for more specific instructions.

6 Availability

STYROFOAM™ SPF Insulation is distributed through an extensive network. For more information, call 1-800-232-2436.

7 Warranty

Not applicable.

8 Maintenance

STYROFOAM™ SPF Insulation has a shelf life of six months when stored dry between 60°F and 90°F. Avoid direct sunlight during shipping and storage on the job site.

Caution should be exercised when opening containers as pressure may be present when material has been exposed to elevated temperatures.

Empty drums are non-returnable and should be disposed of by using current industrial practices in accordance with federal, state or local regulations.

9 Technical Services

Dow can provide technical information to help address questions when using STYROFOAM™ SPF Insulation. Technical personnel are available to assist with any insulation project. For technical assistance, call 1-866-583-BLUE (2583).

10 Filing Systems

- www.dowstyrofoam.com/architect
- www.insulateyourhome.com
- www.sweets.com

DEMILEC

HEATLOK™ 聚氨酯喷涂泡沫保温 热保

HEATLOK
Technical Data Sheet

Spray Foam Insulation
Zero Ozone Depletion Substance, Class I ASTM

HEATLOK 0240 is a two component closed cell spray-applied rigid polyurethane foam system, green in color, formulated to exceed the requirements of CAN/ULC S705.1-98 standard. HEATLOK 0240 is applied exclusively by licensed contractors under the guidelines of CAN/ULC S705.1-98 standard. HEATLOK 0240 is also an excellent air barrier, which has been tested by an independent laboratory: it exceeds 150 times the requirements of NBC 1995, article 5.4.1.2 (CCMC Report 12893-R). Approved by the Ontario Ministry of Housing #99-12-71

HEATLOK 0240 has been evaluated by CCMC since 1992 (Report # 12380-R) for residential use and complies with the intent of the National Building Codes of Canada 1995. This product is also approved by Ontario Ministry of Housing #94-0909.

PHYSICAL PROPERTIES

METHOD	Description	Values
ASTM D1622	Density	232-35 Kg/m3
ASTM C518	Thermal Resistance 90 days @ 230C	6.9 ft2. h.0F/BTU.in
ASTM D2856	Open Cell Content	6.02%
ASTM D1621	Compressive Strength (10%)	174 kPa
ASTM D1623	Tensile Strength	212 kPa
ASTM D2126	Dimensional Stability (% Volume Change @ 28 Days) -200C 1000C 700C,> 97 ± 3% R.H.	 0.47 5.89 2.58
ASTM D2842	Water Absorption (% volume)	0.62
ASTM E96	Water Vapor Permeance (Core)	86.6 ng/Pa.s.m2
A-3136.1 (CNRC)	Water Vapor Permeance (System) 25 mm sprayed on concrete blocks 38 mm sprayed on exterior gypsum board	 36.4 ng/Pa.s.m2 52.9 ng/Pa.s.m2
CCMC 07273	Air Barrier Material Test	0.00014 L/ (s.m2) @75 Pa
ASTM E330	Gust Wind (3000Pa = 225 Km/h)	No Delamination
CAN/ULC	Flame Spread Classification	25<FSC<500
S102M & S127	Smoke Developed	<500
ASTM C 1338	Fungi Resistance	No Fungal Growth

2925 Galleria Drive, Arlington, TX 76011 | T: 817 640 4900 | F: 817 633 2000 | E: info@heatlok.com | www.heatlok.com

LIQUID COMPONENTS PROPERTIES

PROPERTY	ISOCYANATE	RESIN
Color	Brown	Amber
Viscosity @ 26°C	150-350 cps	100-300 cps
Specific Gravity	1.20-1.24	1.20-1.24
Mixing Ratio (volume)	100	100

*See MSDS for more information.

PROCESSING PARAMETERS

Type of Machine	Gusmer HII, D gun, and # 62 mix
Primary Heater (A&B)	41°C
Hose Temperature	41°C
Ambient Temperature	23°C
Thickness per Pass	25 mm
Number of Passes	2
Substrate	Wood

REACTIVITY PROFILE

Cream time	Gel time	Tack free time	End of Rise
0-1 sec.	2 sec.	4-5 sec.	5-6 sec.

RECOMMENDED PROCESSING CONDITIONS

	Values
Primary Heater (A&B)	410C
Dynamic Pressure	4137 kPa
Substrate & Ambient Temperature	>-10°C
Curing Temperature	>-100°F
Maximum Thickness per Pass	50 mm

GENERAL INFORMATION

It is recommended that the foam is covered with an approved thermal barrier in accordance to the local and national building codes when used in buildings and a protective coating when used outside. This product should not be used when the continuous service temperature of the substrate is outside the range of -60ºC to 80ºC.

DEMILEC (USA) LLC.
POLYURETHANE SYSTEMS MANUFACTURER

TECHNICAL BULLETIN
SEALECTION ™ 500
RESIDENTIAL INSULATION

SEMI-RIGID SPRAY APPLIED POLYURETHANE FOAM

SEALECTION 500 is a two-component, open celled, spray-applied, semi-rigid polyurethane foam system. This product is a fully water blown foam system having a very low in-place density. SEALECTION 500 meets the off gassing requirements of CGSB 51.23-92 for new residential construction. SEALECTION 500 has been approved by the Environmental Choice Program of Canada and is listed as an **environmentally friendly product**. SEALECTION 500 complies with the intent of the US Building Codes for foam plastics insulation.

PHYSICAL PROPERTIES			
ASTM	**Description**	**British units**	**SI units**
D 1622	Density	**0.45 – 0.5 lb/ft³**	**7.21 – 8.01 kg/m³**
C 518	Thermal Resistance 2 days @ 76° F, per inch Thermal Resistance 90 days @ 76°F, per inch	**3.81 ft².h°F/BTU** **3.81 ft².h°F/BTU**	**0.671 m².°C/W** **0.671 m².°C/W**
E 283-04	Air Permeance • 3.5in @ 75Pa (25 miles/hr. wind) • 5.5in @ 75Pa (25 miles/hr. wind) • 7.5in @ 75Pa (25 miles/hr. wind) • 7.5in @ 1200Pa (100 miles/hr. wind)	**No air leakage detected** **No air leakage detected** **No air leakage detected** **No air leakage detected**	
	• 7.5in @ 2000Pa (129 miles/hr. wind)	**0.00009 ft³/s.ft²**	**0.028 L/m²s.**
	Sustained Wind Load for 60 minutes @ 1000 Pa (90 miles/hr. wind)	**No damage**	
	Gust Wind Load Test @ 3000 Pa (160 miles/hr.)	**No damage**	
D 1621	Compressive Strength	**0.7 psi**	**4.83 kPa**
D 1623	Tensile Strength	**5 psi**	**34.5 kPa**
E 413-87 **C 423**	Sound Transmission Class (STC) Noise Reduction Coefficient (NRC)	**50** **75**	**See specific wall design**
E 96	Water Vapor Permeance (Dry cup), 1"(25mm)	**5.47 Perms**	**313 ng/Pas.m².**
CGSB 51.23-92	Off Gassing Tests (VOC Emissions)	**Pass (No toxic vapors)**	
E 84	Surface Burning Characteristics (6") • Flame Spread Index • Smoke Development	**Class I** **21** **216**	

Sealection 500 / October 2006

2925 GALLERIA DRIVE • ARLINGTON TX. 76011 • PHONE: (817) 640-4900 • FAX: (817) 633-2000
Web site: http://www.demilecusa.com • http://www.sealection500.com • E-mail: info@sealection500.com

SEALECTION ™ 500

LIQUID COMPONENTS PROPERTIES		
PROPERTY	**ISOCYANATE A 500**	**RESIN B 500F**
Color	**Brown**	**Transparent Clear**
Viscosity @ 77ºF	**180 - 220 cps**	**150-300 cps**
Specific gravity	**1.22-1.25**	**1.09-1.11**
Shelf life*	**6 months**	**6 months**
Mixing ratio (volume)	**100**	**100**

***** Drum unopened, consult MSDS for more information.

All Properties were measured on core samples processed with the parameters listed below:

PROCESSING PARAMETERS		
Type of machine	**Gusmer HF1600, Gap gun # 02 mix chamber**	
Primary heater (A&B)	**130ºF**	**54.5ºC**
Hose temperature	**130ºF**	**54.5ºC**
Ambient temperature	**70ºF**	**21ºC**
Thickness of passes	**4 in**	**10cm**
Substrate	**Plaster board**	

REACTIVITY PROFILE			
Cream time, s	**Gel time, s**	**Tack free time, s**	**End of rise, s**
1 – 2	**3 – 4**	**6 – 7**	**6 – 7**

RECOMMENDED PROCESSING CONDITIONS		
	British units	**SI units**
Primary Heater	**130^{0}F**	**54.5ºC**
Hose temperature	**130^{0}F**	**54.5ºC**
Pressure of mix	**900 psi**	**6205 kPa**
Substrate & Ambient temperature	**> 23ºF**	**>(-5)ºC**
Curing temperature	**> 23^{0}F**	**>(-5)ºC**

GENERAL INFORMATION:

It is recommended that the foam be covered with an approved thermal barrier in accordance with the local and national building codes when used in buildings. This product should not be used when the continuous service temperature of the substrate is outside the range of -60°F (-51°C) to 176°F(80°C).

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Web site: http://www.demilecusa.com • http://www.sealection500.com • E-mail: info@sealection500.com

PRODUCT SPECIFICATION

1. PRODUCT NAME

Icynene® and The Icynene Insulation System® are registered trademarks for polyicynene insulation manufactured by Icynene Inc. Icynene® spray formula is a 1/2 lb density free rise, open celled material.

2. MANUFACTURER

Icynene® is made on site from liquid components manufactured by Icynene Inc. Installation and on-site manufacturing is supplied by independent Icynene Licensed Dealers.

3. PRODUCT DESCRIPTION

Icynene® insulates and air seals at the same time. Its performance is less installation sensitive than factory manufactured insulation materials. It is an effective "breathing" air barrier that can adjust with the building to maintain a seal against energy-robbing air leakage for the life of the building. Convective air movement inside cavities is virtually eliminated, providing more uniform temperatures throughout the building. The result is superior quality construction, with higher comfort levels and lower heating and cooling costs. Energy savings vary depending on building design, location, etc.

Icynene® is applied by spraying liquid components onto an open wall, crawl space or ceiling surface. There they expand 100:1 in just seconds to provide a flexible foam blanket of millions of tiny air cells, filling building cavities and sealing cracks and crevices in the process. It adheres to virtually all surfaces, sealing out air infiltration. Excess material is easily trimmed off, leaving a surface ready for drywall or other finish.

4. TECHNICAL DATA

(Based on Core Samples)

Thermal Performance

Thermal resistance R/in. (RSI/25mm)
ASTM C518: R3.6 hr. ft² °F/BTU
RSI 0.62 m² °C/W

Average insulation contribution in stud wall:
2" x 4" = R13   2" x 6" = R20

The Icynene Insulation System® provides more effective performance than the equivalent R-value of air permeable insulation materials. Icynene® is not subject to loss of R-value due to aging, windy conditions, settling, convection or air infiltration; nor is it likely to be affected by moisture related conditions. A FACT SHEET with R-value data is available upon request.

Air Permeance/Air Barrier /Air Seal

The Icynene Insulation System® fills any shaped cavity, and adheres to all materials, creating assemblies with very low air permeance. No additional interior or exterior air infiltration protection is necessary.

Air permeability of core foam:
ASTM E283 data
0.0049 L/S-m² @75 Pa for 5.25"
0.0080 L/S-m² @75 Pa for 3.25"

In all buildings, adequate mechanical ventilation/air supply should be provided for optimum IAQ (Indoor Air Quality). See ASHRAE Guidelines.

Water Vapor Permeance

Icynene® is water vapor permeable and allows structural moisture to diffuse and dissipate. It will not entrap moisture in materials to which it is applied.

Water vapor transmission properties:
ASTM E96 data

16 perms 941 ng/(Pa•s•m²) @ 3" (76mm) thick
10 perms 565 ng/(Pa•s•m²) @ 5" (127mm) thick

Because of its low air permeance, Icynene® is not infiltrated by moisture-laden air. Computer modeling of moisture movement in walls using a program (MOIST) developed by Doug Burch of the National Institute of Standards and Technology (NIST) suggested that a 1.0 perm rating was not required when Icynene® insulation was used, except in climates as cold or colder than Madison, Wisconsin (7500 Heating degree days). This conclusion was in general agreement with other computer modeling of moisture movement in building envelopes performed in Canada. In those situations that warrant a vapor barrier, the use of low vapor permeable paint on the interior drywall is adequate.

Water Absorption Properties

Icynene® is hydrophobic and does not exhibit capillary properties. It does not wick and is water repellent. Water can be forced into the foam under pressure because it is open celled. Water will drain by gravity rather than travel horizontally or vertically through the foam. Upon drying, thermal performance is fully restored.

Acoustical Properties

Performance in a 2"x4" wood stud wall:

STC Sound Transmission Class - 37

Hz. Freq.	125	250	500	1000	2000	4000
ASTM E90	19	30	31	42	38	46

NRC Noise Reduction Coefficient - 70

Hz. Freq.	125	250	500	1000	2000	4000
ASTM C423	.11	.43	.89	.72	.71	.67

Actual performance is superior than reported test results because of Icynene®'s ability to control air leakage.

Burn Characteristics

Icynene® will be consumed by flame, but will not sustain flame upon removal of the flame source. It leaves a charcoal residue. It will not melt or drip. It should be applied in accordance with applicable building codes.

U.S.A. Specifications
Surface Burning Characteristics of Icynene® ASTM E84

Flame Spread	<20
Smoke Development	<400
Fuel Contribution	0
Oxygen Index ASTM D2863	23%
N.Y. State Fire gas toxicity	LC_{50} –12

CANADA Specifications
Corner Wall Test CAN4-S102 FSC3

Flame Spread	510-530
Smoke Development	95-150

Electrical Wiring

Icynene® has been evaluated with both 14/3 and 12/2 residential wiring (max. 122°F/50°C). It is chemically compatible with all electrical wiring coverings.

Note: For any insulation of knob and tube wiring, please reference local electrical code.

Corrosion

Icynene® did not cause corrosion when evaluated in contact with steel under 85% relative humidity conditions.

Bacterial or Fungal Growth and Food Value

Independent testing conducted by Texas Tech University has confirmed that Icynene® is not a source of food for mold; and as an air barrier, Icynene® reduces the airborne introduction of moisture, food, and mold spores into the building envelope. It has no food value for insects or rodents.

Environmental / Health / Safety

Icynene® contains no formaldehyde or volatile organic compounds. It has been thoroughly evaluated for in-situ emissions by industry and government experts. VOC emmissions are below 1/100 of the safe concentration level within hours following the application of Icynene®. A 24 HR waiting period is recommended for highly sensitive people prior to occupancy.

Not intended for exterior use. Not to be installed within 2" (50 mm) of heat emitting devices, where the temperature is in excess of 200°F(93°C).

5. INSTALLATIONS

The Icynene Insulation System® is installed by a network of Licensed Dealers, trained in the installation of Icynene®. Installation is generally independent of environmental conditions. It can be installed in hot, humid or freezing conditions. Surface preparation is generally not necessary. Within minutes, the foaming process is complete.

6. AVAILABILITY

Check regional yellow pages or contact Icynene Inc. at 800-758-7325 or our website at www.icynene.com.

7. WARRANTY

WHEN INSTALLED PROPERLY IN ACCORDANCE WITH INSTRUCTIONS, THE COMPANY WARRANTS THAT THE PROPERTIES OF THE PRODUCT MEET PRODUCT SPECIFICATIONS AS OUTLINED IN THIS PRODUCT SPECIFICATION SHEET.

8. TECHNICAL

Icynene Licensed Dealers and Icynene Inc. provide support on both technical and regulatory issues. Architectural specifications in CSI 3-Part format are available upon request.

9. RELATED REFERENCES

All physical properties were determined through testing by accredited third party agencies. Icynene Inc. reserves the right to change specifications in its effort to enhance quality features. Please confirm that technical data literature is current.

10. PACKAGING AND STORAGE

Packaging - 55 U.S. gallon open top steel drums

Component 'A'	- 550 lb. per drum
Base Seal®	- Polyisocyanate MDI
Component 'B'	- 500 lb. per drum
Gold Seal®	- Resin

Storage

Component A should be protected from freezing.

Component B can be frozen but must be protected from overheating (120°F/49°C) and prolonged storage above 100°F/38°C. Component B separates during storage and should be mixed thoroughly prior to use.

11. INSTALLATION SPECIFICATIONS

Refer to the Icynene Installer's Manual for expanded information.

ICYNENE INC.
The Icynene Insulation System®
Healthier, Quieter, More Energy Efficient®

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Website: www.icynene.com
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7/03/PSA

Appendix B

Instrumentation

CS500 Temperature and Relative Humidity Probe

1. General

The CS500 Temperature and Relative Humidity probe contains a Platinum Resistance Temperature detector (PRT) and a Vaisala INTERCAP® capacitive relative humidity sensor.

The -L option on the model CS500 Temperature and Relative Humidity probe (CS500-L) indicates that the cable length is user specified. This manual refers to the sensor as the CS500.

2. Specifications

Operating Temperature: -40°C to +60°C

Storage Temperature: -40°C to +80°C

Probe Length: 6.8 cm (2.66 in.)

Probe Body Diameter: 1.2 cm (0.47 in.)

Filter: 0.2 µm Teflon membrane

Filter Diameter: 1.2 cm (0.47 in.)

Housing Material: ABS Plastic

Power Consumption: <2 mA

Supply Voltage: 7 to 28 VDC

Settling Time after power is switched on: 1 second

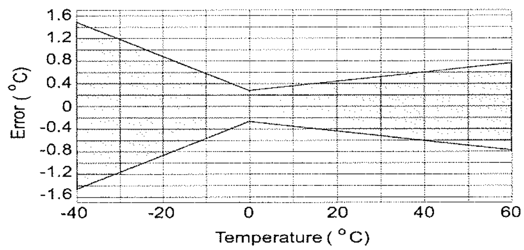
2.1 Temperature Sensor

Sensor: 1000 Ω PRT, DIN 43760B

Temperature Measurement Range: -40°C to +60°C

Temperature Output Signal range: 0 to 1.0 VDC

Temperature Accuracy:



2.2 Relative Humidity Sensor

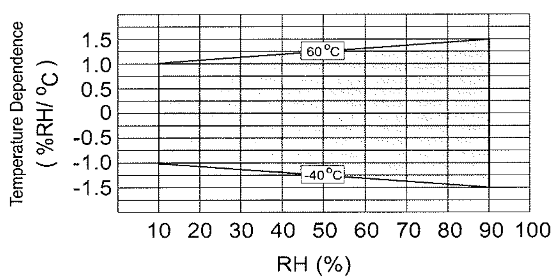
Sensor: INTERCAP®

Relative Humidity Measurement Range: 0 to 100% non-condensing

RH Output Signal Range: 0 to 1.0 VDC

Accuracy at 20°C
unspecified (0 to 10% Relative Humidity)
±3% RH (10 to 90% Relative Humidity)
±6% RH (90 to 100% Relative Humidity)

Temperature Dependence of Relative Humidity Measurement:



Typical Long Term Stability: Better than 1% RH per year

Response Time (at 20°C, 90% response to a steep change in humidity):
15 seconds with membrane filter

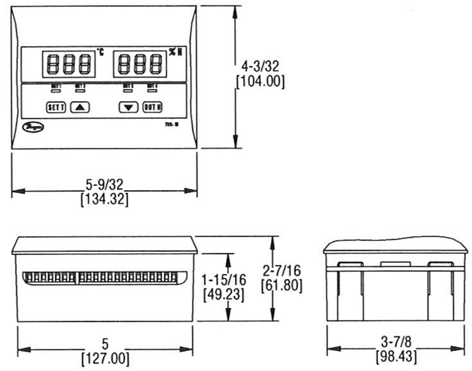
3. Installation

The CS500 must be housed inside a solar radiation shield when used in the field. The 41303 6-Plate Radiation Shield (Figure 1) mounts to a CM6/CM10 tripod or UT10 tower. The CS500 is held within the 41301 by a mounting clamp (Figure 2).

The 41003 10-Plate Radiation Shield (Figure 3) mounts to a CM6/CM10 tripod. The UT12VA 12-Plate Radiation Shield mounts to a UT10 or UT30 tower with the UT018 horizontal mounting arm.

Series THC- Temperature/Humidity Switch

Specifications - Installation and Operating Instructions



Simultaneously measure and control temperature and humidity with the Series THC Temperature/Humidity Switch. The unit offers a 3-digit red display for temperature indication and a 3-digit green display indicating humidity. The Series THC is equipped with four independent relays, two for temperature control and two relays for humidity control.

The unit offers 61 programmable parameters for temperature and humidity control including set point, differential, direct/reverse acting, cycle time, alarm clock time, and decimal point adjustment. In the event of a probe error, the default operating of the relays can be set to open or close. The THC features error or alarm messaging and password protection.

The THC Temperature/Humidity Switch accepts up to two temperature probe inputs and a humidity sensor. A humidity sensor with 0-1V, 0-3V, or 4-20mA output can be used with the Series THC.

SPECIFICATIONS

Measurement Range:
Temperature: -58 to 302°F (-50 to 150°C); Humidity: 0 to 100%RH.
Input: Up to 2 thermistors and 1 humidity sensor.
Output: 4 SPST, 8A relays @ 250 VAC.
Horsepower Rating (HP): 1/3 HP.
Control Type: ON/OFF direction, direct or reverse acting, neutral.
Power Requirements: 110 or 230 VAC (depending on model).
Accuracy:
Temperature: ±0.5% of probe range; Humidity: ±3% of range.
Display: Two 3-digit displays. 1/2" digits.
Resolution: 0.1°.
Memory Backup: Nonvolatile memory.
Ambient Operating Temperature: 32 to 158°F (0 to 70°C).
Storage Temperature: -4 to 176°F (-20 to 80°C).
Weight: 1.17 lb (530g).
Panel Cutout: 5.15" x 2.37" (131 x 111mm).
Front Panel Protection: NEMA 4X (IP65).
Agency Approvals: CE.

INTRODUCTION

Humidity and temperature control all in one unit. This unit features 2 temperature outlets and 2 humidity outlets. Separate temperature and humidity displays.

Temperature Control

3 control options are available: ON-OFF, Neutral and Refrigeration Temperature is controlled by a PTC1000 sensor and a second sensor can be added as a thermostat for defrosting time out control.

Humidity control

2 control options are available: ON-OFF and Neutral.
It can use any one of 3 humidity sensors (0-1V, CRPH03, 4-20mA) all of which can be programmed by parameter.

OPERATING INSTRUCTIONS

Temperature setpoints (ST1 and ST2)

▸ Press SET and let go. Actual setpoint1 **(St1)** appears flashing.
Led **Out1** will flash indicating **St1**.
▸ Press UP or DOWN to increase or decrease setpoint value.
▸ Press SET to confirm new setpoint and actual setpoint 2 **(St2)** will appear flashing.
Led **Out2** will flash indicating it is **St2**.
▸ Press UP or DOWN to increase or decrease setpoint value.
▸ Press SET to confirm new setpoint and exit.

Setpoints for **St1** can vary between a maximum of **rt4** and a minimum of **rt6** while setpoints for **St2** can vary between a maximum of **rt5** and a minimum of **rt7**. If the setpoint desired is outside this range, change the values of **rt4**, **rt5**, **rt6** and **rt7**. Values are changed in the same manner as the other parameters.

Humidity setpoints (SH1 and SH2)

▸ Press SET H and let go. Actual setpoint 1 **(Sh1)** appears flashing.
Led **Out3** flashes indicating **Sh1**.
▸ Press UP or DOWN to increase or decrease setpoint value.
▸ Press SET H to confirm new setpoint and actual setpoint 2 **(Sh2)** will appear flashing.
Led **Out4** will flash, indicating **Sh2**.
▸ Press UP or DOWN to increase or decrease setpoint value.

Fenwal Uni-Curve Series 10k Thermistor — 192-103LET-A01

Note: These sensors formerly manufactured by Fenwal, now mfr under Honeywell — Sensor Accuracy = +/- 0.2°C

Old Curve Fit: $Temp = -0.101(LnR)^3 + 4.346(LnR)^2 - 77.18(LnR) + 446.05$ (in °C) — Curve fit accuracy over range of -20 to 60°C = +/- 0.12°C

New Curve Fit: $Temp = -0.0937(LnR)^3 + 4.143(LnR)^2 - 75.31(LnR) + 440.385$ (in °C) — Curve fit accuracy over range of -20 to 60°C = +/- 0.03°C

Interactive Temp Calculator Using Straube's Eqn

Rmeas (Ohm)	Vmeas (V)	Vsup (V)	Rsense (Ohm)	Rmeas (Ohm)	Ln(Res)	Temp (°C)
	1.00	2.50	10,000	15,000	9.6158	15.9

Enter Measured Resistance OR Measured Voltage, Voltage Supply and Sense Resistor

Published Fenwal thermistor curve 16 data

can't find this on Honeywell version of Fenwal site, but was on old Fenwal site

Temp	Res	Temp	Res	Temp	Res	Temp	Res	Temp	Res	Temp	Res
-50	670,100	-25	130,630	0	32,613	25	10,000	50	3,605	75	1,482
-49	623,682	-24	123,070	1	30,996	26	9,571	51	3,471	76	1,433
-48	580,809	-23	115,991	2	29,469	27	9,163	52	3,343	77	1,387
-47	541,260	-22	109,358	3	28,026	28	8,774	53	3,220	78	1,342
-46	504,665	-21	103,141	4	26,664	29	8,405	54	3,101	79	1,299
-45	470,830	-20	97,313	5	25,375	30	8,053	55	2,988	80	1,258
-44	439,540	-19	91,839	6	24,157	31	7,718	56	2,880	81	1,218
-43	410,529	-18	86,705	7	23,004	32	7,399	57	2,776	82	1,180
-42	383,656	-17	81,888	8	21,912	33	7,095	58	2,676	83	1,143
-41	358,723	-16	77,355	9	20,879	34	6,806	59	2,580	84	1,107
-40	335,615	-15	73,100	10	19,900	35	6,530	60	2,488	85	1,073
-39	314,145	-14	69,098	11	18,973	36	6,266	61	2,400	86	1,039
-38	294,195	-13	65,337	12	18,094	37	6,014	62	2,316	87	1,007
-37	275,646	-12	61,797	13	17,259	38	5,775	63	2,235	88	977
-36	258,390	-11	58,466	14	16,469	39	5,546	64	2,157	89	947
-35	242,329	-10	55,330	15	15,719	40	5,327	65	2,083	90	918
-34	227,358	-9	52,391	16	15,007	41	5,118	66	2,011	91	890
-33	213,433	-8	49,626	17	14,331	42	4,919	67	1,943	92	864
-32	200,440	-7	47,026	18	13,689	43	4,728	68	1,877	93	838
-31	188,315	-6	44,581	19	13,079	44	4,545	69	1,813	94	813
-30	176,998	-5	42,280	20	12,500	45	4,371	70	1,752	95	789
-29	166,434	-4	40,110	21	11,948	46	4,204	71	1,694	96	766
-28	156,562	-3	38,068	22	11,425	47	4,045	72	1,638	97	743
-27	147,337	-2	36,142	23	10,926	48	3,892	73	1,584	98	721
-26	138,704	-1	34,327	24	10,451	49	3,745	74	1,532	99	700
-25	130,630	0	32,613	25	10,000	50	3,605	75	1,482	100	680

Measured Resistance (Ohms) vs Temperature Readings Using New Curve Fit (2004)

Temp	Res	Temp	Res	Temp	Res	Temp	Res	Temp	Res	Temp	Res
-50	646,555	-25	130,458	0	32,639	25	9,999	50	3,607	75	1,478
-49	604,295	-24	122,902	1	31,017	26	9,572	51	3,473	76	1,429
-48	564,936	-23	115,825	2	29,485	27	9,165	52	3,344	77	1,383
-47	528,276	-22	109,195	3	28,038	28	8,778	53	3,222	78	1,337
-46	494,125	-21	102,981	4	26,670	29	8,409	54	3,103	79	1,294
-45	462,306	-20	97,155	5	25,377	30	8,058	55	2,990	80	1,252
-44	432,658	-19	91,692	6	24,155	31	7,724	56	2,882	81	1,212
-43	405,027	-18	86,567	7	22,998	32	7,406	57	2,777	82	1,173
-42	379,272	-17	81,758	8	21,904	33	7,102	58	2,678	83	1,135
-41	355,261	-16	77,243	9	20,867	34	6,812	59	2,582	84	1,100
-40	332,872	-15	73,004	10	19,887	35	6,536	60	2,491	85	1,065
-39	311,991	-14	69,021	11	18,958	36	6,272	61	2,403	86	1,031
-38	292,512	-13	65,280	12	18,077	37	6,020	62	2,318	87	999
-37	274,338	-12	61,762	13	17,243	38	5,780	63	2,237	88	968
-36	257,376	-11	58,455	14	16,452	39	5,551	64	2,159	89	938
-35	241,544	-10	55,344	15	15,702	40	5,332	65	2,084	90	909
-34	226,761	-9	52,417	16	14,990	41	5,122	66	2,012	91	881
-33	212,955	-8	49,662	17	14,315	42	4,922	67	1,943	92	854
-32	200,058	-7	47,067	18	13,674	43	4,731	68	1,877	93	828
-31	188,007	-6	44,624	19	13,065	44	4,548	69	1,813	94	802
-30	176,743	-5	42,322	20	12,487	45	4,373	70	1,752	95	778
-29	166,211	-4	40,153	21	11,938	46	4,206	71	1,693	96	755
-28	156,363	-3	38,107	22	11,416	47	4,047	72	1,635	97	732
-27	147,150	-2	36,177	23	10,919	48	3,894	73	1,581	98	711
-26	138,528	-1	34,357	24	10,448	49	3,748	74	1,529	99	689
-25	130,458	0	32,639	25	9,999	50	3,607	75	1,478	100	669

Appendix C

WUFI Material Data

Component Assembly

Fibreglass 5.5" + Vapour Barrier

Case 1: Low RH
Case 2: Medium RH
Case 3: High RH

○ - Monitor positions

Materials :

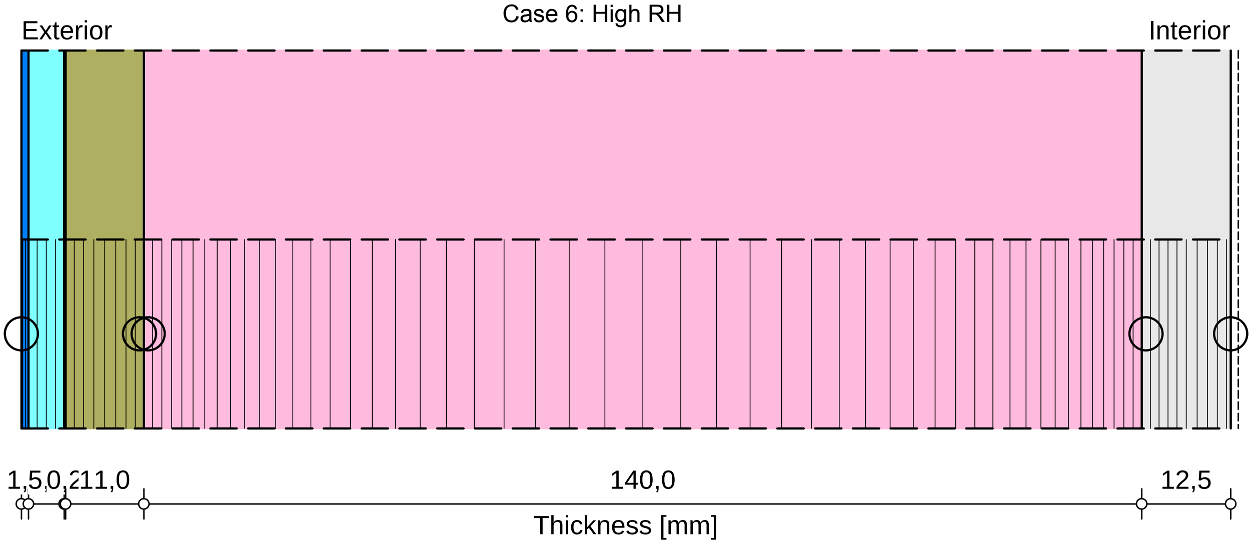
- Vinyl Ventilated
- Air Layer 5 mm
- Spun Bonded Polyolefine Membrane (SBP)
- Oriented Strand Board
- Fibreglass 5.5"
- PE-Membrane (Poly; 0.07 perm)
- Gypsum Board

Sd-Value Int. [m]: 0,6

Component Assembly

Fibreglass 5.5"

Case 4: Low RH
Case 5: Medium RH
Case 6: High RH



◯ - Monitor positions

Materials :

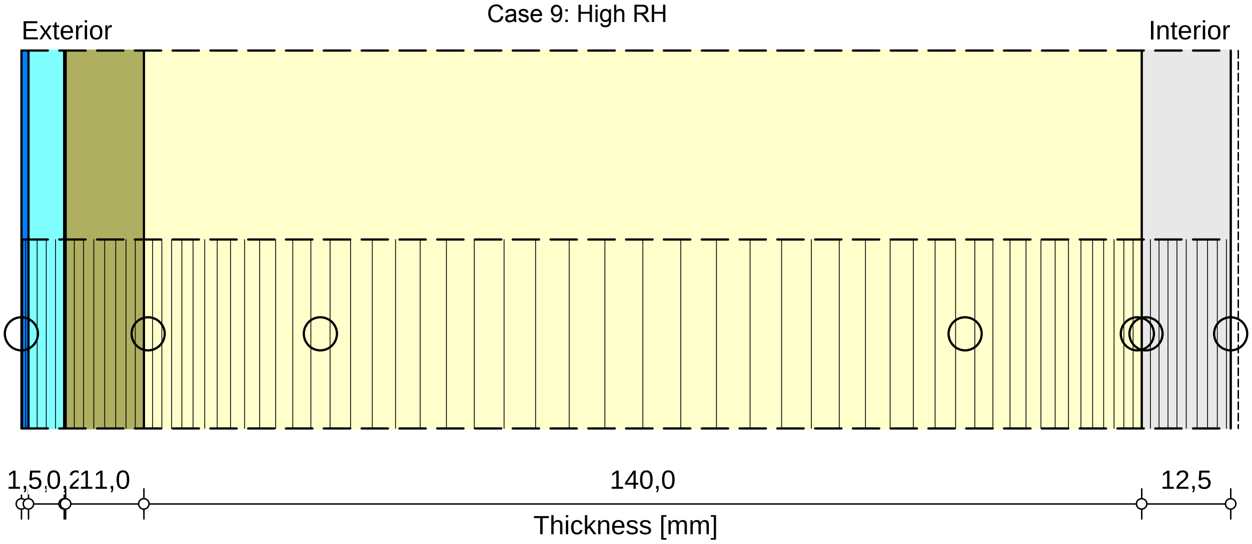
- Vinyl Ventilated
- Air Layer 5 mm
- Spun Bonded Polyolefine Membrane (SBP)
- Oriented Strand Board
- Fibreglass 5.5"
- Gypsum Board

Sd-Value Int. [m]: 0,6

Component Assembly

Open Cell 5.5"

Case 7: Low RH
Case 8: Medium RH
Case 9: High RH



○ - Monitor positions

Materials :

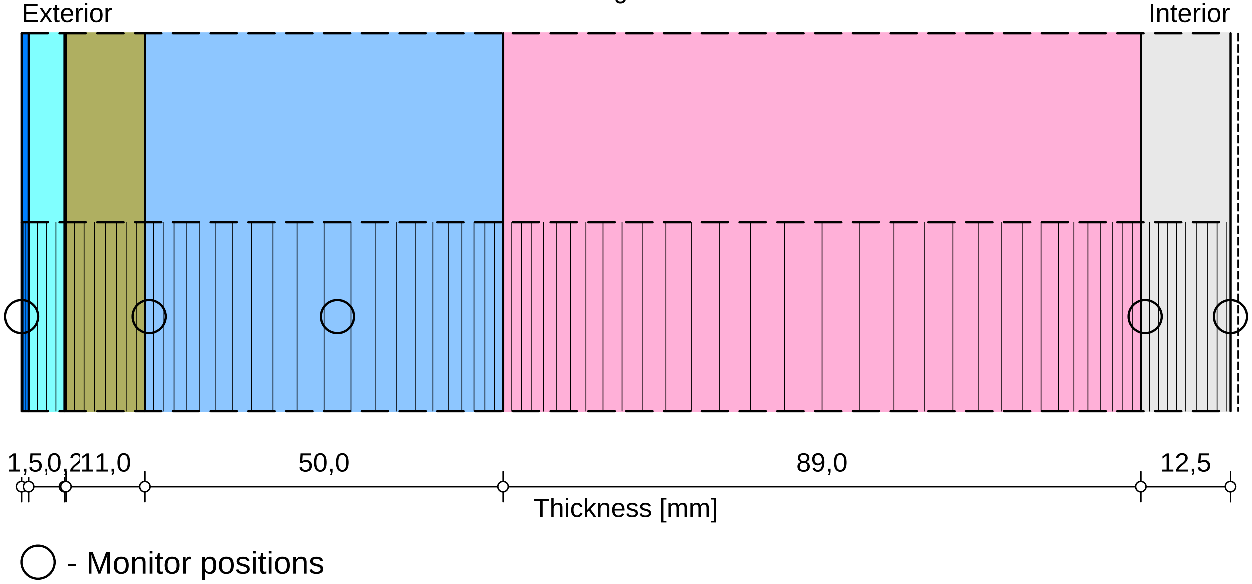
- Vinyl Ventilated
- Air Layer 5 mm
- Spun Bonded Polyolefine Membrane (SBP)
- Oriented Strand Board
- Open Cell 0.5 pcf SPF 5.5"
- Gypsum Board

Sd-Value Int. [m]: 0,6

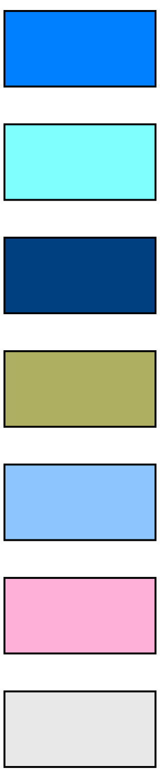
Component Assembly

Closed Cell 2" with remainder as fibreglass batt or air

Case 10: Low RH
Case 11: Medium RH
Case 12: High RH



Materials :



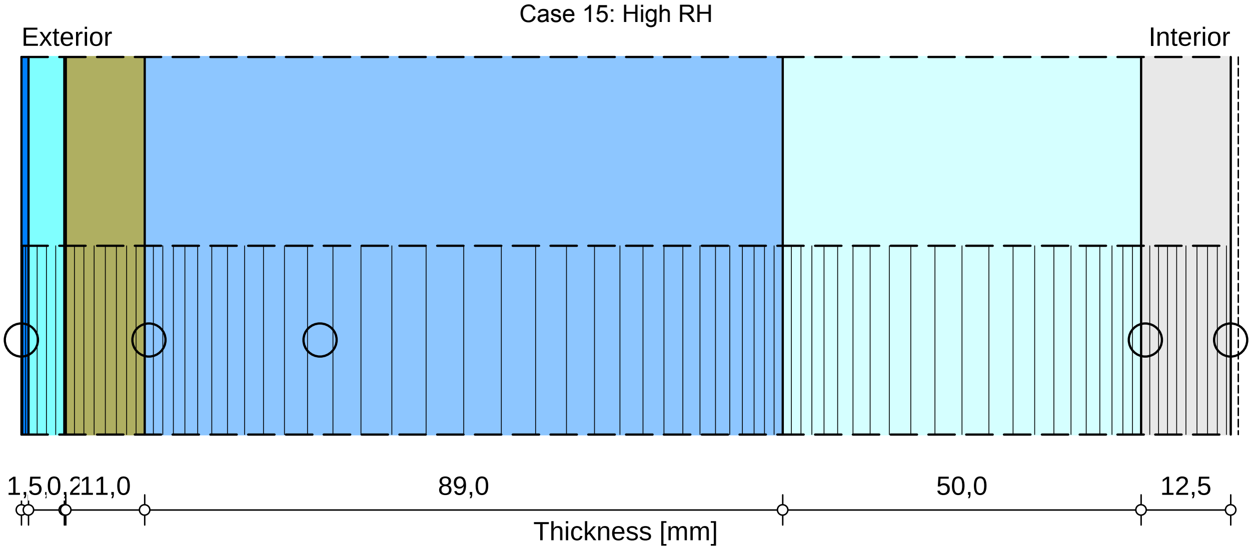
- Vinyl Ventilated
- Air Layer 5 mm
- Spun Bonded Polyolefine Membrane (SBP)
- Oriented Strand Board
- Closed Cell 2pcf SPF 2"
- Fibreglass - R12 (89mm, 3.5 in.)
- Gypsum Board

Sd-Value Int. [m]: 0,6

Component Assembly

Closed Cell 3.5"

Case 13: Low RH
Case 14: Medium RH
Case 15: High RH



○ - Monitor positions

Materials :

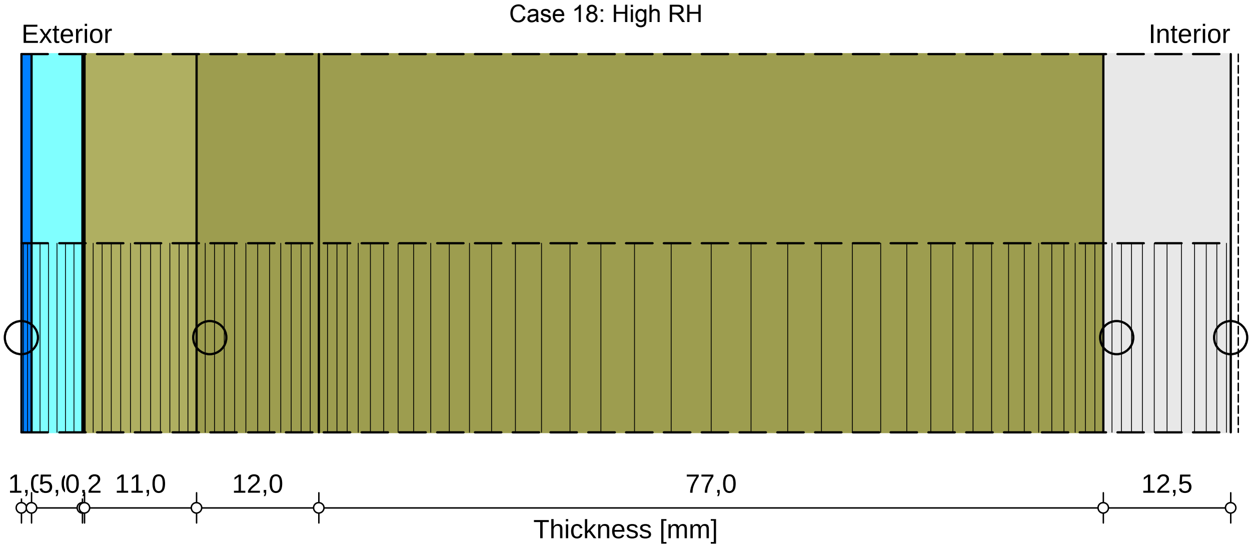
- Vinyl Ventilated
- Air Layer 5 mm
- Spun Bonded Polyolefine Membrane (SBP)
- Oriented Strand Board
- Closed Cell 2pcf SPF 3.5"
- Air Layer 50 mm
- Gypsum Board

Sd-Value Int. [m]: 0,6

Component Assembly

Wood Stud 3.5" (modeled in two sections, inner and outer stud)

Case 16: Low RH
Case 17: Medium Rh
Case 18: High RH



◯ - Monitor positions

Materials :

- Vinyl Ventilated
- Air Layer 5 mm
- Spun Bonded Polyolefine Membrane (SBP)
- Oriented Strand Board
- EW Pine - outer stud
- EW Pine - inner stud
- Gypsum Board

Sd-Value Int. [m]: 0,6

Boundary Condition

Exterior (Left Side)

Location: All locations were cold year except Yellowknife and Inuvik which were user defined climate files. See chapter on computer modeling for details

Orientation / Inclination: North / 90 °

Interior (Right Side)

Indoor Climate: WTA Recommendation 6-2-01/E

User Defined Sine Curve ParameterSee chapter on compter modeling for details

Surface Transfer Coefficients

Exterior (Left Side)

Name	Unit	Value	
Heat Resistance	[m²K/W]	0.0588	Outer Wall
Sd-Value	[m]	----	No coating
Short-Wave Radiation Absorptivity	[-]	.4	
Long-Wave Radiation Emissivity	[-]	.9	
Rain Water Absorption Factor	[-]	0	

Interior (Right Side)

Name	Unit	Value	Description
Heat Resistance	[m²K/W]	0.125	Outer Wall
Sd-Value	[m]	0,6	

Explicit Radiation Balance

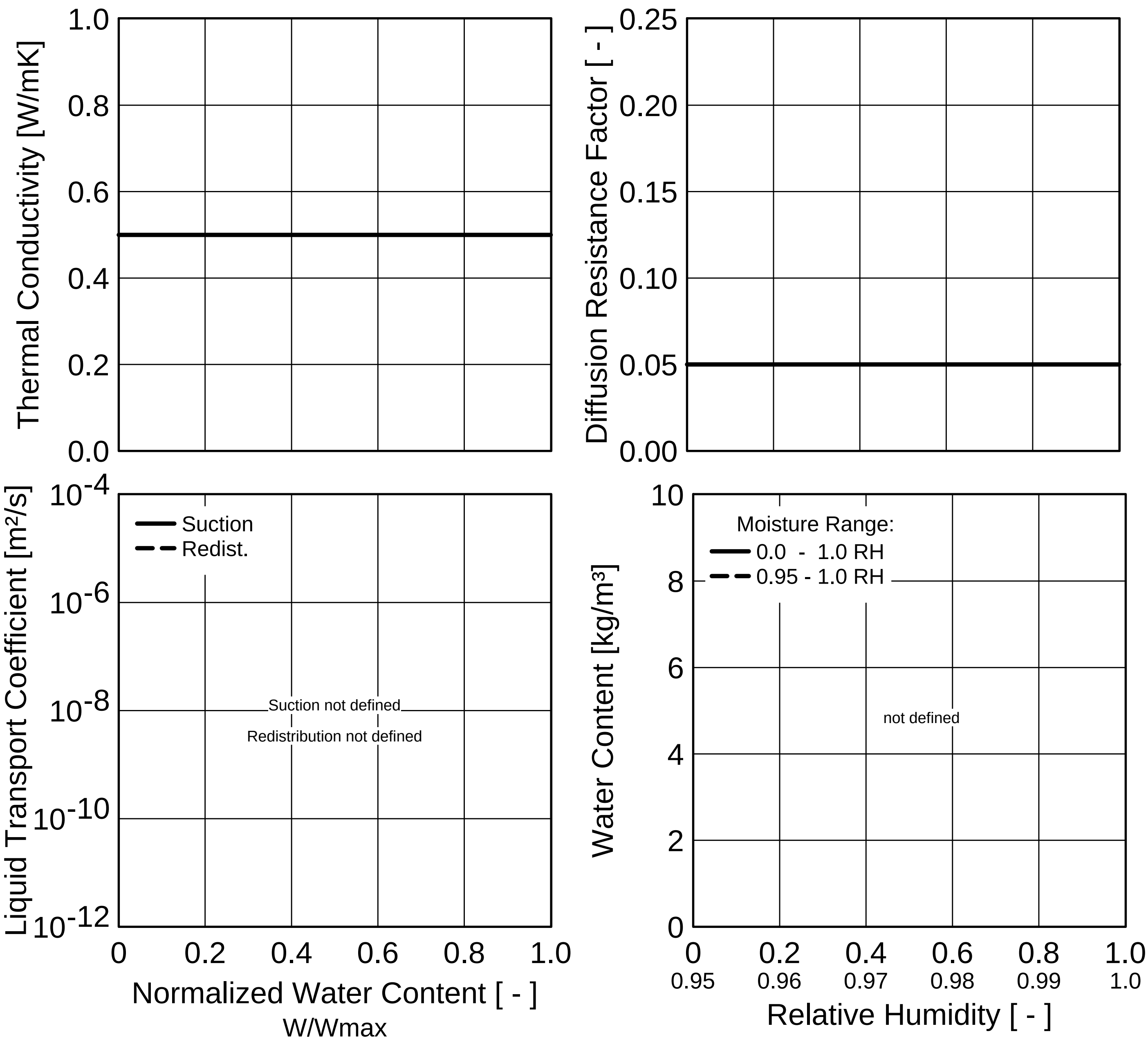
Exterior (Left Side)

Name	Value
Enabled	no

Material : Vinyl Ventilated

Checking Input Data

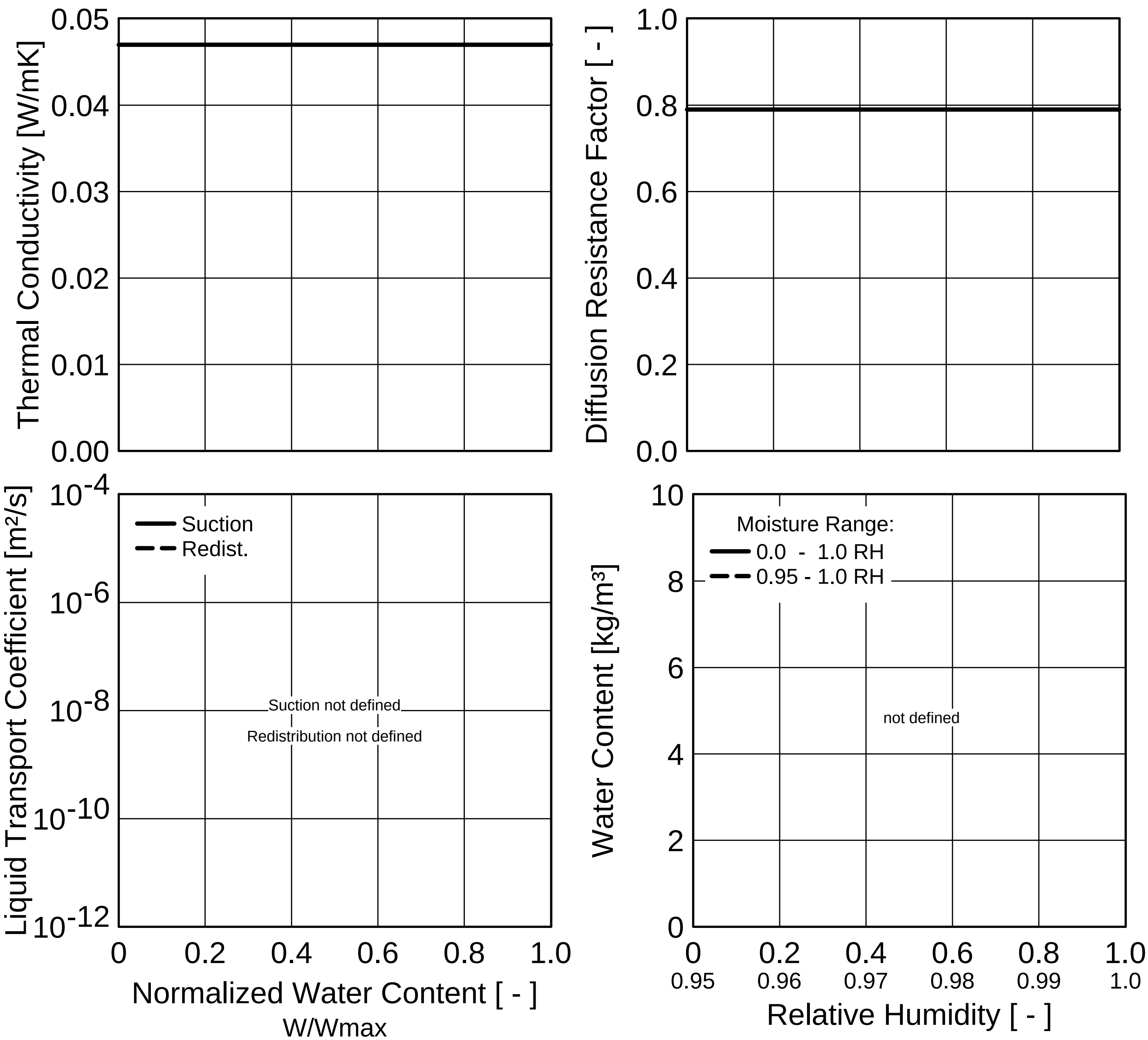
Property	Unit	Value
Bulk density	[kg/m³]	2400,0
Porosity	[m³/m³]	0,001
Specific Heat Capacity, Dry	[J/kgK]	1000,0
Thermal Conductivity, Dry	[W/mK]	0,5
Water Vapour Diffusion Resistance Factor	[-]	0.05



Material : Air Layer 5 mm

Checking Input Data

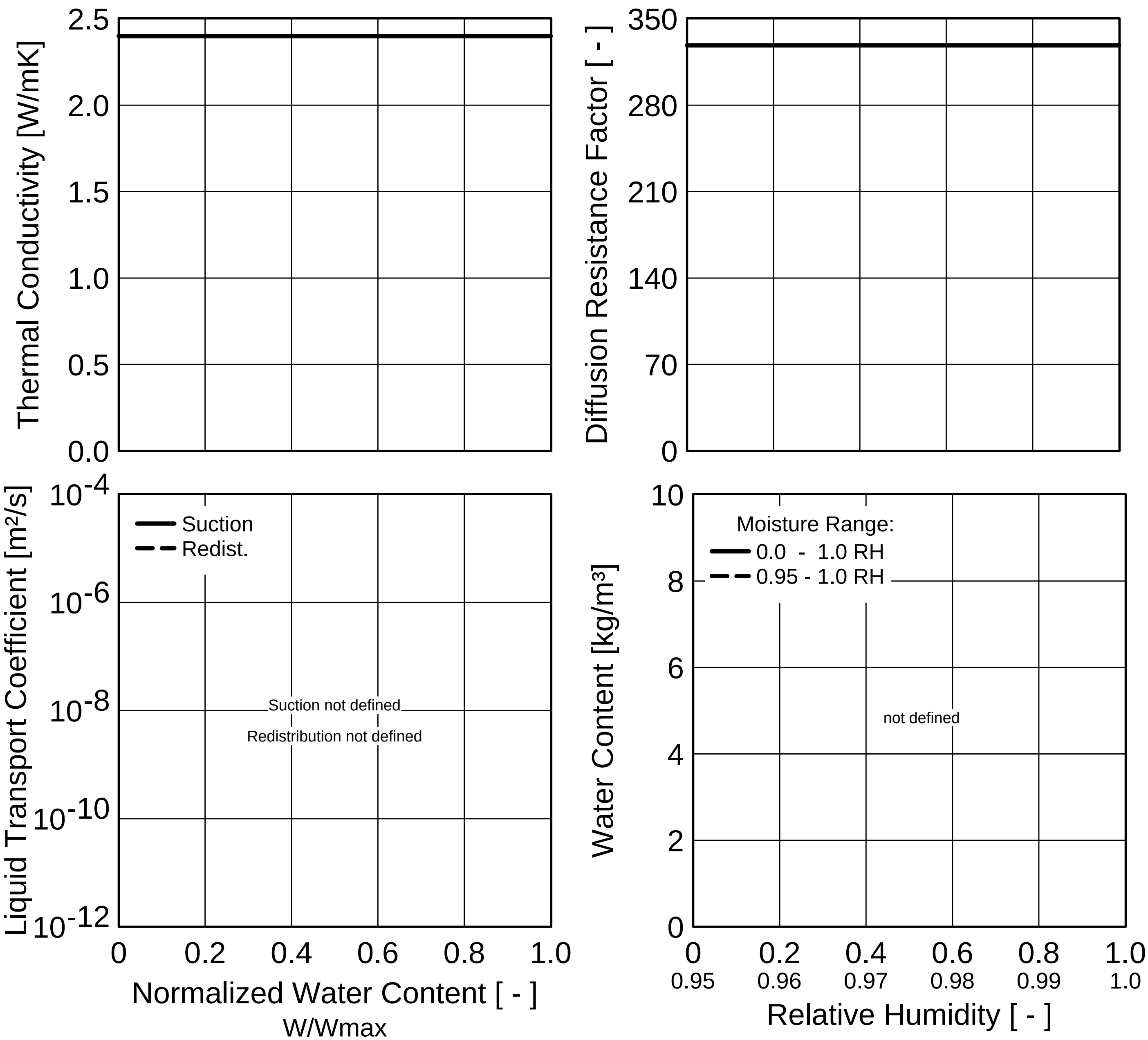
Property	Unit	Value
Bulk density	[kg/m³]	1,3
Porosity	[m³/m³]	0,999
Specific Heat Capacity, Dry	[J/kgK]	1000,0
Thermal Conductivity, Dry	[W/mK]	0,047
Water Vapour Diffusion Resistance Factor	[-]	0,79



Material : Spun Bonded Polyolefine Membrane - Tyvek Housewrap

Checking Input Data

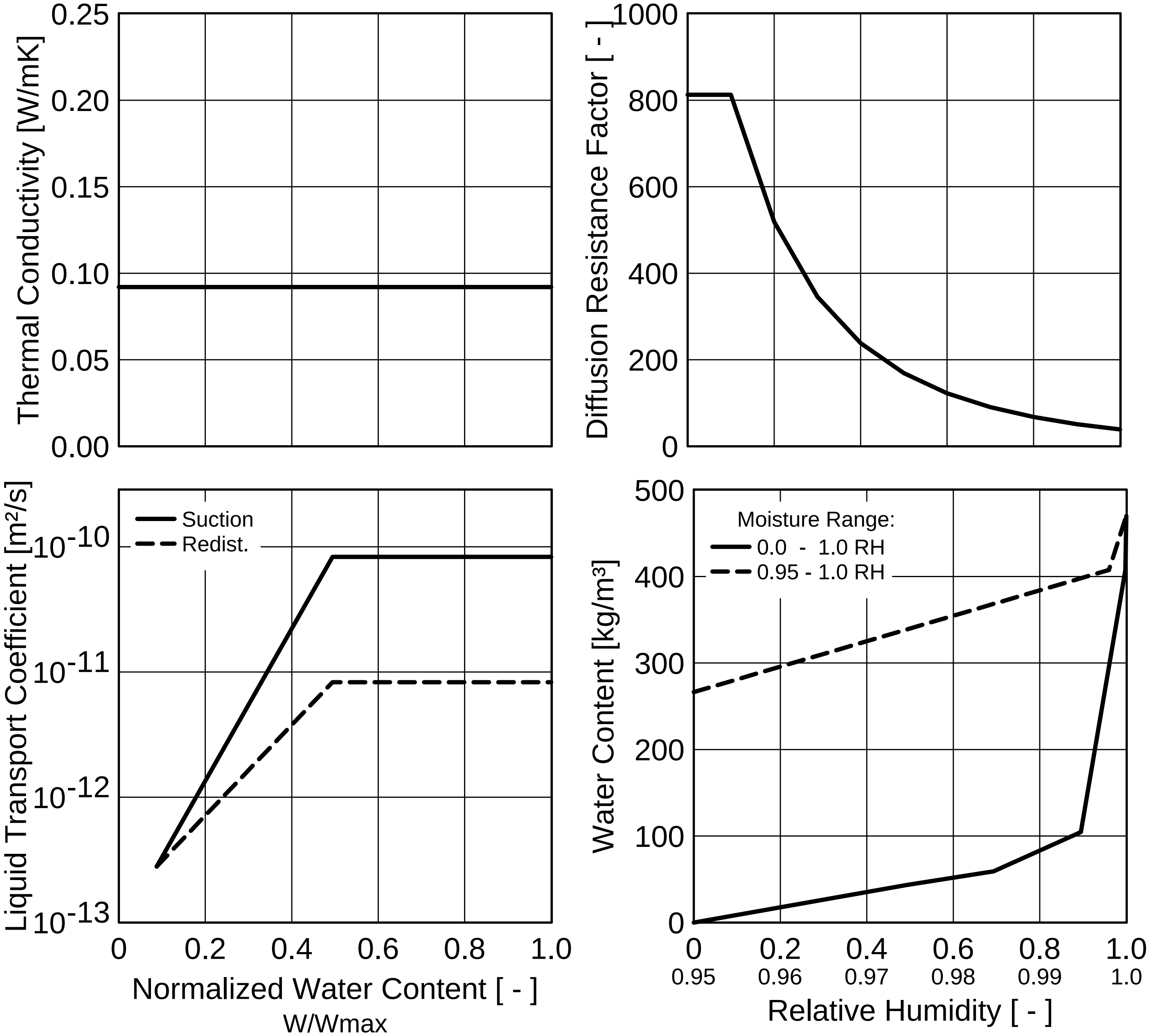
Property	Unit	Value
Bulk density	[kg/m³]	448,0
Porosity	[m³/m³]	0,001
Specific Heat Capacity, Dry	[J/kgK]	1500,0
Thermal Conductivity, Dry	[W/mK]	2,4
Water Vapour Diffusion Resistance Factor	[-]	328,4



Material : Oriented Strand Board

Checking Input Data

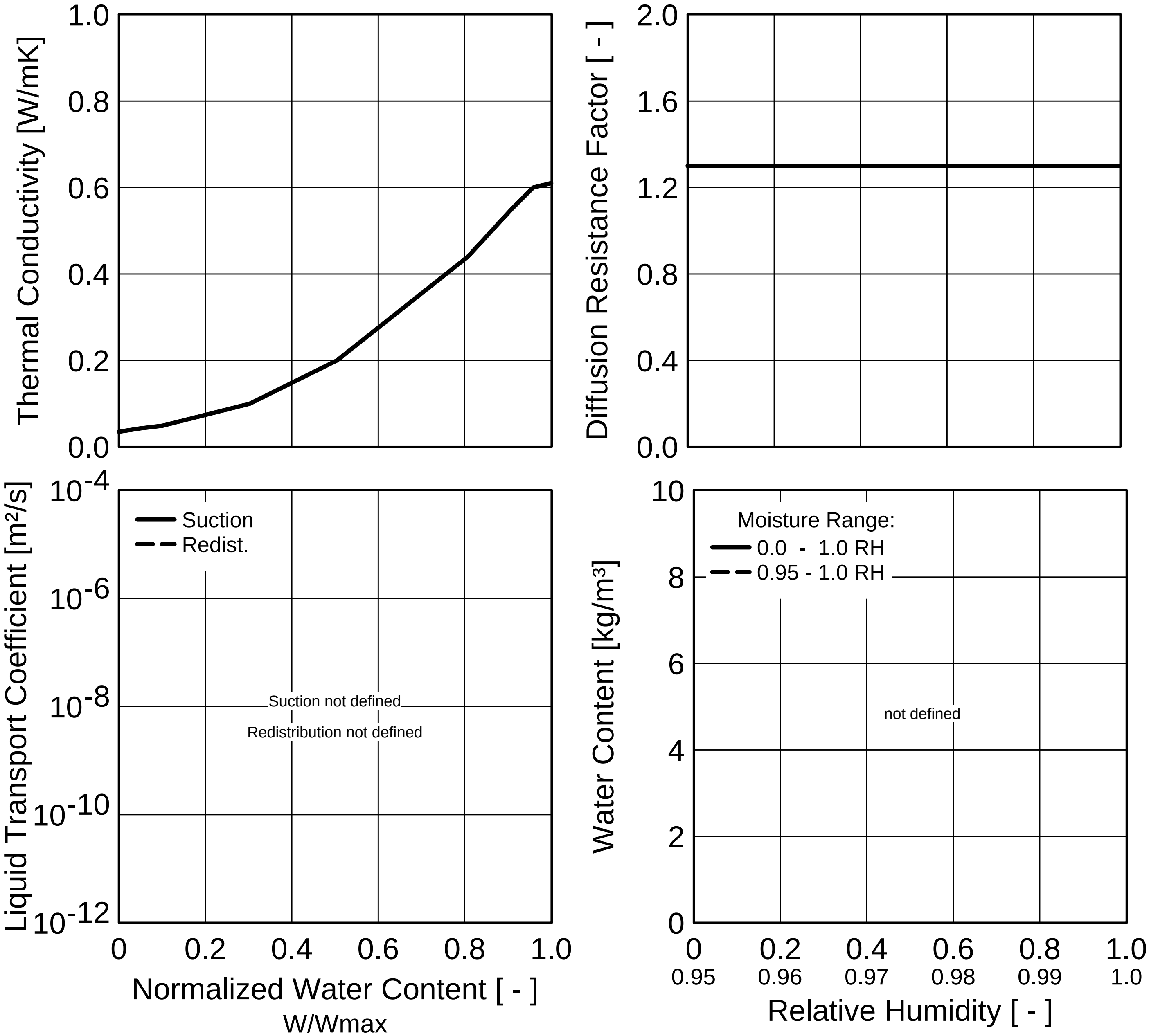
Property	Unit	Value
Bulk density	[kg/m³]	650,0
Porosity	[m³/m³]	0,95
Specific Heat Capacity, Dry	[J/kgK]	1880,0
Thermal Conductivity, Dry	[W/mK]	0,092
Water Vapour Diffusion Resistance Factor	[-]	812,8
Reference Water Content	[kg/m³]	83,3
Free Water Saturation	[kg/m³]	470,0
Water Absorption Coefficient	[kg/m²s^0.5]	0,0022



Material : Fibreglass 5.5"

Checking Input Data

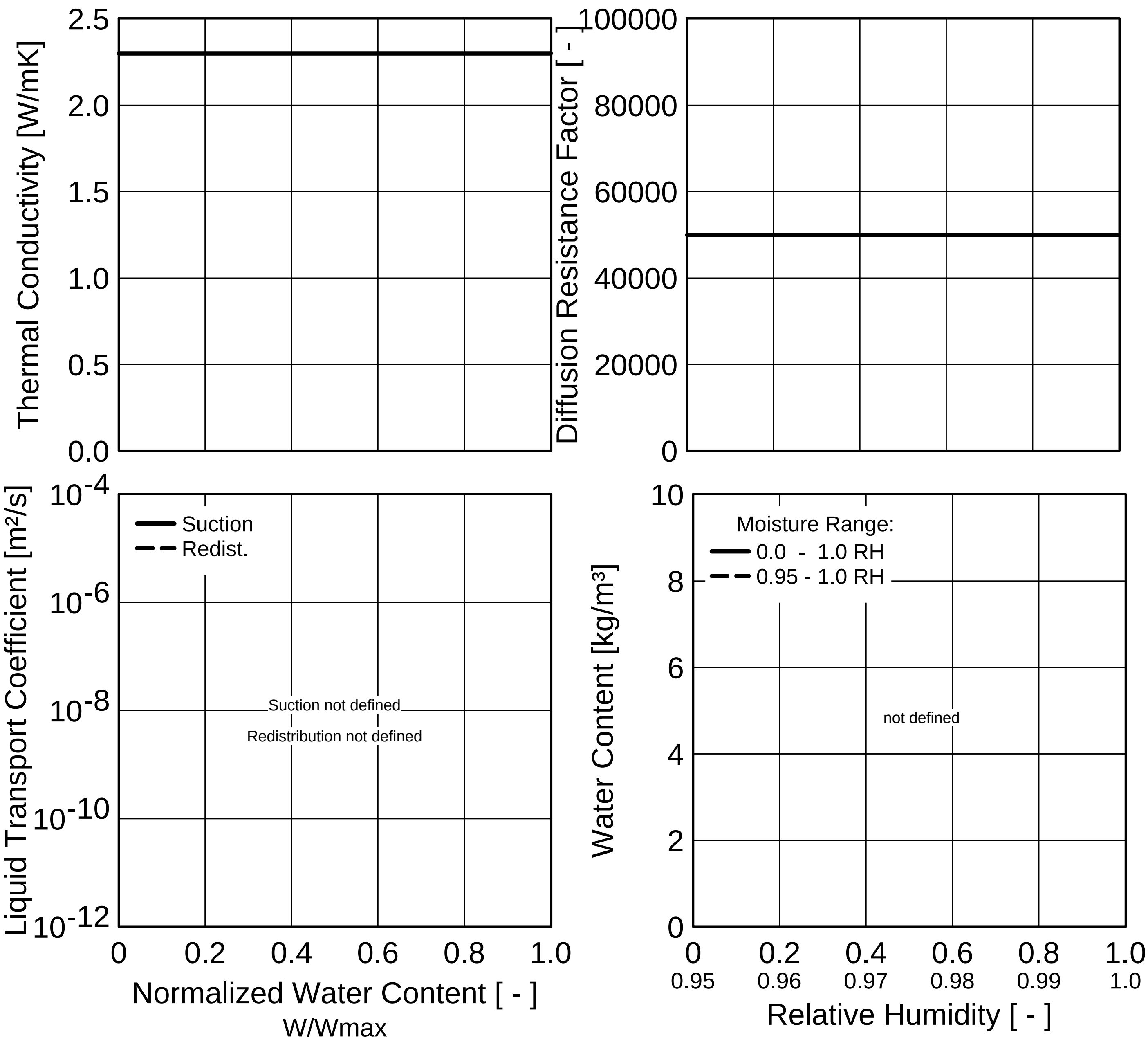
Property	Unit	Value
Bulk density	[kg/m³]	30,0
Porosity	[m³/m³]	0,99
Specific Heat Capacity, Dry	[J/kgK]	840,0
Thermal Conductivity, Dry	[W/mK]	0,035
Water Vapour Diffusion Resistance Factor	[-]	1,3



Material : PE-Membrane (Poly; 0.07 perm)

Checking Input Data

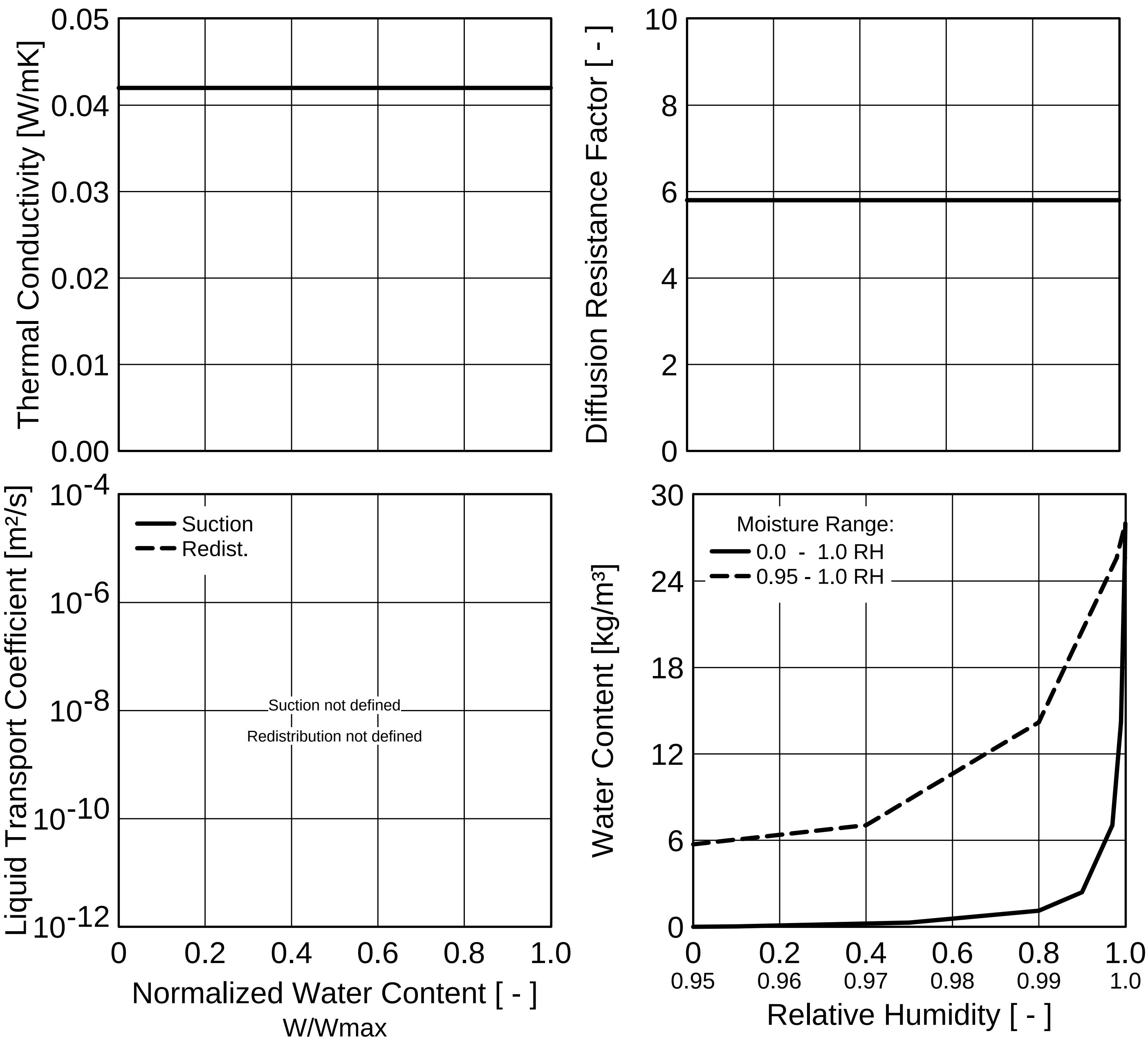
Property	Unit	Value
Bulk density	[kg/m³]	130,0
Porosity	[m³/m³]	0,001
Specific Heat Capacity, Dry	[J/kgK]	2300,0
Thermal Conductivity, Dry	[W/mK]	2,3
Water Vapour Diffusion Resistance Factor	[-]	50000,0



Material : Open Cell 0.5 pcf SPF 5.5"

Checking Input Data

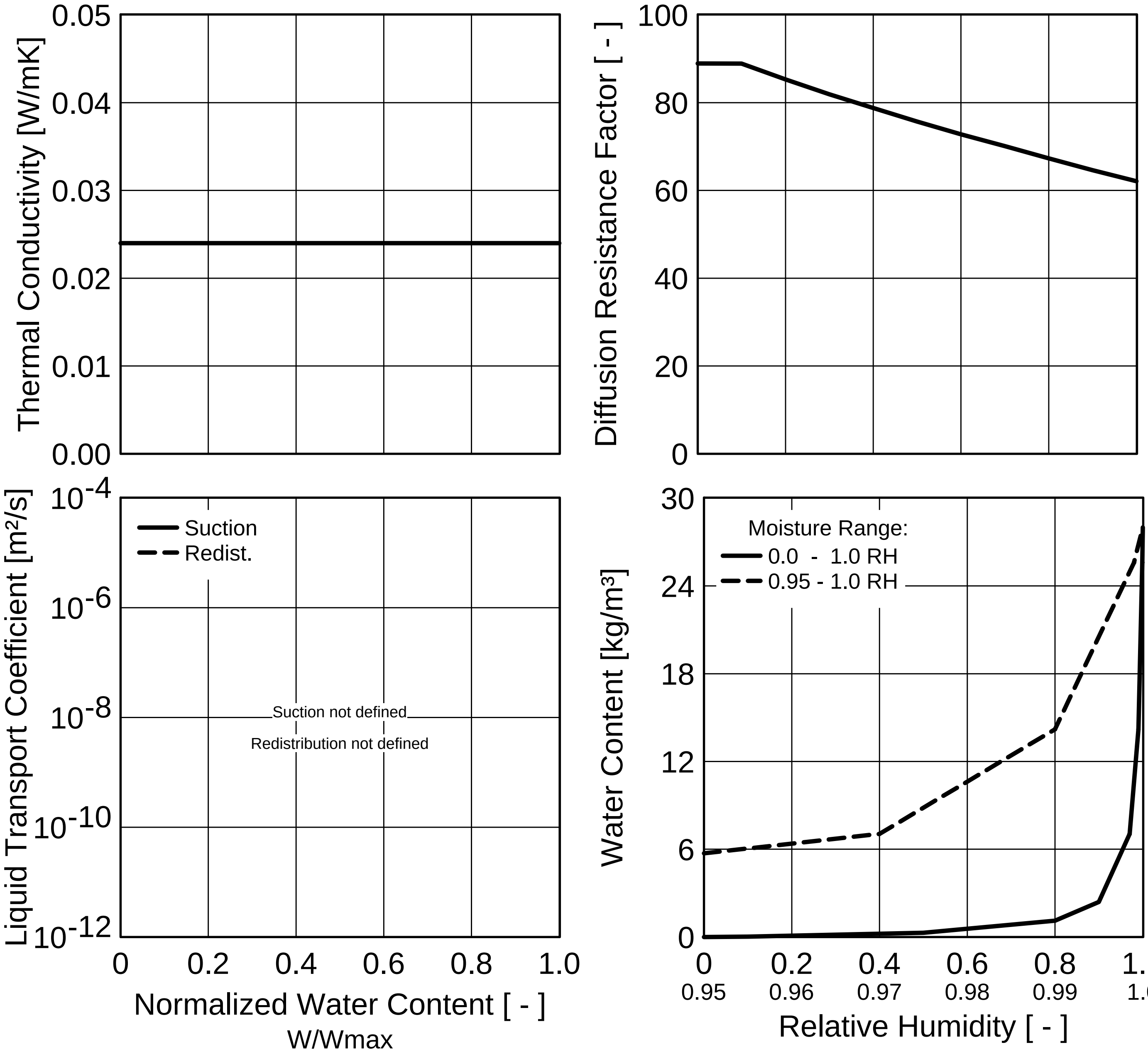
Property	Unit	Value
Bulk density	[kg/m³]	7,5
Porosity	[m³/m³]	0,99
Specific Heat Capacity, Dry	[J/kgK]	1470,0
Thermal Conductivity, Dry	[W/mK]	0,042
Water Vapour Diffusion Resistance Factor	[-]	5,8



Material : Closed Cell 2pcf SPF 2"

Checking Input Data

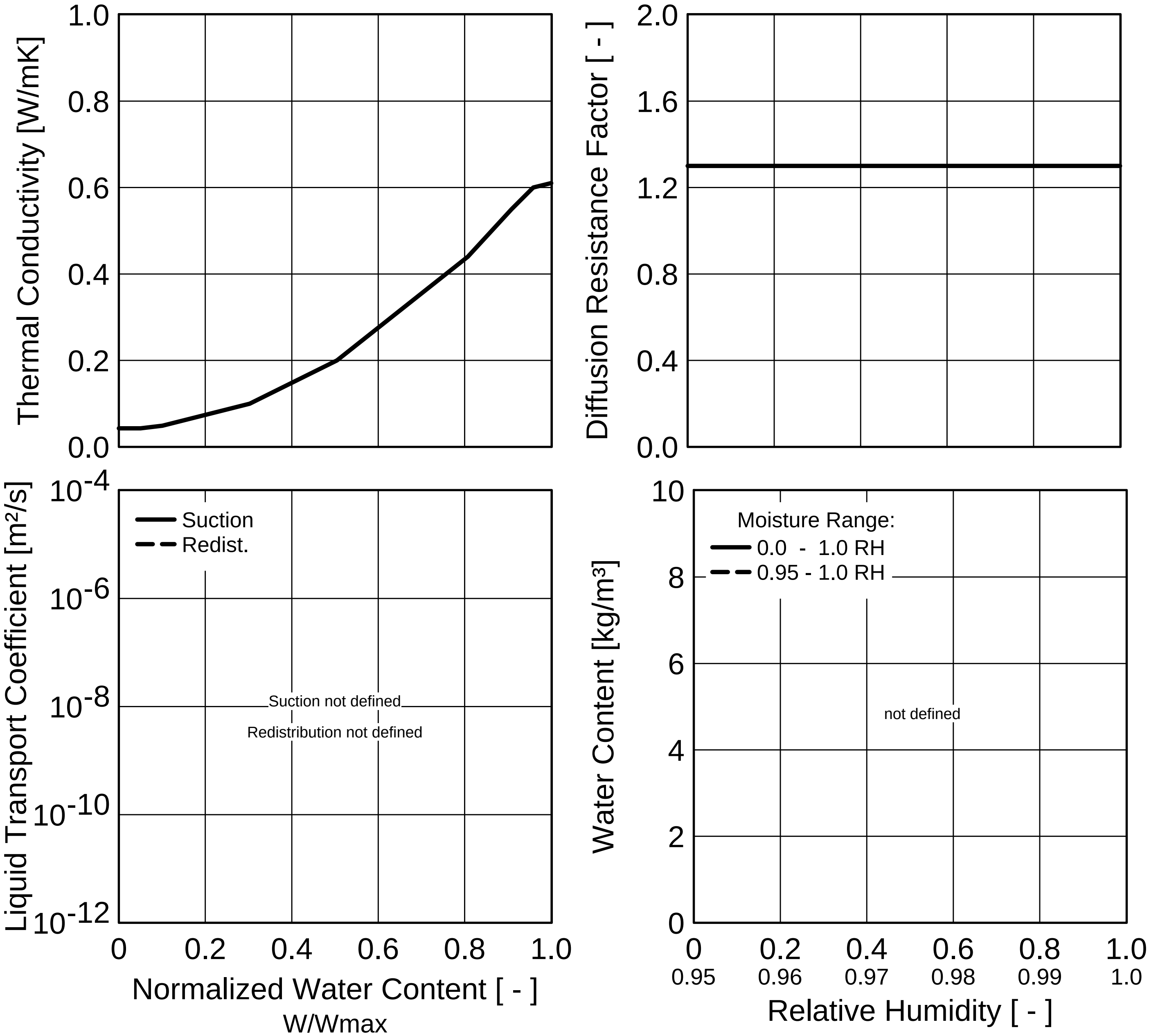
Property	Unit	Value
Bulk density	[kg/m³]	39,0
Porosity	[m³/m³]	0,99
Specific Heat Capacity, Dry	[J/kgK]	1470,0
Thermal Conductivity, Dry	[W/mK]	0,024
Water Vapour Diffusion Resistance Factor	[-]	88,93



Material : Fibreglass - R12 (89mm, 3.5 in.)

Checking Input Data

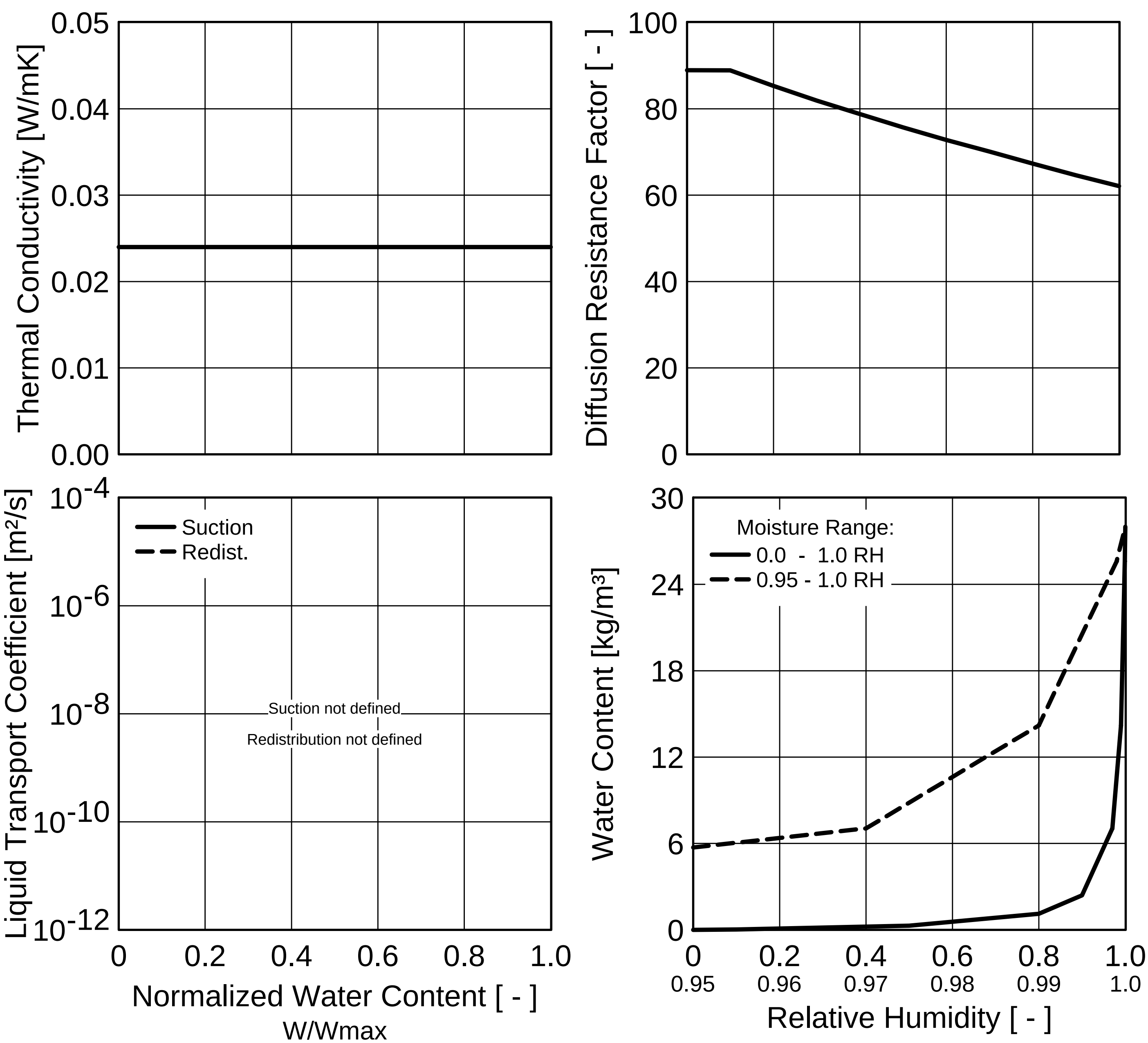
Property	Unit	Value
Bulk density	[kg/m³]	30,0
Porosity	[m³/m³]	0,99
Specific Heat Capacity, Dry	[J/kgK]	840,0
Thermal Conductivity, Dry	[W/mK]	0,043
Water Vapour Diffusion Resistance Factor	[-]	1,3



Material : Closed Cell 2pcf SPF 3.5"

Checking Input Data

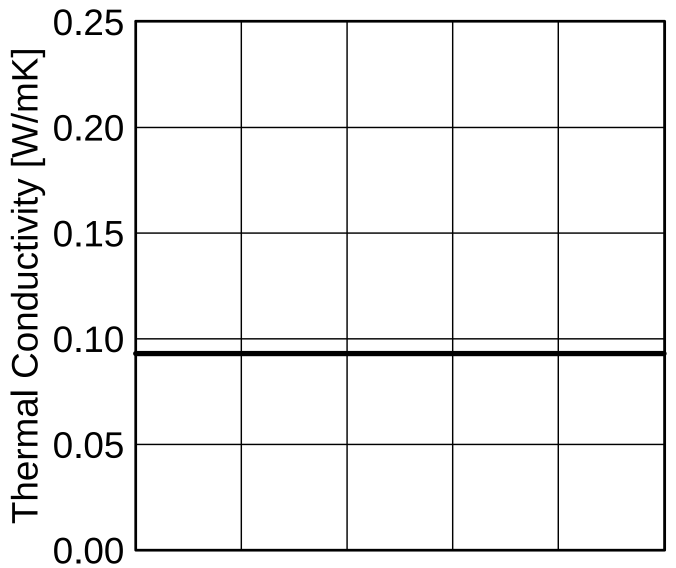
Property	Unit	Value
Bulk density	[kg/m³]	39,0
Porosity	[m³/m³]	0,99
Specific Heat Capacity, Dry	[J/kgK]	1470,0
Thermal Conductivity, Dry	[W/mK]	0,024
Water Vapour Diffusion Resistance Factor	[-]	88,93

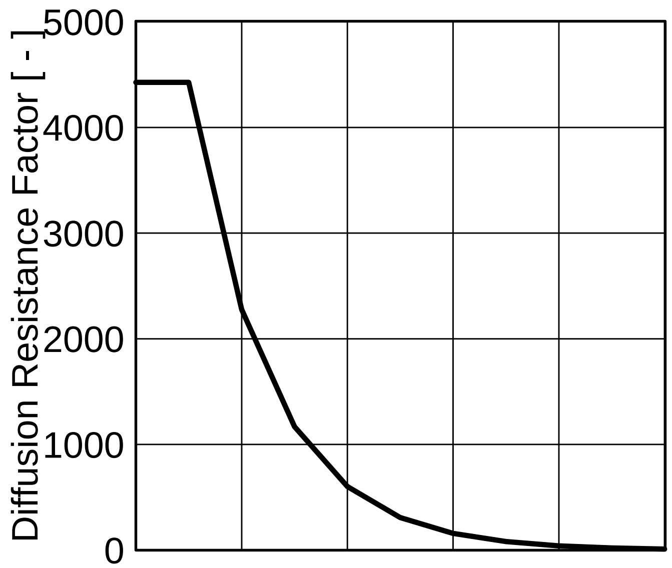


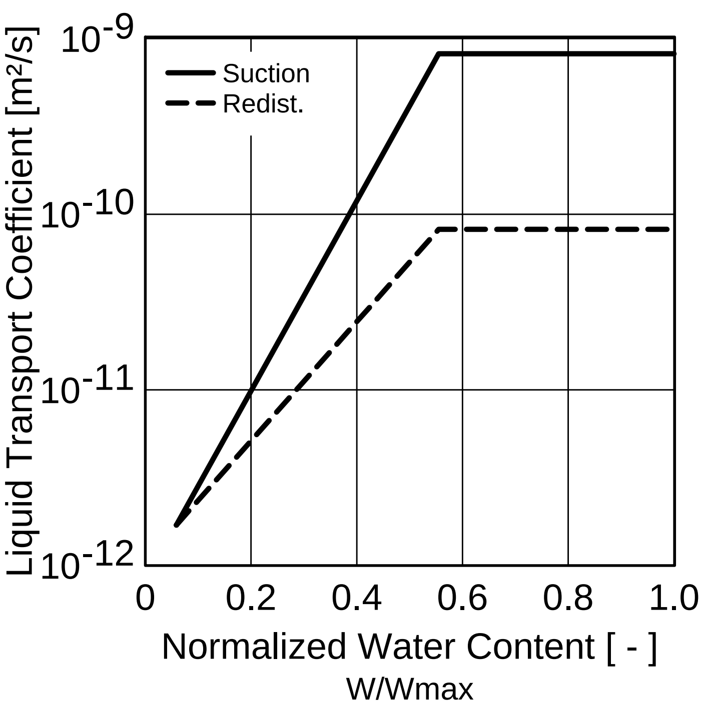
Material : EW Pine - (Eastern white pine)

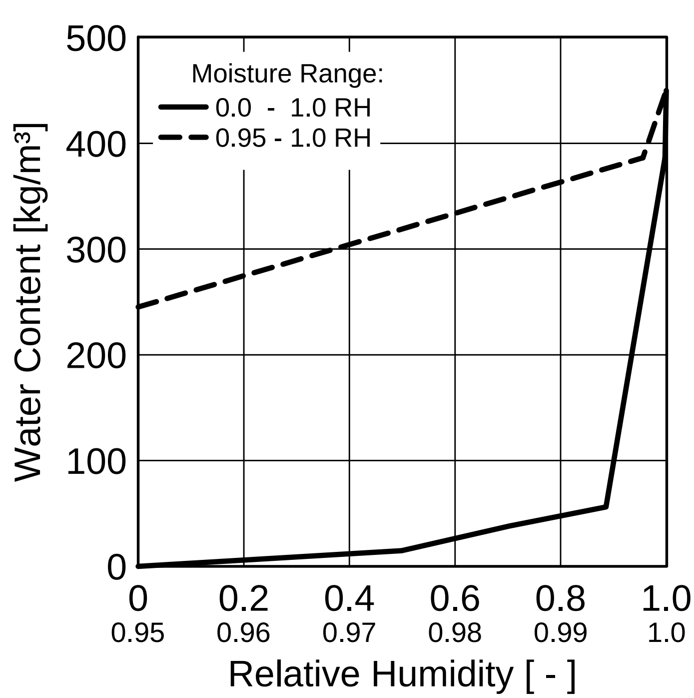
Checking Input Data

Property	Unit	Value
Bulk density	[kg/m³]	460,0
Porosity	[m³/m³]	0,81
Specific Heat Capacity, Dry	[J/kgK]	1880,0
Thermal Conductivity, Dry	[W/mK]	0,093
Water Vapour Diffusion Resistance Factor	[-]	4427,4
Reference Water Content	[kg/m³]	47,7
Free Water Saturation	[kg/m³]	450,0
Water Absorption Coefficient	[kg/m²s^0.5]	0,0066









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Material : Gypsum Board

Checking Input Data

Property	Unit	Value
Bulk density	[kg/m³]	850,0
Porosity	[m³/m³]	0,65
Specific Heat Capacity, Dry	[J/kgK]	850,0
Thermal Conductivity, Dry	[W/mK]	0,2
Water Vapour Diffusion Resistance Factor	[-]	8,3
Moisture-dep. Thermal Cond. Supplement	[%/M.-%]	8,0