A Method for the Assessment of Moisture Conditions of Painted Wood Siding in Historic Wood Frame Buildings

by

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Abstract

There are many wood frame buildings in the Ottawa area with painted wood siding. As vinyl is a popular replacement, most historic buildings continue to use wood due to its heritage value. Painting the wood siding protects the underlying material from degradation from the surrounding exterior environment.

For painted wood siding, periods of high moisture content can lead to premature decay of the wood or cause paint to blister. The role of the paint layer and its importance in protecting wood siding from moisture is the focus in this research. The permeability of the paint layer to vapour and liquid moisture sources is analyzed using WUFI Pro based on the Sd-value and Aw coefficient. Interior and exterior sources of moisture were found to impact the exterior siding. For Ottawa's climate, an exterior paint layer that is permeable ($Sd<=0.5m$) and with a lower Aw coefficient ($<=0.0003\ kg/m^2h^{0.5}$) is recommended.

Acknowledgements

This thesis would not have been possible without the help and support received over these past two years, in particular when considering the virtual nature of the second half of this degree.

I would like to especially thank my supervisors, Professor Mario Santana and Professor Austin Parsons, for guiding me through this research work. It was a pleasure to work with both of them.

I am appreciative to have had the opportunity to be a part of the NSERC CREATE Heritage Engineering Program during my Master's program. A special thanks to the Program Coordinator Laurie Smith for her tremendous support throughout the program; organizing internships, workshops and forums that have helped to inspire the work of this thesis. I would also like to thank Michael Gutland for sharing his knowledge on hygrothermal simulations that was instrumental in getting me started in this research area.

The concept for this thesis is inspired from my internship with Parks Canada's *Built Heritage Section* in the summer of 2020 on linseed oil paint systems. Through the guidance from David Scarlett, Golnaz Karimi, Kym Terry and working alongside Jack Hollinger, as their experience provided greater insight into the science of paints within the context of heritage conservation.

I would also like to thank my family – my parents Marcel, Elaine, my two siblings Danielle and Matthieu, and my partner Andrew for their support and reassurance. A special thanks to my dad for his support with the editing process, and my partner Andrew for assisted in working through various technical aspects.

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A – area

A_w – water absorption coefficient

D_w – capillary transport coefficient

D_φ – liquid conduction coefficient

g_v – vapour diffusion flux density

g_w – liquid flux density

G – weight change

K_n – Knudsen factor

K_1 – permeability coefficient

K_2 – capillary coefficient

L – mean free path

P – water vapour partial pressure

P_s – capillary suction stress

P_L – ambient air pressure

r – pore radius

t – time

Sd – diffusion equivalent air layer thickness

T – temperature

w – moisture content

w_{cap} – capillary saturation moisture content

WVT – water vapour transport

Δx – thickness

$\delta -$ water vapour permeability of medium

δ_{air} – water vapour permeability of air

φ – relative humidity

μ – water vapour diffusion resistance factor

List of Abbreviations

ACH – air changes per hour

CDE – character defining elements

EMC – equivalent moisture content

FSP – fiber saturation point

HCD – heritage conservation district

ICOMOS – international council on monuments and sites

MC – moisture content

NHS – national historic site

RH – relative humidity

VOC – volatile organic compound

Chapter 1: Introduction

1.1 Overview

For many years, wood siding has commonly been used for cladding in wood frame buildings in Canada and throughout many parts of the world. In addition to being an aesthetic feature, the siding is the first line of defense for the building envelope components, protecting materials from degradation from the exterior environment (rain, sun, wind). Often wood siding is also painted, which provides an attractive finish for the building and protects the wood from UV and moisture. Depending on the paint's permeability to liquid and water vapour, the paint layer provides varying levels of protection from moisture. The concept of having a 'breathable' paint, meaning that water vapour can pass through the paint film, has been frequently suggested (in particular for those cases where an insulation retrofit may negatively affect the drying potential of the assembly).

Many studies have observed the sheathing component of wood frame buildings for moisture accumulation and damage (Boardman & Glass, 2020; Finch & Straube, 2007); rarely is the analysis of the wood siding for these buildings prioritized. Therefore, more detailed analysis is needed to understand which moisture sources impact the siding, in particular when it is painted. This research will focus on the wood siding component of a typical pre-1950's wood frame building in Ottawa and analyse the moisture sources as it relates to the paint layer's permeability to its moisture conditions. Using WUFI Pro, a hygrothermal software, this research aims to identify how the permeability properties of different paint systems impact the moisture content of wood siding, and how the moisture content may impact the maintenance cycle. The permeability properties of the paint will be represented in the software using the equivalent diffusion air layer thickness (Sd-value) and the water vapour diffusion resistance factor (μ-value) to represent vapour permeability, and the liquid conduction coefficient (Aw) to represent liquid permeability.

As an introduction to this thesis, an overview of the heritage and environmental perspectives of painted wood siding will be given to help provide context to this research, followed by the motivation, objectives, and outline of this work.

1.2 Background

Heritage Perspective

Historically, the Ottawa Valley has been a vibrant area for the lumber industry, as a result there are many historic and old traditional buildings that are currently, or have been, clad in wood siding. Old buildings, typically defined as pre-1950's, may have certain heritage values and designation in which the character defining elements (CDE's) must be conserved. Not all old buildings have a heritage designation, but due to the time when they were built, certain construction methods were used. Wood frame buildings constructed prior to the 1950's did not contain typical barrier layers as is seen in constructions today, such as an airtight air barrier (some may have contained building paper), a vapour barrier, or thermal insulation (some forms of insulation in the form of straw, wool, sawdust, seaweed, cellulose, etc. may have been used). It was not until 1950 that the National Building Code of Canada made it standard to include certain water vapour resistive properties for the weather resistive barrier (sheathing) and vapour barrier

(Bomberg & Onysko, 2002). In cold climates, the vapour barrier is found on the inside of the wall assembly to impede the flow of water vapour through the wall, lessening the chance for interstitial condensation to occur. Therefore, depending on the climate, it is important to understand the impact of both the permeability of materials and their location within the assembly to avoid damages due to moisture.

The choice in material for exterior siding is evolving away from wood siding and towards more “maintenance free” products such as vinyl or metal. Wood, being an organic material is prone to degradation from UV and moisture, with wood rot being a result of prolonged moisture accumulation. Although the degradation of wood siding is not a structural issue, if unaddressed over time it can allow for further moisture issues and provide for an unattractive façade. Other non-rot moisture issues can be of concern as well, such as higher moisture content within the siding that can impact the adhesion of the paint film resulting in moisture blisters or peeling (Brunt, 1964). Today, a common option for the repair of deteriorating wood siding in buildings is to replace it entirely with an alternative such as vinyl siding which does not rot.

For heritage buildings, the option of using vinyl siding is typically in contravention to the recommendations from heritage organizations, which provide guidelines to conserve any character defining elements of the buildings. Table 1.1 shows various recommendations from International Council on Monuments and Sites (ICOMOS) Wood Committee and Parks Canada that are related to wood and coatings. Based on Principle 12 from ICOMOS, the existing wood siding should be retained, as much as possible, and to make sure only minimal intervention is done to ensure the survival of the construction. Although, if replacements need to be made, Principle 14 recommends replacing portions of the wood siding with 'like' materials, in which materials such as vinyl siding would not be appropriate. Principle 18 gives mention to surface finishes, if it is necessary to renew or replace them, compatible materials and techniques should be used, therefore an understanding of what is compatible is required.

Parks Canada provides similar guidelines towards protecting wood, using the process of understanding, planning and intervention in their approach. Prior to any intervention of coatings and finishes, an understanding of the chemical make-up, condition and compatibility should be assessed. Coatings should only be removed if they are no longer protecting the wood (primarily due to moisture, UV and wear), are damaged or thickly applied. Any new coating that is to be applied should be both physically and visually compatible with the surface.

Table 1.1. Recommendations and Principles for the intervention of heritage buildings with wood and paints/ finishes(ICOMOS International Wood Committee, 2017; Parks Canada, 2003)

	Recommendation/ Guideline
ICOMOS: Principles for the Conservation of Wooden Built Heritage	**12.** … minimal intervention capable of ensuring the survival of the construction …
	14. Any replacement timber should preferably: a. be of the **same species** as the original; b. match the **original in moisture content**; c. have **similar characteristics of grain** where it will be visible; d. be worked using **similar craft methods and tools** as the original.
	18. … the historic structure should be considered as a whole. … Conservation should also include surface finishes such as plaster, paint, coating, wallpaper, etc. … If it is considered strictly necessary to **renew or replace deteriorated surface finishes, the use of compatible materials and techniques** is desirable.

	26. The use of chemical preservatives should be carefully controlled and monitored
Parks Canada Standards and Guidelines	**1. Understanding** the properties and characteristics of wood and its finishes or coatings, such as its species, grade, strength and finish, or the chemical make-up of its coating.
	5. Inspecting coatings to determine their condition and appropriateness, in terms of physical and visual compatibility with the material, assembly, or system
	6. Retaining coatings that help **protect the wood from moisture**, ultraviolet light and wear. Removal should be considered only as part of an overall maintenance program that involves **reapplying the protective coatings in kind**.
	7. Removing damaged, deteriorated, or thickly applied coatings to the next sound layer, using the safest and gentlest method possible, then recoating in kind.
	8. Using the gentlest means possible to remove paint or varnish when it is too deteriorated to recoat, or so thickly applied that it obscures details.
	9. Applying compatible coatings following proper surface preparation, such as cleaning with tri-sodium phosphate.
	10. Ensuring that new coatings are **physically and visually compatible** with the surface to which they are applied in durability, chemical composition, colour, and texture.

Figure 1.1 shows the results from a brief visual survey done via Google Street view in New Edinburgh, a Heritage Conservation District (HCD) within the City of Ottawa. It documents the number of houses with painted/ coloured siding. New Edinburgh was chosen as a sample area within the Ottawa region due to its historic values along with its mix of residential construction types found. In the New Edinburgh Heritage Conservation District Plan, the houses are classified as either Contributing or Non-Contributing to the special character of the HCD (City of Ottawa, 2017). Figure 1.2 shows the buildings surveyed. The siding was distinguished between whether it was wood cladding or an alternative such as vinyl. Since the inspection was done from online images it was at times difficult to identify whether it was wood or vinyl with wood texturing, therefore many buildings were put into a ‘maybe’ category.

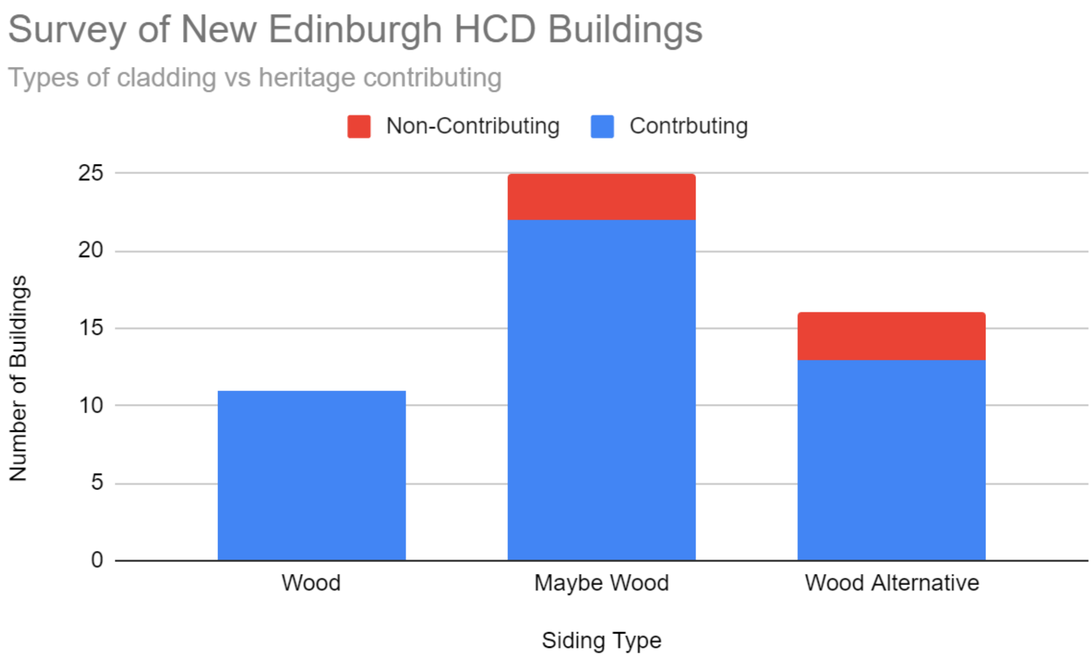


Figure 1.1 Graph showing the distribution of siding material and whether the building heritage contribution

The survey shows that even buildings that were classified as contributing to the character of the neighborhood had undergone changes to the siding, showing the popularity in change from wood to a non-wood material. Although, five of the buildings had other heritage designations (highlighted in Figure 1.2), all of which have wood siding. Theses heritage designations most likely had a role in conserving the use of wood rather than replacing with a new material. Many of the buildings that are depicted in the Figure were either wood siding or vinyl with wood texturing. This shows that most homeowners valued the look of a traditional wood cladding but preferred the lower maintenance of vinyl for siding.

Figure 1.2. Images from Google Street view of houses surveyed in New Edinburgh, with the five heritage designated buildings highlighted in red (Google Maps, 2021)

Another observation from the survey was the frequency in which residential buildings are painted. Google Maps provides street view images from 2007-2020. During this 13-year period, the entire exterior of homes ranged from being repainted 1-3 times. Rather than re-painting based on whether the paint is damaged or deteriorating, occupants may repaint their homes solely for aesthetic purposes. In contrast, for heritage buildings, such as those on National Historic Sites (NHS) that are managed by Parks Canada or other private entities/ levels of government, the maintenance of exterior paint over the life cycle of a building can be costly. That is why a process of understanding and planning is important to ensure the intervention with any new paint is compatible. The term preventative maintenance implies the routine of regular maintenance to prolong service life. Preventative maintenance can be applied to exterior paints, in which paints are maintained through any touch ups that are needed to make sure the paint continues to provide protection to the substrate, as well as to ensure that the paint layer itself has a uniform appearance.

Environmental Perspective

Heritage conservation principles often go in hand with principles of sustainability. For example, from a whole building perspective, conserving buildings ensure that the future generations experience historic buildings and heritage landscapes. If just the wood siding is considered, the environmental impact of the material should be considered. By conserving a piece of wood siding, not only is the heritage material being prolonged for future generations, but if the material is well maintained it can continue to be used, deferring the need for its replacement. Understanding how the paint layer impacts the siding's moisture conditions, whether it be positive or negative, will give insights on how to best protect the material for longer service life.

As mentioned earlier, moisture is the greatest factor for the deterioration of buildings. As the climate continues to change, extreme weather will become more frequent, which will require a more detailed understanding of buildings that need to adapt. For example, how might increased rain fall or changes in humidity of the climate impact the way buildings are designed for moisture protection? Therefore, investigating and better understanding how various moisture sources impact certain building components and how best to adapt in protecting them will be of benefit.

Of note, choosing what paint to use is not as simple as what gives the best protection, but an understanding of the material composition also needs to be considered to determine how the paint may affect the environment and occupants. This research investigates the differences in moisture transfer properties between alkyd, latex (& acrylic) and linseed oil paints, as they are commercially available and widely used in exterior wood applications. These three paint types are also associated with shifting environmental policies within 'paint' industries, which can be seen in Figure 1.3.

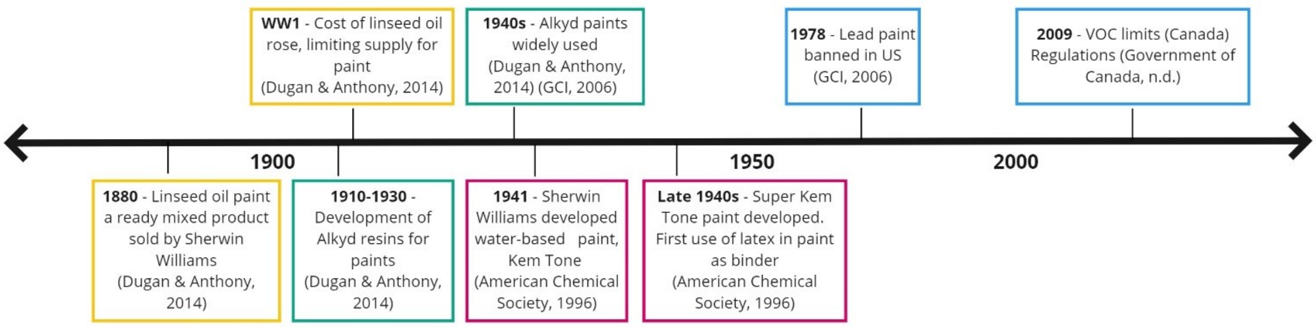


Figure 1.3. Timeline of transition from linseed oil paint to use of synthetic binders such as alkyd and latex

For example, linseed oil paints were initially used with the use of lead pigments as they provided excellent durability and flexibility, although they were found to pose health concerns, which led to the ban of lead in 1978 (Getty Conservation Institute et al., 2006). Other alternatives to linseed oil paint had been developed as the linseed oil stock was limited due to the First World War (Dugan & Anthony, 2014). Alkyds became a popular paint binder and consisted of a mix of natural oils with synthetic alkyd resins and thus required solvent, surfactants, and other additives (Dugan & Anthony, 2014). These solvents evaporate while the paint dries, releasing volatile organic compounds (VOCs) which contribute to ground-level ozone. In 2009, the Canadian Environmental Protection

Act released the Volatile Organic Compound (VOC) Concentration Limits for Architectural Coatings Regulations (Government of Canada, n.d.). Meanwhile, as an alternative to solvent-based paints, water-based paints were developed in 1941, which initially used a binder of casein and linseed oil or tall oil that was then marketed as Kem Tone paint (American Chemical Society, 1996). Later, Super Kem Tone paint replaced the binder with styrene-butadiene latex, in which the polymer microparticles become suspended in water (an emulsion) which then evaporates as the paint dries (American Chemical Society, 1996). Today, water-based paints such as latex uses various types of polymers as the binder, as well as various additives, making the chemical make-up and properties different for various products.

1.3 Motivation

The motivation for this research initially was to further understand the moisture transfer properties of linseed oil paints specifically. As part of this master's program, an internship was conducted with Parks Canada researching linseed oil paint systems. Due to the pandemic, the main method of research was through phone or video interviews to gain the perspectives and experiences of various stakeholders related to linseed oil paints. The scope of the research done was through the lens of heritage conservation to better understand how this paint system impacts the maintenance cycle.

One of the takeaways from the internship was that there is conflicting information on types of paint and how to use them. One of the main concerns was how the paint protects the substrate and how long the paint itself will last. In some cases, latex paints would fail prematurely and be linked to wood rot, while linseed oil paint was believed to be better in protecting the wood from moisture and it would also last longer with cyclic maintenance. From the many interviews conducted, the descriptions of how paints protect wood from moisture sparked the interest to further research the mechanisms, principles, and properties of moisture transport in building materials.

Initially a lab testing thesis was idealized, where the material properties of linseed oil paint versus other modern paints (alkyd/ latex/ acrylic) would be compared. Due to COVID and time restrictions, the thesis shifted to a modeling-based approach; thus, requiring a more in depth understanding of the moisture transport mechanisms, and relying on existing literature and material databases to model the paint properties. This method also allows for differing paint systems to be compared based on their properties rather than solely focusing in on the properties of linseed oil paint.

1.4 Objectives

The objectives of this thesis are driven by the question:

"How does the paint layer's permeability impact the moisture conditions of wood siding?".

The aim of this research is to identify how the various permeability classifications of different paint systems impact the moisture conditions of the wood siding within the building envelope. A better understanding of this will inform which paint systems are best suited for different environmental and material conditions. There are many ways in which this can be determined, for this work the following objectives have been chosen to research this question:

1. Analyse the moisture sources of concern for wood siding.

2. Investigate how the exterior paint layer's permeability to liquid and vapour impact the moisture content of the siding.
3. Relate the moisture content within the wood siding to the maintenance cycle.

To accomplish these objectives the main analysis tool is the hygrothermal software WUFI Pro. It will be used to simulate the moisture conditions within the building envelope. The following themes and sub-questions will also be addressed throughout this research:

- Analyze the moisture sources at the siding
    - How does vapour reach wood siding? Is interior vapour a concern?
- Investigate the impact of:
    - Cladding leakage
    - Back priming
    - Paint layer leakage
    - Cavity insulation
    - Interior relative humidity

1.5 Thesis outline

In support of the objectives stated above this thesis comprises six chapters. Following this introduction, the second chapter 2 provides a review of the key background information based on the review of the pertinent literature available in this field. Chapter 3 outlines the methodology and analysis tools used to conduct this research and the results are then presented in Chapter 4, followed by the discussion and conclusions that then lead to the recommendations and potential for future work.

Chapter 2: Literature Review

To understand how exterior paint impacts the moisture content of wood siding, a deeper dive must be done to distinguish some of the underlying principles of how moisture is transported within building materials along with certain aspects of their properties that enable these mechanisms to occur. This section will explain and discuss some of the work done in this field, leveraging the experience and knowledge of experts, and reviewing the literature on the key aspects related to this research. This includes a review of exterior paint properties and how they behave with moisture, wood properties that affect moisture transport, paint performance, and the impacts of insulation retrofits. As a starting point, the use of hygrothermal simulations will be reviewed followed by the fundamentals of moisture transport in buildings to link all the subsections in this chapter to each other.

2.1 Hygrothermal Simulations

Hygrothermal modeling is used within the field of building science to simulate the transport of heat and moisture across a building assembly. There are many different hygrothermal softwares available to use such as WUDI, Delphin, HYGRIC, COMSOL, WALLDRY, etc, consisting of different considerations for transport mechanisms, driving potentials, and other complexities. Often hygrothermal simulations will be done along side full scale field experiments to validate and compare with the model's calculations, or along with material testing to provide more accurate inputs for the various properties. These simulations can be used to gain information on the drying capacity of wall assemblies and to better understand how different variables impact the wetting and drying of certain materials within the assembly.

2.1.1 Applications

Many studies have been done regarding the use of hygrothermal modeling for wood frame applications in general. To name a few applications, there have been comparative studies done where the components of wall different wall assemblies are varied to observe which assemblies achieve better results (Glass, 2013; Straube & Smegal, 2009), the effect of rainscreen wall systems has been investigated by applying an air gap within the simulation (Finch & Straube, 2007; Hägerstedt & Arfvidsson, 2010), the impact of using different insulation types has been observed (Boardman & Glass, 2020; Straube & Smegal, 2009), the effect of wind driven rain as a wetting mechanism has been studied (Tariku et al., 2015), and even using testing data as a method to improve the simulation input values (Boardman & Glass, 2020; Hägerstedt & Arfvidsson, 2010). Most of these studies mentioned focus on the impacts to the exterior sheathing within the assembly, rarely is the siding specifically investigated, and in addition, rarely is the paint layer specifically analysed in hygrothermal simulations.

A study by Hjort was done in 1998, which focused on modeling in 2D the moisture conditions of painted wood (Hjort, 1998). Their model was developed to address the fact that most models at the time only dealt with moisture in the hygroscopic range and constant diffusivities rather than concentration dependent. The model shows how the moisture is distributed with a piece of wood that has multiple sides painted, but it does not address how the piece wood behaves within a wall assembly application. The siding has been looked at in cases of expe, imental field investigations (Hopkins & Gibbons, 1953; Iliff et al., 1939; Tibbetts & Robson, 1971), particularly regarding its moisture content and paint condition, but for hygrothermal simulations it seems to be of less interest to study the siding specifically. This could be due to the decline in the use of wood as a siding material, therefore materials that are more common such as vinyl for siding, there may be less of a concern about failure occurring due to moisture as they are not prone to decay.

2.2 Moisture Transport in Buildings

As mentioned earlier, moisture is the most significant factor in the premature degradation of building materials, therefore making it a key factor that needs to be controlled within buildings to prolong the service life and material fabric. This section will provide an overview that explains where moisture comes from, how it is transported, stored, and how it can be controlled in buildings to ensure the longer service life for materials.

2.2.1 Moisture Sources

Moisture in buildings can exist in either a liquid, vapour, solid or adsorbed state, of which liquid and vapour present the greatest concern. Materials are constantly absorbing or desorbing moisture as they are exposed to varying interior and exterior moisture sources. Interior sources can include moisture that is generated from occupants, as well as through activities such as cooking, bathing, etc. Exterior types include rain, snow melt, groundwater, and humid outdoor air. Moisture can also be built in during construction if the materials used are not sufficiently dry before installation or if wetting occurs during the construction process (i.e. typically from rainfall). This last source is less prevalent when dealing with historic construction, although built-in moisture can occur in a retrofit scenario where new materials are added or if the building envelope becomes exposed.

The types of moisture sources mentioned, both internal and external to the building, contribute to the wetting of building materials. Figure 2.1 outlines the wetting and drying mechanisms for buildings. As rain, water vapour movement, and ground water wet the building materials, sufficient drying must also occur through the evaporation of water at its surfaces (heat required), a shift in concentration or pressure gradient, drainage space, or ventilation drying (Straube, 1998). Maintaining a balance between wetting and drying mechanisms avoids the possibility for moisture accumulation.

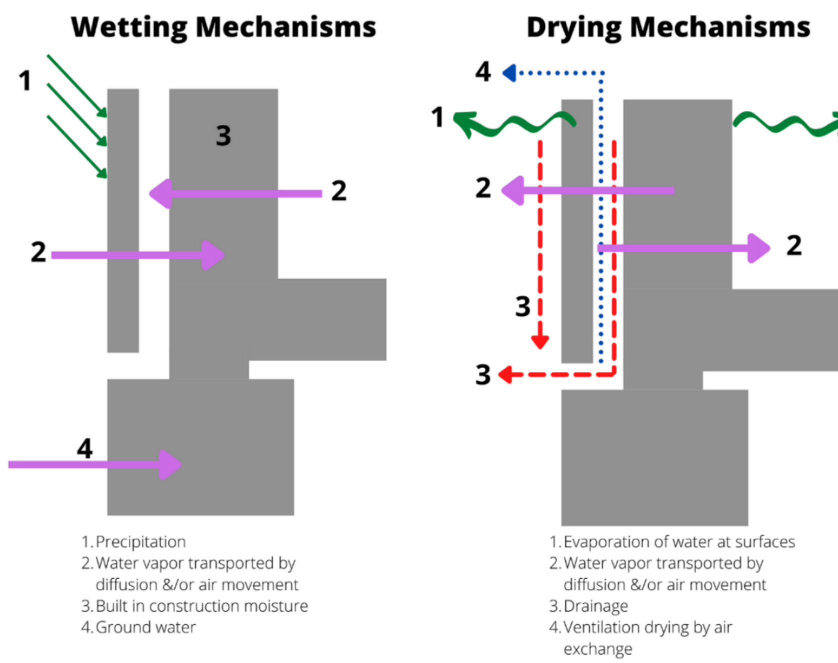


Figure 2.1 Wetting and drying mechanisms for buildings. Based on figure by (Straube, 1998)

Particular to exterior siding, external moisture in liquid form is normally from rain or dew that is absorbed into the siding, especially in leaky cladding systems which also have less of a gap for drainage. Interior sources of moisture have also been studied, where vapour from the interior condenses when the dew point is reached within the assembly, typically occurring in the winter at the cold surfaces in the assembly (winter condensation). An increase in the moisture content of the siding has been observed due to structural details and construction practices as well where control of moisture (i.e. flashing) is not adequate. Iliff et al, notes the addition of fire stops, central heating, increased operating temperatures, increasing construction tightness, and careless workmanship, influence the moisture content of the exterior layers (Iliff et al., 1939).

In addition, although the paint layer is supposed to protect the wood siding from moisture, it has been observed that a paint layer with mechanical defects (holes, cracks, etc), despite having a low permeability to liquid moisture, can let in exterior moisture. Therefore, the permeability properties of a paint layer only apply if it is intact. Solutions have been proposed for how to keep the wood siding from accumulating moisture, such as creating an air space behind the siding, inserting wedges between the siding laps to allow for ventilation, lowering the interior relative humidity (RH) and maintaining the exterior paint layer to avoid mechanical defects (Iliff et al., 1939; J. W. Lstiburek, 1990; W. Rose, 2005).

In the end, moisture sources, in particular bulk water (rainwater), are largely dependent on the design and details of the structure that protect the envelope. Bulk water can enter past the cladding when there is a source of water, a course for the water to enter through and a force that drives the flow of water. As seen in Figure 2.2, the driving forces for bulk water through an opening include capillarity, surface tension, gravity, pressure differences and kinetic energy. The movement of liquid water through the cladding is controlled using various strategies that provide sufficient deflection, drainage, drying and the use of durable materials. For example, flashing and overhangs are provided to deflect the rainwater away from the building, an air gap behind the cladding allows for drainage if water passes through while also providing a capillary break between the liquid water and the rest of the materials within the assembly. One of the limitations of this research is that the construction detail and design specifics as reflected in Figure 2.2 is not factored in the WUFI model thus limiting the level of analysis; subsequently, it is based more on the drying capability of the wall, focusing on the material properties and how moisture is transferred between the components.

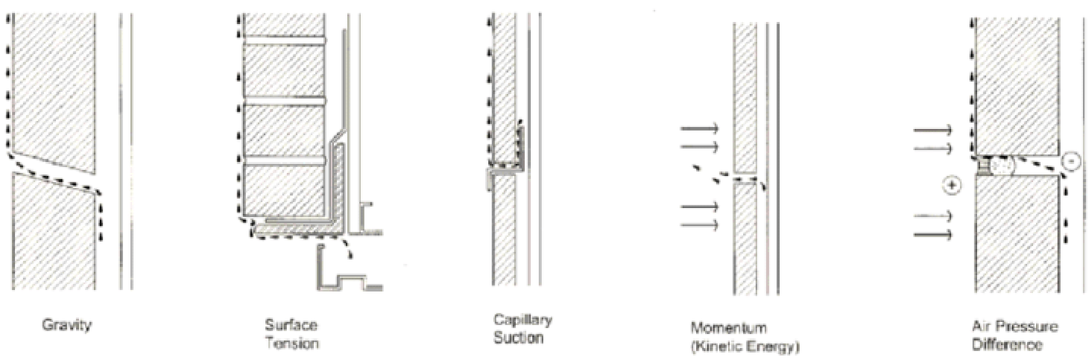


Figure 2.2 Mechanisms for rainwater penetration (Canadian Wood Council, 2000)

2.2.2 Moisture Transport

Within a porous material, moisture can be transported in a liquid, vapour or in an absorbed state. Moisture is transported due to several transport mechanisms that occur under various driving forces (a difference in driving potential between two mediums). Table 2.1 breaks down the various transport mechanisms and driving forces. The main transport mechanisms that will be discussed in this paper are capillary conduction, surface diffusion, vapour diffusion, and convection.

In general, moisture transport is calculated based on a its flux, using equation (1).

$$\boldsymbol{moisture\ flux = -coefficient\ \nabla\ (Driving\ Force)} \quad \textbf{(1)}$$

Where the moisture flux is the rate at which the moisture (vapour or liquid) is transported across a medium, the transport coefficient represents the medium's characteristic to moisture transport (dependent on driving force), and the driving force represents a difference in potential that drives the transport (see Table 2.1) (Kumaran, 2009). The negative sign in the equation represents the direction of transport that occurs opposite to where the potential/ concentration is increasing.

Table 2.1 Moisture driving potentials and transport mechanisms (Kumaran, 2009, Künzel, 1995)

Moisture State	Transport Mechanism	Driving Potential
Liquid	Capillary conduction	Capillary Suction
	Surface Diffusion	Relative humidity
	Hydraulic flow	Total pressure differences
	Electrokinesis	Electrical fields
	Gravitational flow	Height
Vapor	Vapor diffusion	Vapor pressure
	Convection	Total pressure gradient (air pressure)
	Solution diffusion	Vapor pressure

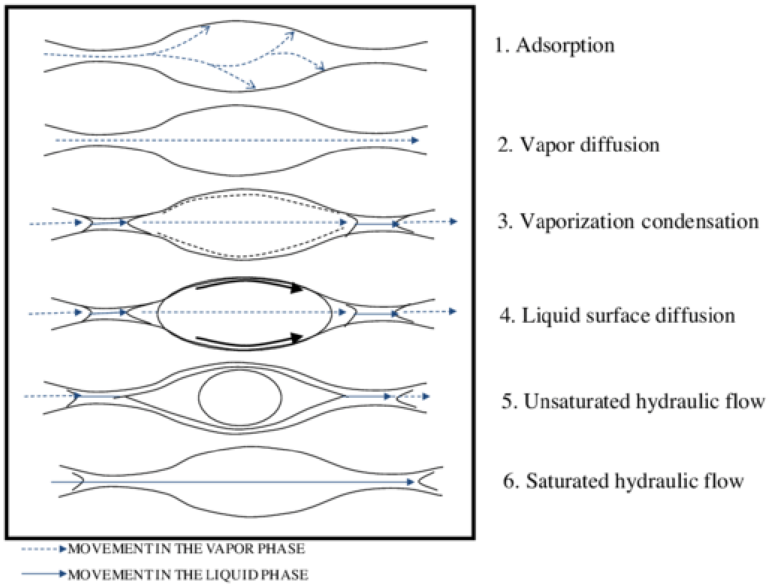


Figure 2.3 States of moisture transport through a porous material (D. A. Rose, 1963)

Figure 2.3 shows the various stages of moisture movement through a porous material. The various stages of water vapour and liquid transport will be discussed further in the next section.

2.2.2.1 Water Vapor Transport

Water vapour is transported through either vapour diffusion driven by differences in vapour pressure, or through mass transport driven by air pressure differentials that allow the movement of moist air. Water vapor transported through mass transport in air is more effective than diffusion, as moisture laden air can carry a significant amount of moisture through a shorter period (Kumaran, 2009; Trechsel, 2001). Although, air flow is less predictable and occurs in isolated areas through gaps in construction, while vapor diffusion is a more evenly distributed process over the area of the wall, it works slowly over a period of days. Trechsel mentions that even though air infiltration moves greater amounts of moisture it does not always mean it causes greater potential for damage.

Diffusion can lead to catastrophic failures as it applies to entire surfaces and for a relatively longer period as well (Trechsel, 2001).   This research will focus on vapour transport through diffusion, as modeling air movement can be difficult as it depends on structural details and can occur in several pathways that are not necessarily known and occur at unknown intensities. To model air leakage, knowledge of the flaws within the assembly must be known/ assumed.

Air Convection

Only a brief overview of air convection will be given as it is not a transport mechanism considered in this study. The driving force for air convection is air pressure differentials. The building can either be under positive, negative of neutral pressure, which can also vary depending on the orientation or height/ level (Trechsel, 2001). It is considered positive pressure when the air pressure is greater inside than outside, and negative pressure if the inside air pressure is less than outside (Trechsel, 2001).

Vapour Diffusion

According to Fick's Law of diffusion, vapour can be modeled using this following equation (2):

$$\boldsymbol{g_v = -\delta \cdot \nabla p} \;\; \textbf{(2)}$$

Where;

g_v = vapour diffusion flux density [kg/m^2 s],

δ = water vapour permeability of medium [kg/Pa s m],

P = water vapour partial pressure [Pa]

Diffusion occurs from areas of high pressure to low pressure. In cold climates during the winter there is a higher vapor pressure inside buildings compared to the exterior environment. In buildings, water vapor transported through diffusion is controlled using materials with a higher resistance to water vapor diffusion, while water vapor transported through air movement is controlled by using continuous air barriers to avoid airflow across the assembly.

For smaller pores in which the mean free path length is greater than the pore diameter, the diffusion process is governed by effusion, or Knudsen transport, as seen in Figure 2.4. This transport mechanism is typically within the micropore region, where the diffusion is governed by collision of water molecules within the pore wall. The Knudsen factor can be calculated using equation (3), in which a factor of $K_n > 1$ means the pore size is very small and effusion will predominate (Krus, 1996).

$$K_n = \frac{L}{2r} \quad (3)$$

Where;

K_n= Knudsen factor

L= mean free path [m]

r= pore radius [m]

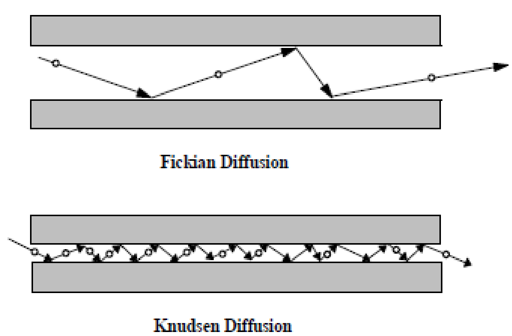


Figure 2.4 Fickian vs Knudsen diffusion based on the pore size (Straube, 1998)

2.2.2.2 Testing Methods – Sd

Water vapor permeability specifies the ability of a material to allow water vapor through it. The property has units of (ng/Pa m s) and is measured, among other testing methods, under certain temperature and humidity conditions according to the ASTM E96 standards using the cup method (ASTM, n.d.). In addition, ASTM D1653 uses the same method, but for organic coating films. For the cup method, the material is sealed to the open mouth of a dish with either water (wet cup) or a desiccant (dry cup) in the dish (Figure 2.5). The weight change of the dish over time is plotted until a straight line fits the plot. The slope of the line represents the water vapor transmission rate (WVT) of the material.

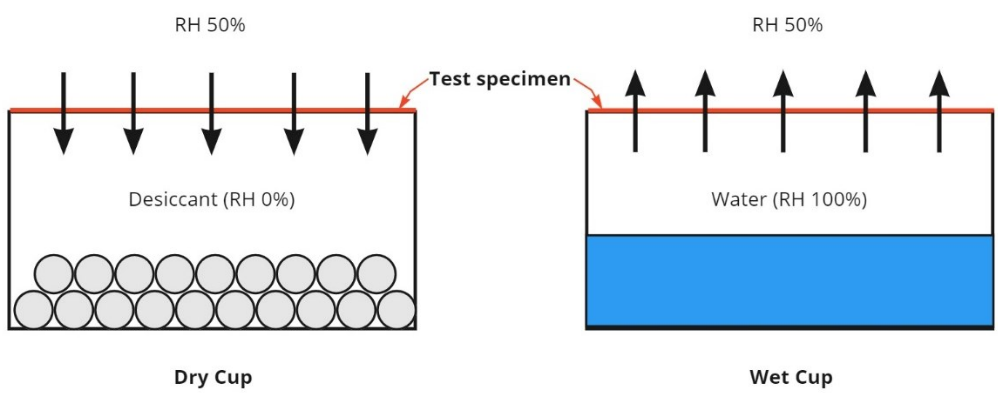


Figure 2.5 Test chamber set up for dry cup and wet cup method

$$\boldsymbol{WVT} = \frac{\boldsymbol{G}}{\boldsymbol{tA}} \quad (4)$$

Where;

WVT= rate of water vapour transmission [g/hm^2]

G= weight change [g]

t= time during which G occurred [h]

A= test area (cup mouth area) [m^2]

To get the permeance from WVT, the following equation can be used:

$$\boldsymbol{Permeance}\ [\boldsymbol{ng}\ /\ \boldsymbol{Pa}\ \boldsymbol{s}\ \boldsymbol{m}^2] = \frac{\boldsymbol{WVT}}{\boldsymbol{\Delta p}} \qquad (5)$$

While permeance is not a physical property of the material, to get the permeability of the material, the permeance is multiplied by the material thickness (ASTM, n.d.-b).

$$\boldsymbol{\delta} = \boldsymbol{Permeance} \cdot \boldsymbol{\Delta x} \quad (6)$$

Where:

δ = permeability of the material [ng/Pa s m]

Δx = thickness of material [m]

Permeance is used for performance evaluation as it represents the property of the component layer rather than the material itself, while permeability is a material property and can be calculated by the permeance multiplied by the material thickness. Distinguishing between the dry or wet cup method is important as the permeability of a material is different under the relative humidity conditions. The dry cup method simulates a vapour drive going into the building, where the RH inside the cup is closer to 0% and the RH outside the cup is typically 50% at room temperature, therefore a weight gain of the cup will be recorded. The wet cup method tests the vapour drive in the opposite direction, in which a weight loss of the cup will be recorded. Dry cup values tend to be less permeable compared to wet cup, as hygroscopic materials are more permeable to water vapour at higher RH values.

The water vapor permeability of paints is specified using the same cup method in European standards, ISO 7783:2018(en), and for building materials using ISO 12572:2016. Although the similar cup method is used, two different variables are used to define the permeability to water vapour, the water vapour diffusion equivalent-air layer thickness (Sd-value) and the water vapor diffusion resistance factor (μ) (International Organization for Standardization, 2018). These values are also used to specify the permeability of the materials within the WUFI software. The water vapour diffusion resistance factor represents the ratio of the diffusion coefficients of water vapour for static air (δ_{air}) and the material (δ), as seen in Eq 7.

$$\boldsymbol{\mu = \frac{\delta_{air}}{\delta}} \quad (7)$$

Where;

$$\boldsymbol{\delta_{air} = 2.0x10^{-7}\frac{T^{0.81}}{P_L}} \quad (8)$$

Where;

T= ambient temperature [K]

P_L= ambient air pressure [Pa]

The Sd value is in meters and represents the equivalent air layer thickness that has the same WVT rate as the tested material. It can be calculated by multiplying the water vapour diffusion resistance factor by the thickness of the material. Understanding both the permeability and Sd/ μ -values are important as the referenced studies on the moisture transfer properties of paints use either metric, therefore converting to a common metric is required. For the WUFI analysis as part of this research, the Sd-value will be used to quantify the vapour permeability.

In North America, materials are classified according to their water vapor permeance [ng/Pa s m^2], which describes the rate at which water vapor can transmit through a unit area of material when there is a vapor pressure difference. In 1950, the first permeance values required by the National Building Code of Canada for the sheathing and vapour barrier were 170-285 ng/Pa S m^2 and 45 ng/Pa s m^2 respectively (Bomberg & Onysko, 2002). Materials are classified based on their permeance to water vapour using the following system:

- Vapor Impermeable (Class 1 VB): <= 5.7 ng/Pa s m^2
- Vapor Semi-Impermeable (Class 2 VB): 5.7 < ng/Pa s m^2 >= 57
- Vapor Semi-Permeable (Class 3 VB): 57 < ng/Pa s m^2 >= 570
- Vapor Permeable: > 570 ng/Pa s m^2

In cold climate construction, a vapor retarder that is within the Class 1 range is added to the warm side of the wall to limit the amount of water vapor that can get into the envelope and potentially condense. Appendix C contains a table with further information on various paint permeability ranges that have been gathered from literature.

2.2.2.3 Liquid Transport

As seen earlier in Table 2.1, there are many transport mechanisms for liquid water. This section will discuss the mechanisms that WUFI uses to simulate liquid water transport through unsaturated porous materials, occurring through surface diffusion and capillary suction. The driving forces are through moisture concentrations and gradients of capillary potential (suction).

Surface Diffusion

As water molecules are adsorbed on the inner surface of the pore walls, a sorptive film is created which increases into a multi-monomer layer as the relative humidity increases. Surface diffusion, or surface flow, occurs as the thicker layers of water molecules (which are more loosely bound than the first layer) moves towards an area that has fewer layers. Therefore, the movement is driven by the gradient of adsorbed water molecules. Straube remarks that one explanation for the moisture dependence of vapour permeability can be rationalized through surface diffusion (Straube, 1998). As the less tightly bound layers move to thinner ones, vapour diffusion continues to transport vapour at an increasing moisture concentration.

Künzel considers surface diffusion as a liquid transport process that is driven by relative humidity (related to moisture content through the moisture storage function). Although, the effect of surface diffusion in WUFI can be considered through two different methods. The first being through the moisture dependence of the μ-value and the second by adjusting the liquid conduction coefficient while keeping the μ-value constant.

Capillary Suction

Capillary suction, or sorptivity, occurs in porous materials in which water is transported through the capillaries due to the surface tension within the pores. Calculating the actual flow due to capillary suction can be difficult, as modeling the pore space, size and interconnectivity can be challenging (Straube, 1998). There are various theories out there to describe the flow of water through capillary pores such as parallel tube model, series models, percolation theory, etc. There are different driving potentials that can be used when describing capillary transport, one method is using the diffusion equation (9) where moisture content is the driving potential.

$$\boldsymbol{g_w = -D_w(w)\nabla w} \quad (9)$$

Where;

g_w= liquid flux density [kg/m2s]

D_w= capillary transport coefficient [m^2/s]

w= moisture content [kg/m3]

In their model, Künzel simulates capillary liquid transport using Darcy's law, equation (10), for laminar flow in water-saturated porous materials, using capillary suction stress as the driving potential (Künzel, 1995);

$$\boldsymbol{g_w = K_1 \nabla P_s} \ (10)$$

Where;

K_1= permeability coefficient [kg/msPa]

P_s= capillary suction stress [Pa]

They then use Kelvin's equation (11), to substitute for the capillary suction stress;

$$\boldsymbol{g_w = -K_2 \nabla (T ln \varphi)} \ (11)$$

Where;

K_2= capillary coefficient [kg/msK]

T= absolute temperature [K]

φ= relative humidity

Differentiating this equation shows that the capillary transport is based on a temperature gradient, although its comparatively small compared to relative humidity and thus is disregarded by Künzel. A new coefficient called the liquid conduction coefficient, D_φ [kg/ms], is used in the following equation, which is driven by the relative humidity.

$$\boldsymbol{g_w = -D_\varphi \nabla \varphi} \ (12)$$

The use of relative humidity as a driving potential means that the moisture transport through materials is continuous at the boundary layers compared to using moisture content as a potential which is material dependent. This method of using relative humidity as the driving potential for liquid moisture is used within WUFI. The relationship of the liquid conduction coefficient and then capillary transport coefficient can be represented as the derivative of the moisture storage function, $\frac{dw}{d\varphi}$, equation (13). As will be explained in a later section, within the capillary moisture region the RH cannot be used to determine means of capillary transport.

$$\boldsymbol{D_{\varphi} = D_{w}\frac{dw}{d\varphi}} \quad (13)$$

2.2.2.4 Testing Methods – Aw

Liquid water adsorption is specified using a liquid moisture adsorption coefficient (Aw), which has units of $kg/m^2s^{0.5}$. This property is used to describe the transport of liquid water when in contact with different materials. ASTM C1794-19 tests for the water adsorption coefficient by partial immersion, which includes monitoring the change in weight as the substrate is partially immersed in water (ASTM, n.d.-a). This standard evaluates the rate at which water is absorbed due to capillary forces, simulating the effect of materials in contact with normal or driving rain. The values from the test can be used to simulate the material properties of capillary active materials in hygrothermal simulations. Paints are usually tested via this method when applied to a substrate to assess how the paint alters the liquid water adsorption, therefore the value is associated to the hybrid system of the two materials rather than to the paint itself.

First, the mass change, Δm_t, must be calculated at each weighing of the sample, and then plotted against the square root of the time, $\sqrt{t}$. The liquid absorption coefficient, A_w, is calculated from the slope of the line (Figure 2.6).

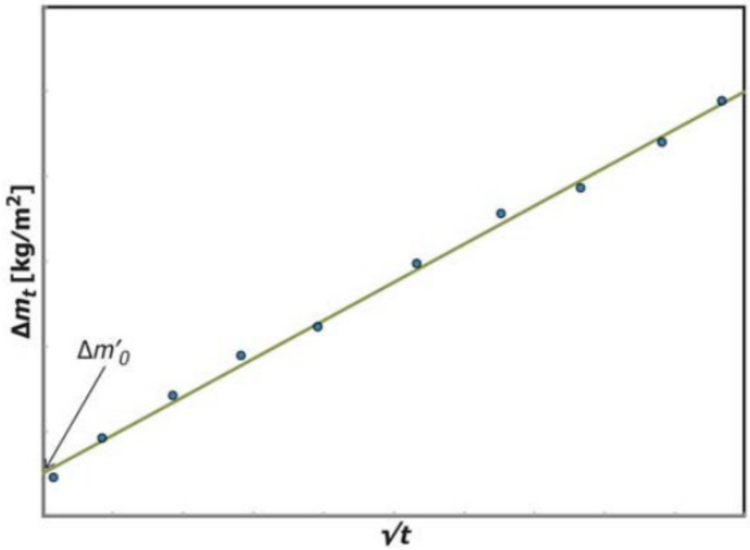


Figure 2.6 Graph showing a linear relationship between the mass gain and square root of time

(ASTM, n.d.-a)

Equation (14) is used to determine the liquid diffusivity, Dw, from the liquid water absorption coefficient, A_w.

$$D_w \approx \left(\frac{A_w}{w_{cap}}\right)^2 \quad (14)$$

Where;

A_w = water absorption coefficient [kg/m^{2}s$^{0.5}$]

w_{cap} = capillary saturation moisture content [kg/m^3]

According to the European Standard ENV 927-2, the liquid water absorption value is recommended based on the end use condition (CEN, 2000). The categories are for stable construction (ie windows) and semi-stable (ie facades), with corresponding absorption values being 175 g/m^2 and 250 g/m^2 respectively. The Aw coefficient will used to simulate the permeability to liquid moisture within the WUFI analysis for this research.

2.2.3 Moisture Storage in Porous Materials

Moisture storage in hygroscopic porous materials is represented using sorption isotherms, which shows the relationship between the moisture content and relative humidity under isothermal conditions. Figure 2.7 shows the various regions within the moisture storage function. Within region A, the hygroscopic region, water vapor absorbs into the pore walls of the material, as the RH increases the layers of water vapor increase until a meniscus is formed from the surface tension of the water. Along with vapour diffusion within the pores, liquid transport through surface diffusion along the pore walls occurs in this region. Region B, the capillary region, is where free water accumulates in the pores up until capillary saturation occurs under normal pressure. Region C is the supersaturated region. In this region the RH can no longer increase, but water can enter through external driving potentials such as gravity, filling any spaces created due to air bubbles in the pores (Straube, 2006).

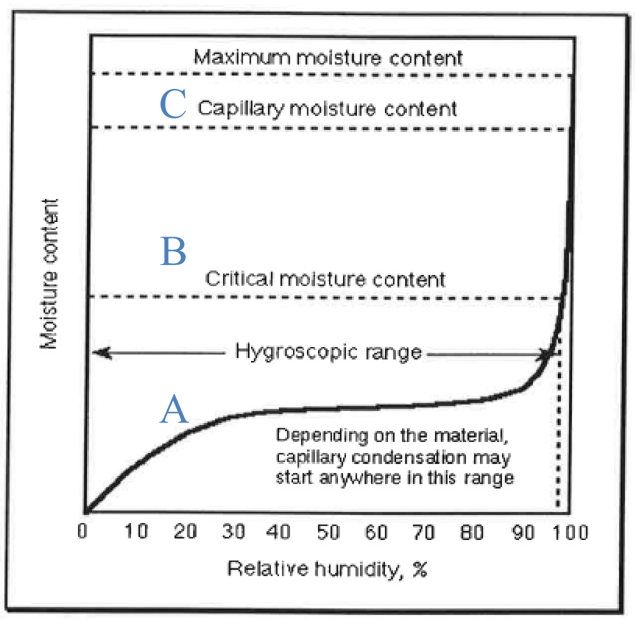


Figure 2.7 Moisture storage function of a hygroscopic porous material (Kumaran, 2001)

2.2.3.1 Moisture Transport in Wood

Wood is a common building material that has been used for many years as it is an abundant and natural resource that provides strength and durability when properly protected from the elements. Being a hygroscopic and porous material, it constantly absorbs and desorbs moisture, although prolonged levels of high moisture can lead to surface mould, or if severe enough, to the decay of the material. The moisture content of wood is constantly fluctuating with the relative humidity and temperature of the surrounding environment, always trying to reach an equilibrium between the two mediums. The equilibrium moisture content (EMC) of wood represents the ideal state at which wood is neither losing nor gaining moisture.

A general sorption isotherm for wood can be seen in Figure 2.8. The desorption is measured by bringing the initially wet wood to its EMC at decreasing RH levels. The adsorption is measured from the dry state to its EMC with successively increasing RH levels (Forest Products Laboratory, 2010). As seen in this Figure, a hysteresis occurs between the adsorption and desorption curve, one theory suggests this is due to the pits causing an ink bottle effect, retaining water longer in the desorption process (Fredriksson & Thybring, 2019).

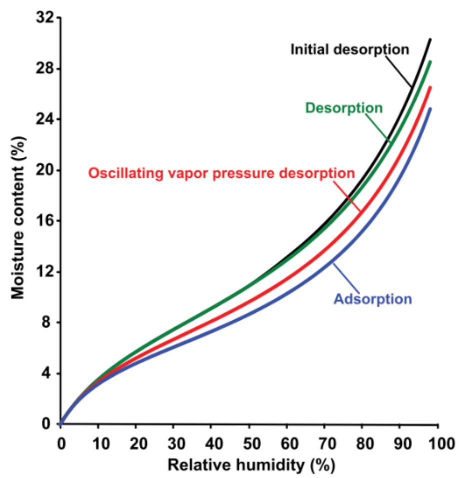


Figure 2.8 Hysteresis between adsorption and desorption of the MC-RH relationship of wood (Forest Products Laboratory, 2010)

In general, wood is divided into two types, softwoods and hardwoods. Figure 2.9 shows the differences in cellular structure between these two wood types. Softwoods, known as gymnosperms, have a simpler structure that consists of cell type fibres. While hardwoods, known as angiosperms, have a structure of cells along with vessels that make the wood more porous. Both wood types have sapwood and heartwood. The heartwood consists of a layer of inactive cells and therefore does not provide moisture transport or food storage within a living tree (Forest Products Laboratory, 2010). The heartwood can also have polymeric extractives (resins) within the cell walls and pores, which can impede the passage of moisture transport. The sapwood layer consists of a mix of both living and dead cells and primarily functions as food storage, along with transport of water and sap along the outer layers.

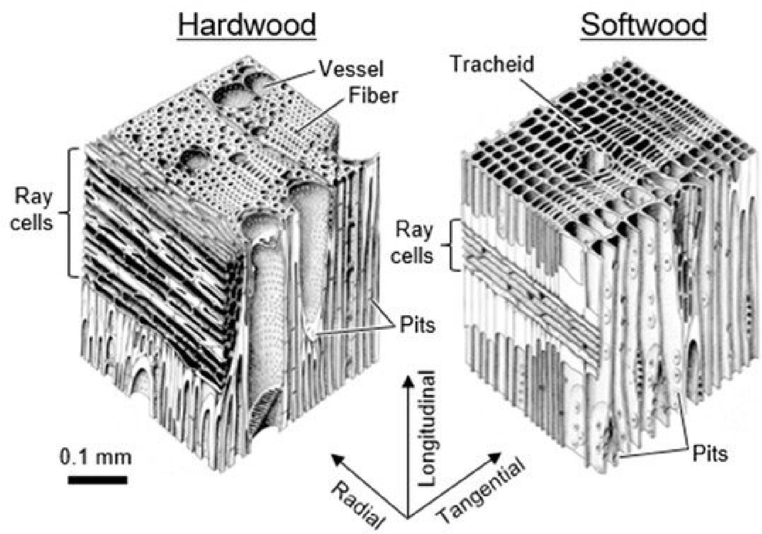


Figure 2.9 Hardwood vs softwood cellular structure (Jakes et al., 2019)

Water is present in wood either as bound or free water, as seen in Figure 2.10. Bound water occurs within the cell walls, while free water is located within the cell lumen and other pockets. Once a tree is felled, first the free water dries out until the Fiber Saturation Point (FSP) is reached, then the bound water evaporates. The moisture content at which the cell walls are completely saturated is known as the FSP. The mechanisms in which moisture is transported are by either capillary flow, or by diffusion of bound water or water vapor. Diffusion occurs within the cell wall. The cell walls have a low permeability therefore the diffusion between cell walls is negligible it happens through lumina and pits that connect the adjacent cells (van Meel et al., 2011).

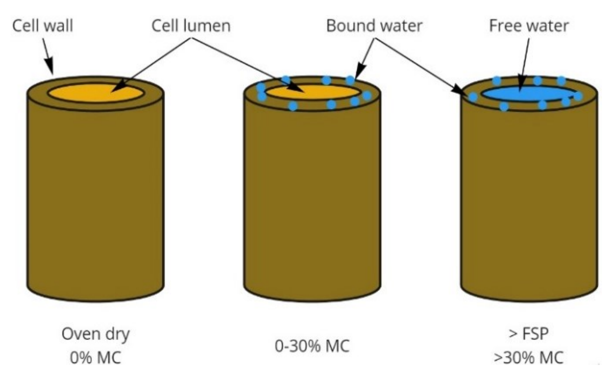


Figure 2.10 Distinguishing between bound and free water within wood cells

The moisture content of wood is a representation of the ratio of the weight of water inside the wood to the weight of the wood completely dry, using equation (15).

$$\boldsymbol{MC} = \frac{m_{wet} - m_{dry}}{m_{dry}}(\mathbf{100\%}) \quad (15)$$

Moisture transport mechanisms differ in wood between the hygroscopic range (0-95/98% RH) and over-hygroscopic range (RH > 95/98%). In the hygroscopic range, which occurs between a MC of 0% to the FSP, only bound water is present within the cell walls, therefore water is absorbed via these walls. Diffusion of bound water is driven by a difference in concentration of water in the cell walls, while diffusion of water vapor is driven through differences in vapor pressure concentrations. Since the cell walls cannot hold any more water and will not expand, the physical and mechanical properties of wood do not change as the moisture content increases. The FSP is typically around a MC of 30%, although will differ among species. Below the FSP is when shrinkage and swelling occur. Above the FSP the cell lumina fills with water until it reaches saturation, which is known as the maximum MC (Fredriksson, 2019). Although, studies have found that that cell walls are not completely saturated until the whole wood specimen was saturated, contradicting the theory that cell wall saturation must occur before capillary condensation occurs in the cavities (Fredriksson, 2019).

In the over-hygroscopic range water uptake occurs via capillary condensation as free water is present within the voids (lumina and pit chambers) outside the cell walls. In this range, water vapor can condensate below the saturation vapor pressure and is dependent on the pore dimensions. The smaller the pores the lower the relative humidity required for condensation to occur (Fredriksson, 2019). As mentioned, there are no dimensional changes to the wood in this range, although there is more risk for fungal degradation to occur.

Mold and Decay Conditions

In general, fungal growth requires a source of infection, food source, moisture, oxygen and suitable temperature. Under certain conditions and time durations of humidity/ moisture content and temperature, wood can be at risk of moisture damage. The environmental conditions and duration that may put wood at risk of mold will be different for the risk of decay. Mold fungi is not of concern regarding the loss or degradation of wood material. Rather it is a surface condition that may cause discoloration and can be potentially harmful to human health (if found in interior environments). Viitanen has developed a mathematical model for growth of mold fungi which is dependent on the temperature and RH and is expressed in terms of a mold index (0-6) (Hukka & Viitanen, 1999). Although there are various types of molds that exist, the model should be interpreted as representing mixed mold species and indicates the possibility for mold activity occurring on the surface. This mathematical model is available through WUFI as an extension, WUFI-VTT, in which the results of a hygrothermal simulation can be analyzed.

While conditions for mold does not necessarily mean that decay will eventually follow, it does represent an area of increased local moisture content. For decay/ rot fungi, spore germination requires higher moisture levels compared to mold fungi. The conditions for decay are less clear within the literature, although rough guidelines are given as to when decay may be more likely to occur. It has been the guideline for some time that wood, if kept below a MC of 20%, is not at risk of decay (Carll & Highley, 1999). Decay is most likely to occur once above the FSP (~30% MC), but the guideline of 20% MC is used in design criteria to ensure decay fungi is inhibited. The duration at which this moisture content needs to be is less known as a guideline. Although, the optimum temperature for decay fungi is within the region of 21-32°C and thus moisture content that goes above the FSP in wintertime (low temperatures) for a few months is less of a concern (Carll & Highley, 1999). Lee et al proposes an acceptance criterion for wood-based products to be the 7-day running average moisture content of the material greater than 28%, irradicating any spikes in moisture that dry out quickly (Lee et al., 2019). Depending on the fungi species, once decay has started, if the MC falls back below levels for decay the fungi become dormant, but once the MC reaches fiber saturation it can be revived, a term called anabiosis (Findlay, 1950).

2.3 Exterior Paints for Wood

Paints have been used as a decorative and protective material for centuries, consisting of various compositions and raw materials. Within buildings, exterior paints provide both an attractive finish and a protective layer to the underlying substrate. With respect to historic buildings, paints are usually chosen with regards to the compatibility of the material and the pigments to match historically accurate colors. When painting wood, the pigments in the paint provide protection from lignin degradation from the sun's ultraviolet rays. Another important protective function of the paint comes from the cured binder and pigments as a barrier against moisture. This section will go further into the general composition of paints followed by a brief overview of three commercially available paints that will be investigated in this research. In addition, there will be an overview of paint film properties with further research into how paints behave with moisture.

2.3.1 Composition of paints

Before discussing the properties of various paints, it is important to understand their main components, in general, they are three:

- a binder,
- solvent (or vehicle), and
- pigments.

The *binder* is what binds the pigments together and forms the paint film, whether the film formation occurs through evaporation of the solvent (waterborne paints), oxidation (oil-based paints), or a combination of both. The *solvent* is what thins the mixture and aids in application of the paint to achieve a more uniform layer. The solvent is a volatile compound and evaporates during the drying phase. *Pigments* are used to give the paint its colour and can either be from natural (e.g. raw earth pigments) or synthetic (engineered molecules) sources. They also provide a barrier mechanism in the paint, protecting the underlying substrate from ultraviolet degradation. In addition to these three main components, most modern coatings also contain various additives such as fillers, biocides, thickeners, wetting agents, defoamers, etc. to give the paint certain properties.

2.3.2 Types of paints

The three types of commercially available paints that are chosen to be part of this research are: Linseed Oil, Alkyd and Latex paints. The rationale for selecting these three follows.

Linseed Oil Paint

Linseed oil paints have been around for hundreds of years as the oil is harvested from pressed flax seeds from the flax plant (Allbäck & Allbäck, 2004). The paint is composed of the pressed linseed oil (which acts as the binder and vehicle) and pigments, and can require, at times, the use of solvents for thinning. The raw form of the oil must be purified to remove proteins prior to using it as a coating. The raw oil takes a long time to dry so it is less commonly used in paints, instead boiled linseed oil is used as it dries faster. Contrary to its name, it is not boiled, but is made by adding metallic dryers such as manganese to speed up its drying rate. Historically lead was used to aid in the drying times and increase the film durability but has since been banned due to being hazardous to health. Linseed oil paint was selected for this research due to its historical application, appreciating that it is available commercially.

Alkyd Paints

Alkyd paints use alkyd resins as the binder, which are polyesters modified with fatty acids. Vegetable oils such as linseed are used in alkyds due to their fatty acid compositions which give the paint its cross-linking potential, flexibility, gloss, and compatibility with solvents (Ploeger et al., 2008). Alkyds are classified by their oil length, which indicates the fatty acid percentage: short, 35-45%, medium, 46-55%, long, 56-70% and very long, >70% (Ploeger et al., 2008). These paints can be advantageous due to their corrosion protection, durability, high gloss, and fast dryness (Sansonetti et al., 2016). Alkyd paints can either be solvent borne, or water borne. Conventional solvent borne alkyd paints dry by evaporation of the solvent and cure by oxidation of the binder. Due to the limitations of VOCs, waterborne alkyd paints were developed to limit the use of solvents. Given its popularity and wide use in many building applications is the rationale for it to be included in this research.

Latex Paints

The term latex is a general name for paints that consist of an emulsion of polymer microparticles. The binder consists of resin, which can be polymers, such as acrylic or polyvinyl acetate as but a few examples. These paints are water-based emulsions, meaning the pigments and binders are suspended in water and thus dry by evaporation of the water and cures as the polymers fuse to form a film (Dugan & Anthony, 2014). For similar reasons to that of the Alkyd paint, it too is included in this research work.

Both latex and alkyd paints typically contain additives, such as thickeners or surfactants, to give certain properties to the product. Surfactants are of concern in terms of moisture as they tend to increase its sensitivity if used in significant quantities (Gezici-Koç et al., 2018; Williams & Knaebe, 2000).

Of course, there are other types of paints used in the context of historic building maintenance, such as traditional mixes like lime wash, casein paint, etc. Because these paints are not typically sold pre-mixed commercially and as such they were not included in this research.

2.3.3 Adhesion and Moisture Blistering

Paint properties can be divided into different categories; those that are *decorative*, such as gloss and sheen, and those that are *essential*, such as adhesion and film integrity, and those that are *specific* to certain applications, such as corrosion resistance, liquid water resistance, etc. These properties are related to the film of the paint and are constantly changing overtime as the paint film ages, noting that the most tested properties are usually quantified for a newly formed film.

Adhesion

Adhesion of the paint film is determined by the strength of the bonds formed between the paint and the substrate. There are various forms and theories for adhesion. Adhesion between the paint and substrate is generally achieved through adsorption, mechanical interlocking and chemically. Mechanical interlocking is provided by the surface roughness of the substrate, but also the through penetration of the paint into the pores of the substrate that is dependent on both the pore and molecule size of the substrate and binder. The molecule size of linseed oil paints, and alkyd paints to some degree, allow for penetration into the wood substrate, while the molecule size of latex/acrylic is too large. Primers are typically used for the first coat when painting, as it will penetrate the substrate and provide a surface for the subsequent paint coats to adhere to (Browne, 1933).

It is known that the moisture content of the substrate weakens the adhesion between the paint-substrate interface, negatively impacting the service life of the paint and siding (Ahola, 1995; Brunt, 1964; Hopkins & Gibbons, 1953; Iliff et al., 1939; Tibbetts, 1966; Williams et al., 2000; Yamasaki, 1965). Recommendations are provided for the various levels of moisture content when applying paint to wood to ensure the optimal adhesion of the paint. For example, paint being applied to exterior wood should optimally be at a moisture content of no more than 15%, and for interior wood 12%. Multiple studies have found that coatings applied to wood substrates at higher moisture contents notably decreased the ability for it to adhere (Ahola, 1995; Bardage & Bjurman, 1998; Sonmez et al., 2009).

Moisture Blistering

Less is known about the impact of the moisture content throughout the service life of the siding. For example, at what duration and level of moisture content throughout its service life will the paint layer start to lose its adhesion? It is evident that moisture plays a role in the blistering and ergo its subsequent loss of adhesion to the wood substrate. In taking a closer look at the various mechanisms that cause blistering to occur there are two moisture related theories that primarily lead to this: volume expansion (swelling); or osmotic pressure (Kunke, 1981; Touyeras et al., 1997). Touyeras et al considers the relationship of osmotic pressure and blistering on polymer substrates, which include critical limits of elasticity and breaking loads of the paint film (Touyeras et al., 1997). Brunt investigates the impact of swelling on the blistering of paint layers as an alternative theory to blistering via pressure, suggesting that no pressure is needed to lift the paint layer. Rather an increase in volume causes swelling, which is followed by a loss in adhesion (Brunt, 1964). He mentions that a period of uninterrupted contact (several days) with a liquid is required (water is not the only liquid to cause blistering), therefore according to Brunt moisture blistering will not occur below 100% RH.

Hopkins and Gibbons observed a seasonal tendency with blistering when the wood MC was above 20% (Hopkins & Gibbons, 1953). In the late winter/ spring blistering would occur, as the MC was the greatest at that time of year. Another report explains that the seasonal moisture blistering is due to condensation from water vapour within the walls after the frost starts to melt; while other moisture sources, such as plumbing leaks, will not be seasonal and be more localized (Forest Products Laboratory, 1970).

Paint Properties and Moisture Blistering

Different paint types are susceptible to blistering based on various factors. One of the factors includes its pigmentation and the nature of its binder. Brunt explains that the acidity of the pigment can cause the binder to shrink (under acid conditions) of swell (under alkaline conditions) if the binder is of polar character (Brunt, 1964). Binders that dry under oxidation, such as oil-based paints (linseed oil and oil-alkyds), have more polar groups, which make them more susceptible to swelling or shrinking based on the acidity of the pigment. The degree of penetration is another factor to consider, as it increases the adhesion to the substrate. Emulsions, due to their larger molecule size, do not penetrate much into the substrate compared to linseed oil paint or other solvent-based paints. Ahola found that penetrating paints are less susceptible to an increase in water content in comparison with emulsions (Ahola, 1995).

2.3.4 Factors that Affect the Water Transport Properties

The manner in how paints manage moisture entering the wood substrate (in liquid and vapour form) is critical. The key to protecting wood is finding the optimal balance in preventing the ingress of liquid water, while allowing for any water vapor to escape (permeable to water vapor). This way the paint provides protection from rain but does not entrap in any water vapor which may need to dry towards the exterior. Both the water vapor permeability and the liquid adsorption factor are important properties when discussing the transport of movement through not only the paint layer, but all materials in the building envelope. Other factors that influence the water transport of films include the ratio of pigments to binder, film thickness, age, temperature, and film defects.

Moisture can get across a paint film either through defects (cracks/ holes) in the film or through the paint itself (based on its permeability). Within the paint film there are various transport pathways, depending on the porosity, that allow for capillary transport or diffusion of water vapour (de Meijer & Nienhuis, 2006). The porosity can occur at a micrometer level where air inclusions or defects decrease the effective thickness or provide channels for transport. At the nanometer level where voids are created from the particles in the paint. Figure 2.11 shows the nanometer range for the porosity of a waterborne coating and its resulting moisture transport pathways.

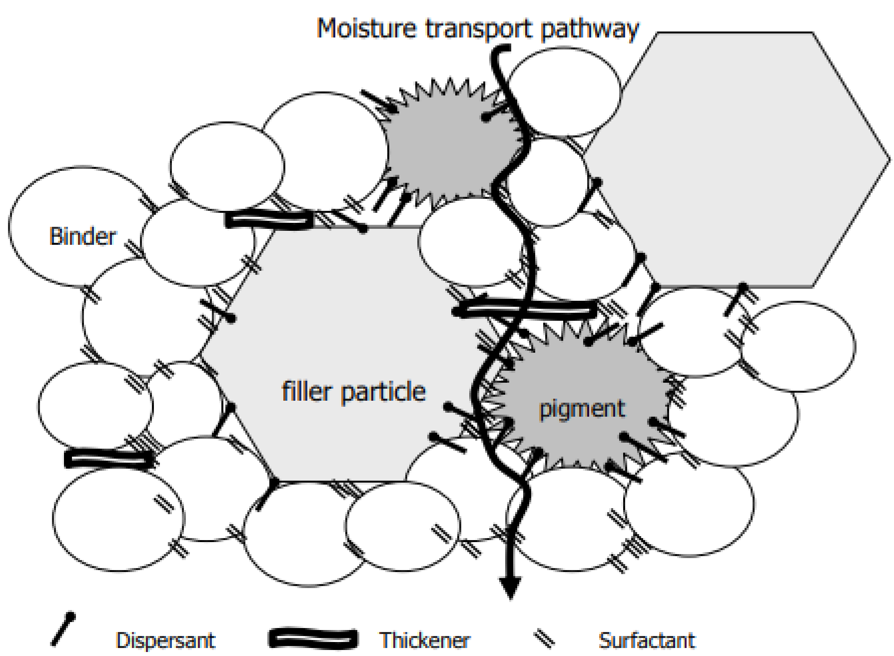


Figure 2.11 Moisture transport pathways through paint film (de Meijer & Nienhuis, 2006)

Film Thickness

The permeability of paint is dependent on its thickness. The thicker the film, if intact, the less transmissive it will be to both vapour and liquid, allowing for greater moisture protection and coating durability. Although, the performance of applying multiple thin coats compared to one thick coat may differ as a thicker coat can increase the probability of flaws occurring (Graystone, 2001). Supporting this idea, various studies have found an increase in the Sd-value (decrease in permeability) as the number of paint layers (thickness of entire paint system) increases (Šadauskiene et al., 2009; Šemjakin et al., 2016).

Ageing of Film

The testing data from literature used for the moisture transport properties of the various paints represents an initial understanding of the material properties. The paint films, like most materials, are in a constant state of change. One of the more notable states of change occurs when the paint film dries to a cured film that provides the protection against moisture. Over time, the films age and degrade at different rates based on the exposure to various environmental conditions. Edwards describes the aging cycle in relation to moisture impedance as an initial period of little change, followed by a sharper increase in impedance as the film hardens, which is then followed by a decrease in the moisture impedance (Edwards & Wray, 1936). The rate at which these properties change depends on the overall durability of the paint.

Pigmentation

Uemoto et al, tested the water absorption of various latex paints on concrete and mortar substrates, it was found that the paints with low pigment/binder ratios provided good barriers for water penetration, but would slow down the evaporation process where any residual water needed to escape (Uemoto et al., 1998). While Graystone notes that an increase in pigmentation slows down diffusion and reduces the permeability as the pathways for diffusion are more indirect (Graystone, 2001). De Meijer explains that the pigment/fillers in a paint formulation are less permeable than the binder, which is why an increase in pigmentation decreases the paint's permeability (de Meijer & Nienhuis, 2006). An increase in permeability can also be found with increased pigmentation, for example if the pigment is not wetted by the binder or is coated with a water sensitive material. As well, if the pigment volume concentration is above the critical level, then voids can arise (de Meijer & Nienhuis, 2006; Graystone, 2001).

Temperature

De Meijer & Militz tested the rate of moisture sorption of several paints on spruce samples (de Meijer & Militz, 2001); intuitively, this is expected as the increase in temperature correlates to faster moisture diffusion. Lighter coloured paints have been studied to have greater moisture contents compared to darker paints, as they absorb less energy from the sun (Grüll et al., 2013).

Film Defects

Grüll & Truskaller observed the sensitivity of coating systems (film forming, non-film forming) to mechanical film defects (knife cuts of 0-5mm depth) (Grüll & Truskaller, 2014). It was seen that non-film forming coatings with penetration down to the depth of the cut prevented moisture ingress due to their hydrophobic ingredients. Although the film forming coatings allowed for significantly higher water permeability, indicating that the moisture protection is from the film rather than the hydrophobic additives. This shows the benefit of using a paint system that penetrates deeper into the substrate for increased protection from moisture despite film defects.

2.4 Wood and Paint Interactions

Earlier, it was explained how moisture is transported within wood and the damages that can occur. This section will look at the characteristics of wood and how they affect the durability of the paint.

Using a paint finish will not necessarily prevent decay of the wood but should function to lower the range of moisture within the wood. Decay issues in painted wood may occur in situations where moisture is able to get into the wood under the paint film. This can occur either from interior moisture sources or through defects in the film where the moisture is unable to dry out properly. Rowell et al provide an overview regarding the role that moisture has in the durability of coatings (Rowell & Bongers, 2017). They explain that moisture absorbed through the end grain of wood can result in swelling and failure of the coating as moisture weakens the interface between the two materials. A failure such as a crack in the wood can have negative consequences for the wood, as water can then penetrate the wood, resulting in potential conditions for decay.

2.4.1 Wood Characteristics Affecting Paint

Williams et al. summarizes how various wood properties affect the service life of finishes. Properties such as growth rate, density, ring orientation, knots and extractives were found to impact the finish (Williams et al., 2000). These properties vary among species of wood, thus must be understood when choosing to paint wood.

Density and Grain Characteristics

The density, or specific gravity, of wood is one of the most important factors in affecting the paint adhesion. Higher density woods shrink and swell less than lower density woods. Having a lower density wood is more favourable as it reduces the stress on the paint film from dimensional changes that occur with shrink and swelling of the wood.

There is a difference in density based on the growth rate and rings of wood. The growth rings are comprised of a lighter band, known as earlywood and a darker band, known as latewood. The latewood band is composed of smaller cells with thicker cavities, thus is denser. If the difference in density between the bands is large enough, the abrupt change in density can cause adhesion issues due to the stresses from swelling. In addition, having an edge grain vs flat grain cut impacts the paint adhesion. As seen in Figure 2.12, flat grain boards have wider bands of latewood, therefore will shrink and swell more compared to an edge grain board.

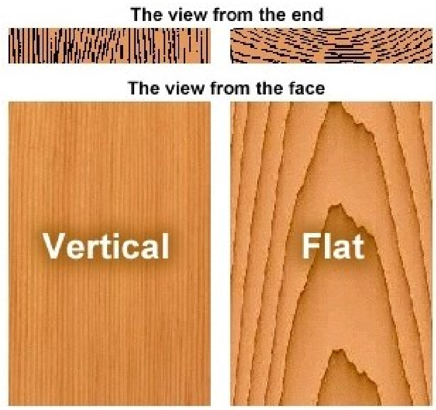


Figure 2.12 Vertical and flat grain cuts for wood (Jasco Forest Products Ltd, n.d.)

Knots and Extractives

Knots are imperfections in the wood that represents where the branch was incorporated with the stem. Depending on the grade of lumber, knots of various sizes and shapes will be present in the cut of wood. Knots are usually denser and contain resins that may bleed out and discolour the paint surface if not properly treated.

The heartwood (darker layer inner of the sapwood) contains extractives, such as tannins and polyphenolics, which contribute to the natural decay resistance of some wood species. These extractives can also discolour the paint film if not properly treated as well.

2.5 Impact of Insulation Retrofits

Traditionally buildings were constructed to allow moisture to move and "breathe" across the envelope (J. W. Lstiburek, 1990). In pre-1950's wood frame construction, the cavity space was left uninsulated to allow moisture laden air to move in and out. Since then, in modern construction and energy retrofitting interventions include adding insulation to the walls and creating a more airtight barrier. Insulation retrofits in existing buildings allow for energy savings and occupant comfort; whereas some of these retrofits can have negative consequences on the wood frame construction as it alters the drying potential of the wall system. It is important to ensure that any retrofit strategy does not result in greater accumulation of moisture in the assembly, therefore an understanding of the moisture and thermal dynamics of the assembly must first be done. In particular, insulation retrofits have been found to be a leading issue in paint failures on wood siding as it promotes higher moisture levels (Lstiburek, 1990).

2.5.1 Insulation Retrofit Options

One of the less intrusive retrofit measures includes adding insulation to the stud cavities (if not already present). This can be done by various methods (blown in or removing the sheathing to place batts). This method is the least intrusive and does not change the thickness of the wall, but the amount of insulation is constrained to the thickness of the stud cavity. In some climates, the achieved RSI value still does not meet code targets for energy efficiency or airtightness and furthermore invasive insulation retrofits must be explored (Baker, 2013). Thermal bridging of the stud cavity also reduces the effective RSI that the retrofit can achieve.

To obtain a greater RSI value, exterior or interior insulation can be added in addition to cavity insulation. Adding insulation externally to the stud cavity is another retrofit option that can also act as the air barrier and the advantage of keeping the structural elements in the assembly at a more even temperature throughout the year reducing the risks of condensation (Troi, 2014). Although there are reasons for not opting to use exterior insulation especially for historic buildings as it can alter the facade, even if placed under existing siding it can be a challenge to keep the detailing around windows and doors (Arumägi et al., 2015; Baker, 2013; Smith, 1978). In addition, there may be insufficient space due to neighbouring buildings or the roof overhang may not be sufficiently wide enough to provide proper protection to the new wall thickness (Smith, 1978). Depending on the permeability of the insulation used, exterior insulation can reduce the drying to the exterior, therefore it is important to manage the bulk water entry into the wall by creating the air space (Baker, 2013).

If exterior insulation is not a compatible retrofit option, adding insulation to the interior side of the cavity can be done. This method is less intrusive to the exterior heritage fabric, although it reduces the interior area of the building. There are concerns with adding interior insulation as it makes the walls colder in the winter, increasing the risk of condensation (Baker, 2013; Smith, 1978).

2.5.2 Heritage Guidelines - Insulating Walls

Castele and Webb reviewed existing guidelines for insulating the walls of heritage buildings, finding discrepancies between recommended retrofit procedures (Castele & Webb, 2019). The insulation types, vapor control methods, location, and the decision to use insulation in walls differed between the various sources, some being contradictory to each other. It highlighted the need for a better understanding of best practices when it comes to using insulation within the walls of historic buildings. Although, the best procedure may be to first understand the existing materials and moisture balance of the building assembly prior to undertaking any retrofits, especially as the solution differs between climates and construction types.

2.5.3 Insulation Related Paint Failures

Lstiburek studied the failure of exterior paints on wood siding in buildings that have had recent insulation retrofits within the cavity or using insulating sheathing (Lstiburek, 1990). In the study the failures had occurred after a couple of years including peeling paint, warped siding and cupping after the insulation was added. Four different categories of cases were described to explain how insulation might induce problems for the siding and paint. In each of the cases, the insulation reduces the drying potential of the exterior components, but this is also dependent on the type of blown insulation used.

Chapter 3: Methodology

This section will give an overview of the methods used to analyze the moisture conditions of painted wood siding. There are two analysis tools that are used to support this, they are the Dew Point method and WUFI Pro. Given the prominence of WUFI Pro it is the key tool that underpins the analysis supporting the methodology used in this research. By contrast, the Dew Point method is limited in its ability to analyse moisture transport, as it only considers vapour diffusion. However, tangentially for this work there was utility in utilizing the Dew Point method as it allowed comparisons to be made with WUFI Pro as it relates to the contribution from vapour sources at the siding's interfaces. The Dew Point method is further explained in Appendix D, and it provides the analysis and results obtained.

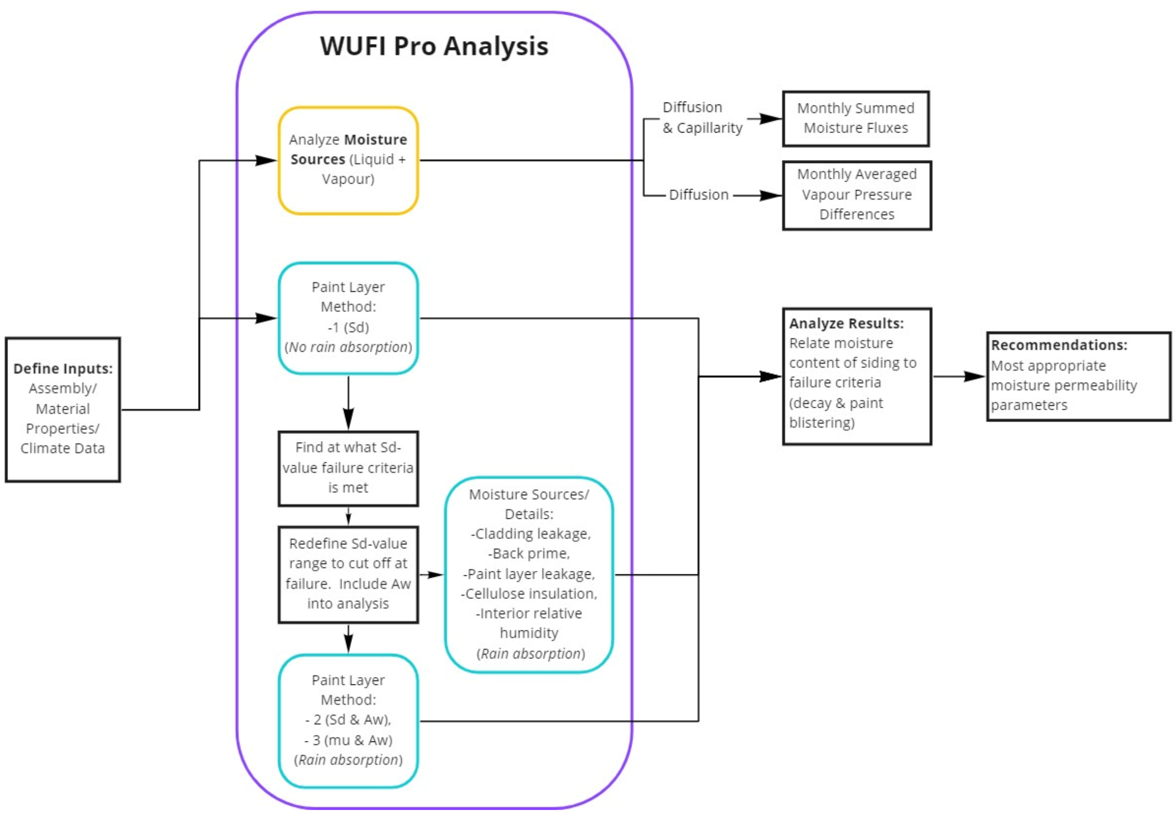


Figure 3.1 Methodology workflow

The methodology for this research is depicted in the workflow at Figure 3.1. As an overview, the defined inputs for the building structure are entered into WUFI Pro and from the analysis the results are provided. The analysis of the findings shows how the permeability of the paint layer, represented in terms of its Sd-value and Aw coefficient, effects the moisture conditions of the wood siding. In particular, it illustrates which vapour and liquid permeability combinations are most favourable, and flags if there are permeabilities that put the siding or paint layer at risk of failure due to moisture. From this, recommendations can be made as to the most appropriate application for given building assemblies within their respective environments. Analysis of the moisture sources are also produced as this provides insight into the moisture conditions.

3.1.1 Building Assembly

The building assembly used for this research is based on the ones typically used in pre-1950's wood framed buildings. Wood frame buildings during this time typically did not contain vapour barriers, nor an air space behind the siding (rainscreen), seldom did they contain insulation, and they were usually drafty. Figure 3.2 and Table 3.1 outlines the material components selected for the idealized pre-1950's building assembly. The detail of the siding is not of importance for this research as WUFI Pro only considers the 1-D transport across a uniform surface. The air flow across the assembly is not considered in this research as it is difficult to quantify especially as its pathways are multi-dimensional.

Table 3.1 Wall Assembly Material Components

Material Category	Type
A. Exterior Paint	Colour – white
B. Cladding	Eastern white pine
C. Building Paper	60-minute building paper
D. Sheathing	Spruce board sheathing
E. Cavity	Air cavity –89mm
F. Interior Finishing	Spruce board sheathing

*detail/style of siding not considered

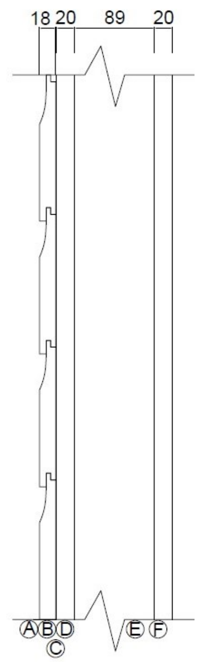


Figure 3.2 Wall Assembly Cross Section

3.2 Building Envelope Simulation

As mentioned earlier, the moisture conditions within the wood siding of the wall assembly were analyzed to assess the trends in moisture content of the exterior paint layer's permeability. The first analysis uses the Dew Point method for every hour of the year to examine the vapour pressure profile and determine where the condensation plane occurs. Solar radiation is taken into consideration by adjusting the surface temperature, but rain absorption or moisture redistribution from the condensation plane is a limitation of the Dew Point method and therefore not captured as part of the analysis. In using the WUFI software, it considers both moisture movement from vapour diffusion as well as liquid transport through capillary conduction & surface diffusion, and unlike the Dew Point method it includes rain absorption and a more in-depth solar radiation contribution. Both the Dew Point method and WUFI software use similar climatic conditions (temperature and relative humidity) and wood frame construction assembly as depicted for the wall assembly in Figure 3.2. Of note, the wood siding is analyzed from a wall assembly perspective, ergo the importance of understanding and factoring in the impact of the interior's relative humidity as a moisture source that can affect the siding material.

3.2.1 WUFI Analysis

To analyze the contribution from both vapour and liquid sources, the transient hygrothermal software WUFI Pro 6.5 was used. This software was chosen as it is widely used for hygrothermal analysis throughout industry. In addition, it has undergone multiple validation studies resulting in positive feedback, there is plenty of instruction on how to use it online, it is easy software to learn, but necessitates sufficient knowledge and experience when choosing the right inputs and the interpreting of results obtained, and lastly a student license for it use is available. Specifically for this research work, WUFI Pro was used, which is the 1-D version within the WUFI Software Family. Furthermore, a 1-D as opposed to 2-D analysis version was chosen as the construction as the modeling did not involve any detailed or complicated geometries. Given that it is a 1-D analysis it does not include the impact of thermal bridging for wood studs. In addition, the effect of air pressure differentials is not considered, thus the analysis takes place at the neutral pressure plane where the air pressure differential is zero.

As part of this research, the rationale for comparing the hygrothermal software results with those obtained from the Dew Point analysis is beneficial in assessing the overall impact that liquid sources, such as rain, water leakage, as well as how water vapour that has condensed are distributed within porous materials. Table 3.2 shows the heat and moisture mechanisms considered by WUFI. While it includes many more heat and moisture transport mechanisms in comparison with the Dew Point method, there are still major transport mechanisms that are not considered, such as: vapour convection as airflow is difficult to model within the assembly, or ground water uptake through capillaries as a moisture source.

Table 3.2 WUFI Moisture and Heat Considerations (WUFI, n.d.)

	Heat	**Vapour**	**Liquid**
Included	• thermal conduction • enthalpy flows through moisture movement with phase change • short-wave solar radiation • nighttime long-wave radiation cooling	• vapor diffusion • solution diffusion	• capillary conduction • surface diffusion
Not Included	Convective heat transport by air flows has been disregarded since it is usually difficult to quantify and rarely one-dimensional	Convective vapor transport by air flows has been ignored	Seepage flow through gravitation, hydraulic flow through pressure differentials, as well as electrokinetic and osmotic effects have not been included

3.2.1.1 Material Properties

The material properties seen in Table 3.3 are taken from the WUFI database. The properties include density, porosity, specific heat capacity, thermal conductivity, and water vapour diffusion resistance of the material. It should be noted that the results of the simulation are dependent on the accuracy of the inputs, so there exist limitations to using the material properties in the database rather than doing the testing on the actual materials in use. For example, Boardman and Glass conducted a study where they used WUFI to simulate various wood frame wall assemblies and compared it to measured results. Based on their work they were able to improve the accuracy of their hygrothermal model inputs (Boardman & Glass, 2020). For this research, a base case assembly that does not include a paint layer is used to compare varying simulation cases.

Table 3.3 Material Properties for WUFI Simulation

Material	Thickness [m]	Density [kg/m^3]	Porosity [m^3/m^3]	Specific Heat Capacity [J/kgK]	Thermal Conductivity [W/mK]	Water Vapour Diffusion Resistance [-]
Eastern White Pine	0.018	460	0.81	1880	0.093	4427*
60-minute Building Paper	0.001	280	0.001	1500	2.3	144*
Spruce	0.02	400	0.9	1880	0.086	552*
Air layer 90mm; without additional moisture capacity	0.09	1.3	0.999	1000	0.523	0.17
Spruce	0.02	400	0.9	1880	0.086	552*

*Moisture dependent water vapour diffusion resistance, value shown is for RH = 0%, see Appendix E for moisture storage functions

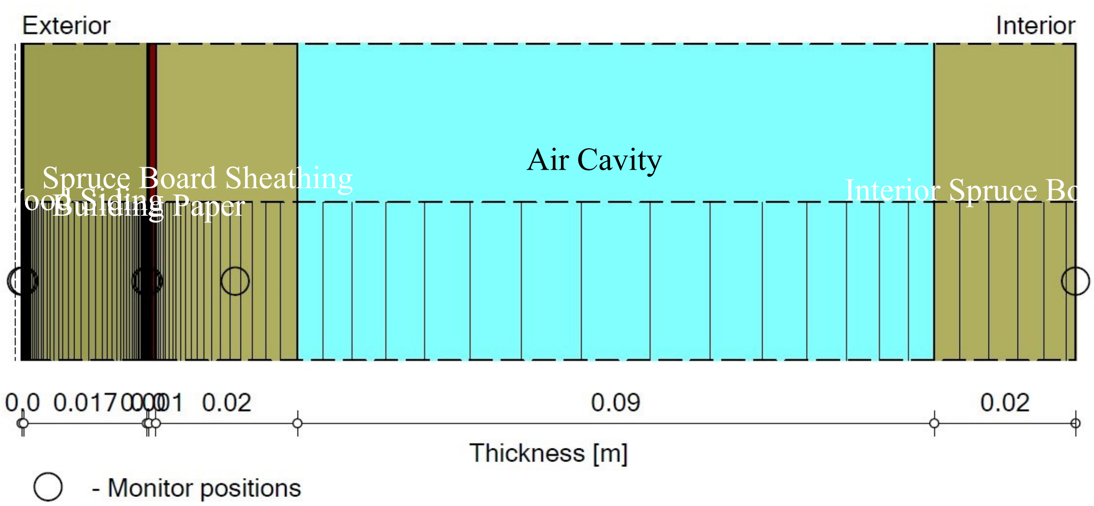


Figure 3.3 Assembly components as seen in WUFI

Figure 3.3 shows the wall assembly components as entered within WUFI. The exterior siding is broken down into three layers to distinguish the moisture content at the outer (0.3mm), mid (17.4mm) and inner (0.3mm) portions of the wood. This was done to get greater insight into how moisture is locally distributed within the siding. Especially as localised areas of high moisture at the outer siding will provide increased conditions for paint failure due to moisture. The outer layer will be more sensitive to changes in the exterior environment, whereas the inner layer will be more sensitive to the interior environment, and the mid layer will show more of an average moisture content. Had the siding been simulated as one layer, as opposed to the three layers depicted in Figure 3.4, the results would show the average moisture content throughout the material producing less accurate results. This method was used by Lstiburek et al for the sheathing layer, as moisture failure of the sheathing is typically associated with its interior or exterior face (Lstiburek et al., 2016).

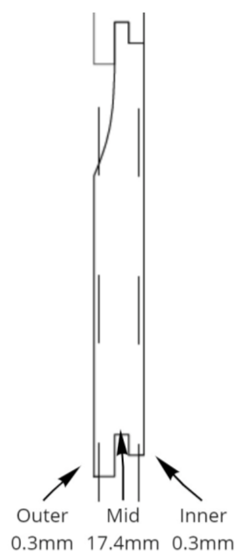


Figure 3.4 Outer, mid and inner layers of the wood siding

3.2.1.2 Sources and Sinks

In addition to the moisture source from rain adhering to the exterior and absorbing into the wood siding, additional moisture sources can be specified. The base case scenario does not include any additional moisture sources. Additional moisture sources will be explained in the simulation cases section.

3.2.1.3 Boundary Conditions

Table 3.4 WUFI Boundary Conditions

	Base Case	***Other Cases***
Orientation	Northeast	Northeast
Inclination	90º	90º
Building Height/ Driving Rain Coefficients	Short building, height up to 10m R1[-] = 0; R2[s/m] = 0.07 Rain Load = Rain*(R1+R2*Wind Velocity)	Short building, height up to 10m R1[-] = 0; R2[s/m] = 0.07 Rain Load = Rain*(R1+R2*Wind Velocity)
Exterior		
Heat Resistance [m2K/W]	0.0588 (External wall)	0.0588 (External wall)
Sd-value [m]	No coating	Range: 0.5-2.0m
Short-Wave Radiation Absorptivity [-]	0.4 (Wood – untreated)	0.2 (White paint)
Ground Short-Wave Reflectivity [-]	0.2	0.2
Adhering Fraction of Rain [-]	0.7 or 0 (if want no rain absorption)	0.7 or 0 (if want no rain absorption)
Interior		
Heat Resistance [m2K/W]	0.125	0.125
Sd-value [m]	No coating	No coating

Exterior Climate

The exterior conditions are modeled using data from 2010-2019 as measured from the Ottawa International Airport. This data captures temperature, relative humidity, short and long wave radiation, wind speed and its direction, rain, and air pressure. Figure 3.5 shows the summed solar radiation and driving rain based on the various orientations, noting that the Southwest one receives the most solar radiation, whereas the East one experiences the greatest driving rain. The Northeast direction was chosen for the orientation for the assembly as it has a large driving rain load and the lowest solar radiation exposure, thus simulating a worst-case orientation for moisture.

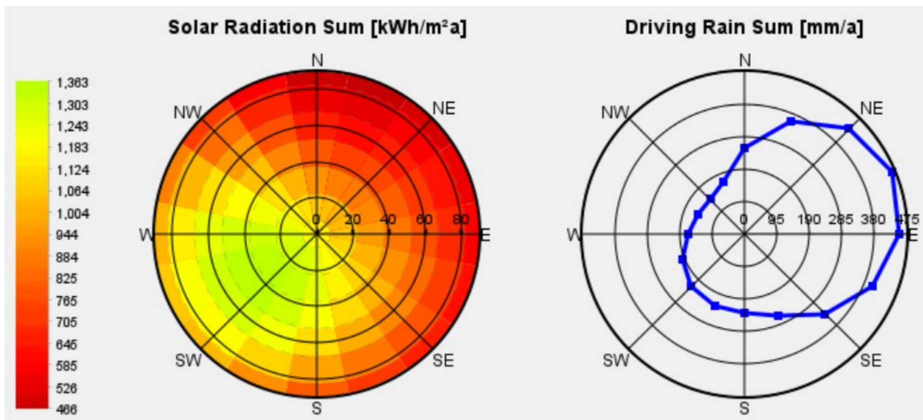


Figure 3.5 Solar radiation sum and driving rain sum based on orientation

Interior Climate

The interior climate is simulated using the ASHRAE 160 method, in which the heating only option was selected with a heating set point of 21.1ºC, as it is the default setting (ASHRAE, 2016). The moisture generation rate is based on a two-bedroom occupancy, the air exchange rate was set for standard construction (0.2), and the building volume set to 500m^3. Interior RH control via AC or dehumidification was not selected, although within this ASHRAE method WUFI caps the RH levels at 70%. Figure 3.6 shows the interior temperature and relative humidity simulated by WUFI.

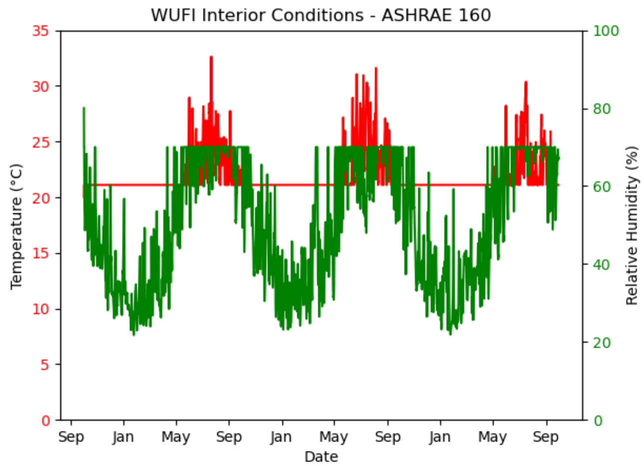


Figure 3.6 Interior conditions in WUFI based on ASHRAE 160

Initial Conditions

The initial water content of the materials was set to reflect the dynamic equilibrium of the construction. The base case assembly, as depicted earlier in Table 3.4, was run for three years in order to illustrate the trends. The water content profile from these runs was then exported to a file which is then used as the initial conditions for the rest of the simulations. For the Eastern White Pine siding, the equilibrium moisture content in the summer was around 9-10%, which seems low compared to the rule of thumb for the exterior EMC for wood typically used in Ottawa's climate which is closer to15%. The EMC of the wood will depend on the moisture storage function of the species. Within the material properties in WUFI for Eastern White Pine, the moisture storage function shows that for a RH of 70-80% the EMC of the wood is around 8%.

3.2.1.4 Numerical Considerations

The calculation period covered a three-year timeframe with one hour time intervals. A three-year period was chosen in order to observe the trends in moisture content. For example, to see if moisture accumulation or further drying occurs in the various seasons. Both heat and moisture transport (vapour diffusion and capillary conduction) calculations were also factored in.

3.2.1.5 Simulation Cases

In total there are three methods and five cases that were run through the WUFI software as depicted in Figure 3.7 and Table 3.5. Each depicts differing conditions that for the most part are assessed against the same range of permeability levels. The three methods and five cases are explained further in this section, and they are as follows:

- Three different paint layer methods;
    - Method 1 – Sd (Vapour);
    - Method 2 – Sd & Aw (Vapour and Liquid)
    - Method 3 –μ & Aw (Vapour and Liquid)
- Five different moisture cases
    - Case 1 - Rain leakage behind cladding
    - Case 2 - Back priming the wood siding
    - Case 3 - Rain leakage through the paint layer
    - Case 4 - Insulating the cavity with cellulose
    - Case 5 - Interior relative humidity levels

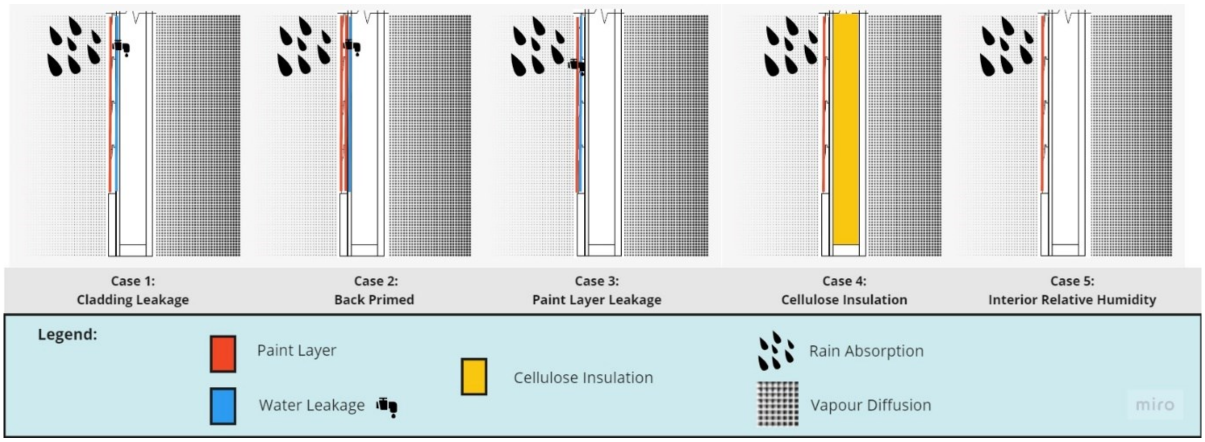


Figure 3.7 Outline of WUFI simulation cases – three methods not shown in image

Method 1 – Sd Vapour:

This first method focuses on the effects of the paint layer's vapour permeability. Only the Sd-value is specified through the exterior surface transfer coefficients. The adhering fraction of rain was set to 0 so that no rain absorption is modeled.

Method 2 – Sd & Aw (Vapour and Liquid)

This next method uses the same approach to model the vapour permeability, but this time it includes the Water absorption coefficient, Aw, to assess the liquid permeability, therefore rain absorption is factored in. The Aw coefficient is a property that needs to reflect the material properties, as it changes the way liquid is absorbed and distributed within the material. The material properties of the outer 0.3mm siding was adjusted to more accurately represent the liquid absorption of the paint layer. This is the reason why such thin layers were chosen for the outer and inner layers, as it better represents the moisture permeability of a paint applied to it.

Method 3 - μ & Aw (Vapour & Liquid)

The third method for modeling the paint film uses the same method as the second one above, with the exception that a different method is used for vapour permeability. Rather than changing the Sd-value within the 'Surface Transfer Coefficients' tab, the μ-value is adjusted in the material properties. For the outer wood layer, Eastern White Pine, the μ-value is moisture dependent, meaning it changes with the relative humidity. Since the moisture dependence of the permeability is not accounted for in any of the other cases, the μ-value is set to a constant value. To calculate the μ-value that corresponds to the same Sd-values, the following equation was used, with a paint layer, thickness of the 0.0003m:

$$\mu = \frac{Sd}{\Delta x} \quad (16)$$

Case 1 - Rain leakage behind cladding:

This next round of simulations includes a moisture source to represent rainwater leaking behind the cladding and absorbing into the building paper. Figure 3.8 shows the inputs in WUFI to assign the moisture source, where 1% of the driving rain is absorbed up to 0.003m into the building paper, with a cut off at free water saturation. The purpose of this first case is to show how a moisture source behind the cladding is affected by a less permeable paint layer.

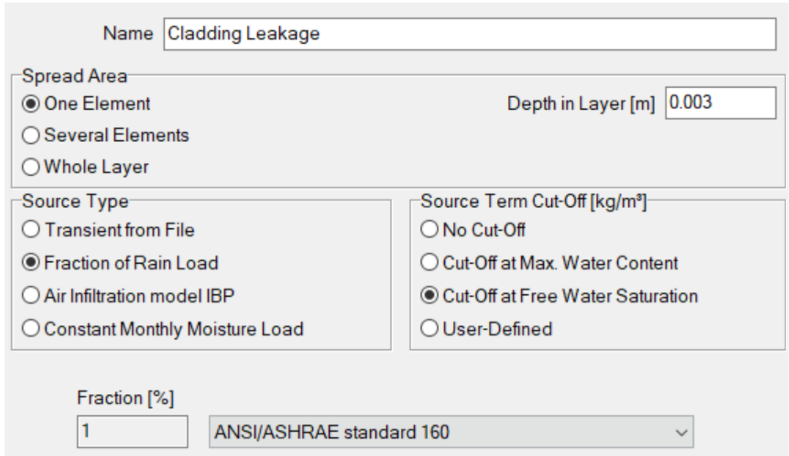


Figure 3.8 Moisture source settings for rain leakage behind cladding

Case 2 - Back priming the wood siding:

Back priming of the siding is when the sides and back side of the siding is painted to provide full protection from interior moisture sources, such as when water gets behind the siding. This technique aims at reducing the amount of moisture absorbed through both capillary and vapour diffusion sources. The purpose for back priming is to increase the retention of the exterior paint by inhibiting moisture from entering the siding from the interior (Burke et al., 2009). Back priming can be done in situations where the wall does not have an air cavity behind the cladding, although using an air cavity in combination with back priming would be even more effective as the air cavity provides a capillary break and ventilation of the siding (J. W. Lstiburek, 1990).

In this case, the rain leakage moisture source used in the previous case is applied for this one to observe how effective the back priming is at avoiding moisture content increases due to leakage. To simulate the back priming of the siding, two paint layers need to be modeled: one for the exterior of the siding; and the other for the interior face of the siding. A combination of Methods 2 and 3 was used since an Sd-value via the Surface Transfer Coefficients cannot be specified within the wall. The exterior paint layer is modeled using Method 2 (Aw & Sd), while the back priming paint layer is modeled using Method 3 (Aw & μ).

Case 3 - Rain leakage through the paint layer:

The permeability values of the paint layer are only significant if the paint layer is intact. If there is a hole or other defects within the film, the Aw coefficient of the paint is no longer what governs the liquid absorption through the paint film. Since WUFI is not able to model any defects in the material components, another moisture source type was used to represent water leakage past the paint film. The moisture source was kept at 1% of the driving rain to represent a smaller defect in the film. The exterior permeability is modeled using Method 2 (Aw & Sd).

Case 4 - Insulating the cavity with cellulose:

Many of the paint failures due to moisture found in the literature cited insulation retrofits as the culprit for increasing moisture in the siding resulting in paint blistering and loss of adhesion. Therefore, to model this a case was created where the air cavity is swapped for cellulose insulation to observe whether it increases the moisture content of the painted siding in comparison to the wall with the air cavity. To further understand the effects of insulation retrofits on the moisture content of the siding should include exploring the different types and placements of insulation. Since this research is not focused on insulation effects, only the effect of using cellulose was simulated.

Case 5 – Interior relative humidity:

The interior relative humidity within a building can be a significant moisture source. To assess what level of interior RH results in adversely affecting the siding, the RH levels in this case were modified to determine the threshold level. In scaling the interior RH, the sine curve option in WUFI was used. This in turn models the interior RH using a sine curve based on the mean value and amplitude. Figure 3.9 shows the three RH curves used, where the mean values are 50%, 60% and 70% with amplitudes of 10%. The maximum amplitude is in August and the lowest in February.

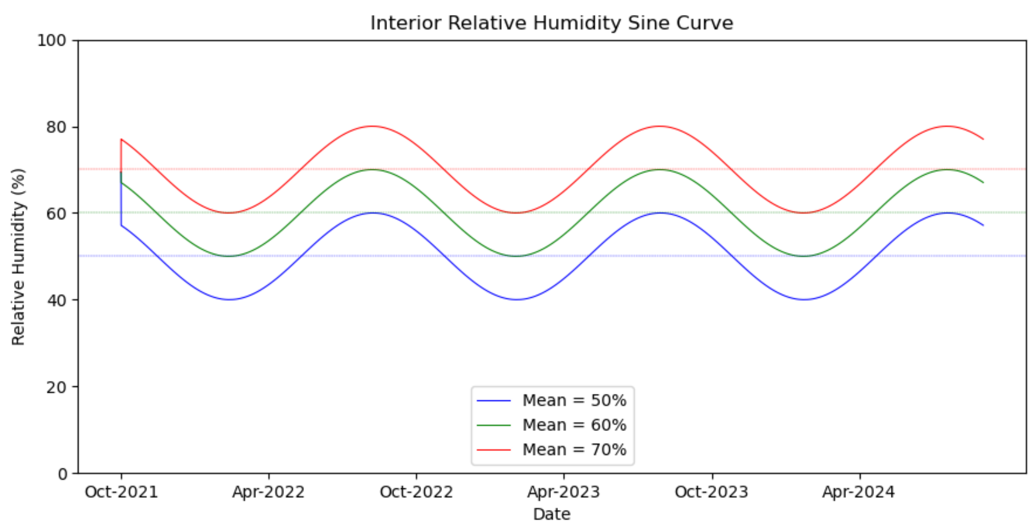


Figure 3.9 Interior RH since curves used for Case 5

Table 3.5 summarizes the three methods and five cases that were described above.

The Sd-values for Method 1 ranges from 0.3m-33m so that the values reflect the range of permeability classifications; 0.3m-0.5m being permeable, 1.0-2.0m semi-permeable, 4.0m semi-impermeable, and 33m impermeable. Based on the results from Method 1 the Sd-range was modified, capping the range once the failure criteria were reached. As a result, this capped Sd range is used for the remainder of the simulations which include liquid transport. The Aw values were chosen based on the classification from ENV 927-2 for liquid absorption based on the end condition of the substrate. An Aw of 0.0003 $kg/m^2h^{0.5}$ is the maximum value for a stable end use condition, while 0.0005 $kg/m^2h^{0.5}$ is the maximum for a semi-stable end use condition.

Table 3.5 Outline of Simulation Methods

Simulation Method	Number of Cases	Paint Layer Vapour Permeability	Paint Layer Liquid Permeability	Moisture Sources
Method 1	6	• Sd-values: 0.3m, 0.5m, 1.0m, 2.0m, 4.0m, 33m	• Ignore rain absorption	• No additional moisture source
Method 2	7	• Sd-values: 0.3m, 0.5m, 1m	• Aw: 0.0005 & 0.0003 $kg/m^2h^{0.5}$	• No additional moisture source
Method 3	7	• μ = 1000, 1666, 3333	• Aw: 0.0005 & 0.0003 $kg/m^2h^{0.5}$	• No additional moisture source
Case 1: Cladding Leakage	7	• Sd-values: 0.3m, 0.5m, 1.0m	• Aw: 0.0005 & 0.0003 $kg/m^2h^{0.5}$	• 1% driving rain, 0.003m into building paper
Case 2: Back Priming	17	• Exterior Sd-values: 0.3m, 0.5m, 1.0m • Back prime μ = 1000, 1666, 3333	• Aw: 0.0005 $kg/m^2h^{0.5}$	• 1% driving rain, 0.003m into building paper
Case 3: Paint Layer Leakage	7	• Sd-values: 0.3, 0.5m, 1.0m	• Aw: 0.0005 & 0.0003 $kg/m^2h^{0.5}$	• 1% driving rain, 0.0003m into mid wood siding
Case 4: Cellulose	7	• Sd-values: 0.3m, 0.5m, 1.0m	• Aw: 0.0005 & 0.0003 $kg/m^2h^{0.5}$	• No additional moisture source
Case 5: Interior Relative Humidity	7	• Sd-values: 0.3m, 0.5m, 1.0m	• Aw: 0.0005 $kg/m^2h^{0.5}$	• Mean RH 50%, 60%, 70%

3.2.1.6 Analysis Criteria

This section provides an overview of how the criteria for the simulations were analyzed. To begin with, the WUFI results were analysed for damages manifested through wood rot and/ or paint blistering on the siding. From each of the WUFI simulations the moisture content data from the outer, mid, and inner layers of the siding were exported to be used as inputs to create figures in Python. This data was plotted to permit the analysis of the siding material in determining whether the moisture content attained failure criteria levels for the various permeabilities. The two critical moisture content levels are 20% and 30%. The decay of the wood or blistering of the paint becomes less of a concern when the moisture content remaining below 20%, whereas moisture levels above 20%, though time dependant, presents a greater risk of failures. Generally, a moisture content level above 30% defines the wood as being saturated. Should it remain in this state for a prolonged period (several days) there is risk of the onset of decay in wood occurring. As well, at 30% MC the risk of blistering and loss of adhesion of the paint film is significantly elevated. However, this risk for the most part is eliminated in cold temperatures (i.e. below 0 ^{o}C).

3.3 Limitations

With almost all simulation models there are limitations when trying to replicate reality. The work for this research is no different as both software and process related limitations exist. The section will discuss these limitations for this work.

3.3.1 Methodology limitations

Ideally with most modeling, verification is often done through field testing. One of the main limitations for this research is that the was no specific field testing or validation to replicate that which has been simulated. Nevertheless, the modeling used for this research comes with a relatively high degree of accuracy given the validation work done by those who developed it. Although, the type of modeling done for this work is not reliant on the precise properties of the paint layer, rather it is testing a range of values that can help to better understand how these properties can be modeled for future simulations. As well, the methodology used in this research mainly considers the results for a paint layer that has no imperfections or other inadvertent ways for moisture to get past the film. The simulations are also not able to fully assess how a paint with greater penetration into the substrate might protect the siding from moisture. In addition, the material properties are never stagnant overtime and are changing as the paint layer ages and is exposed to the elements, which is not fully factored in this research. Due to COVID and time related restrictions the initial scope of this research was constrained in preventing material testing and fieldwork. It does however present an opportunity in the future for this to be done.

3.3.2 Software limitations

WUFI

While WUFI is a considerable improvement from the Dew Point method, as its analysis capability is more sophisticated, it too still has its limitations. Air leakage is a major source of movement of water vapour, but it is a difficult transport mechanism to model as there are many pathways for airflow. As well, there is no consideration for ground water uptake due to hydrostatic pressures, which can be responsible for a considerable amount of moisture if the siding is in contact with the ground.

As mentioned earlier, the effects of the building's construction detail (i.e. joints, flashing, lapping of siding, or building paper), workmanship, imperfections and the ageing process of materials used could not be factored in due to software limitations. The simulation of materials within the assembly is based on the accuracy of the material properties listed in the software's material library.

Chapter 4: Results

The following chapter presents the results of the WUFI analysis, incorporating the applicable figures to represent the findings. The results will be further deliberated on in Chapter 5. As previously mentioned, the Dew Point method work has been included in Appendix D, which includes results obtained.

4.1 Analysis

The first aspect to be analyzed from the WUFI outputs are the moisture sources in which the moisture flux at the siding interfaces is examined, followed by an analysis of the vapour pressure differences. Then, changes in the moisture content of the siding layers will be investigated using the various modeling methods for the paint layer's permeability and the change in the moisture sources.

4.1.1 Moisture Source Analysis

The moisture sources (vapour and liquid) are analysed to see how the moisture moves in and out of the siding. Figure 4.1 shows the MC of the base case wood siding (i.e. no paint) at its outer, mid, and inner points during rain events as measured over a three-year time period. From the information it can be seen that the spikes in the outer siding's MC levels significantly increased, in most cases above the FSP, whenever larger rain events (> 0.5mm) occur. The elevated levels of moisture content at this layer are not of significant concern as the Figure reflects a drop in MC levels back to its EMC shortly after a rain event. At this layer large fluctuations occur with changing weather patterns as would be expected. Like the outer layer, the mid layer also reflects MC fluctuations, as would be expected, however the peaks that correlate with the respective rain events are attenuated more, noting that few of these peaks exceed the FSP. The inner layer shows much more stable moisture conditions that are below the FSP throughout the time-period shown. It could be concluded from this analysis that MC over a representative three-year period for the given weather patterns is not a driving factor that necessitates protection of the wood from degradation due to moisture. Nevertheless, prudence dictates that protecting the wood would reduce moisture and lessen shrinking/ swelling fluctuations that effects other aspects of the building structure.

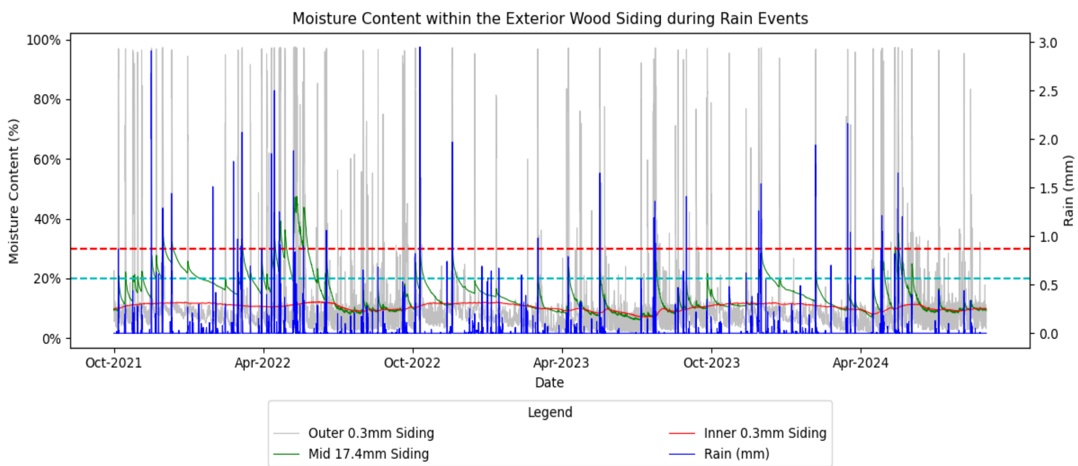
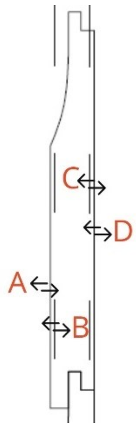


Figure 4.1 Moisture content of outer, mid, and inner layer of wood siding over three years and hourly rain fall

4.1.1.1 Moisture Flux Analysis

To investigate the moisture content of the wood siding further, the moisture flux at the interfaces of each layer is analysed. The moisture flux indicates the flow of moisture, via diffusion or capillarity, over the surface area of the wood. The interfaces can be seen in the Figure 4.2. A positive flux means moisture movement to the right of the interface, while a negative flux means moisture movement to the left. Therefore, depending on the interface of concern, the sign can mean either drying or wetting depending on the direction.



A = Exterior air to left side of Outer Siding

B = Right side of Outer Siding to left side of Mid Siding

C = Right side of Mid Siding to left side of Inner Siding

D = Right side of Inner Siding to Building Paper

Figure 4.2 Moisture flux interfaces

Figure 4.2 shows the summed flux per month at each interface in the final year of the simulation (2024). Interfaces A & B show the greatest contribution from capillary moisture, which indicates rain absorption effects. The capillary flux is positive, therefore the rain absorption is wetting the wood, as expected. In comparison, interfaces C and D show minor impact from capillary moisture flux, therefore rain absorption has less impact on the inner surface of the wood siding. Moisture flux via diffusion at the outer interfaces (A & B) are all negative, meaning the diffusion is outward to the exterior. The greatest diffusion flux occurs in May and June where the capillary flux is also the greatest, showing that the outer siding wets via capillarity and dries via diffusion. The inner interfaces (C & D) have a negative flux (wetting from interior) in the fall and winter months and positive fluxes (drying to interior) in the spring and summer months. Overall, the total flux for the outer siding is balanced between diffusion and capillarity, while the inner interfaces show a trend of total flux being negative (wetting) in the winter and positive (drying) in the late spring/ early summer. The significance of this analysis provides greater insight into moisture movement trend patterns and how it correlates to the drying and wetting of the siding.

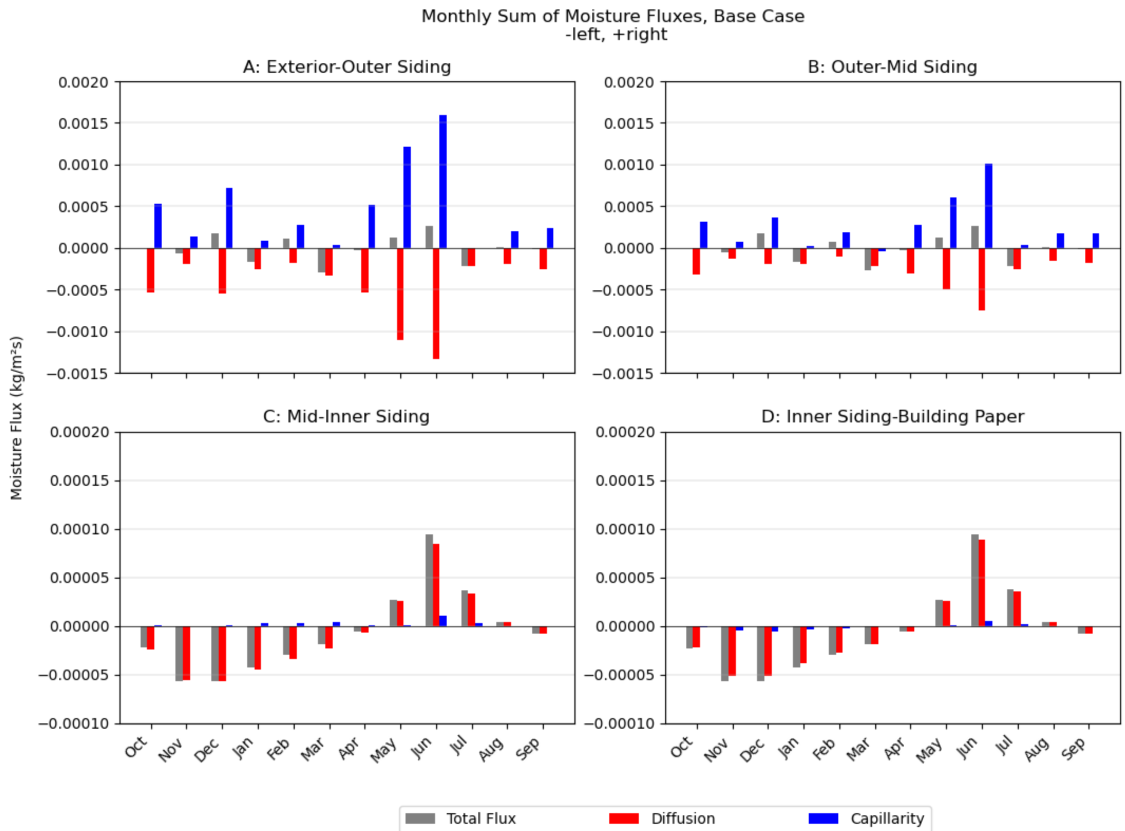


Figure 4.3 Monthly sum of moisture fluxes for the base case

The next section investigates the pressure differentials and how drying and wetting occurs via diffusion.

4.1.1.2 Vapour Pressure Analysis

The average vapour pressure difference was analysed for each month in the last year (2024) of the WUFI simulation. The vapour pressure difference is between the: i) outer siding (under the paint layer) to the interior (diffusion to interior); and ii) outer siding to the exterior (diffusion to exterior), as seen in Figure 4.4. The positive values represent drying while the negative represent wetting.

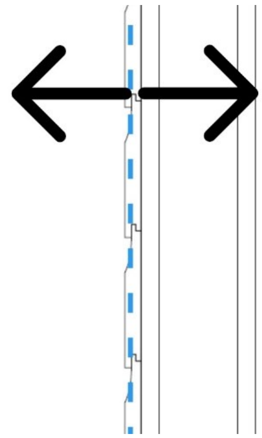


Figure 4.4 Diagram of where vapour pressure difference is calculated

Figure 4.5 represents the base case which shows greater wetting from the interior in the winter months with the drying to the exterior increasing in the summer. Without a paint layer, the outer siding is more open to diffusion to the exterior, but still gets wetted from the interior. Figure 4.6 show the vapour pressure differences for various permeabilities of the exterior paint layer. An Sd-value of 0.5m and below is considered diffuse open, or permeable to water vapour. The amount of drying to the exterior has significantly decreased from the base case, but there is still the opportunity for diffusion to the exterior as a drying mechanism in the summer months. Above 0.5m, diffusion to the exterior is largely reduced, and in May-August inward diffusion starts to occur. This analysis shows the impact that the paint layer has on reducing the drying capabilities of the wood to the exterior.

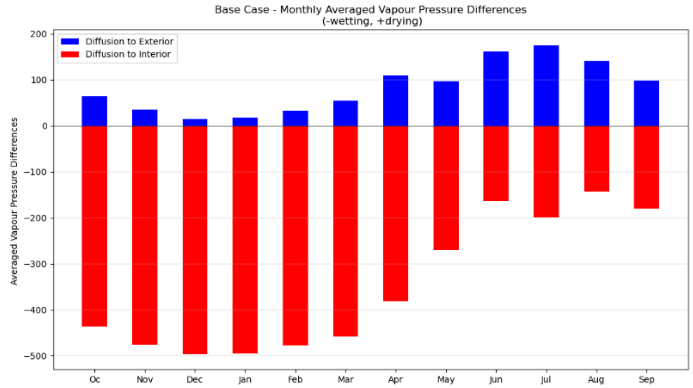


Figure 4.5 Base case monthly averaged vapour pressure differences at the outer siding

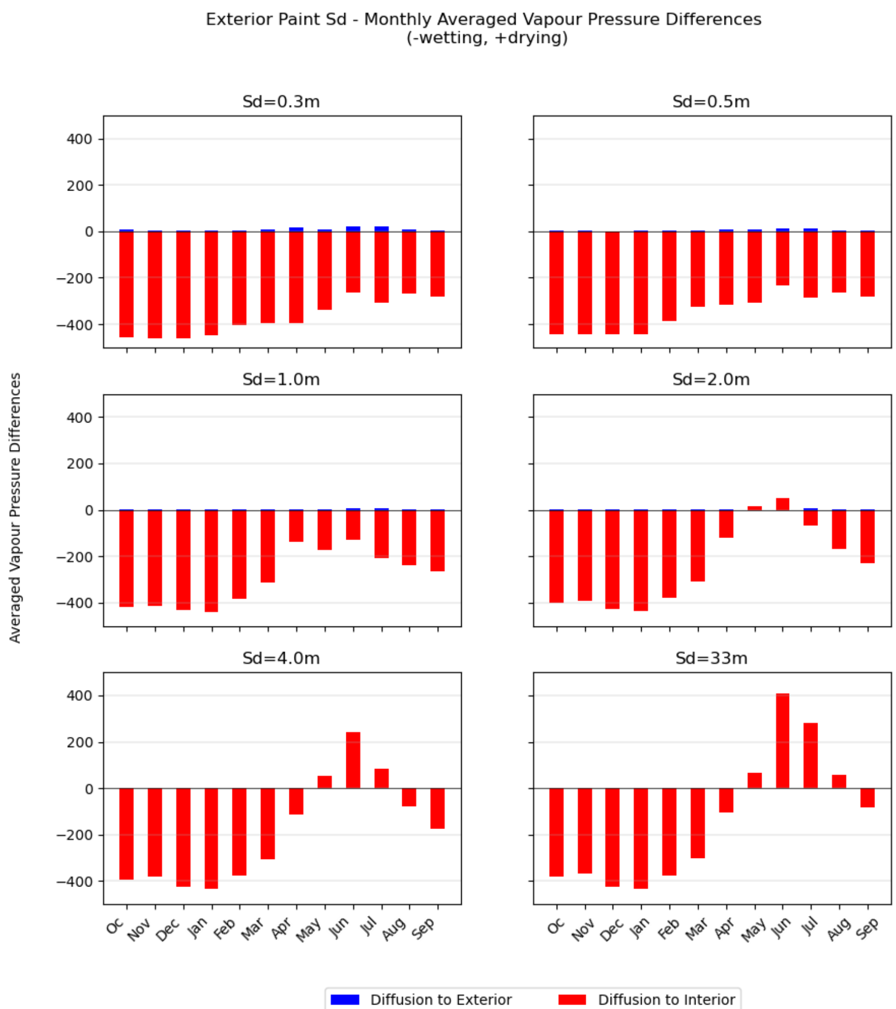


Figure 4.6 Averaged monthly vapour pressure differences underneath the paint layer

4.1.2 Paint Layer Method Results

This section will present the results from the paint layer methods. The three methods use various combinations for modeling the vapour and liquid permeability of the exterior paint layer. The Sd-value and μ-value are used to represent the vapour permeability, while the Aw coefficient is used to represent the liquid permeability.

4.1.2.1 Method 1: Vapour (Sd-value)

This first method looks only at the vapour permeability of the paint layer, ignoring the effects of rain absorption. Figure 4.7 shows that the base case for the outer layer has several spikes in the MC, even without rain absorption, noting that the spikes show rapid changes in MC due to exterior RH. The spikes go above the 20% (dry) and 30% (FSP) thresholds, in the spring and summer months, but they return to safe levels quickly, therefore there are no indications of any issues with respect to wood decay, noting that large and frequent changes in MC below the FSP can cause dimensional changes that increase the stress within the wood. These rapid shifts in MC can be smoothed out using a paint layer, where the spikes in MC are leveled out to a curve that shifts with the seasonal changes. Both the base case mid and inner layers are shown to be below the 20% threshold reflecting stable conditions with less dynamic fluctuations.

In the model the Sd-value of the exterior paint layer is increased from 0.3-33m. For the outer layer, the first winter initially shows MC levels above the 20% threshold for Sd-values of 0.5-1.0m, and above 30% for 2.0-33m. The subsequent winter seasons shows an increase in the maximum MC levels. For all Sd-values, the MC decreases to around 10% or less in the summer months, which shows that the siding can dry sufficiently during this season. Only an Sd-value of 0.3m maintains the MC levels below the 20% threshold throughout the entire three years. The Sd range for the following simulations will be capped at 1.0m, as an Sd-value greater than 2.0m shows prolonged periods above the FSP, increasing the risk for damages to occur from excessive moisture.

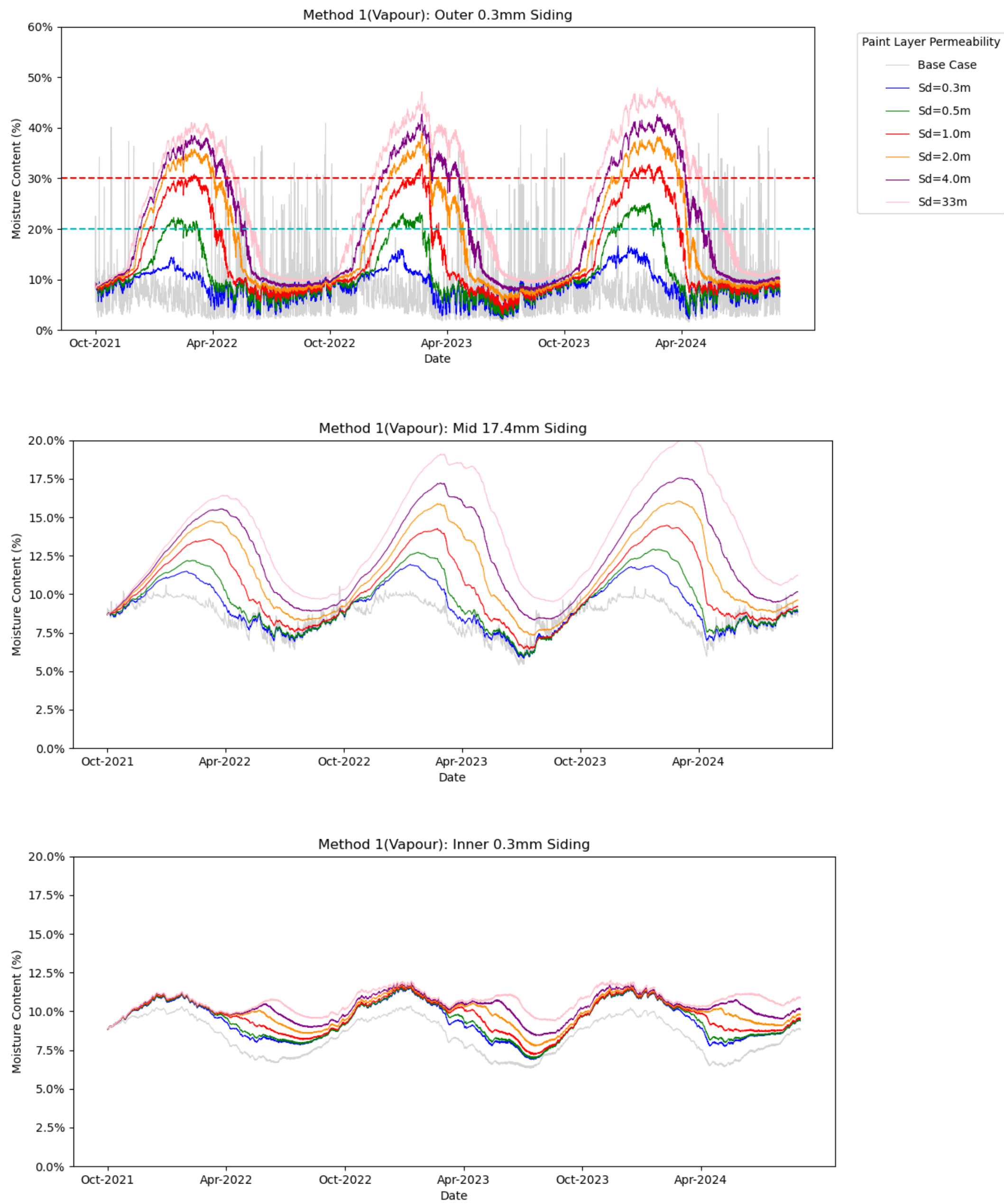


Figure 4.7 Method 1 moisture content results for the outer, mid and inner siding layers

4.1.2.2 Method 2: Vapour (Sd-value) & Liquid (Aw)

This next method considers both vapour and liquid sources, as rain absorption is included in this method. To account for how the paint layer resists liquid absorption, the Aw is adjusted in the material properties of the outer siding layer. In Figure 4.8, the lines of lighter colour for the same Sd-values shows the effect of decreasing the Aw. In general, the lower the Aw, the less liquid from driven rain will be absorbed into the wood. Looking at the outer layer, in comparison with the previous method, the maximum moisture levels reached in the winter is much higher, with values exceeding 40% at the peak in the first year. By the second year, a paint layer with an Sd-value of 0.3m and Aw value of $0.0003 kg/m^2h^{0.5}$ is shown to maintain MC levels below 20% during the winter. For an Sd of 1.0m in the last two years, with either Aw values, the levels remain above the 30% threshold in the winter, but for a shorted period as compared to the first winter. Irrespective of the permeability value, the outer siding shows that it still dries out in the summer season over the three period.

The mid and inner layers remain within safe MC limits throughout the three years, with decreased MC levels associated with lower Aw values. The base case conditions for the mid layer shows more spread-out spikes in MC followed by gradual drying, while the addition of the paint smooths the MC levels to be less than 20%.

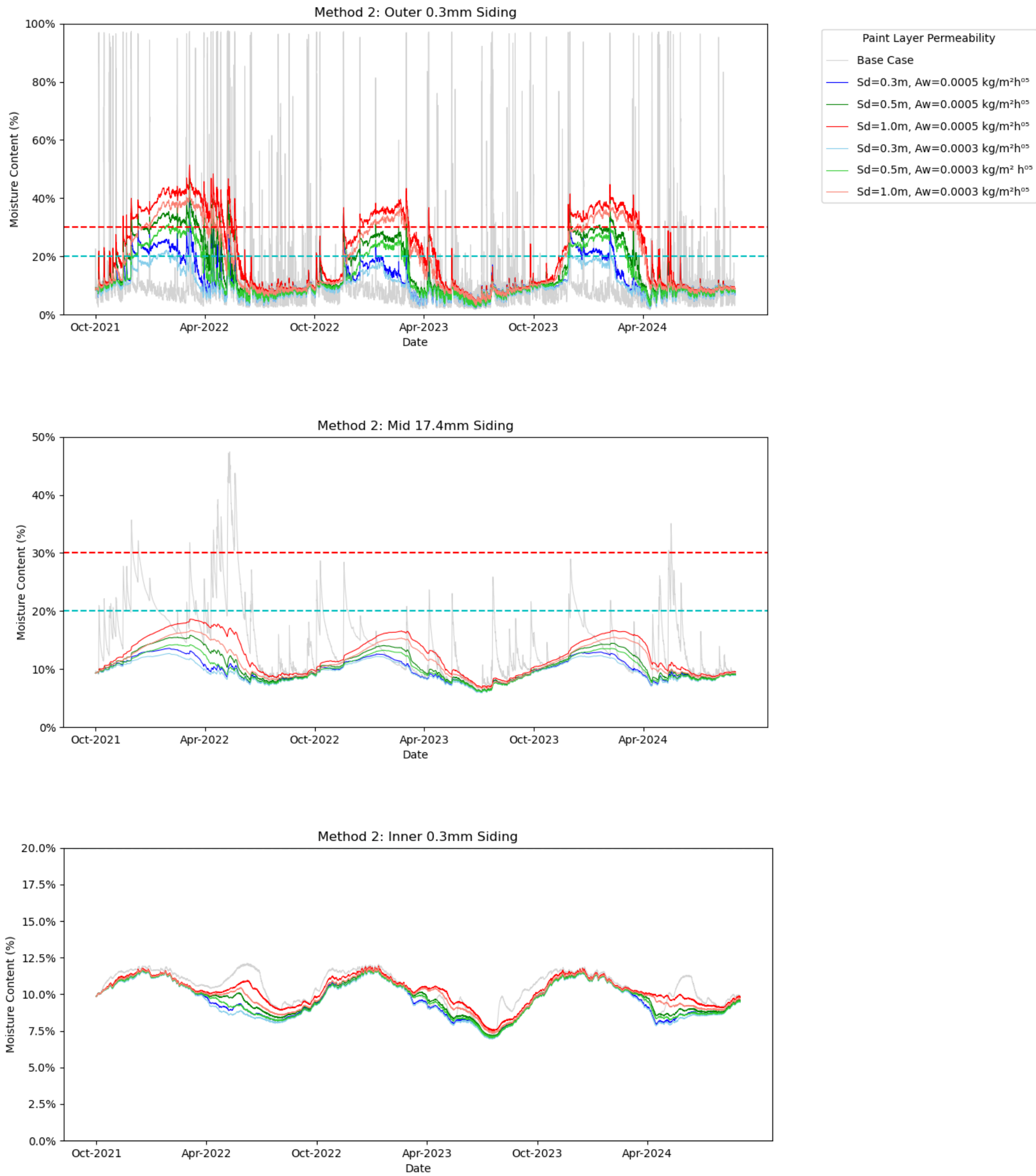


Figure 4.8 Method 2 moisture content for the outer, mid, and inner layers of the siding

4.1.2.3 Method 3: Vapour (μ) & Liquid (Aw)

The third paint layer method changes the way in which the vapour permeability is inputted into WUFI. Rather than using the Sd-value as a surface transfer coefficient on the exterior, the material properties for the μ-value of the outer siding layer is unlocked and changed. In theory, this method should be a viable option as the μ-value is equal to the Sd-value divided by the material's thickness. The paint layer thickness is equal to the thickness of the outer layer of the siding and the same range of Sd and Aw as per the previous method was used.

It was expected that this method would show comparable results to those from Method 2, although when examining Figure 4.9 the inner and mid layers look similar, whereas the outer layer does not. In particular, none of the layers show any difference in moisture content when the Aw value is changed. For the outer layer, the MC values are all kept below 20%, which seems somewhat counterintuitive as even Method 1, which did not include rain absorption, increased above 30%. It is peculiar that this method does not model liquid absorption in the same manner when the method for the Aw value remained the same. There may be an error with changing the μ-value from being a moisture dependent value that varied depending on the RH to being a constant value, thus impacting the way liquid is transferred via surface diffusion. It is important to consider the differences in how the vapour permeability is represented using the μ-value vs the Sd-value. The Sd-value represents a certain vapour permeability as an exterior layer property that is not directly part of the wood siding itself. The μ-value is changed through the material properties of the outer layer of siding, therefore the location at which the permeability is defined is different when using the Sd vs μ-value. In future work, this method could be improved upon, perhaps by adding an additional 0.3mm layer inward from the outer layer to evaluate the localised moisture conditions directly under the paint film.

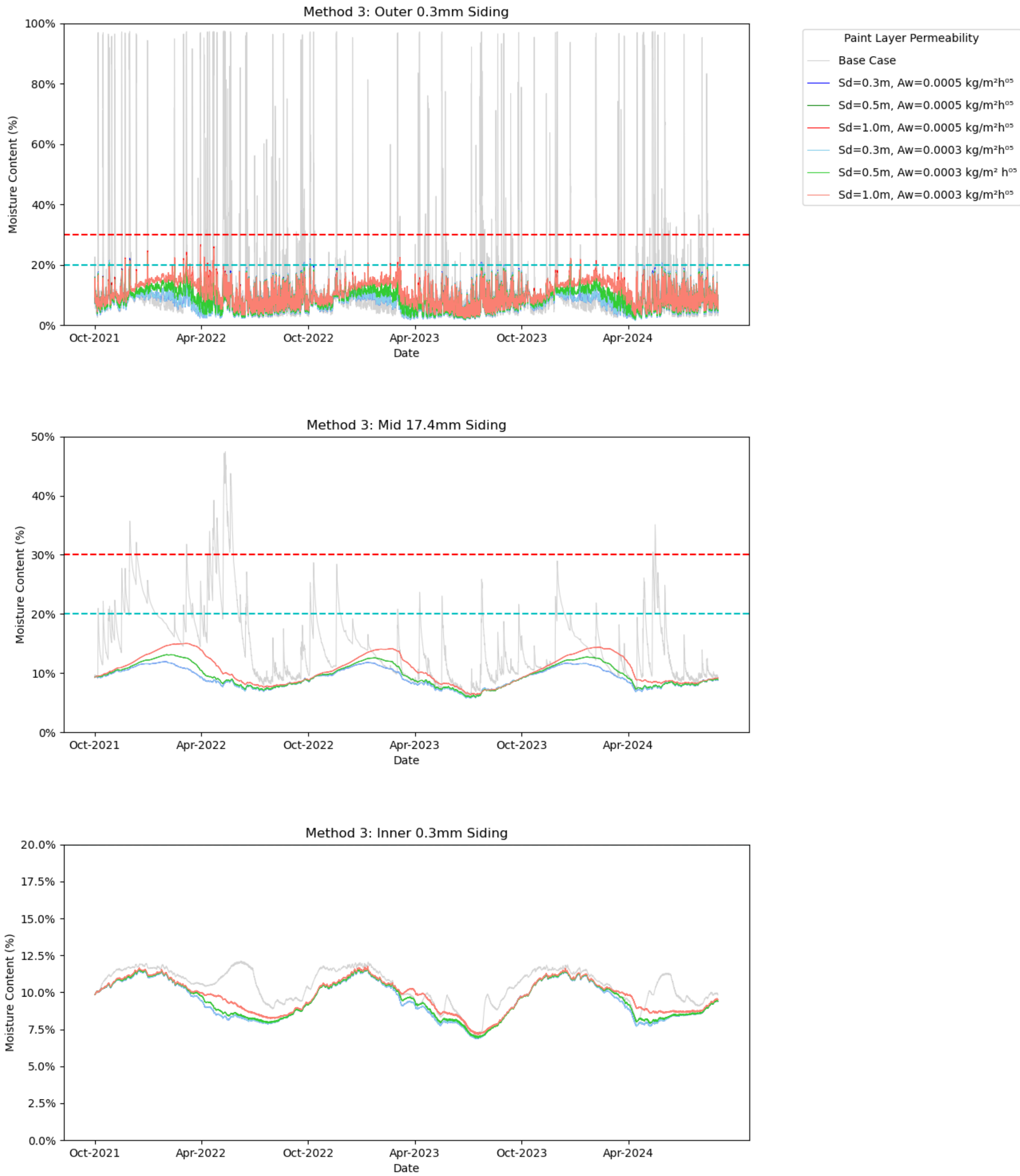


Figure 4.9 Method 3 moisture content results for the outer, mid, and inner layers of siding

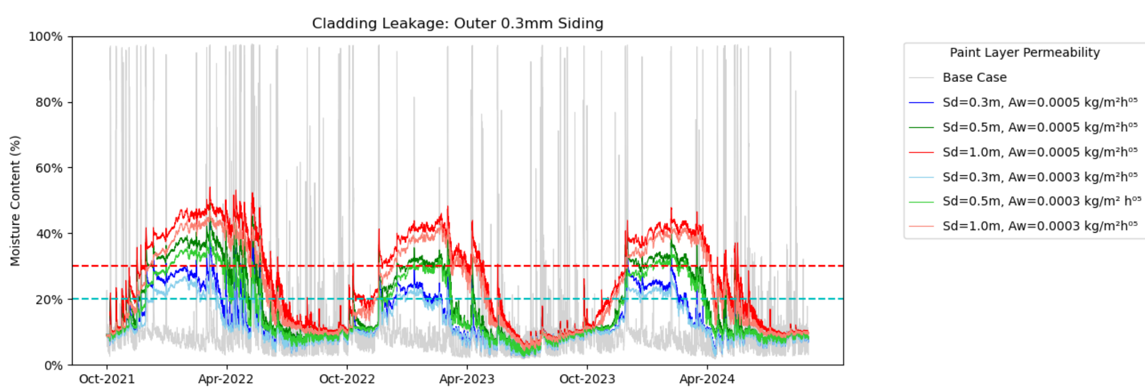
4.1.3 Moisture Case Results

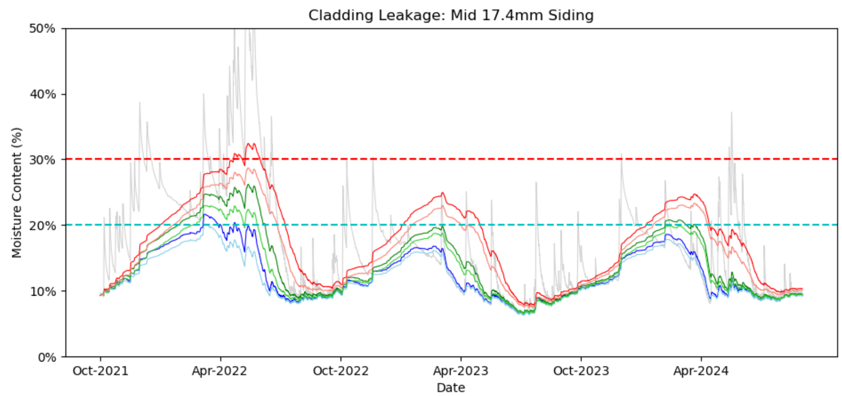
This section provides an overview of the moisture content results from the WUFI simulation Cases 1-5, where the moisture sources were altered mainly to reflect the various defects or change in composition for the respective cases.

4.1.3.1 Case 1: Cladding Leakage

This case shows the impact of rain leakage that makes its way behind the cladding and into the building paper. It is of interest to see how a source of liquid water entering from the back of the siding dries out. The paint layer is modeled using Method 2 (Sd & Aw). In general, this case shows there to be an increase in the moisture content levels can be seen in all the layers of the siding.

For the inner siding, spikes in the MC levels occur, no matter the Sd or Aw value of the exterior paint. Although there is a difference during the summer months where the moisture dries out slower with a less permeable paint layer. The mid layer shows higher moisture content maximums and greater separation between the various Sd-values. When the exterior Sd is below 0.5m, the levels stay below a MC of 20% in the second year. With an Sd of 1.0m, the moisture levels go above 20% in the winter and eventually reaches less than 20% in the spring/ early summer. Again, the outer layer shows an even higher moisture content compared to the outer layer in Method 2, with maximums reaching over 50%. The outer and mid layer show how having a less permeable exterior paint layer makes it more difficult for any interior sourced moisture to dry out.





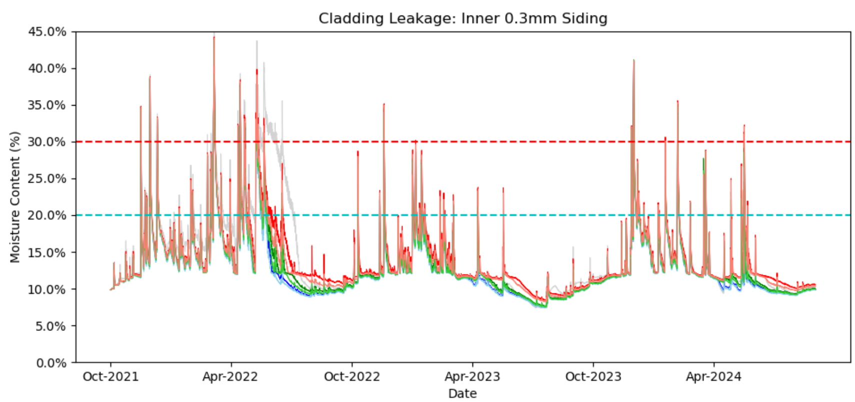


Figure 4.10 Case 1 cladding leakage moisture content results for the outer, mid and inner siding

4.1.3.2 Case 2: Back Priming

The previous method showed how interior sourced moisture can impact the drying potential of painted wood siding. This next case will investigate the effectiveness of the back priming in reducing the moisture content in cases with interior sourced liquid moisture. To model the paint layer, a combination of Methods 2 and 3 are used, since an Sd-value assigned as a surface transfer coefficient cannot be added for a layer within the wall, therefore the µ-value method is used to model the back primed layer by changing the inner siding's material properties. To reduce the number of simulations, the Aw was kept at 0.0005 $kg/m^2h^{0.5}$ for each of the cases. The same moisture source is used from the cladding leakage.

Figure 4.11 shows that a greater back prime Sd-value provides lower moisture levels. Even if the Sd-value of the exterior paint is 1.0m, a back prime Sd of the same value keeps the moisture levels below 20% at the mid layer, although it still results in a MC level above 30% for the outer layer. The best-case results, to keep the MC levels for all three layers below 20%, is seen using an exterior paint layer with an Sd-value below 0.5m (higher permeability) and a back prime layer with a Sd-value greater than 1.0m (lower permeability). Therefore, back priming should be an effective method at reducing the moisture levels in the siding provided that water is prevented from getting past the back priming layer, as that could lead to degradation from moisture being trapped in the siding. For future work, it should be investigated how the back priming technique impacts the rest of the wall assembly components, notably the sheathing. There may be negative consequences for other components on the wall assembly if too impermeable of a back priming layer is provided.

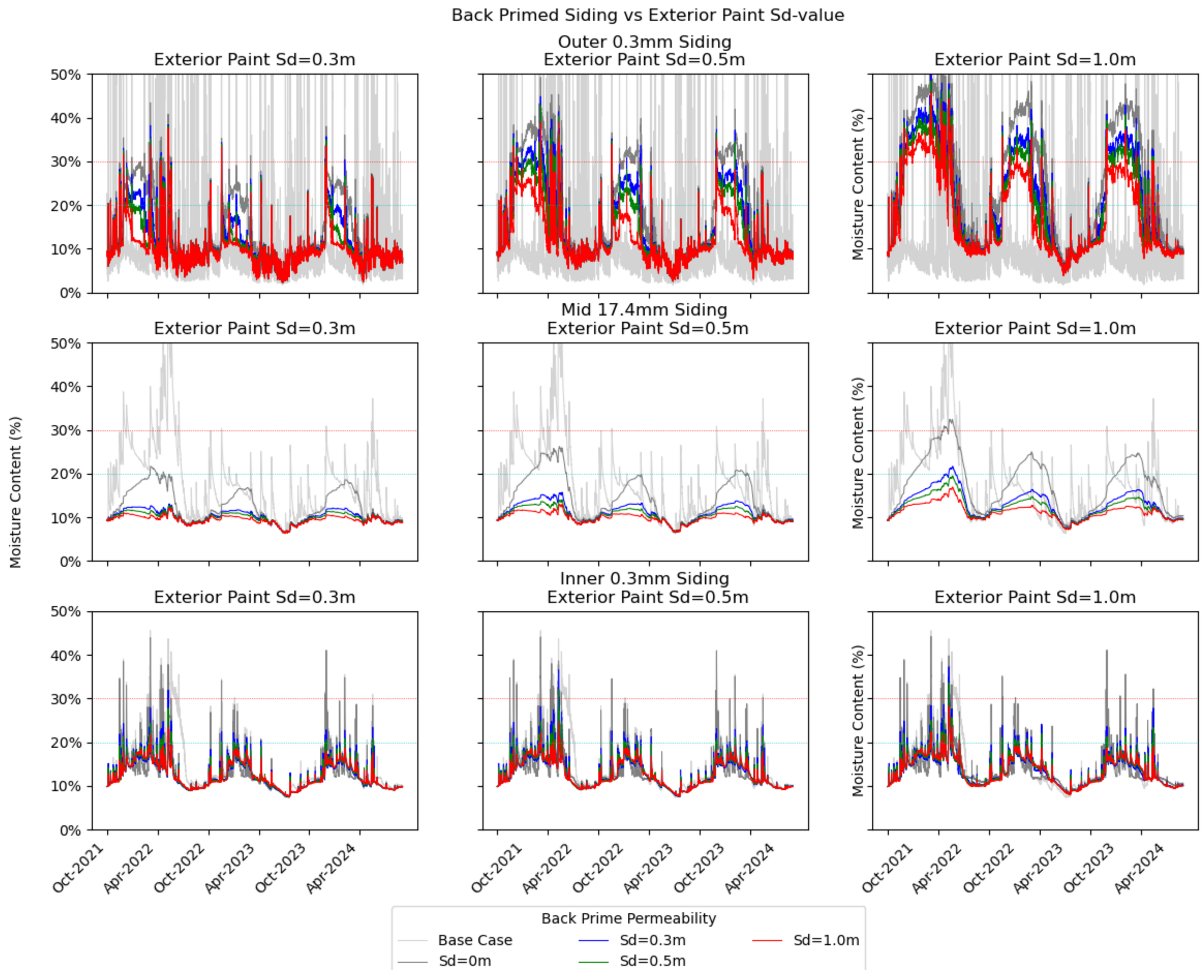
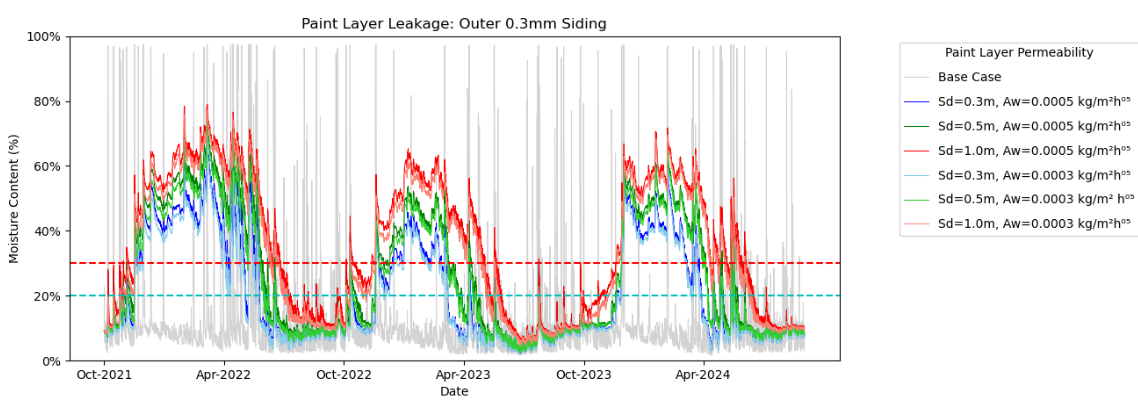


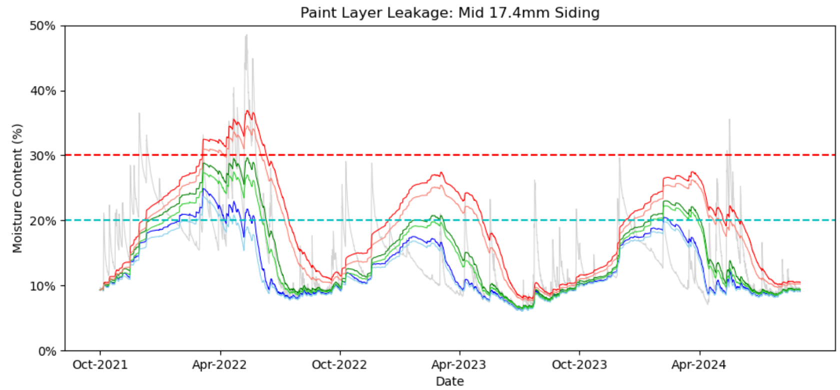
Figure 4.11 Case 2 back priming moisture content results for the outer, mid, and inner layers of siding

4.1.3.3 Case 3: Paint Layer Leakage

This case investigates the effect of liquid moisture getting past the exterior paint layer due to imperfections such as holes or defects that results in water to get in directly. To achieve this, a moisture source was added in WUFI consisting of absorption of 1% of the driving rain into the mid layer of the siding. Of note, a WUFI limitation for this case is that although the driving rain is being modeled to enter through the hole/ defect, there is no ability for the software tool to address the additional drying potential from the wood to the exterior from the hole/ defect. As this is a 1D simulation, this method does not take into account the size or shape of the defect which would impact the amount of water that is absorbed past the paint. For further investigation into modeling the impacts of a paint defect, a 2D simulation may allow for the size of the defect to be analysed along with specifying different properties of that area to indicate the absence of paint covering the substrate.

As expected, the results show a significant increase in the moisture levels, mainly impacting the outer and mid layers. Not surprising, of all the cases analyzed, this case shows the largest maximum moisture content for the outer siding, attaining values above 70% at the peaks. The rise in moisture levels show that with an increasing Sd-value, the moisture has a slower drying potential during the spring months, thus prolonging the amount of time spent above a critical moisture content threshold.





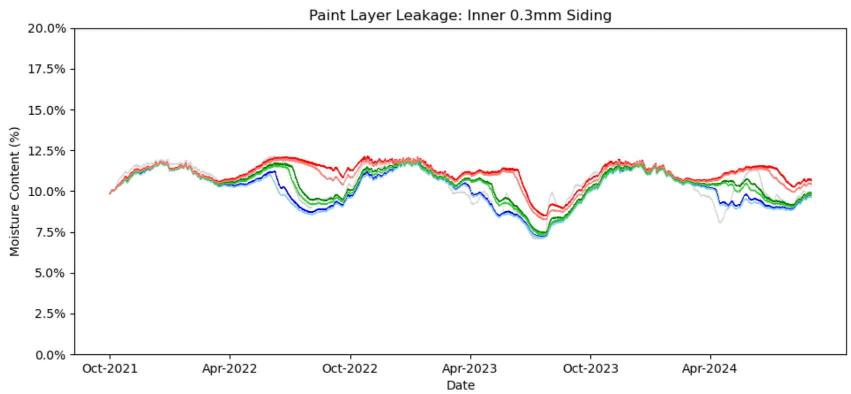
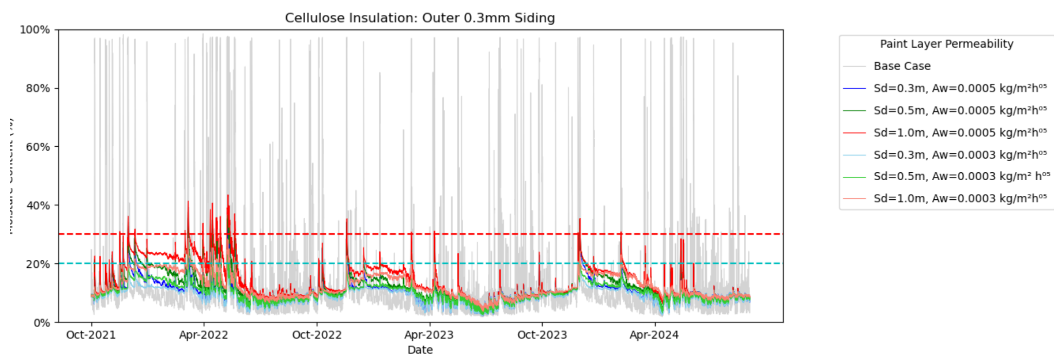


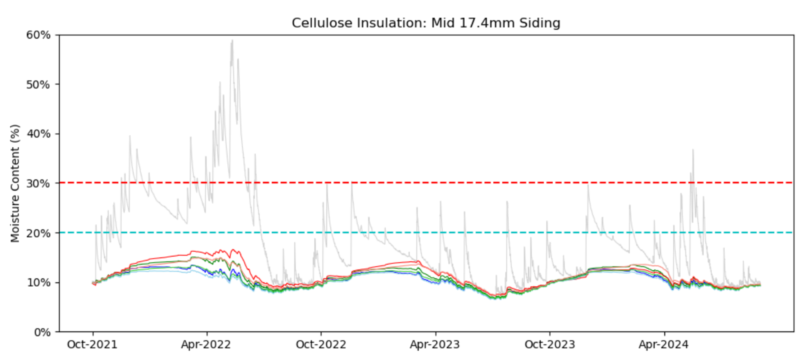
Figure 4.12 Case 3 paint layer leakage moisture content results for the outer, mid, and inner layers of the siding

4.1.3.4 Case 4: Cellulose Insulation

This case was added given that some retrofit factors in the addition of cavity insulation. For this case Method 2 for the paint layer was used, and no additional moisture sources were added. This round of simulations was done with the intent of better understanding how insulation might increase the moisture content of the siding, which was mentioned earlier in Chapter 2 as being a culprit for blistering of the paint.

The figures show that the presence of insulation mainly impacts the mid and inner layers, which both show higher moisture contents compared to those shown in Method 2. This is expected as the insulation increases the amount of interior sourced moisture causing more layers to saturate from vapour diffusion, this was also seen through the Dew Point method at the inner and outer sheathing, which can be found in Appendix D. Although, the outer siding shows moisture content levels which are lower than Method 2. Even with the least permeable paint layer (Sd=1.0m), the outer siding rarely goes above the 30% threshold. The results from this round does not give enough evidence to interpret the impact of insulation retrofit. The impact of the paint layer's permeability as aligned with various insulation retrofits should be investigated in future work, through varying insulation types, positions, and thicknesses. Noting the impacts of adding a vapour barrier should also be factored in.





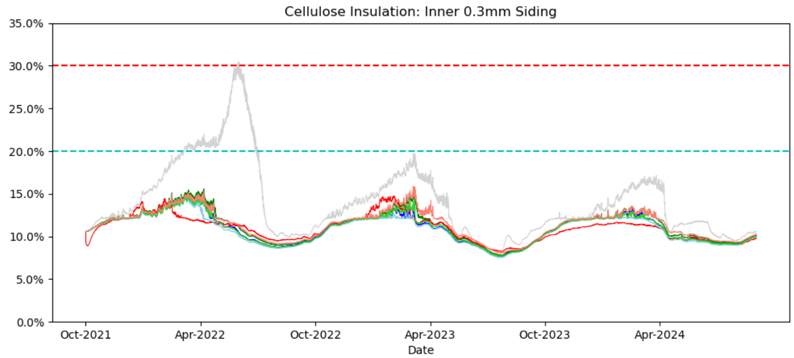


Figure 4.13 Case 4 cellulose insulation moisture content results for outer, mid, and inner layers of the siding

4.1.3.5 Case 5: Interior Relative Humidity

The final case investigates interior RH as a source of moisture and was simulated using the sine curve method in WUFI to quantify its changes. The interior RH levels were set at a mean of 50%, 60% and 70%, with an amplitude of 10% for each respective figure for the mid layer.

Figure 4.14 clearly shows that the interior RH has a significant impact on the MC of the siding. A mean RH of 70% puts the siding at risk of moisture accumulation if the exterior paint has an Sd-value greater than 1.0m. Even if the MC drops below 20% briefly, the peak in the winter keeps increasing for each successive year. This analysis clearly illustrates the impact of interior RH and its effect on the potential material degradation that would ensue if left unaddressed. This points to the significance of applying a vapour barrier internal to a building assembly if interior humidity levels cannot be minimized.

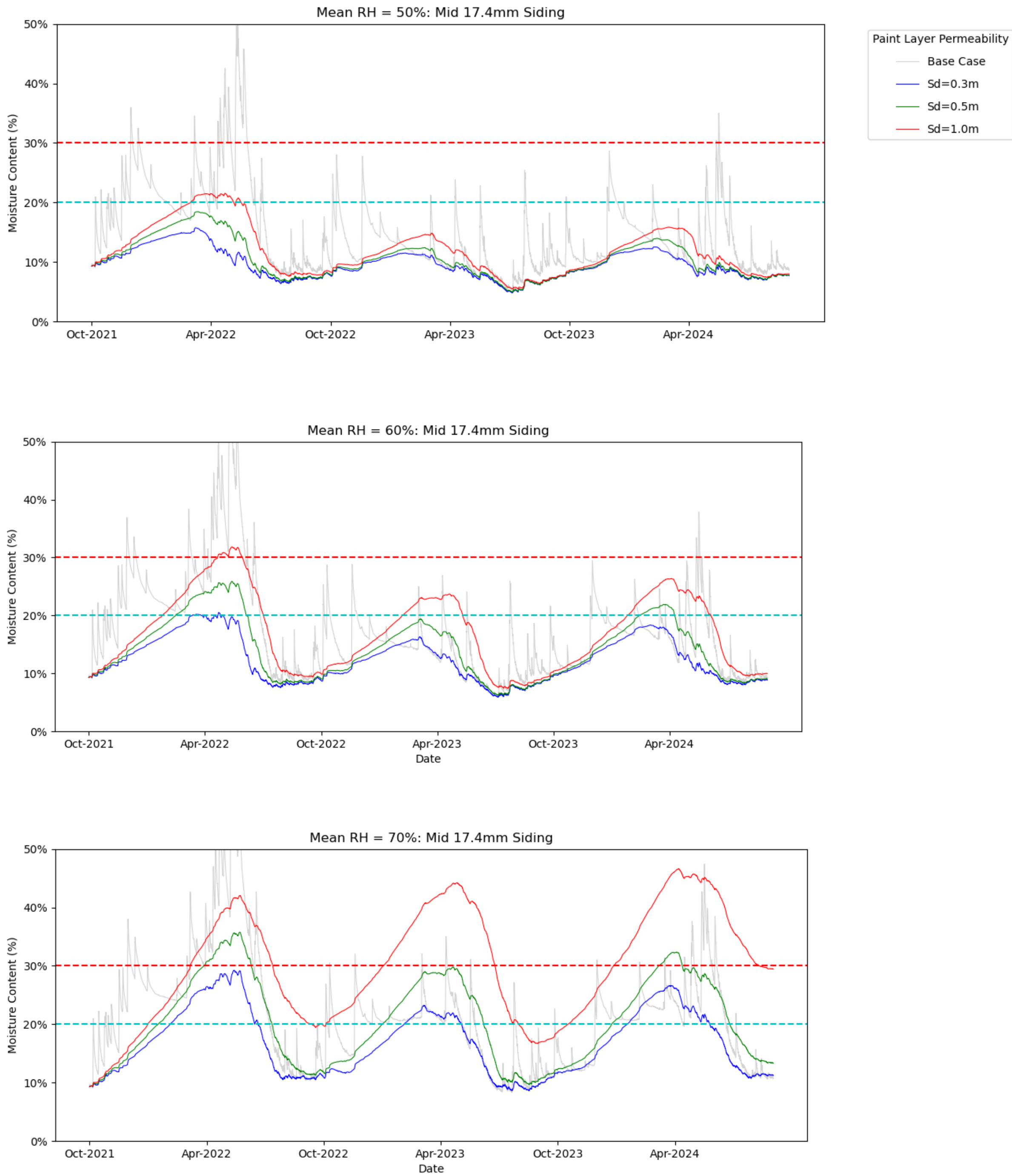


Figure 4.14 Case 5 interior RH moisture content results for the mid layer of siding

This chapter provided insight into the results obtained from the various methods and cases that were run through WUFI Pro. The benefit of this work provides objective clarity as to the behaviour of the moisture content as assessed in the defined wall assembly that was exposed to the varying changes in environmental conditions as applied to the modification depicted in each of the methods/ cases. This information will be discussed in the next chapter, in which the key aspects will be applied to assessing how moisture content impacts the various failure criteria.

Chapter 5: Discussion

The results from this research confirms that the paint layer plays an important role in controlling the moisture conditions within exterior wood siding. The findings from the results obtained will be further elaborated in this chapter, identifying some of the key themes and findings that will in turn support the recommendation provided in Chapter 6.

Moisture Sources

The impacts from both the permeability to vapour and liquid sources are important to understand. Through the moisture source analysis, it was shown that within the wall assembly there are both exterior and interior sources that effect the wood siding. Both the WUFI simulations and the Dew Point analysis showed that interior sourced vapour has a greater effect on the wood siding as the vapour permeability of the exterior paint layer decreases; namely, the effects are more noticeable at Sd-values greater than 1.0m.

The base case scenario of the moisture content at the outer layer of the siding shows that wind driven rain absorbed in the material is an acute source of moisture. It results in moisture spikes occurring above 90%, but conversely it can dry quickly when rain ceases and therefore does not present a major degradation concern due to moisture damage. As reflected in Case 3, paint layers that are damaged present the greatest concern leading to material degradation – reaffirming the importance of correct application and maintenance. This phenomenon represents a higher consequence for the wood siding if paints of lower vapour permeability are used.

Seasonal Trends and Failure Criteria

From the results obtained in Chapter 4, it depicts a seasonal cycle of which the siding has increased MC levels in the winter, then starts to generally decrease in the spring with drier levels occurring in the summertime in the Ottawa region. In winter, the moisture content in the siding's outer layer would typically exceed 20%, and for exterior paint layers with a lower vapour permeability they exceed 30%. According to the analysis criteria, once the FSP is reached in the wood siding for a prolonged period (months), decay will likely occur: however, keeping wood below 20% prevents this from happening. Importantly, the temperature should also be considered when discussing the impacts of moisture content as it becomes less of a factor in cold weather.

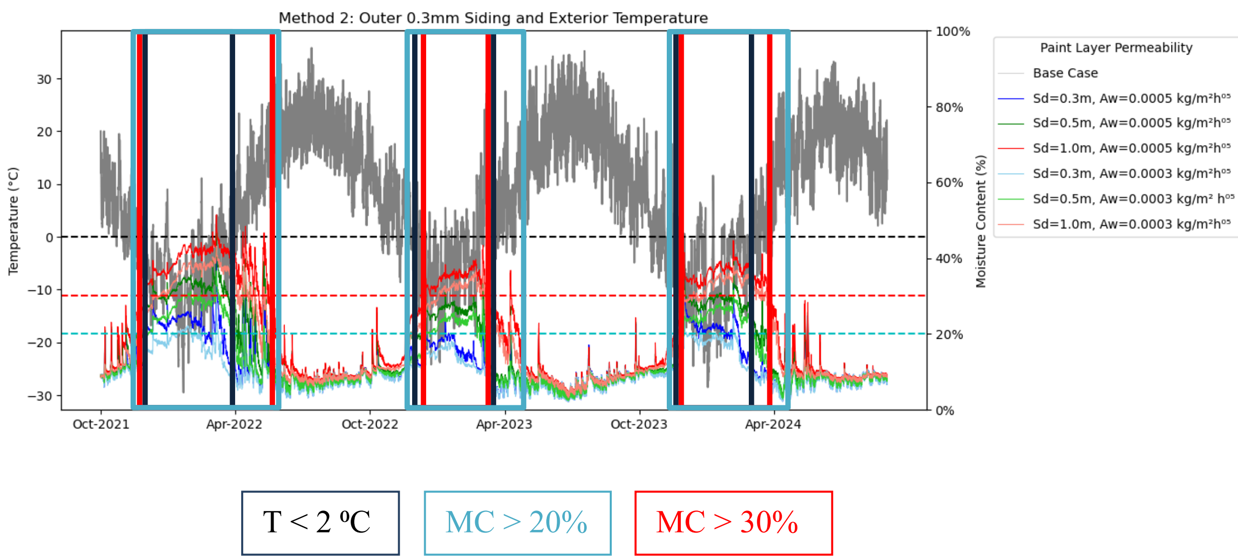


Figure 5.1 Seasonal trends of moisture content and exterior temperature

Figure 5.1 shows how the wintertime peaks in wood siding moisture content are associated with the decrease in temperature. The moisture content goes well above the FSP over the winter, but the temperatures are too cold to support decay. As mentioned earlier, the optimum temperature range for decay is 21-32ºC, although in general decay can occur between 2-38ºC. The figure shows that with a less permeable exterior paint layer there is greater concern for decay the longer the moisture content stays above FSP in the spring where the temperature is within the optimum range for decay. Table 5.1 shows the duration (in days and months) at the outer siding layer above critical levels (20% & 30%) of the best- and worst-case combinations for each method and case (excluding method 3 and case 4). The table also shows how the durations differ when the temperature range (T>2ºC) is factored in. Case 4, paint layer leakage (Sd=1.0m, Aw=0.0005kg/m^{2}h$^{0.5}$), and Case 5, interior RH (Sd=1.0m, RHin= 70%), show the worst-case scenarios where the MC is over 30% while the temperature is above 2ºC for a duration of around 3 months within the year. It should be noted that the outer layer is a thin layer of the siding and thus would represent very localised decay.

This seasonal trend in moisture content also has an impact on the blistering of the paint layer. It is known that high moisture contents can lead to moisture blisters between the paint layer and wood surface. Many studies have observed a seasonal trend to blistering, usually occurring during the late winter and spring months in areas where the wood is excessively wet behind the paint. This is in accordance with what is depicted in Figure 5.1, as the spring is seen to have high moisture contents which would promote the formation of paint blisters. The winter is less of a concern for blistering, as low temperatures will retard the formation of blisters. In the spring, the temperature begins to increase, and the moisture levels start to decrease causing the wood to become drier, although the drying period is prolonged when the paint layer is less vapour permeable. Therefore, to reduce the formation of paint blisters, a more permeable paint would be beneficial, noting that the formation of blisters also depends on other factors such as the temperature, paint thickness, age, binder type, and the penetrating ability of the paint. Further information is needed to better understand the duration required to promote these conditions, as well as when moisture blisters lead to complete loss of adhesion or rupture. This presents an opportunity for future work.

Table 5.1 Duration of the best- & worst-case scenario of the outer siding layer above certain criteria

		Duration in Days (months)* **							
		2022		2024		2022		2024	
Case*	Best/Worst**	*>20%*	*>30%*	*>20%*	*>30%*	*>20% >2ºC*	*>30% >2ºC*	*>20% >2ºC*	*>30% >2ºC*
M1 – Sd	Sd = 0.3	0	0	0	0	0	0	0	0
	Sd = 33	182 (6)	125 (4.1)	234 (7.8)	167 (5.5)	68 (2.3)	41 (1.3)	105 (3.5)	60 (2)
M2 – Sd & Aw	Sd = 0.3 Aw = 0.0003	29 (0.9)	0	8 (0.2)	0	3 (0.1)	0	1 (0.03)	0
	Sd = 1.0 Aw = 0.0005	203 (6.7)	172 (5.7)	148 (4.9)	121 (4)	72 (2.4)	54 (1.8)	40 (1.3)	24 (0.8)
C1 – cladding leakage	Sd = 0.3 Aw = 0.0003	106 (3.5)	1 (0.03)	79 (2.6)	0	14 (0.5)	1 (0.03)	5 (0.2)	0
	Sd = 1.0 Aw = 0.0005	238 (7.9)	190 (6.3)	197 (6.5)	140 (4.6)	104 (3.5)	71 (2.4)	77 (2.5)	40 (1.3)
C2 – back prime	Sd, ext = 0.3 Sd, BP = 1.0	22 (0.7)	3 (0.1)	10 (0.3)	0	12 (0.4)	3 (0.1)	2 (0.06)	0
	Sd, ext = 1.0 Sd, BP = 0	238 (7.9)	190 (6.3)	197 (6.5)	140 (4.6)	104 (3.4)	71 (2.3)	77 (2.5)	40 (1.3)
C3 – paint layer leakage	Sd = 0.3 Aw = 0.0003	189 (6.3)	166 (5.5)	131 (4.3)	107 (3.5)	61 (2)	46 (1.5)	28 (0.9)	16 (0.5)
	Sd = 1.0 Aw = 0.0005	268 (8.9)	230 (7.6)	240 (8)	186 (6.2)	132 (4.4)	99 (3.3)	113 (3.7)	78 (2.6)
C5 – RH interior	Sd = 0.3 RH = 50%	124 (4.1)	6 (0.2)	14 (0.5)	0	22 (0.7)	4 (0.1)	2 (0.06)	0
	Sd = 1.0 RH = 70%	248 (8.2)	205 (6.8)	342 (11.4)	229 (7.6)	115 (3.8)	86 (2.8)	208 (6.9)	111 (3.7)

*Method 3 and Case 4 not included in table due to the obscure results
**Best = green, Worst = red
***Results do not represent continuous durations

Exterior Paint Layer and Moisture

It is clear that having an exterior paint layer with a higher permeability to water vapour and a lower permeability to liquid water yields the optimal moisture conditions within the outer siding, as well as the mid and inner layers. These results are specific to Ottawa's climate but would be applicable to most cold climates where the vapour drive is predominately towards the exterior.

To put the results from this research into context, the values for vapour permeance and liquid absorption were gathered from various sources to provide a range of properties for different commercially available paint types. Since not all paints with the same binder type have the same overall composition, as well testing parameters such as thickness used and environmental conditions, the ranges obtained are quite varied and should be taken as approximations. The range of values used in the simulations are outlined in the red box in Figure 5.2 & 5.3. Appendix D contains more information of specific permeability values for various paint types found within the literature. Comparing the findings from literature can also be difficult as different units or metrics are used. Most paints, which include latex/acrylic, linseed oil, alkyd, can be classified within the vapour permeable range, but also in semi-permeable range. In addition, these values are classifications of permeance which does not consider the thickness of the paint layer, therefore the thicker and greater number of paint layers that are applied will further reduce the overall permeance of the exterior paint layer. Paint is usually applied as a system, consisting of a primer followed by 1-2 topcoats. The primer and paint typically have different properties in terms of permeability, and thus the permeability of the entire system needs to be considered. It is not a requirement for manufacturers to provide the permeability information within product specifications, which can make it difficult to identify which paint product is suitable based on the permeability recommendations.

Sd (m)	Permeance (ng/m2sPa)	Permeance Classification	Sd Classification
0.01	18762	Vapour Permeable (>570 ng/Pasm2)	Diffuse Open
0.05	3752		
0.1	1876		
0.2	938		
0.3	625		
0.4	469	Class 3 VB (58-570 ng/Pasm2)	
0.5	375		
1	188		Diffuse Blocking
1.5	125		
2	94		
3	63		
4	47	Class 2 VB (5.8-57 ng/Pasm2)	
5	38		
33	5.7	Class 1 VB (<5.7 ng/Pasm2)	
1500	0.1		Diffuse Proof

Liquid Absorption (kg/m2h0.5)	ENV 927- 2
0.000001	Stable
0.00001	
0.0001	
0.0003	
0.0005	Semi-Stable
0.001	Non-Stable
0.005	

Figure 5.2 [Right] Vapour permeability classification range used

Figure 5.3 [Left] Liquid permeability classification range used

Maintenance

To prolong the performance of a paint layer, conducting cyclical maintenance is necessary. In some cases, the exterior paint layer in building structures is often neglected to the point where it reaches a fully degraded state. The performance of the paint is evaluated by the length of time it stays intact until it needs to be removed (normally by scrapping) and then replaced. Typically, the exterior paint layer on buildings is part of the maintenance routine, where the paint layer is refreshed as the binder degrades. This practice is encouraged when using linseed oil paints, when the pigments start chalking it is a sign that the binder needs to be refreshed by reapplying another coat of paint or oil. In addition, other historic paint types that were not mentioned such as distemper or whitewash are highly permeable paints, however, they are less resistance to liquid water. They were also used knowing that the binder will wear away over time under the exposed exterior conditions, and thus a tradition of maintaining the integrity of the binder in order to protect the substrate was the common ideology. Conversely, today the expectation is that paints are both durable and resilient that can withstand the test of time in adverse climate conditions.

Exterior Siding Moisture Control - Recommendations from Literature

There are other ways in which the moisture content of the siding can be controlled. As seen from the WUFI simulations, the paint layer works well to keep moisture conditions within safe levels as long as the paint layer remains intact, and moisture is prevented from finding alternative pathways to the wood material. Back priming was one method that was explored through this research, which showed a positive effect in reducing the absorption from the interior side of the wood siding. Lstiburek mentions the practice of back-priming as a measure that reduces the amount of moisture absorbed from both capillarity and vapour diffusion but does not eliminate it (J. W. Lstiburek, 1990). They mention that for it to be effective the back-prime layer must be more impermeable than the exterior paint film. The back priming analysis from this research showed the same findings, namely being favourable in reducing the MC levels of the siding. Although in practice it is rarely done where two different paint types will be used for the exterior and back prime layer. To further understand the implications of back priming, the moisture content of the materials inward to the siding should be analysed in future work to assess whether having a more impermeable back priming layer increases the risk for damages elsewhere in the assembly.

Most post-1950's constructions include a vapour barrier on the warm side of the wall assembly which reduces the amount of vapour that is transported from the interior to exterior in winter. None of the assemblies in the WUFI analysis included a vapour barrier as they reflected the typical pre-1950's wood frame buildings, however, the option to add a vapour barrier when calculating its effect when retrofitting the walls of heritage buildings can be inserted.

Another aspect that is considered when constructing a new wood frame building is the inclusion of cladding that incorporates an air space behind it. Either through applying the siding onto strapping or using a specialized rain screen system, the air space provides a capillary break between the back of the siding and allows for increased air flow to promote drying (Finch & Straube, 2007). Lastly, another method is to insert wedges in between the rows of boards to allow for increased airflow across the siding (J. W. Lstiburek, 1990). The last two recommendations (air space, wedges) consider air convection as a wetting/drying mechanism, which was not considered as a mode of moisture transport in this research, while the first two recommendations (back priming, vapour barrier) are based on wetting/drying via vapour diffusion.

Hygrothermal Modeling as an Analysis Tool

Using WUFI and the methodology used in this research to conduct a hygrothermal analysis is a useful approach to better inform decisions related to various conservation work for historic buildings. For example, for pre-1950's buildings preparing to receive an energy retrofit, such as adding insulation to the walls and/ or the addition of a vapour barrier, the various types and thickness of materials to be used can be simulated in a hygrothermal software to better understand its effect on the heat and moisture dynamics within the assembly. In addition, if the siding needs to be painted/ re-painted, WUFI can be used to assess how the moisture conditions at the siding will change as a result of the retrofit, and the paint layer can be chosen based on the minimum required permeability to allow for an acceptable drying potential of the wood siding. Noting that the accuracy of the results is only as precise as the information being entered, which is why additional material testing may prove beneficial in certain circumstances in obtaining the actual properties of the building components to be used.

Chapter 6: Conclusion

The aim of this research was to assess how the paint layer's permeability impacts the moisture condition of exterior wood siding. The results obtained could then be used to facilitate the appropriate selection of paint types based on their respective properties that best meet the optimal values that prolong the life cycle of wood siding for a given environment. To achieve this the moisture conditions of the wood siding in a pre-1950's wood frame construction was analyzed using the Dew Point method and WUFI Pro. The approach in achieving this compared base case simulation to various scenarios as reflected in the three methods and five cases (see Chapter 4) that were used in assessing the respective paint layer's permeability to vapour and liquid, each being modified and exposed to different environmental conditions.

Based on the analysis of the idealized pre-1950's wall assembly situated in the Ottawa region, it was assessed that the optimal moisture conditions for the wood siding under the various cases simulated, is with a paint layer that is more vapour permeable (Sd-value less than or equal to 0.5m) and a less permeable to liquid (Aw value of 0.0003 $kg/m^2h^{0.5}$ or less). These findings are based on the specific parameters of this study and do not account for all the design complexities involved in the details of a wall assembly.

The main findings link back to the objectives that were introduced at the beginning of this thesis. It was shown that interior vapour is a moisture source of importance for wood siding and that it should not exceed a RH mean of 70% for this given wall assembly. The ability to achieve this points to the importance of having a permeable paint that has the capacity to sufficiently permit the drying of the wood siding. Additionally, the technique of back priming the siding also showed to have an effect in decreasing its moisture content when interior sources of moisture are present, in which optimal results were shown when the exterior paint layer is more vapour permeable, while the back priming paint layer less permeable. Although, these findings do not investigate other impacts that back priming may have on the entire wall assembly.

This research further identified that various permeability values can cause elevated moisture levels which can lead to the undesirable conditions that causes paint to blister. The seasonal changes in moisture content, notably in the spring when its above 20%, and coupled with the rise in temperature, makes the environment more conducive to trigger the onset of blistering in the paint layer. Using a less vapour permeable exterior paint can prolong the amount of time during this period in which the outer siding would likely remain above critical moisture levels, thus increasing the risk of blistering.

The impact of introducing insulation into the cavity without a vapour barrier was investigated through both the Dew Point method and WUFI analysis. It showed that the moisture levels in the wood siding was consistently below the failure criteria thresholds. However, the results obtained was cause for further questioning as the literature pointed to the phenomena that when insulation is added it increased the likely occurrence of blistering of the painted siding. This was not evident through the WUFI analysis result from this research and merits further work.

Simply put, wood decay results from excessive moisture and to prevent this from occurring the levels of moisture in wood needs to be adequately controlled, allowing for sufficient drying to occur. The work from this research was aimed at further advancing the body of knowledge that seeks to better understand the implications that moisture has on painted wood siding, in particular through the lens of hygrothermal simulations.
To that end, there are aspects of this work that were not conclusive and requires further research, thus providing future opportunities that will be discussed next.

Recommendations for Future Work

This research was conducted under the limitations of the scope described earlier, and within resources and the limitations resulting from doing this during a pandemic. As a result, one of the areas not addressed was the material testing aspect for the wall assembly. Should the opportunity present itself in the future, testing the various material properties of the paint used in this research for their vapour permeability and liquid absorption of the paint could be carried out to better compare and classify the different types of binders. However, the approach and results obtained from this research provides a good base to work from in confidently applying the findings of this work in the absence of it being validated through field work.

Outside of the scope of this research further work should be done to: i) assess the impact that the paint layer has on substrates other than wood siding, ii) factor air convection as a moisture source into the analysis, iii) investigate the effects that the details of the siding have on the moisture conditions whether it is through simulations or field testing, iv) provide a deeper study into the use of various insulation types and retrofit methods and how it impacts the moisture conditions at the siding, v) conduct a full sensitivity analysis to assess which properties have the most impact on the wood siding's MC, and vi) lastly, it would be of interest to find a mathematical relationship that can be modeled to show the correlation between the moisture content of the outer wood surface and the blistering of the paint.

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Appendices

Appendix A - Glossary of Terms and Definitions

Heritage Conservation District (HCD): defined under Part V of the Ontario Heritage Act – is a geographically defined area within a municipality that is noted for its distinct heritage character.

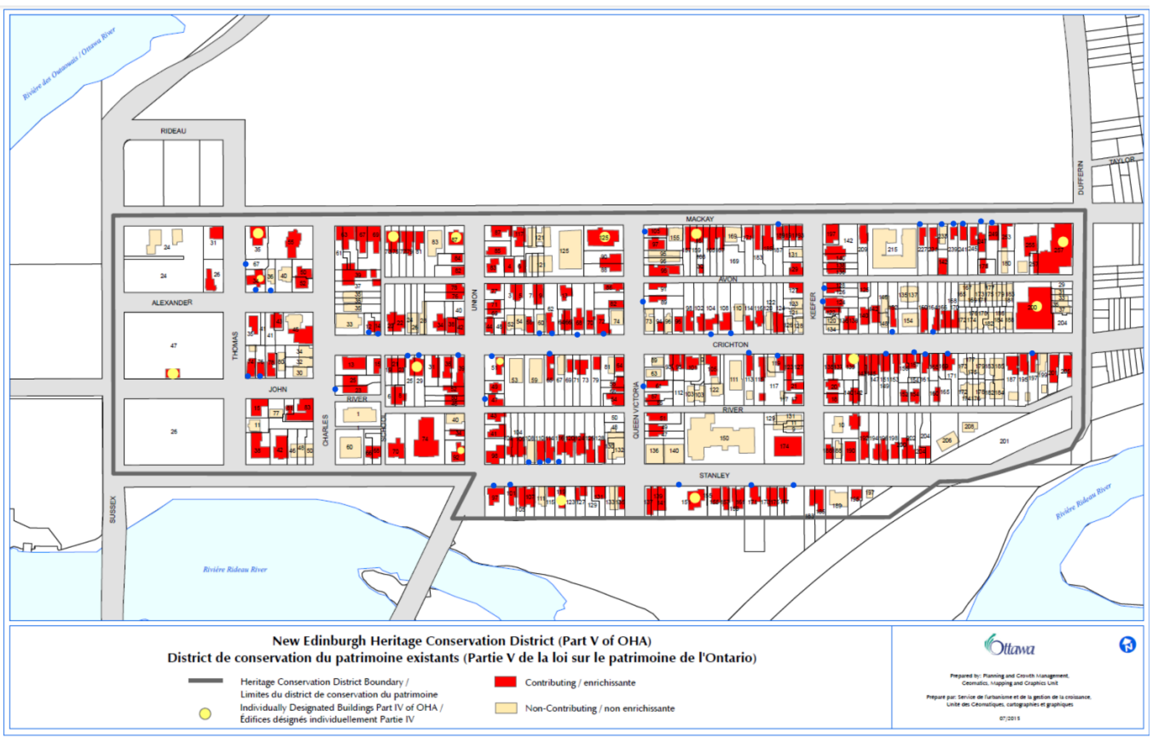


Figure A.1 A map of the New Edinburgh HCD. The blue dots indicate the buildings included in the survey. (City of Ottawa, 2017)

Character Defining Element (CDE): The materials, forms, location, spatial configurations, uses and cultural associations or meanings that contribute to the heritage value of an historic place, which must be retained in order to preserve its heritage value (Parks Canada, 2003).

Maintenance: Routine, cyclical, non-destructive actions necessary to slow the deterioration of an historic place. It entails periodic inspection; routine, cyclical, non-destructive cleaning; minor repair and refinishing operations; replacement of damaged or deteriorated materials that are impractical to save (Parks Canada, 2003).

Minimal Intervention: The approach that allows functional goals to be met with the least physical intervention (Parks Canada, 2003).

Diffusion Equivalent Air Layer Thickness (Sd): Thickness of a static air layer that has, under the same conditions of measurement, the same water-vapour transmission rate as the coating tested (International Organization for Standardization, 2018).

Water Vapour Diffusion Resistance Factor (μ): Factor that indicates how many times greater the water-vapour resistance of a material is compared with a layer of static air of the same thickness at the same temperature and pressure (International Organization for Standardization, 2018).

Liquid Absorption Coefficient (Aw): Mass of water absorbed by a test specimen per face area and per square root of time (International Organization for Standardization, 2002).

Appendix B - Heritage Guideline Overview

Table B.1 . Full version - Recommendations and Principles for the intervention of heritage buildings with wood and paints/ finishes(ICOMOS International Wood Committee, 2017; Parks Canada, 2003)

Wood	
ICOMOS: Principles for the Conservation of Wooden Built Heritage	**12.** Interventions should follow the criteria of the **minimal intervention capable of ensuring the survival of the construction**, saving as much as possible of its authenticity and integrity, and allowing it to continue to perform its function safely. However, that does not preclude the possible partial or even total dismantling of the structure if: a. repairs carried out *in situ* and on original elements would require an unacceptable degree of intervention; b. the distortion of the structure is such that it is not possible to restore its proper structural behaviour; c. inappropriate additional work would be required to maintain it in its deformed state.
	14. Any replacement timber should preferably: a. be of the **same species** as the original; b. match the **original in moisture content**; c. have **similar characteristics of grain** where it will be visible; d. be worked using **similar craft methods and tools** as the original.
	18. In the case of interventions, the historic structure should be considered as a whole. All materials, including structural members, in-fill panels, weatherboarding, roofs, floors, doors and windows, etc, should be given equal attention. In principle, as much as possible of the existing material, as well as earlier repair works, should be retained if they do not prejudice the stability of the structure. **Conservation should also include surface finishes such as plaster, paint, coating, wallpaper, etc**. The **original materials, techniques and textures should be respected**. If it is considered strictly necessary to **renew or replace deteriorated surface finishes, the use of compatible materials and techniques** is desirable.
	26. The use of chemical preservatives should be carefully controlled and monitored and should be used only where there is an assured benefit, where public and environmental safety will not be affected and where there is the expectation of significant long-term improvement
Parks Canada Standards and Guidelines	**1. Understanding** the properties and characteristics of wood and its finishes or coatings, such as its species, grade, strength and finish, or the chemical make-up of its coating.
	5. Inspecting coatings to determine their condition and appropriateness, in terms of physical and visual compatibility with the material, assembly, or system
	6. Retaining coatings that help **protect the wood from moisture**, ultraviolet light and wear. Removal should be considered only as part of an overall maintenance program that involves **reapplying the protective coatings in kind**.
	7. Removing damaged, deteriorated, or thickly applied coatings to the next sound layer, using the safest and gentlest method possible, then recoating in kind.
	8. Using the gentlest means possible to remove paint or varnish when it is too deteriorated to recoat, or so thickly applied that it obscures details.
	9. Applying compatible coatings following proper surface preparation, such as cleaning with tri-sodium phosphate.
	10. Ensuring that new coatings are **physically and visually compatible** with the surface to which they are applied in durability, chemical composition, colour, and texture.

Appendix C – Paint Permeability & Results Summary

Table C.1 Sd and permeance values of various paint types

Literature - Permeability Values				
Paint Type	**Sd-value (m)**	**Permeance (ng/Pasm2)**	**Notes**	**Testing Standard**
WUFI - material library				
Acrylic concrete paint	0.1		-no thickness mentioned	
Acrylic facade paint	0.3			
Latex paint 1	0.2			
Latex paint 2	0.7			
Silicate paint	0.01			
Stucco, **acrylic** (without driving rain)	1			
2017 ASHRAE Handbook - Fundamentals: Water Vapour Permeance (ASHRAE, 2017)				
Exterior paint, white lead and **oil on wood siding**	0.3-1.1	17-57	-For 3 coats -Dry cup values -Sd values converted from permeance	
Exterior paint, white lead/zinc oxide and **oil on wood**	0.37	51		
Styrene/butadiene **latex coating**	0.03	629		
Polyvinyl accetate **latex coating**	0.06	315		
Water Vapour Transmission Properties of Linseed Oil Paints (Šemjakin et al., 2016)				
1-layer **linseed oil** primers	0.1-0.2		thickness: 0.0008-0.0062mm	-EVS-EN ISO 7783 standard
1-layer **linseed oil** paints	0.2-0.9		thickness: 0.0113-0.0269mm	
2-layer **linseed oil** paints	0.4-0.9		thickness: 0.0178-0.0407mm	
Water Vapour Transmission Properties of Natural Paints (Ruus et al., 2011)				
Linseed oil paint		558-1300	t = 0.0062-0.0133mm	-EVS-EN ISO 7783-1:2001
Alkyd paint		514		
The impact of exterior finish vapour resistance on the moisture state of building walls (Šadauskiene et al., 2007)				
Acrylic 1	0.73 0.78 0.85		t = 0.08mm t = 0.16mm t = 0.24mm	-LST EN ISO 12572:2001 standard

Acrylic 2	0.75 0.81 0.86			

Table C.2 Findings from studies on paint permeability

Literature - Permeability Studies			
Paint Type	**Permeability metric used**	**Notes**	**Findings**
Water Permeability of Exterior Wood Coatings: Waterborne Acrylate Dispersions for Windows (Hýsek et al., 2018)			
Waterborne acrylate dispersions	-Water absorption (g/m2) -Water vapour adsorption and desorption (g/m2)	-EN 927-5 (2006)	-film thickness above 0.11mm provided required water repellency -values dependent on producer of coating -permeability affected by pigmentation -4-layered coatings were less permeable than 3-layered of same thickness
The measurement of the moisture transfer properties of paint films using the cup method (Goossens et al., 2004)			
Waterborne styrene acrylic dispersion (**latex**)	-Water vapour transfer (kg/s Pa)	-three thicknesses used: 120, 250, 400um -free paint films	-permeability depends on moisture content of paint
Characterization of waterborne acrylic based paint films and measurement of their water vapor permeabilities (Topçuoğlu et al., 2006)			
Waterborne **acrylic** based paints	-Water vapour permeability (moles/s cm kPa)	-binder contents varied: 40%, 30%, 20%, 10%	-structure of paint film changes from denser to more porous with decrease in binder content -low binder content leads to higher pigment concentration and a non-homogeneous pigment distribution which increases the water vapour permeability -water vapour permeability increases as binder content decreases
Comparison between laboratory water permeability tests and wood moisture content of full-scale window frames (de Meijer, 2002)			

Water based **acrylic** dispersion	-Water absorption (g/m2 72h) -Vapour absorption (g/m2 14d) - Vapour desorption (g/m2 14 d)	-EN 927-5 (liquid water) -EN 927-4 (water vapour)	-Variation in wood MC only partly controlled by permeability of coating. Construction related factors cause large differences in wood MC. -water absorption values all below limit for stable end-use -water borne coating has higher water permeability than solvent borne -a high solid topcoat gave strong reduction in water permeability -while paint has the lowest water absorption
High solid solvent based **alkyd**			
Water based **alkyd** emulsion			
Solvent based **alkyd**			
Moisture conditions in coated wood panels during 24 months natural weathering at five sites in Europe (Grüll et al., 2013)			
Water-based **acrylic** paint opaque, medium build	-Liquid water permeability	-EN 927-5	-duration of rainfall events more important than the amount of rain -high winter and low summer wood moisture contents -MC influenced by type of binder and film thickness -high film thickness contributes to better moisture protection, higher coating durability and longer maintenance intervals -high film thickness has negative consequences of low permeability - if moisture enters in gaps/ defects, it is released very slowly -solvent borne alkyd stains maintained lower levels of MC than water-based acrylic
Water-based **acrylic** paint opaque, high build			
Water-based **acrylic** stain semi transparent, low build			
Water-based **acrylic** stain semi transparent, medium build			
Water-based **acrylic** stain semi transparent, high build			
Semi-transparent **alkyd**			

Table C.3 Summary of durations for the various methods and cases

		Duration in days							
		2022		2024		2022		2024	
Case	Best/Worst	>20%	>30%	>20%	>30%	>20% >2ºC	>30% >2ºC	>20% >2ºC	>30% >2ºC
Method 1	Sd = 0.3	0	0	0	0	0	0	0	0
	Sd = 0.5	42	0	70	0	2	0	6	0
	Sd = 1.0	103	7	123	49	14	1	26	3
	Sd = 2.0	145	80	145	97	40	11	37	23
	Sd = 4.0	167	104	183	127	57	26	66	35
	Sd = 33	182	125	234	167	68	41	105	60
Method 2	Sd = 0.3 Aw = 0.0005	111	4	72	1	18	0	6	0
	Sd = 0.5 Aw = 0.0005	159	98	110	16	41	14	18	16
	Sd = 1.0 Aw = 0.0005	203	172	148	121	72	54	40	24
	Sd = 0.3 Aw = 0.0003	29	0	8	0	3	0	1	0
	Sd = 0.5 Aw = 0.0003	122	19	98	1	13	2	10	0
	Sd = 1.0 Aw = 0.0003	177	121	138	87	54	23	32	14
Case 1	Sd = 0.3 Aw = 0.0005	142	13	93	3	29	4	10	0
	Sd = 0.5 Aw = 0.0005	194	153	136	90	66	38	31	8
	Sd = 1.0 Aw = 0.0005	238	190	197	140	104	71	77	40
	Sd = 0.3 Aw = 0.0003	106	1	79	0	14	1	5	0
	Sd = 0.5 Aw = 0.0003	167	86	124	47	48	8	25	1
	Sd = 1.0 Aw = 0.0003	210	174	173	131	82	61	57	33
Case 2	Sd, ext = 0.3 Sd, BP = 0	142	13	93	3	29	7	10	0
	Sd, ext = 0.3 Sd, BP = 0.3	94	4	29	1	18	4	4	0
	Sd, ext = 0.3 Sd, BP = 0.5	36	3	19	1	15	3	3	0
	Sd, ext = 0.3 Sd, BP = 1.0	22	3	10	0	12	3	2	0

	Sd, ext = 0.5 Sd, BP = 0	194	153	136	90	66	38	31	8
	Sd, ext = 0.5 Sd, BP = 0.3	163	75	107	4	45	15	16	0
	Sd, ext = 0.5 Sd, BP = 0.5	151	21	93	2	35	8	9	0
	Sd, ext = 0.5 Sd, BP = 1.0	117	6	27	1	24	5	4	0
	Sd, ext = 1.0 Sd, BP = 0	238	190	197	140	104	71	77	40
	Sd, ext = 1.0 Sd, BP = 0.3	209	176	155	120	78	58	46	23
	Sd, ext = 1.0 Sd, BP = 0.5	205	166	141	86	74	48	39	7
	Sd, ext = 1.0 Sd, BP = 1.0	196	137	125	7	68	29	27	0
Case 3	Sd = 0.3 Aw = 0.0005	199	180	138	110	69	0	35	19
	Sd = 0.5 Aw = 0.0005	225	200	162	136	91	72	53	37
	Sd = 1.0 Aw = 0.0005	268	230	240	186	132	99	113	78
	Sd = 0.3 Aw = 0.0003	189	166	131	107	61	46	28	16
	Sd = 0.5 Aw = 0.0003	208	196	153	131	78	68	45	31
	Sd = 1.0 Aw = 0.0003	257	221	222	174	122	93	105	66
Case 5	Sd = 0.3 RH = 50%	124	6	14	0	22	4	2	0
	Sd = 0.5 RH = 50%	176	109	103	2	57	23	16	0
	Sd = 1.0 RH = 50%	208	181	139	70	77	62	39	16
	Sd = 0.3 RH = 60%	139	11	91	3	28	7	10	0
	Sd = 0.5 RH = 60%	190	142	133	78	64	35	34	6
	Sd = 1.0 RH = 60%	227	188	194	141	96	69	82	42
	Sd = 0.3 RH = 70%	146	15	103	5	33	9	15	0
	Sd = 0.5 RH = 70%	200	164	155	115	71	48	46	20
	Sd = 1.0 RH = 70%	248	205	342	229	115	86	208	111

Appendix D - Dew Point Analysis

D.1 Dew Point Background

The purpose of conducting a Dew Point analysis is to observe the contribution that the vapour transport adds to the moisture conditions of the siding. The calculations used for the temperature, vapour and relative humidity profile can be seen in Figure D.1.1. It is a steady state analysis method typically done for certain values of temperature and relative humidity, in which the relative humidity profile can indicate areas within the wall assembly where moisture accumulation may start to occur. This analysis method is based on Fick’s equation for diffusion and models the movement of water vapour based on the vapour pressure gradient and materials’ resistance to the movement of water vapour.

The Dew Point analysis calculations were done initially in MicroSoft Excel for every hour for one year (8,760 hours). To further streamline the analysis, Python was used to simulate the correction of the vapour pressure profile once saturation occurs.

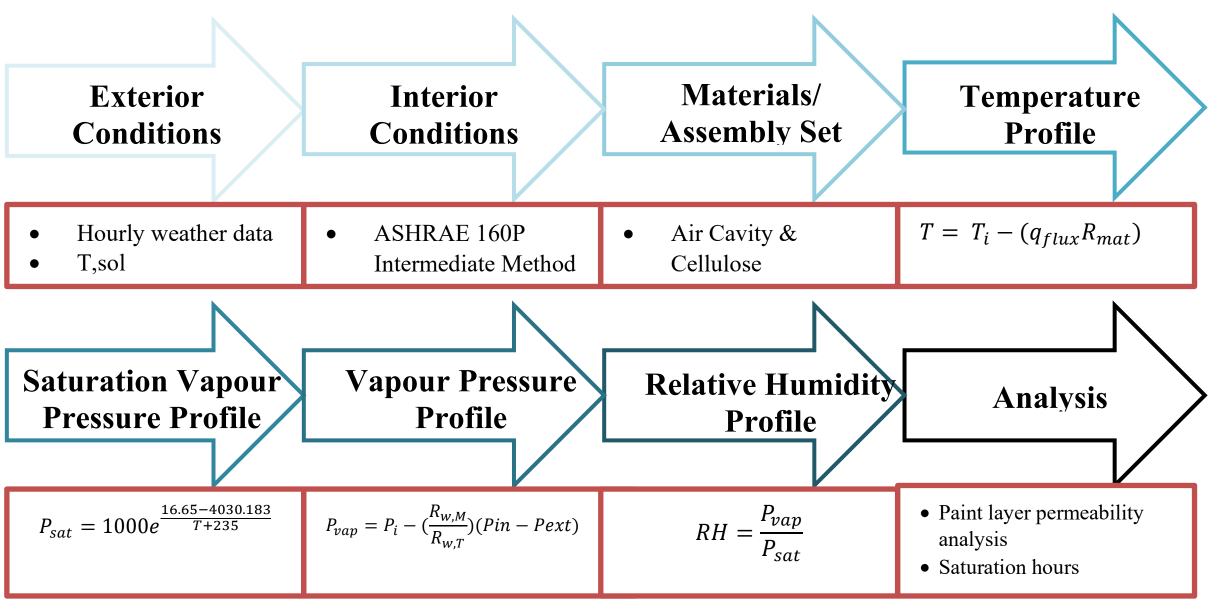


Figure D.1.1 Workflow for Dew Point method

Exterior Conditions

The Dew Point analysis was done for every hour for an entire year, using weather data recorded from the Ottawa International Airport for 2019. The exterior temperature was adjusted to factor in solar radiation of the exterior surface temperature as recalculated using Sol-air temperature (Scheuneman, 1982). The solar absorption coefficient (α) and exterior thin film layer for convection and radiation were estimated based on this recalculation as depicted in Table D.1.1. In achieving further directional granularity, a Sun Path chart for the Ottawa area was used to transpose the solar radiation data for the Southern, Western, Northern and Eastern orientations. Based on this information, the Northern orientation was used to calculate the Sol-air temperature as it will reflect the least amount of drying potential due to solar radiation.

Table D.1.1 Exterior Surface Coefficients

Solar Absorption Coefficient (α)	**h,conv [W/m^{2}K]**	**h,rad winter [W/m^{2}K]**	**h,rad summer [W/m^{2}K]**
0.6	17	17	5.7

Interior Conditions

In determining the interior conditions for temperature and relative humidity that underpins the Dew Point method the ASHRAE 160P Design Criteria for Moisture Control in Buildings Intermediate method was used. Of note, this ASHRAE method was also used for the WUFI software simulations as will be explained later. Incorporating this ASHRAE method, the interior temperature is determined as a function of the exterior temperature accordingly:

- If $T_{ext} <= 18.3^oC$, $T_{in} = 20^oC$

- If $T_{ext} > 18.3^oC$, $T_{in} = T_{ext} + 2.8^oC$

The interior relative humidity is determined from the calculated interior vapour pressure which uses the equation below, noting that this method assumes there to be no dehumidification or air-conditioning within the building.

$$\boldsymbol{p_i = p_{o,24h} + \frac{c\dot{m}}{Q_{ventilation}}} \quad \textbf{(17)}$$

Where:

p_i= indoor vapour pressure [Pa]

$p_{o,24h}$= 24-hour running average outdoor vapour pressure [Pa]

c= constant equal to 1.36x10^5 [m^2/s^2]

$\dot{m}$= design moisture generation rate [kg/s]

$Q_{ventilation}$= design ventilation rate [m^3/s]

$\boldsymbol{Q_{ventilation} = Iv/3600}$ **(18)**

Where:

I= ventilation rate [Air Changes/h]

v= volume of building [m^3]

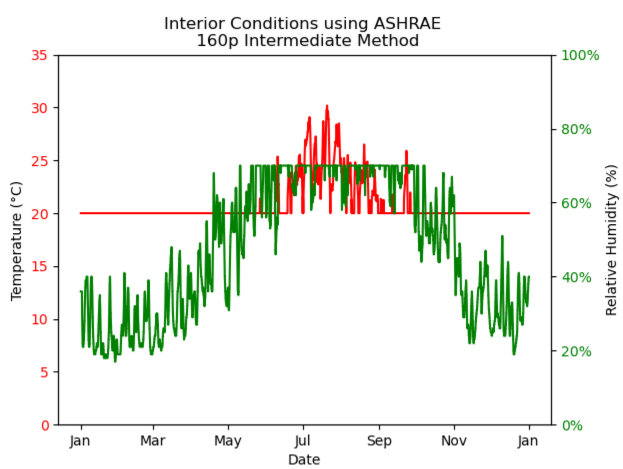


Figure D.1.2 Interior conditions using ASHRAE 160p Method

Material Properties

The material properties required for the Dew Point analysis include the material thickness (m), thermal conductivity (W/m K) and permeability (ng/Pa s m). The material properties were taken from the material library in WUFI, except for the permeability which required modifications. In WUFI, the vapour resistance for materials is inputted as the vapour diffusion resistance factor, μ (-), while the dew point analysis considers the vapour resistance (Pa s m^2/ng), the reciprocal of permeance. In addition, for some materials in WUFI μ is moisture dependent, which considers the liquid transport effects of surface diffusion. Since the dew point analysis does not consider how permeability changes with relative humidity, the μ at an RH of 50% was used to represent the vapour resistance for the dew point analysis. The conversion used for μ to vapour resistance is as follows (WUFI wiki, n.d.):

$$\boldsymbol{Permeance\ (Perm) = 3.28/Sd} \quad \textbf{(19)}$$

$$\textbf{Permeability (Perm inch)} = \mathbf{129/\mu} \quad \textbf{(20)}$$

Perm Inch → Permeability (g/Pasm) = $\textbf{Perm inch} * \mathbf{1.45x10^{-9}}$ **(21)**

In addition, it is assumed that the paint layer has a thickness of 0.3mm, as this is typically the recommended coat thickness for three layers of paint.

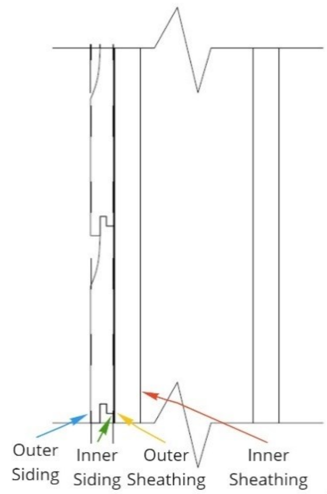


Figure D.1.3 Layers analyzed as part of the Dew Point analysis

Limitations

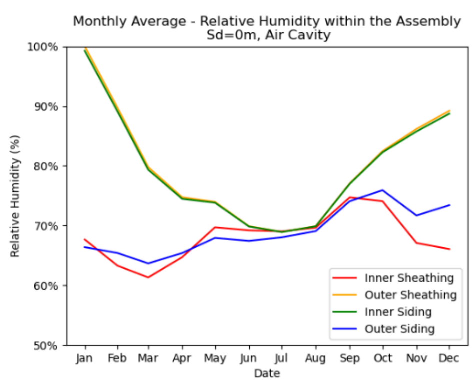
It is known that the Dew Point method should not be used as the sole method for analysing moisture conditions within a building assembly due to its limitations. The method only considers vapour movement via diffusion, excluding the effects of vapour movement via air convection, capillary conduction, and rain as a moisture source. As well, once a material shows saturation the method does not consider whether the material is hygroscopic, neglecting the distribution of the saturated moisture or how it is stored. The way in which the Dew Point method was applied has its limitations, specifically as a steady state method that was used to calculate the condensation plane for every hour of the year makes it less accurate as the dynamic properties that are prevalent are not properly captured.

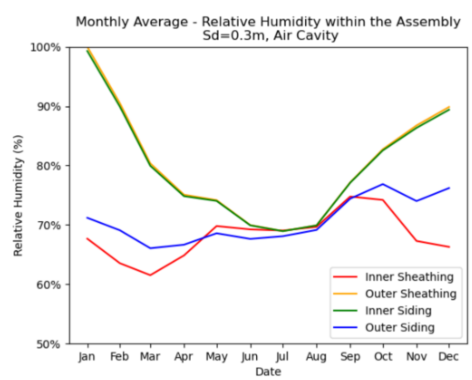
D.2 Dew Point Results

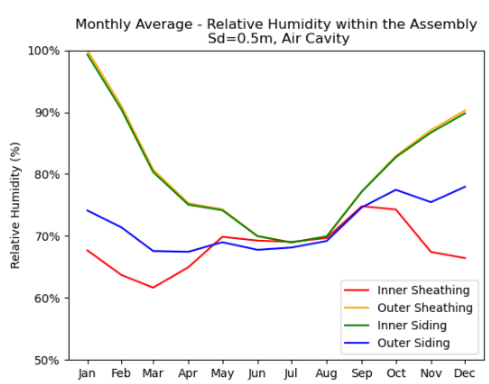
Air Cavity

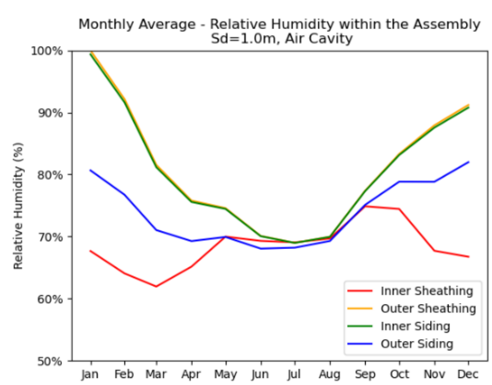
Table D.2.1 Air Cavity - Hours at Saturation Based on the Exterior Paint Sd

	Hours at Saturation					
Interface	*Sd=0m*	*Sd=0.3m*	*Sd=0.5m*	*Sd=1.0m*	*Sd=2.0m*	*Sd=4.0m*
Inner Sheathing	24	25	25	36	41	53
Outer Sheathing	712	757	790	838	931	1082
Inner Siding	27	30	30	38	43	61
Outer Siding	0	0	0	17	250	1127









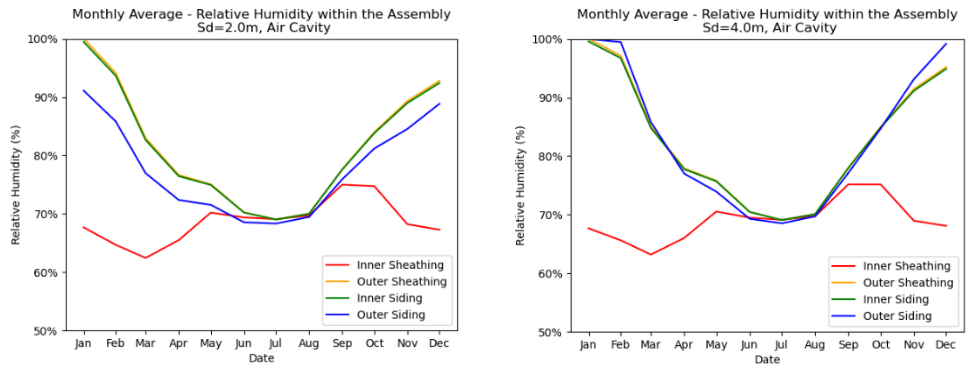
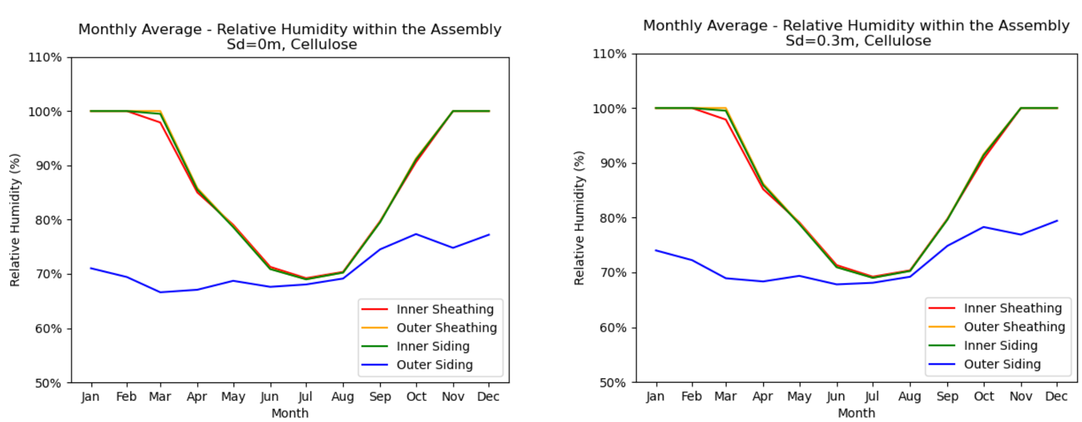


Figure D.2.1 Air Cavity – Monthly averaged RH values at the four interfaces based on Sd-value

Cellulose Insulation

Table D.2.2 Cellulose - Hours at Saturation Based on the Exterior Paint Sd

	Hours at Saturation					
Interface	*Sd=0m*	*Sd=0.5m*	*Sd=1.0m*	*Sd=1.5m*	*Sd=2.0m*	*Sd=4.0m*
Inner Sheathing	2998	3019	3039	3075	3123	3207
Outer Sheathing	3006	3063	3099	3174	3281	3443
Inner Siding	2641	2696	2729	2801	2898	3018
Outer Siding	0	0	0	14	321	1310



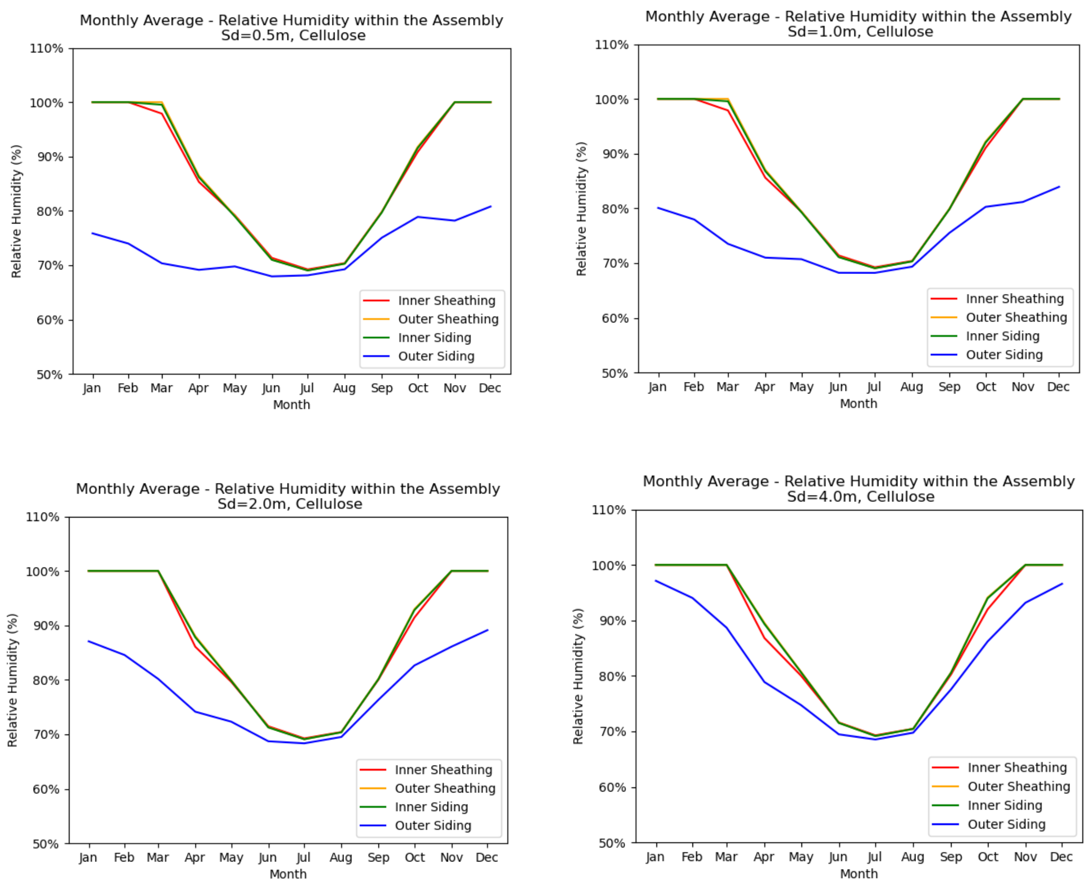


Figure D.2.2 Cellulose Insulated Cavity - Monthly averaged RH values at the four interfaces based on Sd-value

Results Analysis

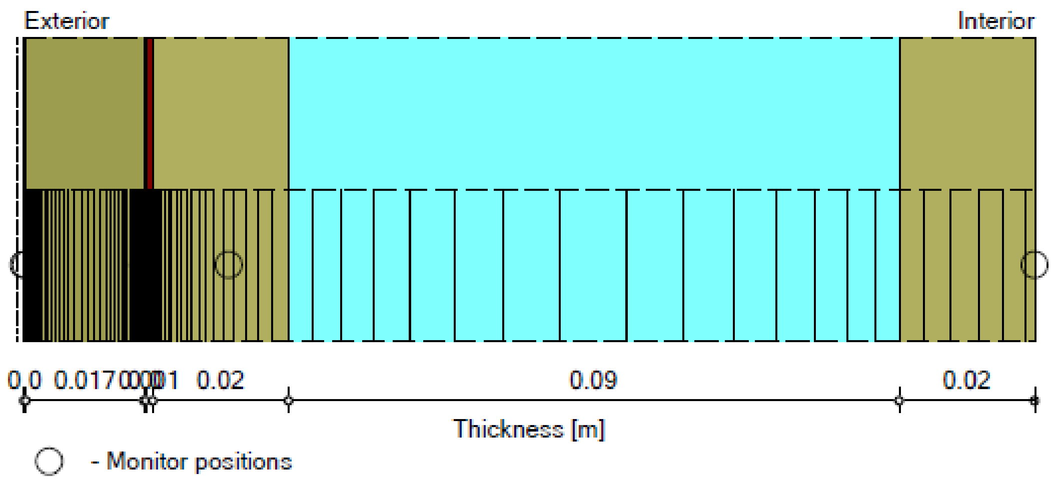
Above an Sd-value of 1.0m, for both the air can cellulose wall, the outer siding layer begins to saturate, with a large jump in saturation hours at an Sd of 4.0m. At Sd-values below 2.0m, there are no concerns for condensation reaching the outer siding. For the air cavity wall, at Sd=4.0m the outer siding has the most saturation hours. The overall results show the same trends as the WUFI analysis, where the winter times shows increased moisture and the summer months the moisture decreases and an equilibrium among the layers is reached.

Appendix E - WUFI

E.1 Cases – Component Assembly

Method 1: Sd (Vapour)

Case: Method 1: Sd 0.3



Materials:

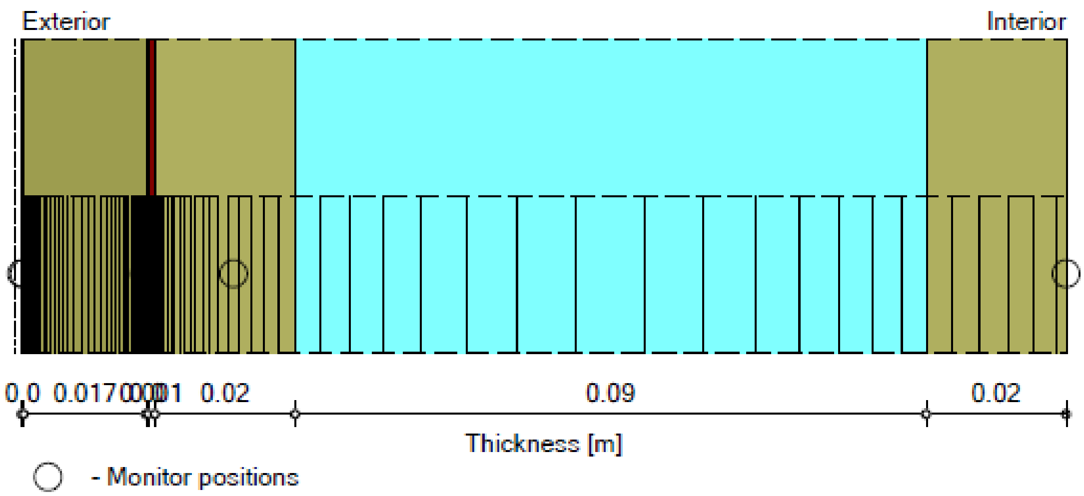
- Eastern White Pine	0.0 m
- Eastern White Pine	0.017 m
- Eastern White Pine	0.0 m
- 60 minute Building Paper	0.001 m
- Spruce	0.02 m
- Air Layer 90 mm; without additional moisture capacity	0.09 m
- Spruce	0.02 m

sd-Value Ext. [m]: 0.3

Total Thickness: 0.149 m
R-Value: 0.83 (m² K)/W
U-Value: 0.985 W/(m² K)

Method 2: Sd & Aw (Vapour and Liquid)

Case: Method 2: Sd = 0.3, Aw = 0.0005



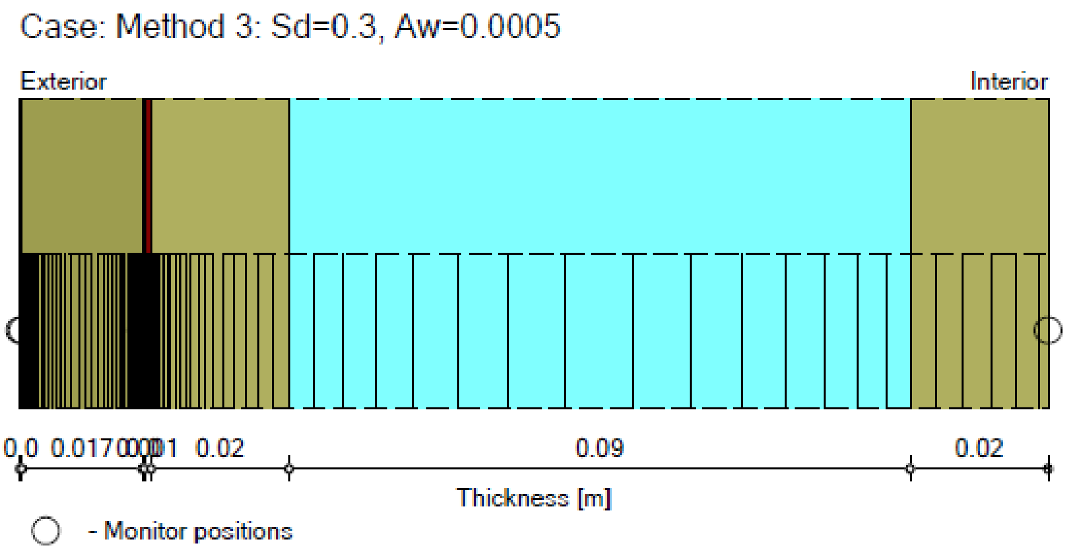
Materials:

- *Eastern White Pine - Aw = 0.0000083	0.0 m
- Eastern White Pine	0.017 m
- Eastern White Pine	0.0 m
- 60 minute Building Paper	0.001 m
- Spruce	0.02 m
- Air Layer 90 mm; without additional moisture capacity	0.09 m
- Spruce	0.02 m

sd-Value Ext. [m]: 0.3

Total Thickness: 0.149 m
R-Value: 0.83 (m² K)/W
U-Value: 0.985 W/(m² K)

Method 3: μ & Aw (Vapour and Liquid)



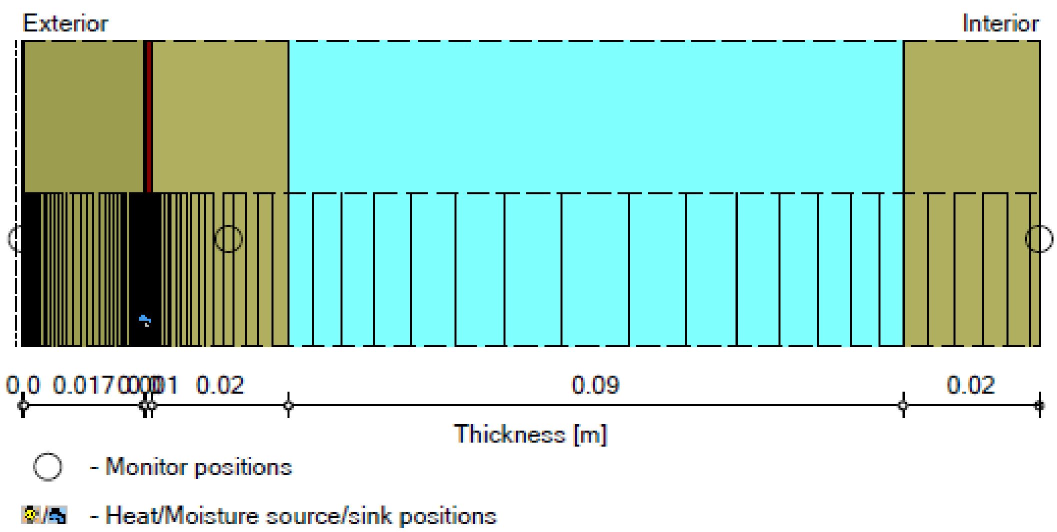
Materials:

- *Eastern White Pine - Aw=0.0000083, mu=1000	0.0 m
- Eastern White Pine	0.017 m
- Eastern White Pine	0.0 m
- 60 minute Building Paper	0.001 m
- Spruce	0.02 m
- Air Layer 90 mm; without additional moisture capacity	0.09 m
- Spruce	0.02 m

Total Thickness: 0.149 m
R-Value: 0.83 (m² K)/W
U-Value: 0.985 W/(m² K)

Case 1: Cladding Leakage

Case: Case 1: Sd=0.3, Aw=0.0005



Materials:

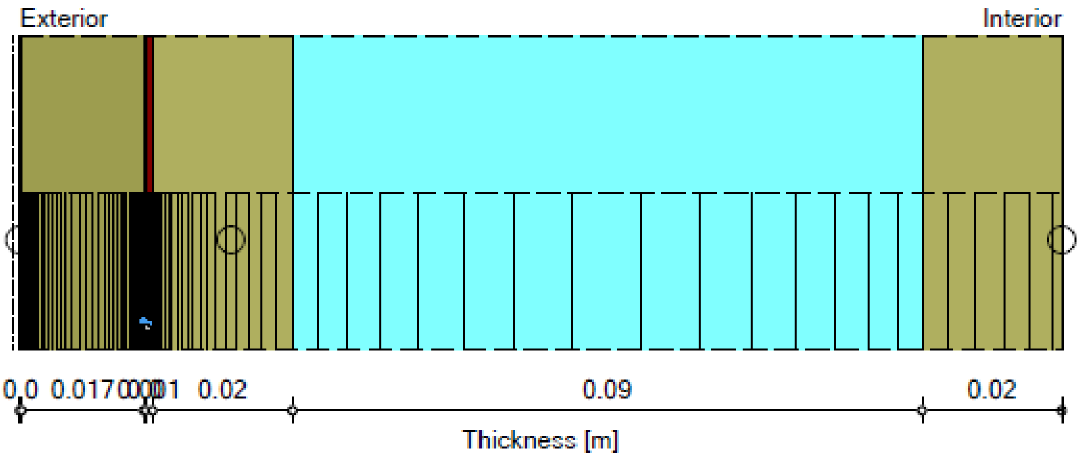
	- *Eastern White Pine - Aw=0.0000083	0.0 m
	- Eastern White Pine	0.017 m
	- Eastern White Pine	0.0 m
	- 60 minute Building Paper	0.001 m
	- Spruce	0.02 m
	- Air Layer 90 mm; without additional moisture capacity	0.09 m
	- Spruce	0.02 m

sd-Value Ext. [m]: 0.3

Total Thickness: 0.149 m
R-Value: 0.83 (m² K)/W
U-Value: 0.985 W/(m² K)

Case 2: Back Prime

Case: Case 2: Sd=0.3, BP=0



- Monitor positions

- Heat/Moisture source/sink positions

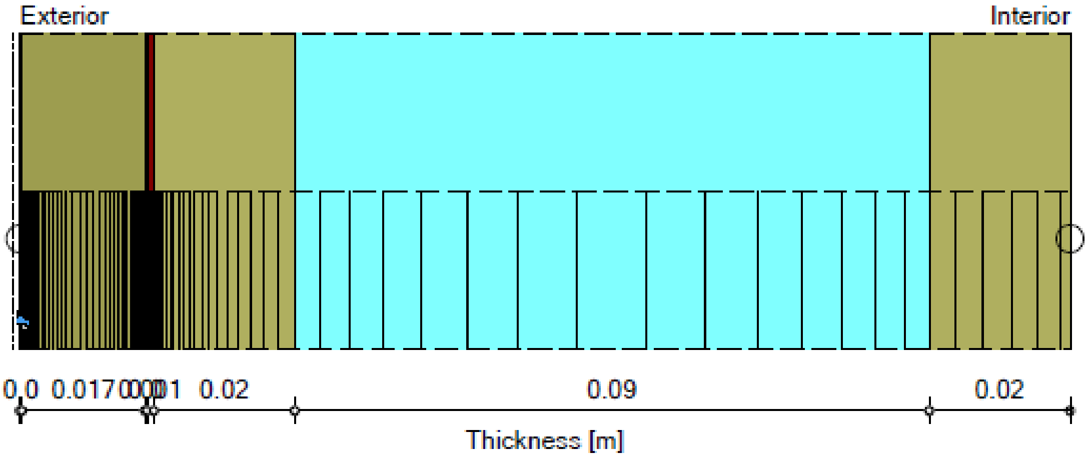
Materials:

	- *Eastern White Pine - Aw=0.0000083	0.0 m
	- Eastern White Pine	0.017 m
	- Eastern White Pine	0.0 m
	- 60 minute Building Paper	0.001 m
	- Spruce	0.02 m
	- Air Layer 90 mm; without additional moisture capacity	0.09 m
	- Spruce	0.02 m

sd-Value Ext. [m]: 0.3

Total Thickness: 0.149 m
R-Value: 0.83 (m² K)/W
U-Value: 0.985 W/(m² K)

Case: Case 3: Sd = 0.3, Aw = 0.0005



- Monitor positions

- Heat/Moisture source/sink positions

Materials:

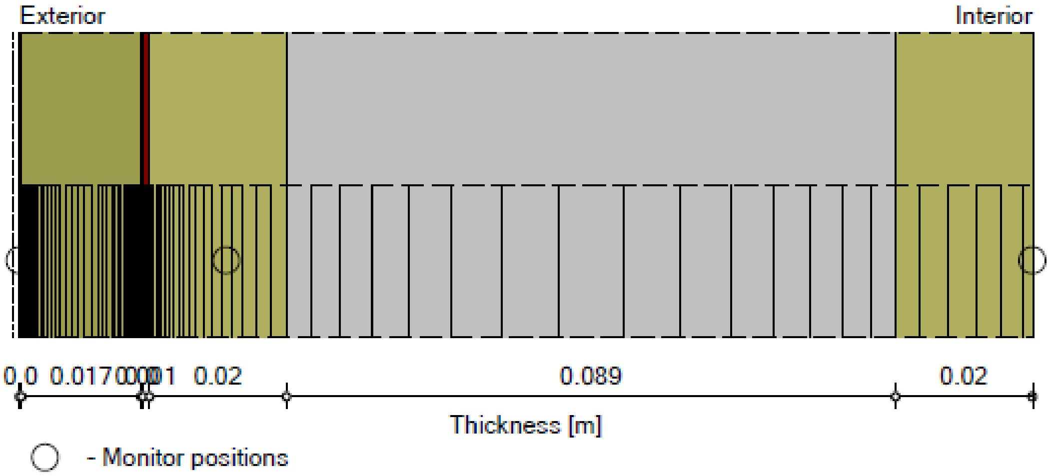
- *Eastern White Pine - Aw = 0.0000083	0.0 m
- Eastern White Pine	0.017 m
- Eastern White Pine	0.0 m
- 60 minute Building Paper	0.001 m
- Spruce	0.02 m
- Air Layer 90 mm; without additional moisture capacity	0.09 m
- Spruce	0.02 m

sd-Value Ext. [m]: 0.3

Total Thickness: 0.149 m
R-Value: 0.83 (m² K)/W
U-Value: 0.985 W/(m² K)

Case 4: Cellulose

Case: Case 4: Sd = 0.3, Aw = 0.0005



Materials:

	- *Eastern White Pine - Aw = 0.0000083	0.0 m
	- Eastern White Pine	0.017 m
	- Eastern White Pine	0.0 m
	- 60 minute Building Paper	0.001 m
	- Spruce	0.02 m
	- Cellulose Fiber Insulation	0.089 m
	- Spruce	0.02 m

sd-Value Ext. [m]: 0.3

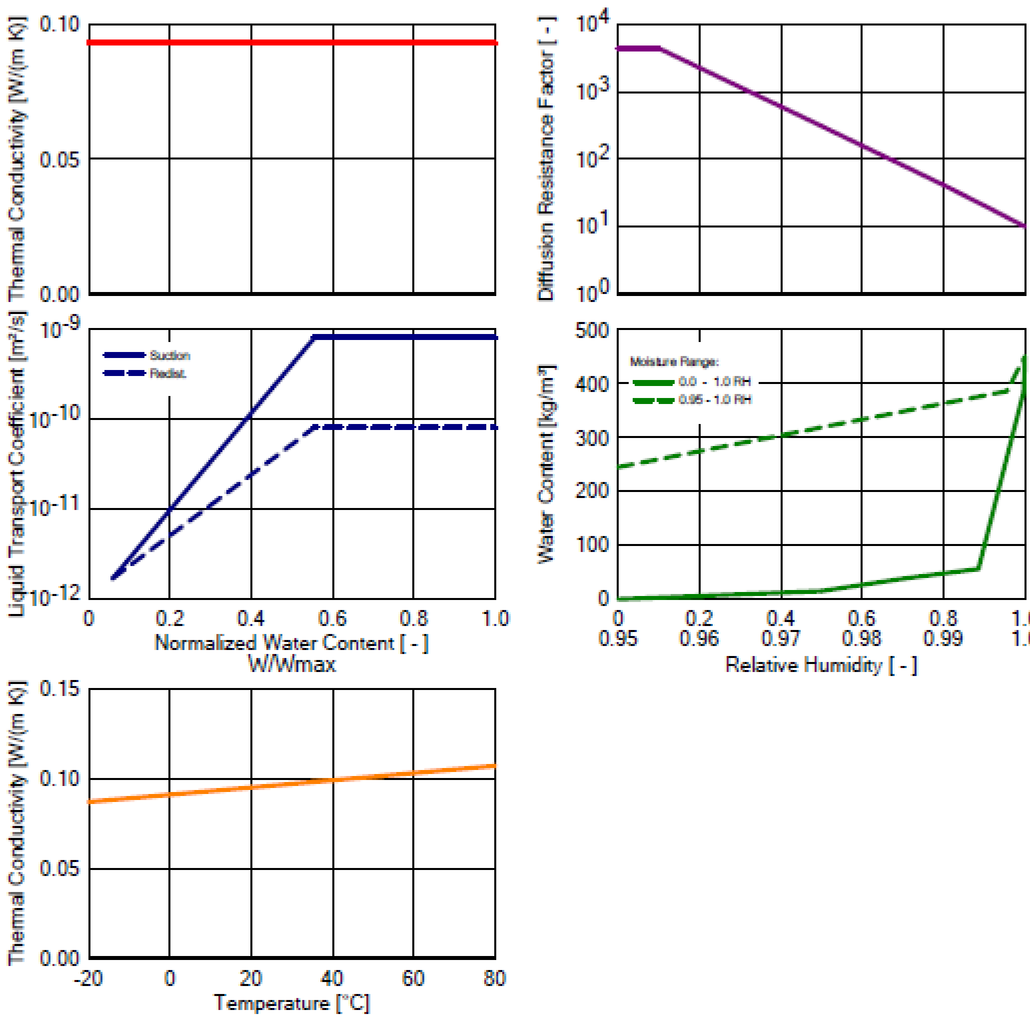
Total Thickness: 0.148 m
R-Value: 3.13 (m² K)/W
U-Value: 0.302 W/(m² K)

E.2 Material Properties

Eastern White Pine

Material: Eastern White Pine

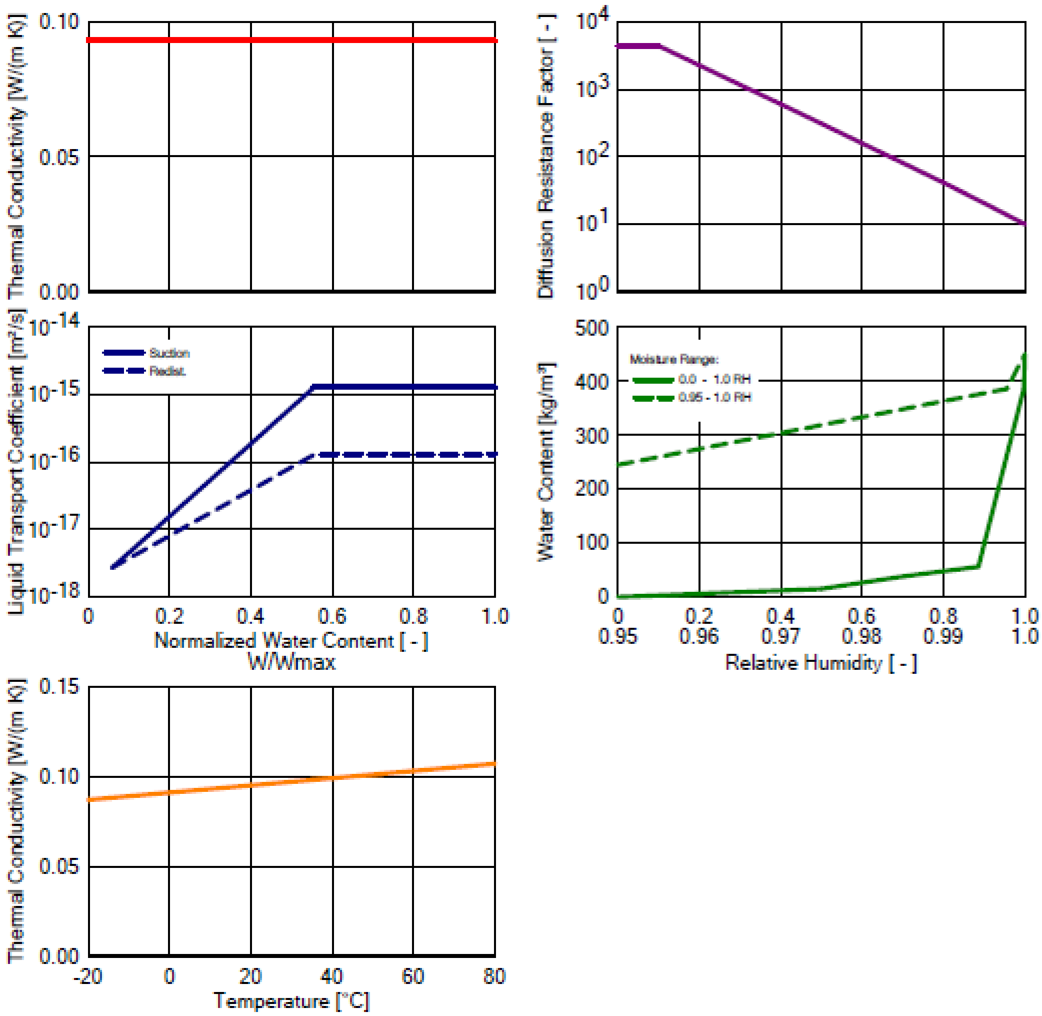
Property	Unit	Value
Bulk density	[kg/m³]	460
Porosity	[m³/m³]	0.81
Specific Heat Capacity, Dry	[J/(kg K)]	1880
Thermal Conductivity, Dry, 10°C	[W/(m K)]	0.093
Water Vapour Diffusion Resistance Factor	[-]	4427.4
Reference Water Content	[kg/m³]	47.7
Free Water Saturation	[kg/m³]	450
Water Absorption Coefficient	[kg/(m² s^0.5)]	0.0066
Temp-dep. Thermal Cond. Supplement	[W/(m K²)]	2.00000E-4



Eastern White Pine – Unlocked, Aw = 0.0005 kg/m2h0.5 (0.0000083 kg/m2s0.5)

Material: *Eastern White Pine - Aw = 0.0000083

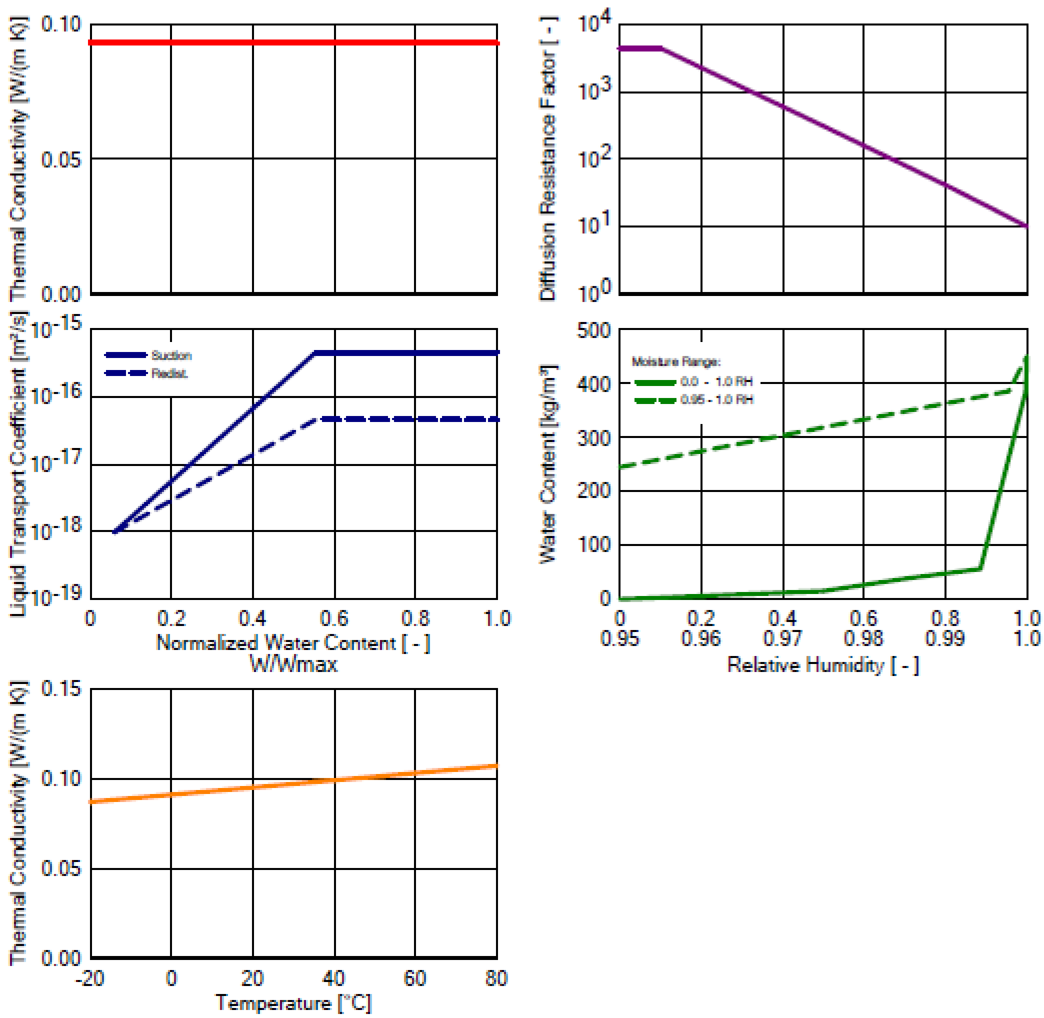
Property	Unit	Value
Bulk density	[kg/m³]	460
Porosity	[m³/m³]	0.81
Specific Heat Capacity, Dry	[J/(kg K)]	1880
Thermal Conductivity, Dry, 10°C	[W/(m K)]	0.093
Water Vapour Diffusion Resistance Factor	[-]	4427.4
Reference Water Content	[kg/m³]	47.7
Free Water Saturation	[kg/m³]	450
Water Absorption Coefficient	[kg/(m² s^0.5)]	8.3330E-6
Temp-dep. Thermal Cond. Supplement	[W/(m K²)]	0.0002



Eastern White Pine – Unlocked, Aw = 0.0003 kg/m2h0.5 (0.000005 kg/m2s0.5)

Material: *Eastern White Pine - Aw = 0.000005

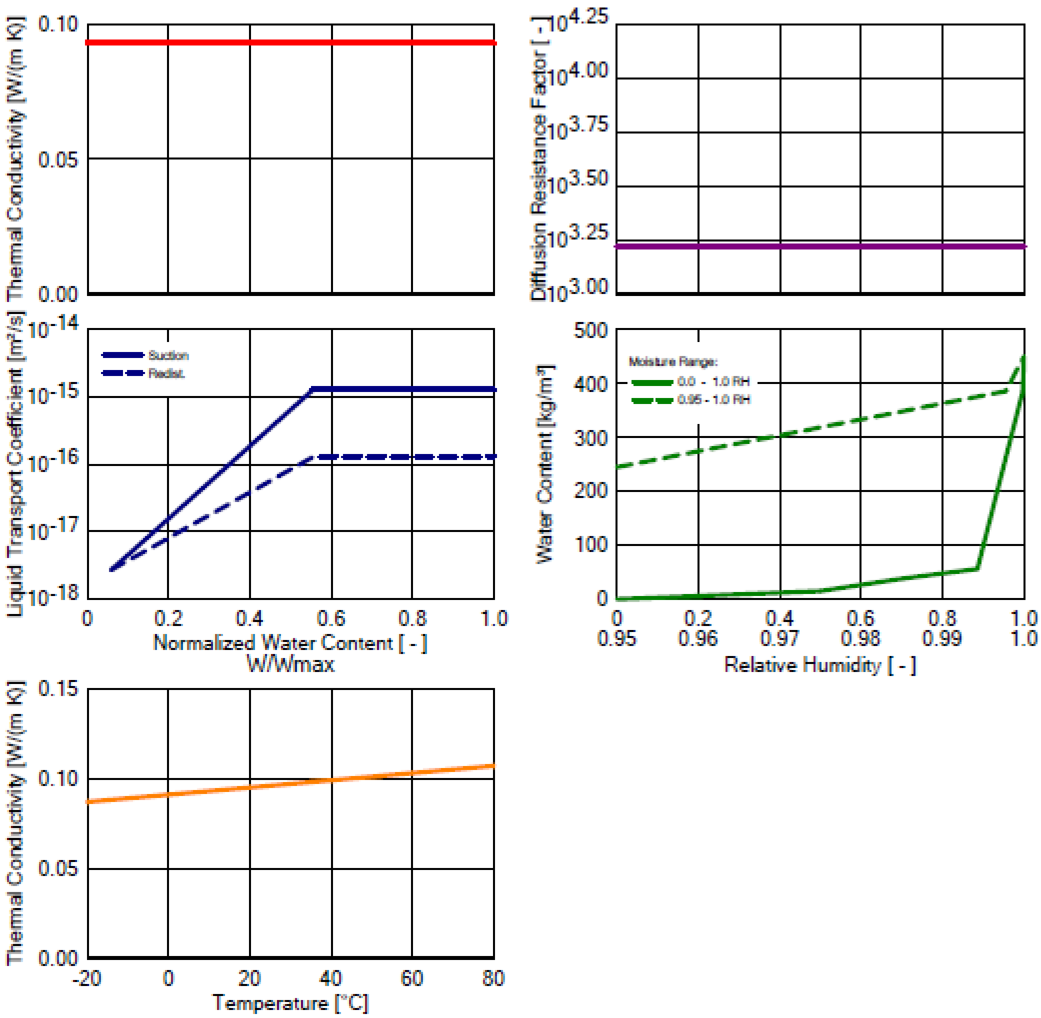
Property	Unit	Value
Bulk density	[kg/m³]	460
Porosity	[m³/m³]	0.81
Specific Heat Capacity, Dry	[J/(kg K)]	1880
Thermal Conductivity, Dry, 10°C	[W/(m K)]	0.093
Water Vapour Diffusion Resistance Factor	[-]	4427.4
Reference Water Content	[kg/m³]	47.7
Free Water Saturation	[kg/m³]	450
Water Absorption Coefficient	[kg/(m² s^0.5)]	0.000005
Temp-dep. Thermal Cond. Supplement	[W/(m K²)]	0.0002



Eastern White Pine – Unlocked, Aw = 0.0005 kg/m2h0.5 (0.0000083 kg/m2s0.5) & μ=1666

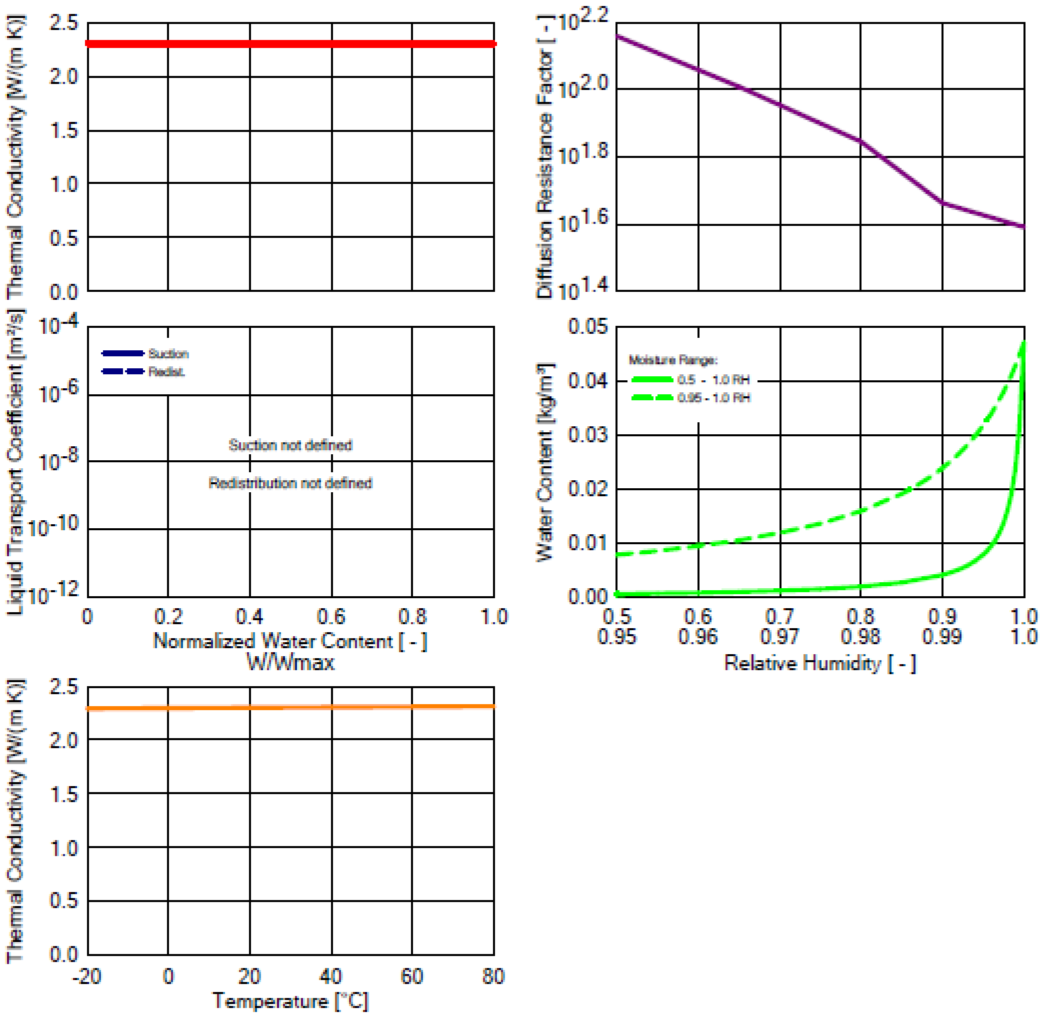
Material: *Eastern White Pine - Aw=0.0000083, mu=1666

Property	Unit	Value
Bulk density	[kg/m³]	460
Porosity	[m³/m³]	0.81
Specific Heat Capacity, Dry	[J/(kg K)]	1880
Thermal Conductivity, Dry, 10°C	[W/(m K)]	0.093
Water Vapour Diffusion Resistance Factor	[-]	1666
Reference Water Content	[kg/m³]	47.7
Free Water Saturation	[kg/m³]	450
Water Absorption Coefficient	[kg/(m² s^0.5)]	8.33000E-6
Temp-dep. Thermal Cond. Supplement	[W/(m K²)]	0.0002



Material: 60 minute Building Paper

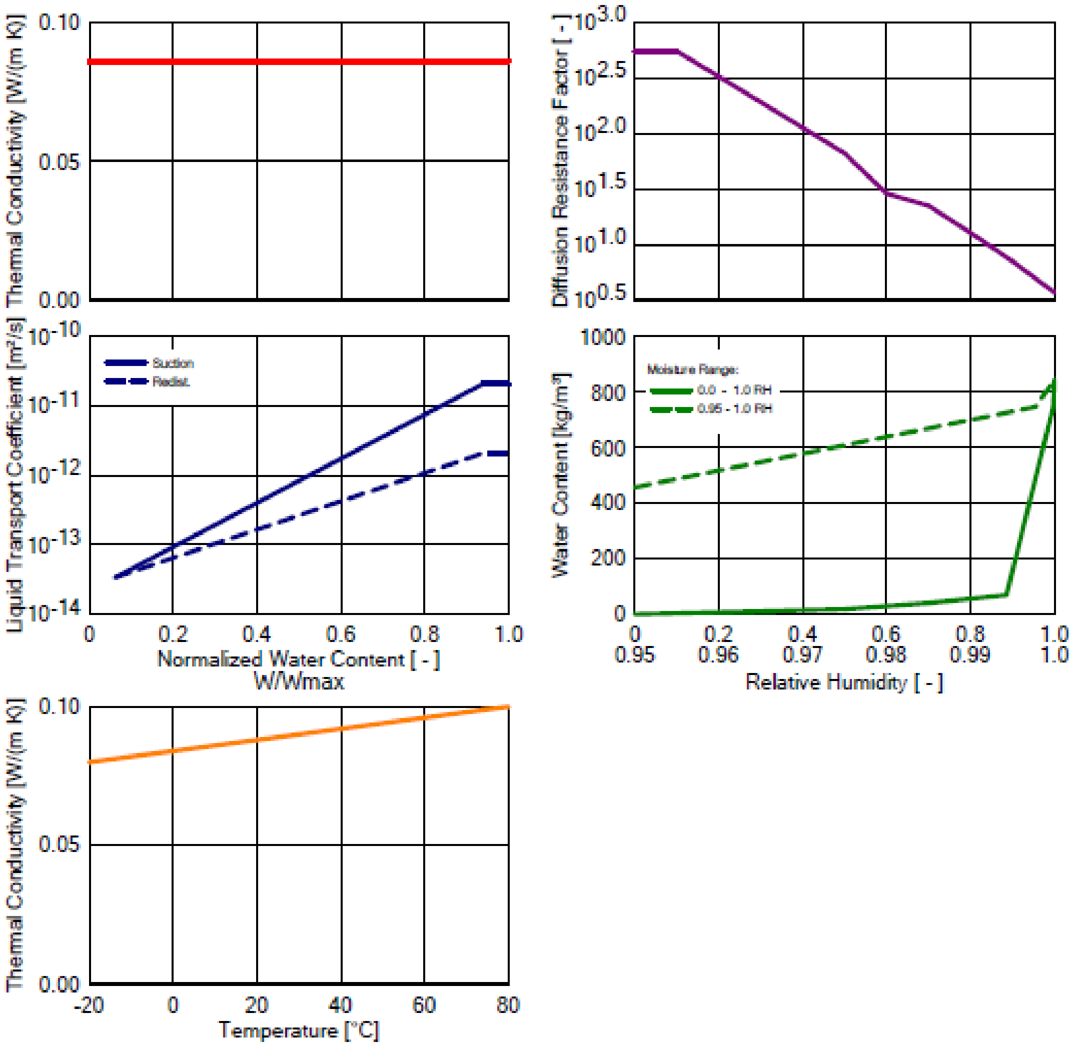
Property	Unit	Value
Bulk density	[kg/m³]	280
Porosity	[m³/m³]	0.001
Specific Heat Capacity, Dry	[J/(kg K)]	1500
Thermal Conductivity, Dry, 10°C	[W/(m K)]	2.3
Water Vapour Diffusion Resistance Factor	[-]	144
Temp-dep. Thermal Cond. Supplement	[W/(m K²)]	2.00000E-4



Spruce

Material: Spruce

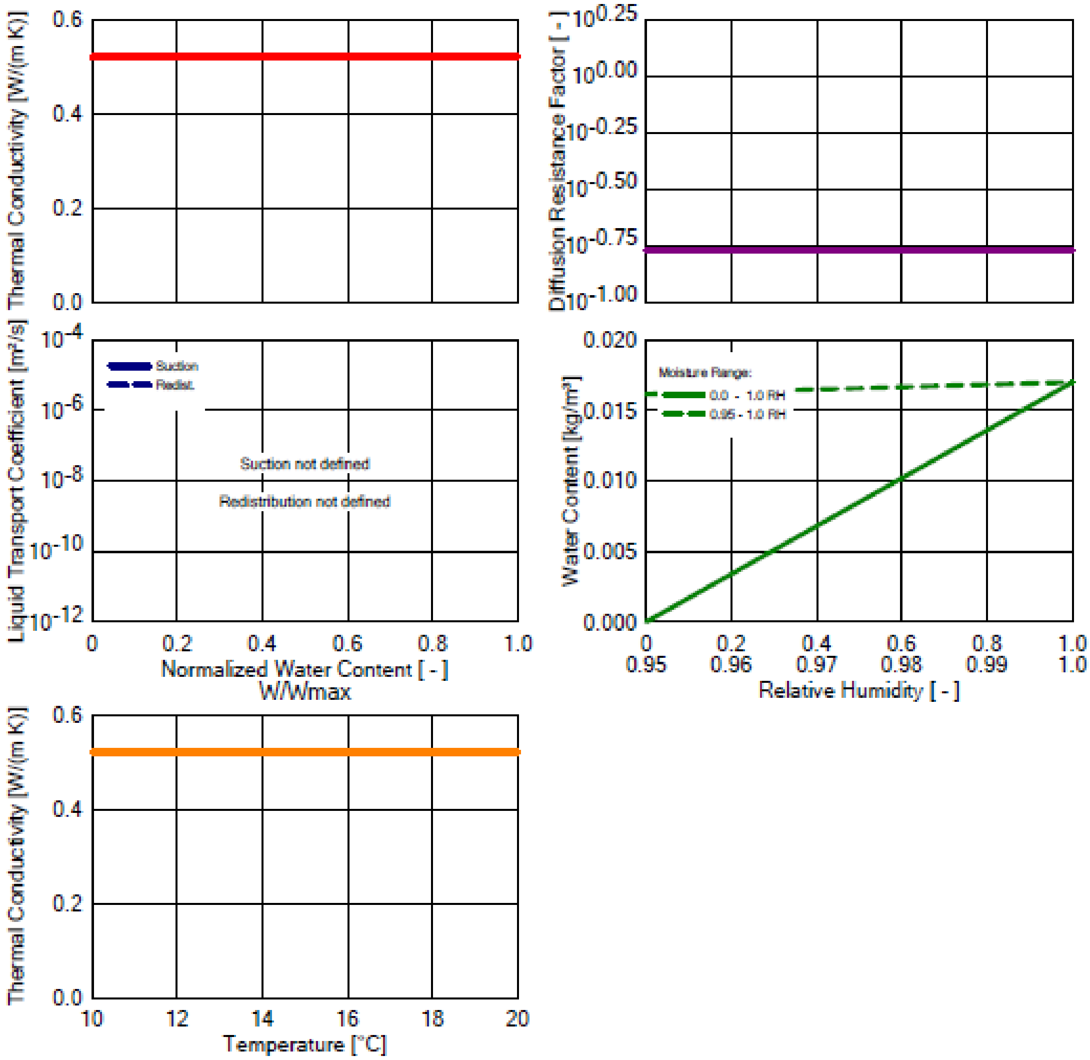
Property	Unit	Value
Bulk density	[kg/m³]	400
Porosity	[m³/m³]	0.9
Specific Heat Capacity, Dry	[J/(kg K)]	1880
Thermal Conductivity, Dry, 10°C	[W/(m K)]	0.086
Water Vapour Diffusion Resistance Factor	[-]	552
Reference Water Content	[kg/m³]	55.8
Free Water Saturation	[kg/m³]	845
Water Absorption Coefficient	[kg/(m² s^0.5)]	0.002
Temp-dep. Thermal Cond. Supplement	[W/(m K²)]	2.00000E-4



Air Space 90mm; without Additional Moisture Storage Capacity

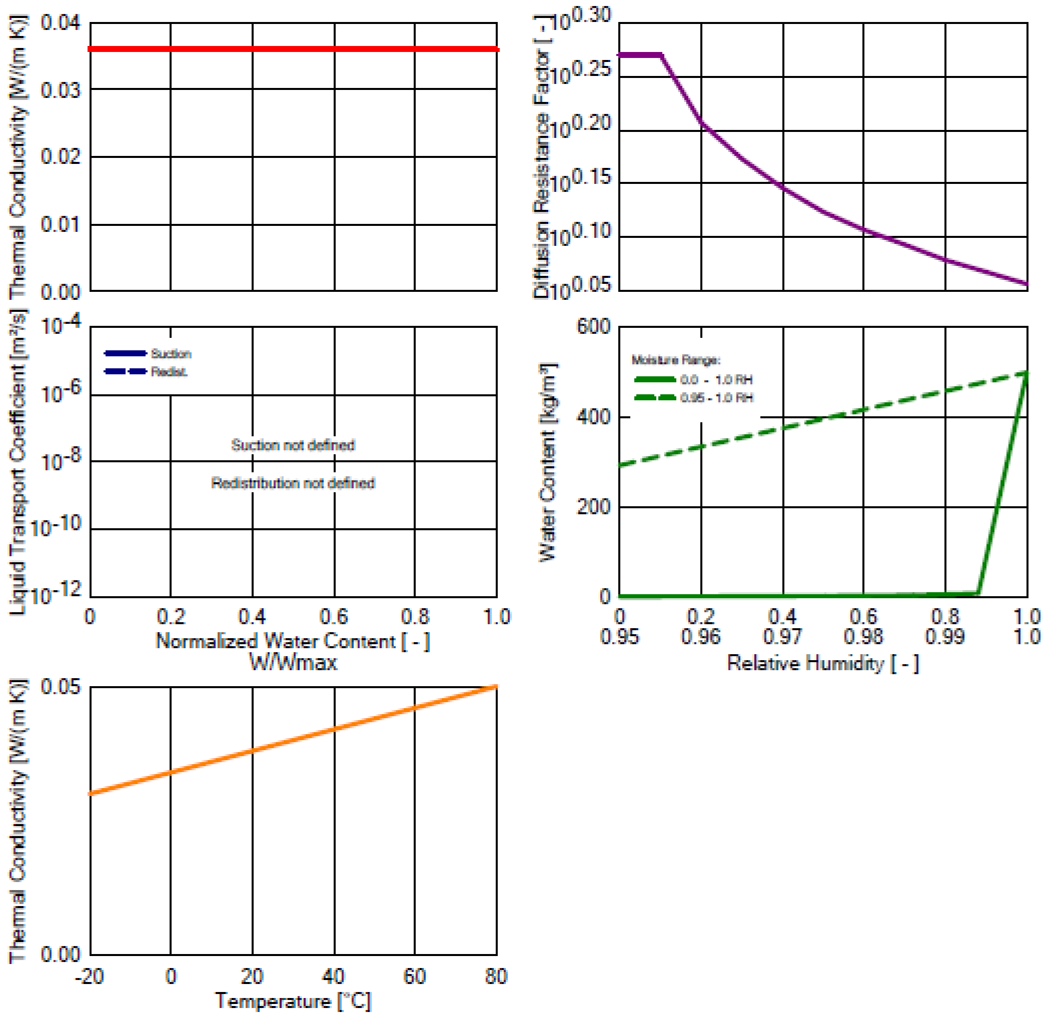
Material: Air Layer 90 mm; without additional moisture capacity

Property	Unit	Value
Bulk density	[kg/m³]	1.3
Porosity	[m³/m³]	0.999
Specific Heat Capacity, Dry	[J/(kg K)]	1000
Thermal Conductivity, Dry, 10°C	[W/(m K)]	0.523
Water Vapour Diffusion Resistance Factor	[-]	0.17



Material: Cellulose Fiber Insulation

Property	Unit	Value
Bulk density	[kg/m³]	30
Porosity	[m³/m³]	0.99
Specific Heat Capacity, Dry	[J/(kg K)]	1880
Thermal Conductivity, Dry, 10°C	[W/(m K)]	0.036
Water Vapour Diffusion Resistance Factor	[-]	1.86
Temp-dep. Thermal Cond. Supplement	[W/(m K²)]	2.00000E-4



E.3 WUFI Moisture Source

Cladding Leakage

60 minute Building Paper

Name	Type		
Cladding Leakage	*Moisture Source; Fraction of Rain Load*		
	Depth in Layer	[m]	0.0003
	Cut-Off at Free Water Saturation	[kg/m³]	0
	User-Defined	[%]	1

Paint Layer Leakage

Eastern White Pine

Name	Type		
Paint Leakage	*Moisture Source; Fraction of Rain Load*		
	Depth in Layer	[m]	0.0003
	Cut-Off at Free Water Saturation	[kg/m³]	450
	User-Defined	[%]	1