Hygrothermal Performance of Insulated, Sloped, Wood-Framed Roof Assemblies

by

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A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Applied Science
in
Civil Engineering

Waterloo, Ontario, Canada, 2008

Author’s Declaration

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

I understand that my thesis may be made electronically available to the public.

Christopher James Schumacher

Abstract

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Roofs are the single enclosure element common to artificial shelters constructed by all cultures in all climate regions. The hygrothermal performance of insulated, sloped, wood-frame roof assemblies has long been of interest to building scientists and building codes alike. Requirements for the ventilation of roof assemblies have been included in building codes for more than 50 years, however moisture problems still occur. Unvented roof assemblies have been suggested as an alternate and potentially superior solution. While unvented roofs have become relatively common in the warmer southern climates of North America, some technical issues remain unclear and the need exists for further study and demonstration of the hygrothermal performance of both ventilated and unvented roof assemblies in northern climates.

This thesis seeks to improve the understanding of the hygrothermal performance of ventilated and unvented, insulated, sloped, wood-framed roof assemblies using field measurement, analytical calculation and computer simulations.

A review of existing literature and current industry experience and practice was prepared. Five categories of research needs were identified: roof leaks, air leakage, vapor diffusion, roof temperature and ice dams. Air leakage, vapor diffusion and roof temperature are addressed by the research work described in this thesis.

The connection between attic moisture problems and air leakage was confirmed through field investigation. Analysis suggests that the benefits of improved ceiling air tightness may not be realized until extremely low levels of air leakage are achieved. Problems may be more easily mitigated through control of indoor relative humidity levels. Attic ventilation can assist in mitigating moisture problems, but it is not as effective as the preventative measures.

An unvented cathedral ceiling roof assembly was constructed at a test house in Vancouver BC and monitored for several years. The assembly was insulated with air impermeable, vapor permeable sprayed polyurethane foam insulation and without the use of a vapor barrier. The assembly performed adequately, however a strong connection between indoor humidity levels (i.e. vapor pressure) and sheathing moisture content was identified. When strict control of indoor humidity is not possible, modeling should be conducted to establish the vapor permeance required reduce to winter time vapor diffusion so that the moisture content of the North-facing roof sheathing does not exceed 20%.

A side-by-side field monitoring study of six ventilated and unvented roof assemblies was undertaken at a test hut in Coquitlam BC. The test demonstrated that both ventilated and unvented roof assemblies can perform satisfactorily; frost and condensation are not a concern when the indoor humidity is reasonable, the ceiling plane allows minimal air leakage, roof temperatures do not remain cold for extended periods and the ventilation is straightforward. Under these conditions the unvented cathedralized roof assemblies exhibited only slightly higher peak wintertime sheathing moisture contents. The application of two heavy coats of latex paint as a vapor control layer on the inside surface of the foam insulation was demonstrated to be ineffective.

Monitored sheathing and shingle temperatures of four pairs of ventilated and unvented roof assemblies in an Atlanta GA test hut confirmed that peak summertime sheathing and shingle temperatures are reduced by ventilation, however the study also suggested that there is little difference between the sheathing and shingle temperatures recorded in a conventional (ventilated) cathedral ceiling roof assembly and an unvented cathedral ceiling assembly.

The WUFI 4.1 Pro software program was used to predict the performance of the unvented roof assembly employed at the Vancouver BC test house. Good agreement was achieved between predicted and measured sheathing temperatures and moisture contents, demonstrating the potential to predict the performance of unvented roof assemblies. Further work should be done to assess the impact of moisture storage in the wood framing, material property assumptions and boundary conditions. The WUFI 4.1 Pro software should considered for the simulation of ventilated attic roof assemblies.

Acknowledgements

This thesis has been a long time in production and many have had a hand in moving it to completion.

I would like to thank Dr. John Straube, Marguarite Knechtel and others in the Dept. of Civil Engineering for refusing to let me give up when the demands and challenges of work, family and school seemed impossible to balance.

Dr. Eric Burnett, Dr. Don Onysko and Dr. Joseph Lstiburek have long been mentors. Through the years they have endured hours of discussion on and debate over building science problems. In both difficult and happy times they have shared their experience, their wine and their scotch freely. Their sincere (and sound) scientific, business and personal advice continues to be greatly appreciated.

I have also had the fortune of working with many good "up and coming" building scientists from the University of Waterloo's Building Engineering Group (BEG), the Pennsylvania State University's Building Enclosure Testing Laboratory (BeTL) and Building Science Corporation (BSC). Thanks are owed to Randy VanStraaten, Xing Shi, Joseph Pinon, Kohta Ueno, Alex Lukachko, Aaron Townsend, Peter Baker, Jonathan Smegal, Graham Finch, Christopher Black and Aaron Grin. Together we have worked on numerous building science research projects, argued both building technology and building physics and shared many great trips.

Finally, I would like to express my gratitude to my wife and family for their support and tolerance as I put in innumerable long days at work and too many nights and weekends in front of a laptop.

Dedication

This thesis is dedicated to my grandparents: Fredrick & Marjorie Luscott and Jerome & Norma Schumacher.

Table of Contents

List of Figures

List of Tables

Chapter 1
Introduction

1.1 Introduction

Roofs are an important part of the building enclosure system; they play a significant architectural role in defining the form of the building; they protect the contents and occupants from rain, sun, snow, and other climatic loads. Roofs are the single enclosure element common to artificial shelters constructed by all cultures in all climate regions.

People have constructed roof assemblies for several millennia. The form, construction techniques and materials are widely varied. In North America and Northern Europe insulated, sloped, wood-framed roof assemblies have emerged as the dominant roof construction for low-rise residential buildings. Builders, designers and product manufacturers have significant experience with this form of roof construction and yet problems are still encountered. The hygrothermal performance of insulated, sloped wood-frame roof assemblies has long been of interest to building scientists and building codes alike.

Model building codes were introduced in North America in the late 1940s. Requirements were included in these codes for the ventilation of attics assemblies. These requirements persisted for more than 50 years, reinforced by the belief that ventilation was the only means of addressing the problems of attic condensation and ice dams in the winter and high attic temperatures in the summer. This conventional wisdom has been challenged on several bases: vent openings can allow wind driven snow and rain or hot embers from fires to enter the roof assembly (Lstiburek 2006, Rudd 2005); in cold, wet climates ventilation can actually increase the moisture levels of wood sheathing and framing (TenWolde and Rose 1999); in hot climates ventilation can bring warm, humid air into contact with cool drywall surface or the cold surfaces of air conditioning ductwork and equipment, creating potential condensation problems (Lstiburek 1993). Unvented roof assemblies have been developed to address some of these issues.

Interest in and adoption of unvented roof assemblies has increased since the early 1990s, driven by several changes in the low-rise residential market: new requirements for higher insulation levels; wider adoption of more moisture sensitive building materials; growing use of cathedral ceiling (i.e. compact) roof assemblies; and increasing complexity of roof and ceiling geometries. These changes have raised new questions about the practicality and performance of conventional ventilated roof assemblies. Unvented roof assemblies have been accepted as a real alternative in the warm, humid climate of the American southeast, however many questions still remain regarding the performance of unvented roof assemblies in colder climates.

The construction industry is slow to change and has a tendency to make decisions on the basis of tradition, rumor and money rather than technical merit. However, the technical issues remain unclear and the need exists for further study and demonstration of the hygrothermal performance of both ventilated and unvented roof assemblies in northern climates.

1.2 Objectives

The objective of the research work described in this thesis is to improve the understanding of the hygrothermal performance of ventilated and unvented, insulated, sloped, wood-framed roof assemblies using field measurement, analytical calculation and computer simulations.

1.3 Approach

The research began with a review of the state of current industry practice and existing literature related to the construction of insulated, sloped, wood-framed attic assemblies in all climate zones across North America. This was followed by a study of the moisture physics related to the hygrothermal performance of roof assemblies. The moisture physics were then applied to the analysis of a collection of four field investigation and measurement projects. Predictive tools were developed to aid in further research and practice.

Chapter 2 of this thesis offers a background discussion on current North American approaches to the construction of insulated, sloped, wood-framed roof assemblies. Chapter 3 continues this study of roof assemblies with a review of selected literature, addressing theory, simulation, measurement and current practice. A summary of the relative moisture physics is provided in Chapter 4. Chapter 5 follows with the summary and analysis of an Ottawa ON field investigation and three field research studies: a test house in Vancouver BC, a test hut in Coquitlam BC and a test hut in Atlanta GA. Simple analytical models and a more detailed hourly simulation program were used to extend the analysis and discussion in Chapter 6. Finally, conclusions are drawn and recommendations made in Chapter 7.

1.4 Scope

In North America insulated, sloped, wood-framed roof assemblies are commonly employed in the construction of low-rise residential buildings. While most of the analysis and discussion in this thesis centers on residential building applications, the moisture physics and many of the conclusions drawn will also apply to low-rise commercial buildings that have sloped, wood-framed roof assemblies.

This thesis does not address low-slope compact roof assemblies constructed with wood joists, even though much of the physics would still be applicable.

No climate limitations were placed on the review of existing literature and theory, however the field studies considered in this thesis are only representative of the marine, mixed humid and cold climate regions represented in Figure 1.1.

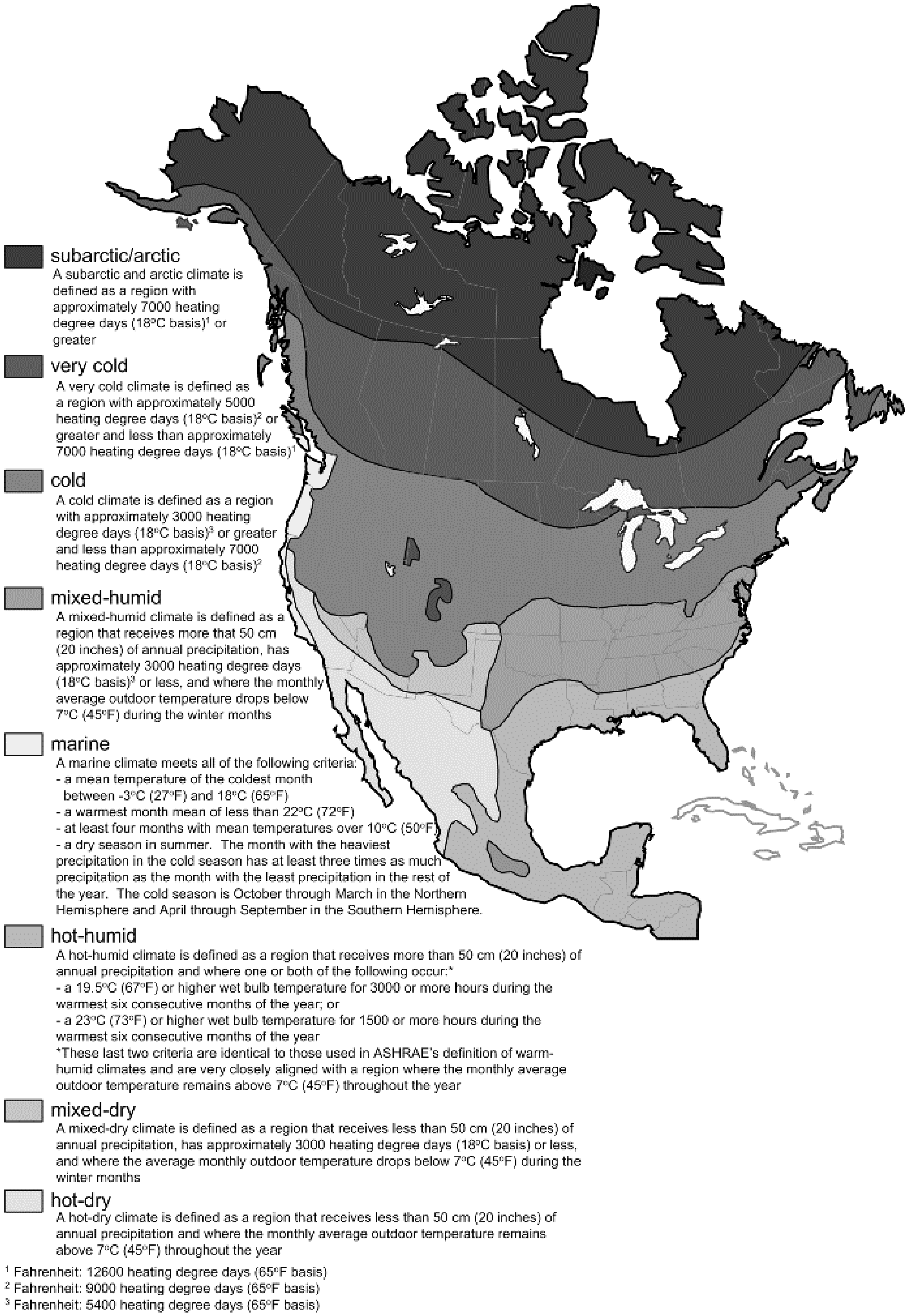


Figure 1.1 – Lstiburek's climate zone classification map (Lstiburek 2005)

Chapter 2

Background

2.1 The Roof as Building Enclosure Element

The building enclosure is any part of the building that separates the outdoor environment from the indoor environment and moderates the influence of the former on the later. It is convenient to describe building enclosure elements based on their location, geometry & function. Figure 2.1 illustrates the building enclosure elements that are typically found in a low rise residential building. The roof enclosure elements are located above the conditioned space, separating the indoor environment from the outdoor environment above.

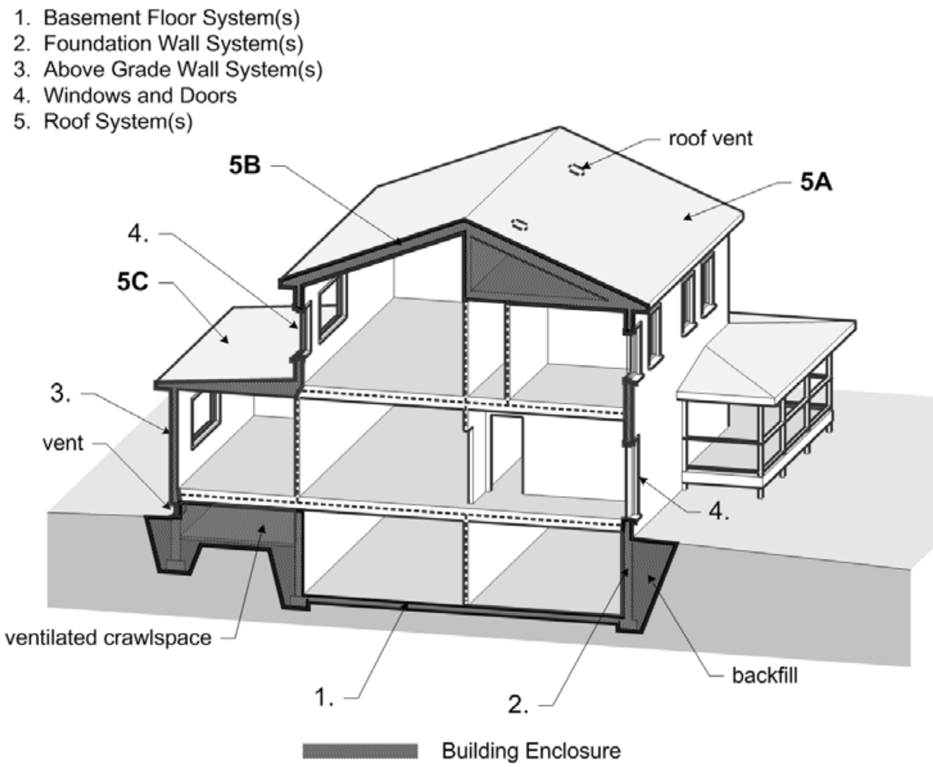


Figure 2.1 – Typical building enclosure elements (adapted from Straube & Burnett 2005)

Building enclosures are almost always three-dimensional multi-layer assemblies; they comprise all layers between the interior finish and the exterior cladding. The geometry of any enclosure element is usually dictated by architectural intent and requirements. Figure 2.1 illustrates three types of roof assemblies: 5A) an attic roof assembly, 5B) a cathedral ceiling assembly and 5C) a low-slope roof assembly.

Finally, building enclosure elements can be characterized and analyzed based on the physical functions they serve. These functions fall into four groups: support, control, finish and distribute (Straube and Burnett 2005).

2.1.1 Support Functions

The roof assembly must support a number of structural loads and distribute these to beams, load bearing walls or other supports. Eventually all loads on the building must be transferred to the earth, usually at the foundation level. The roof must support its own weight and any loads applied from the interior or exterior side of the assembly. These may include snow, wind, people, mechanical equipment and decorative architectural elements.

2.1.2 Control Functions

The roof assembly moderates the effect of the outdoor environment on the indoor by controlling or limiting the energy (e.g. heat, light and sound) and mass (e.g. air, liquid water, water vapor, snow and ice) transfer through the enclosure. The level of control exercised usually depends on the desired indoor environmental conditions (e.g. temperature, humidity, sound and light levels, etc.); the capacity of mechanical systems to make up any difference between the desired conditions and those resulting from the moderation provided by the enclosure; and the cost of constructing, operating and maintaining the enclosure and mechanical systems.

2.1.3 Finish Functions

The inner- and outermost layers of the roof assembly are readily visible to and may, depending on the building, be touched by the building occupants and the public. As a result these layers often have aesthetic (e.g. color, texture and reflectance) and maintenance (e.g. frequency of cleaning or replacement) requirements in addition to any related to support, control and distribution.

2.1.4 Distribute Functions

In North America it is extremely common to distribute electrical, plumbing and HVAC services through roof assemblies. In most cases these include wiring for lights and communication, sewer vent stacks and bathroom exhaust fans. In some regions entire heating and cooling systems (i.e. equipment and ductwork) are located in the roof assembly. This practice is becoming more common and is will be discussed in more detail later as it creates some special challenges.

2.2 Insulated, Sloped, Wood-Framed Roof Assemblies

The focus of this thesis is on insulated, sloped, wood-framed roof assemblies. This rather specific label says a lot about how these building enclosure elements satisfy the functions identified above. All roof assembly elements have as one of their primary functions the *control* and exclusion of rain from the indoor environment. Sloped roof assemblies achieve this by shedding or draining rain down and away from the roof surface. The slope minimizes head pressures and contact time of water on the roofing, making possible the use of relatively water permeable roofing materials such as wood and concrete, and discontinuous roof systems such as shingles, shakes and tiles (i.e. systems constructed of discrete elements with joints that are not waterproof).

Wood-framed roof assemblies are so named because a frame or system of discrete wood members is used to *support* the load of the roofing on top, finish on the bottom and any equipment that may be placed in or on the roof. The wood frame also carries the weight of any snow load on the roof assembly and resists the push and pull exerted by the wind. Two types of wood frames are common in North America: trusses which are factory assembled, shipped to site, and then lifted into place; stick-built frames comprising rafters, collar ties and ceiling joists that are assembled piece-by-piece in place. The type of wood frame employed depends on the desired form of the roof assembly, material and labor availability, transportation costs and site accessibility.

Finally, most building codes in North America require that roof assemblies be constructed with at least a minimum level of thermal insulation to *control* the movement of heat between the indoor and outdoor environment. This is done to assure reasonable levels of thermal comfort and minimize HVAC system energy use. The type of insulation used and its location in the roof assembly varies from region to region and is influenced by cost, spatial constraints, and strategy for controlling the movement of air and water vapor.

A review of research papers and current industry journal articles reveals that the most contentious issue surrounding insulated, sloped, wood-framed roof assemblies today is whether to encourage or exclude the movement of outdoor air through the roof enclosure. In short, the question is: “Should we build ventilated or unvented roof assemblies?” The remainder of Chapter 2 is dedicated to a discussion of the differences between and motivation behind these two approaches to roof assemblies.

2.3 Ventilated Roof Assemblies

Ventilated roof assemblies are generally accepted as convention for low-rise residential buildings throughout North America. In cold climates roof assemblies are ventilated to control ice dams by minimizing roof temperatures and to remove moisture that is introduced by warm, moist indoor air which leaks into the roof assembly. In warm climates roof assemblies are vented to expel hot air from the attic space with the intent of reducing cooling loads and roof surface temperatures.

2.3.1 Ventilated Attic Roof Assemblies

The attic roof geometry is formed when the roofing is installed over a sloped or pitched surface that is supported by one structural member while the interior (i.e. ceiling) finish is installed on a horizontal plane and supported by a different structural member. A ventilated attic is created by connecting the attic space to the outdoors through the use of a distributed (usually upper and lower) system of vent openings as illustrated in Figure 2.2.

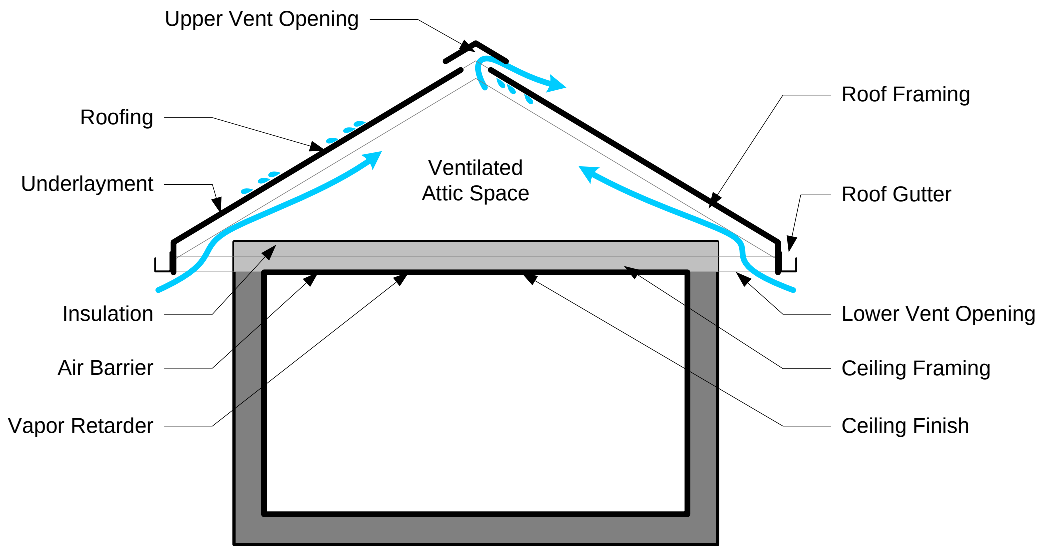


Figure 2.2 – Ventilated attic roof assembly

At least two separate framing members (i.e. the roof and ceiling framing members) are required to serve the support function for the ventilated attic roof assembly. These can either be rafters and ceiling joists or the top and bottom chords of a truss.

Rain (i.e. liquid water) is controlled by the roofing, which sheds the water from the roof slope, and the gutters, which prevent the water from dripping off the roof onto the walls below. Composite (i.e. asphalt or fiberglass) shingles are the most common, although cedar shakes, metal panels and concrete or clay tiles are also used as roofing for low-rise residential buildings.

The roofing also provides the first layer of control snow and ice; however it is common in some regions to also install an underlayment in the form of felt paper, a synthetic equivalent or even a self-adhered membrane. The underlayment is installed to prevent rain or melt-water that penetrates the shingles from coming in contact with the roof sheathing.

Heat transfer is limited by insulation which is installed on top of the ceiling plane. Fiberglass batt, cellulose and blown-in-batt are commonly used as the insulation because they provide high insulating value per dollar.

In cold climates water vapor is primarily controlled by a vapor barrier or retarder that is installed on the warm side of the insulation. Polyethylene sheet is the most common vapor control product, although several vapor barrier paints are available for application to the inside of the ceiling finish.

Air movement (i.e. leakage) between the indoor space and the attic is limited by an air barrier which is also typically located on the warm side of the insulation. In cold climates it is fairly common for joints in the polyethylene vapor barrier to be sealed with tape or acoustic sealant to create a continuous air barrier over the ceiling plane. Special attention must be paid to electrical, plumbing and mechanical penetrations. As an alternate approach the drywall can be sealed to appropriate structural members and penetrations to achieve the same goal.

Ventilation is provided as a means of controlling (i.e. removing) small amounts of moisture that may be introduced to the attic by roofing leaks, air leakage or vapor diffusion. The 2006 International Residential Code (i.e. the US model code) and the 2006 Ontario Building Code both require that ventilated attic roof assemblies have a vent area equal to at least 1/300th of the insulated roof area (IRC 2006, OBC 2006).

2.3.2 Ventilated Cathedral Ceiling Roof Assemblies

Architectural goals sometimes require that the ceiling be moved off the horizontal plane and up on a slope below the roof plane to create a cathedral ceiling. Cathedral ceiling roof assemblies are generally ventilated in a manner similar to attic roof assemblies. Figure 2.3 depicts the resulting assembly.

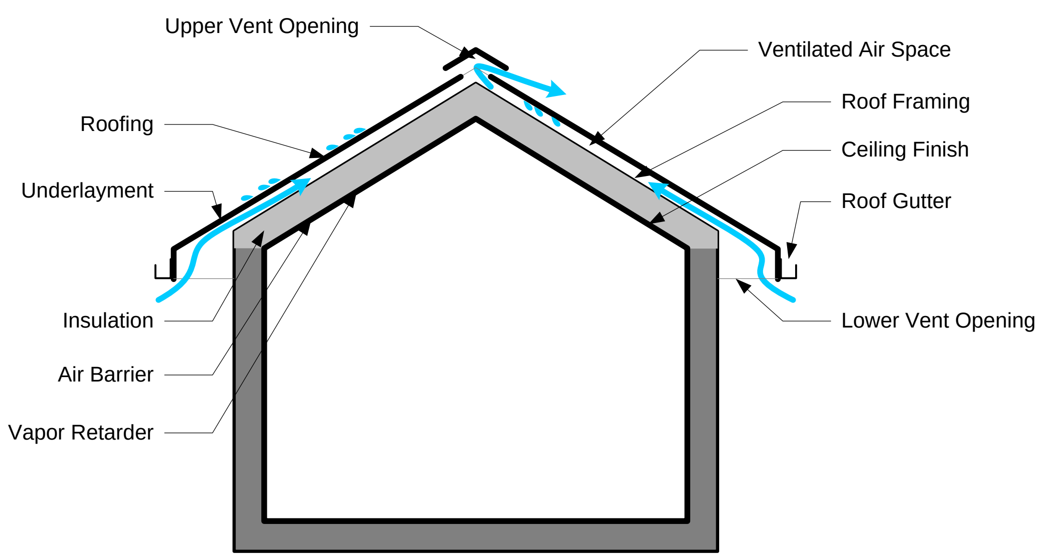


Figure 2.3 – Ventilated cathedral ceiling roof assembly

The materials and function of the ventilated cathedral ceiling roof assembly are virtually the same as the ventilated attic roof assembly with two major exceptions: the structural frame and the ventilation space.

Support for cathedral ceiling roof assemblies is typically provided by rafters, parallel chord trusses or scissor trusses. If rafters are used outward thrust must be resolved by collar ties installed below the ridge or the walls that rafters bear on. If two opposing parallel chord trusses are used outward thrust may still need resolution (i.e. unless an appropriate moment connection is made at the peak of the trusses). A scissor truss is self contained and produces no outward thrust, but the slope of the ceiling plane will not be the same as the slope of the roof.

Cathedral ceiling roofs are usually compact assemblies in that there is minimal space between the ceiling finish on the bottom and the roofing on the top. Ventilation air space and any insulation installed between the framing members often compete for the same limited space. In some regions it code officials require builders to install baffles (e.g. preformed foam or site fabricated using dimensional lumber and a sheathing membrane); in others insulation is installed without any means of assuring a minimum ventilation air space dimension.

The 2006 International Residential Code requires a minimum 25 mm (1 in.) clearance between the top of the insulation and the bottom of the sheathing; the 2006 Ontario Building Code requires a minimum 63 mm (2.5 in.) clearance. Both codes require that cathedral ceiling roof assemblies have a minimum vent area equal to $1/150^{th}$ of the insulated ceiling area (IRC 2006, OBC 2006).

2.4 Challenges for Ventilated Roof Assemblies

Code requirements for ventilation of attic and cathedral ceiling roof assemblies have existed in North America for over 50 years. While ventilated roof assemblies are accepted as convention throughout North America, they have been faced with several challenges. This section provides an overview of the challenges identified in recent literature.

2.4.1 Fire Spread

Numerous authors have noted the danger that attic vents pose to the spread of fire. Quarles reports on research at the University of California Fire Research Laboratory which demonstrates that vents, when located on the underside of open-eaves or soffits, are “almost immediately penetrated under flame impingement exposures” (Quarles 2002). Vents have been identified as a problem in wildfire zones (Rose and TenWolde 2002) and in row house fires (Blom 2001). Unvented roofs have been suggested as a potentially safer solution in the event of a fire (Rudd 2005, Lstiburek 2006).

2.4.2 High Winds

High winds drive air into roof vents on the windward side of the building, pressurizing the roof assembly and increasing the uplift forces on the roof. This effect is amplified when vented soffits, which often comprise thin perforated vinyl or aluminum profiles, collapse during high wind events. Lstiburek suggests that unvented roof assemblies perform better than ventilated because they have stronger soffit construction that is less prone to collapse (Lstiburek 2006).

2.4.3 Snow and Rain Entry

When wind and precipitation simultaneously, snow or rain can be carried into vents and deposited inside the roof assembly where it may come into contact with insulation or moisture sensitive materials. The 2006 International Residential Code requires that “ventilating openings (be) protected against the entrance of rain or snow” (IRC 2006). In full scale tests of the performance of six different vented eave designs from Norway and Greenland researchers found that snow accumulation in the attic varied between 4% and 353% of the accumulation on the ground. Snow accumulated in an open eave assembly at a rate that was 734% of that on the ground (Thiis et al. 2007).

The authors report that vent openings have been closed to eliminate the problem of snow entry, but caution that this approach can create new problems with ice dams.

2.4.4 Coastal Regions

In coastal regions salt spray can also be carried into vent openings, where it can accelerate corrosion of metal structural components such as truss plates and steel beams. This effect can only be minimized by eliminating vent openings to exclude salt laden air from the roof assembly.

A review of Canada Mortgage and Housing (CMHC) field surveys identified a pattern of moisture problems in coastal climates with prolonged periods without warm temperatures or sunshine (Walker and Forest 1995). Under these conditions the ventilation does not have sufficient capacity of remove moisture from a roof assembly and, may even add moisture to it.

2.4.5 Sound Transmission

It has been suggested that vents openings are associated with loud outdoor sounds (e.g. nearby airport traffic) being transmitted into the building (Rose and TenWolde 2002).

2.4.6 HVAC Equipment and Ductwork

In many cities throughout the US Southwest and Gulf States houses are constructed on slabs-on-grade rather than basements. HVAC equipment and ductwork in these houses are typically located in the attic space to prevent the loss of precious floor space to mechanical rooms. The ductwork is often leaky so a portion of the conditioned air escapes into the attic and outdoors through the vents, wasting energy. Furthermore, the equipment and ductwork are typically poorly insulated so warm moist outdoor air can come in contact with and condense on cold surfaces causing corrosion and promoting mold growth.

Potential energy and durability advantages may be realized by moving the insulation and air barrier system to the underside of the roof deck to create an unvented attic assembly in which HVAC equipment and ductwork can be installed, protected and easily serviced (Rudd 2005, Lstiburek 2006).

2.5 Changes in the Low-Rise Residential Market

Over the last 10-20 years changes in the low-rise residential market have made it increasingly difficult to construct effective ventilated roof assemblies. This section explains several of these changes and how they have impacted the construction of ventilated roof assemblies.

2.5.1 Higher Insulation Levels

Code requirements for the minimum thermal performance of all building enclosure elements have increased over the last two decades. It is speculated that the sustainable building movement and energy security issues will continue to drive the industry to higher levels of insulation (Lstiburek 2007).

As insulation levels increase the energy flow through the enclosure decreases as do the potential to evaporate water and the vapor pressure difference that drives the movement of water vapor out of the enclosure. Higher insulation levels also result in lower temperatures in the outer layers of the assembly. Lower temperatures translate to higher relative humidity levels, higher moisture contents and more favorable conditions for mold growth and decay.

A connection has been made between increasing levels of thermal insulation on the ceiling plane and the frequency of problems in ventilated attic roof assemblies (Samuelson 1998).

2.5.2 Moisture Sensitive Building Materials

As insulation and moisture levels have increased so has the moisture sensitivity of building materials. Many of the oldest building materials (e.g. stone and brick) exhibited little sensitivity to moisture. Older wood-based building materials such as timber and board lumber under went little processing, and as a result retained much of their natural resistance to mold and decay. Modern, engineered panel products such as plywood, oriented strand board (OSB) and medium density fiberboard (MDF) undergo increasing levels of processing, changing and damaging the wood cells. Each of these is more susceptible to water, mold and decay in the last. Finally, paper and cardboard building products are the most highly processed and easily damaged by water or attacked by mold.

Engineered wood products are more sustainable because they make better use of raw materials. The fact that they are more sensitive to moisture means that designers will have to learn to use them properly and builders will have to be more careful to protect them during construction (Lstiburek 2007).

Ventilated attic assemblies were once thought to make up for air leakage between the indoor space and the attic. This measure proved effective in preventing moisture problems in roofs with board sheathing and plywood; however it may not prove sufficient when more moisture sensitive materials such as OSB are employed.

2.5.3 Need for Compact Roof Assemblies

Two architectural / housing design trends have created greater need for compact roof assemblies. First, increasing real estate prices have encouraged homeowners to look at making better use of the space in their houses. Newspaper articles provide homeowners with guidance on the issues involved with finishing basement and attic spaces (McClintock 2004). Realty magazines report that, in 2006 homeowners could expect to recoup a respectable 79.9% of the cost of renovating an attic (Realtor Magazine 2006). Developers have realized that, in an expensive market, finished attics can be a selling point (Chongchua 2004). Finally, in a June 2005 AIA survey (American Institute of Architects 2005), 49% of respondents reported an increase in the number of finished basement and attic spaces. An increasing number of attics are being finished as rooms rather than annexed ventilated spaces defined by ceiling below and roof sheathing above.

Secondly, the ceilings of North American houses are growing in both height and complexity. Fifty seven percent of the respondents in the 2002 Builder Practices Survey (National Association of Home Builders 2002) reported using ceiling heights of 9ft or higher. Similarly, 66% of the respondents of the 2003-2004 Consumer Preferences Survey (NAHB Economic Group, 2004) expressed a desire for ceiling heights of 9 ft or more. These studies suggest a growing demand for larger volume spaces.

One way of creating the feeling of larger space without significant increase in volume is through the use of varying ceiling heights (Wilson & Boehland, 2005). Exterior walls are constructed at 8 to 9 ft. while the ceiling is projected upwards on a slope.

Compact roof assemblies such as cathedral ceilings permit additional rooms to be created in lieu of attics or the ceilings of main rooms (i.e. foyers, great rooms, etc.) to be raised to the underside of the roof to create a feeling of spaciousness. Questions have been raised about the effectiveness of ventilation strategies for cathedral ceiling roof assemblies.

2.5.4 Complex Roof and Ceiling Geometries

Fifty some years ago, when roof ventilation requirements were incorporated in the first model codes, simple gable and hip roof geometries were common. These tended to have one or two ridge lines (e.g. typical of an L-shaped plan) as illustrated in Figure 2.4 and Figure 2.5. More recently roof and ceiling geometries have become much more complicated; they often incorporate valleys, hips, multiple dormers as illustrated in Figure 2.6 or coffered and tray ceilings with numerous penetrations for lights and speakers as illustrated in Figure 2.7.

Building scientists assert that effectively ventilated airspaces cannot be created in roofs that have complex geometries (Rose and TenWolde 2002). Concerns are also raised over the ease of achieving air barrier continuity (i.e. preventing air leakage) between the indoor space and the attic when the complex, frequently penetrated ceilings are employed (Rudd 2005, Lstiburek 2006).

Figure 2.4 – Older house with simple roof geometry (single ridge line)

Figure 2.5 – Older house with simple roof geometry (two ridgelines)

Figure 2.6 – Newer house with complex roof geometry (dormers, valleys and many ridge lines)

Figure 2.7 – Complex ceiling in newer house (numerous penetrations for lights and speakers)

2.6 Unvented Roof Assemblies

Unvented roof assemblies have been suggested as an alternate approach to roof construction because they address many of the challenges faced by conventional ventilated roof assemblies. Unvented roof assemblies do not have vent openings that may facilitate the spread of fire; make possible the pressurization and premature failure of the roof assembly under high winds; allow the entry of wind-driven snow and rain, permit the admission of salt-laden moist air in coastal climates, the provide a path for sound entry. Unvented roof assemblies also create conditioned spaces in which HVAC equipment and ductwork can be installed without sacrificing performance or increasing the risk of mold growth and associated indoor air quality problems.

Unvented roof assemblies may also better meet the demands of the changing low-rise residential market: in cathedral ceiling roof assemblies the elimination of a ventilation air space makes room for higher levels of insulation; moisture sensitive materials such as ceiling finishes are protected from wetting events such as wind-driven snow and rain; compact roof assemblies can be constructed without concern over the effectiveness of ventilation air spaces; complex roof and ceiling geometries can be constructed with effective air barrier systems (i.e. at the underside of the roof rather than the ceiling) and without the need for complicated ventilation strategies.

2.6.1 Unvented Cathedralized Attic Roof Assemblies

The geometry of an unvented cathedralized attic roof assembly is the same as its unvented counter part; the roofing is installed over a sloped surface that is supported by one structural member while the ceiling finish is installed on a horizontal plane and supported by a different structural member. The main difference between these two types of roof assemblies is in the location of the air barrier system, vapor retarder (if applicable) and insulation. In the ventilated attic these are all located at or immediately on top of the ceiling finish. In the unvented cathedralized attic the insulation is installed in contact with the underside of the roof sheathing, the air barrier is either integral with the insulation or installed over the inside face of the insulation as illustrated in Figure 2.8.

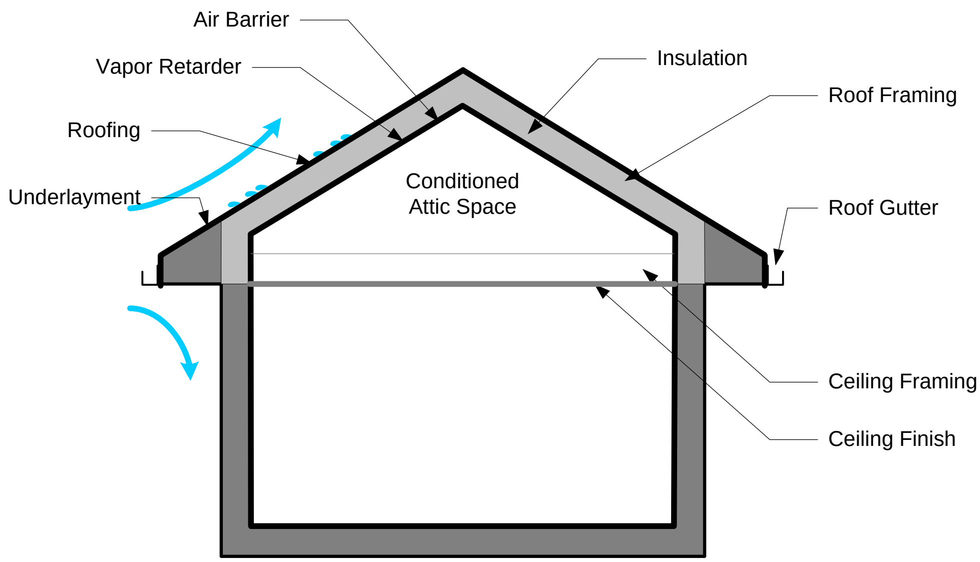


Figure 2.8 – Unvented cathedralized attic roof assembly

In cold climates unvented cathedralized attic roof assemblies are typically insulated with air impermeable open- or closed-cell sprayed polyurethane foam (ocSPF and ccSPF). If a vapor retarder is to be used, it should also be installed at the inside face of the insulation.

In hot climates unvented cathedralized attic roof assemblies are most often constructed using ocSPF, although dense-pack cellulose and spray-applied mineral fiber insulations are also used. Vapor retarders are not typically installed in unvented cathedralized attic roof assemblies in hot climates.

The 2006 IRC does not set any limitation on the air permeability of insulation for unvented roof assemblies, however a revision has been proposed: “In climate zones 5, 6, 7 and 8, any air-impermeable insulation shall be a vapor retarder, or shall have a vapor retarder coating or covering in direct contact with the underside of the insulation” (Rudd 2008).

2.6.2 Unvented Cathedral Ceiling Roof Assemblies

Unvented cathedral ceiling roof assemblies are similar to ventilated cathedral ceiling roof assemblies in that the ceiling finish is installed on a slope below the roof plane.

The control layers in the unvented cathedral ceiling roof assembly are located in the same locations as those in the unvented cathedralized attic: insulation is installed on the underside of the roof sheathing; the air barrier system is either integrated with the insulation or installed on the inside of it; and the vapor retarder, if used, is installed on the inside of the insulation. Since the ceiling finish in the unvented cathedral ceiling roof assembly is installed immediately inside the insulation, the vapor retarder can take the form of a paint applied to the inside of the ceiling finish.

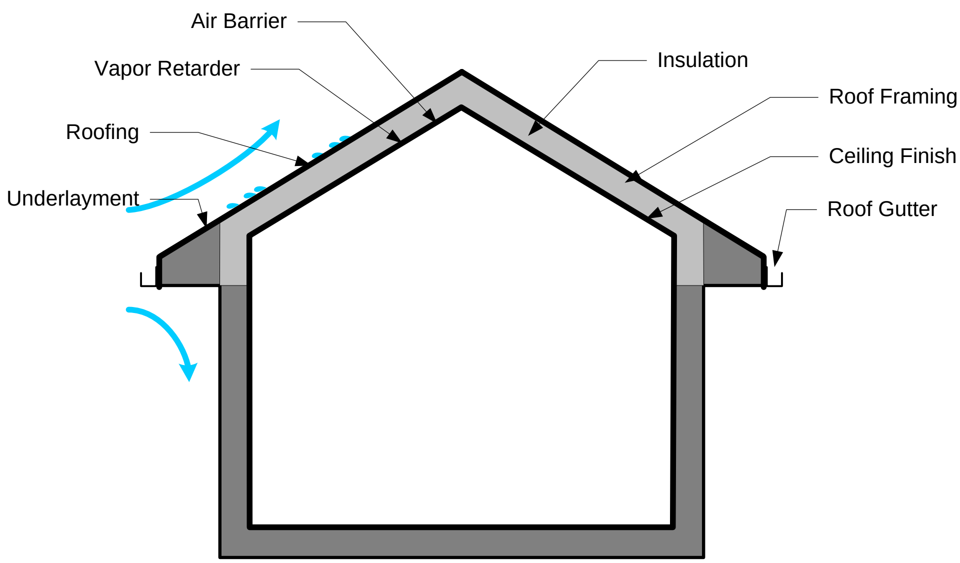


Figure 2.9 – Unvented cathedral ceiling roof assembly

2.7 Challenges for Unvented Roof Assemblies

Unvented roof assemblies are proposed as an alternative that addresses several of the challenges faced by conventional ventilated roof assemblies. They are however not without challenges of their own. This section addresses the two biggest challenges.

2.7.1 Control of Air Movement

Roof assemblies are typically ventilated in the hopes that the ventilation air will remove any incidental moisture from the inside of the assembly. Ventilation air rarely has sufficient capacity to remove moisture introduced by roof leaks, the largest potential source of incidental moisture. It does however have sufficient capacity to remove moderate amounts of moisture introduced through air leakage. Ventilation is eliminated in unvented roof assemblies, as is the potential drying that it can provide. It therefore becomes extremely important to establish (an) effective air barrier system(s) to control the movement of air between the indoor space and the roof assembly. Failure to do so may result in moisture accumulation in the roof sheathing and wood frame.

2.7.2 Control of Roof Surface Temperature

Roof assembly ventilation is employed to reduce the temperature of the roofing in hot climates. This can be beneficial because high roof temperatures are thought to adversely affect the durability of roofing products such as composite shingles. The degree to which unvented roof assemblies result in higher roof temperatures and the actual impact of this temperature exposure are debated.

Similarly, in cold climates, roof assembly ventilation is employed to reduce the temperature of the roof surface to achieve a “cold roof” in the hope that this will reduce the frequency of ice dams. Ice dams occur when the temperature at the interface between the roofing and any accumulated snow exceeds 0°C (32°F), causing the snow to melt. Melt water runs down the roof until it reaches cooler portions of the roof assembly (usually over the eave) where it freezes. An “ice dam” forms when melt water continues to accumulate and freeze. A slab or sheet of ice forms as melt water is backed up behind the ice dam. This traps water against the roofing, causing a build up of hydrostatic pressure and forcing water through any joints or holes in the roofing as illustrated in Figure 2.10.

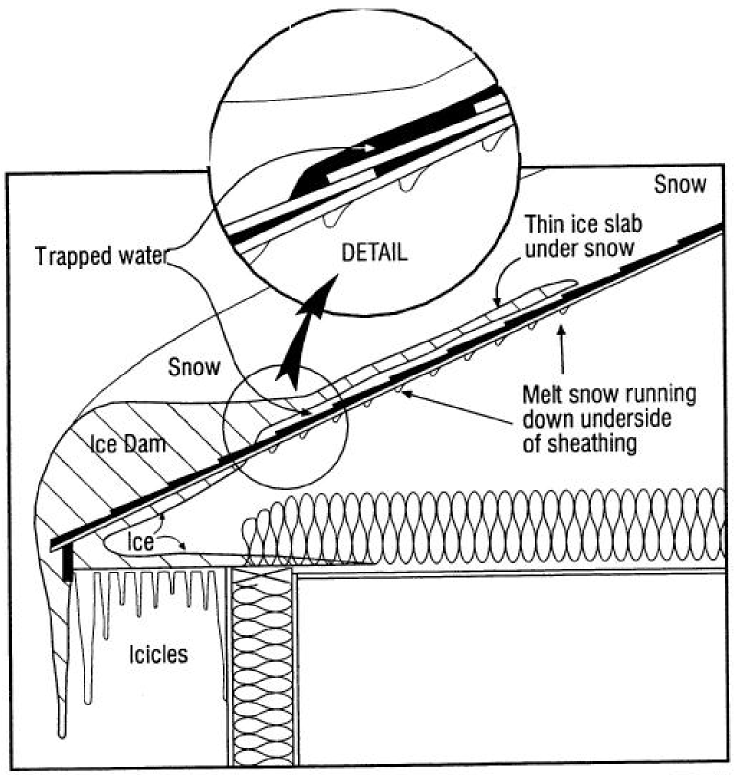


Figure 2.10 – Anatomy of an ice dam (CMHC 1998)

Ice dams can still occur in well ventilated roof assemblies when significant snow accumulations insulate the roof so that even small amounts of heat bring the roofing temperature above freezing.

Some building scientists suggest that attic ventilation is no longer needed to control ice dams because today’s well insulated roof assemblies do not permit much heat transfer (Samuelson 1998). Still, it is advisable to install a waterproof underlayment beneath the shingles to prevent any potential melt water from penetrating the roof sheathing.

Chapter 3
Literature Review

This chapter provides a summary of the literature review undertaken as part of the thesis research work. A significant amount has been written on the performance of roof assemblies and this literature review is by no means exhaustive. It does however provide an overview of the most important theory, research (measurement and simulation) and practice that guide this thesis.

The earliest published connections between roof moisture performance and attic ventilation were made between 1933 and 1937 by Browne and Teesdale, both from the US Forest Products Laboratory (Rose 2001). The first research work on the topic was conducted by Rowley and others at the University of Minnesota in 1939 (TenWolde 1997). In 1942 the Federal Housing Administration (FHA) set a requirement for attic spaces to be constructed with vent openings that had a total area equal to 1/300th of the insulated ceiling area. These attic ventilation requirements were later incorporated in the first Model Building Codes, introduced in 1948 through 1950 (Rose 1999).

3.1 Theory

3.1.1 Handegord, G.O. (1966)

Canadian Building Digest CBD-73 "Moisture Considerations in Roof Design," describes the state of knowledge in 1966. Diffusion and air leakage are identified as mechanisms that move indoor moisture into the attic. Handegord points out that it is nearly impossible to exclude all of this vapor migration and it is therefore logical to design a roof assembly that can deal with some moisture entry.

3.1.2 Handegord, G.O. and Baker, M.C. (1968)

The same author wrote another roof-related Canadian Building Digest with M. C. Baker two years later. CBD-99, "Application of Roof Design Principles," deals primarily with commercial compact low-slope compact roof assemblies and identifies the required functions of the roof component of the building enclosure. Compact low-slope roofs are not the focus of this thesis, however, they are similar in many aspects to unvented roof assemblies and the same requirements apply.

3.1.3 Baker, M.C. (1969)

Another Baker article, CBD-112, "Designing Wood Roofs to Prevent Decay," discusses moisture accumulation, storage and drying in wooden roof assemblies. Again the digest deals specifically with commercial compact low-slope type roofs with structural wood decks; however many of the principles are applicable to modern wood-framed roof assemblies.

Baker identifies the importance of controlling air movement between the conditioned space and the roof assembly; a principle that holds true for all roof assemblies. He also points out the challenges created when vapor barriers are installed on the interior side of an assembly that has a vapor impermeable roofing on the outside. This issue is one that designers either ignore or struggle to deal with today. Baker recommends the use of insulation on the exterior side of the structural deck. This exterior insulation increases the temperature of the deck during cold weather, thereby increasing its condensation resistance. Finally, Baker suggests the introduction of a vented airspace between the roof deck and the underside of the roofing. This would allow any moisture in the roof to dry to the outside through the ventilation air, bypassing the vapor resistance of the roofing.

3.1.4 TenWolde, A. and Rose, W.B. (1999)

TenWolde and Rose have written numerous papers on topics related to wood-frame roof systems. "Issues Related to Venting of Attics and Cathedral Ceilings," a paper from the 1999 ASHRAE summer conference proceedings, presents a review of the history and theory of attic ventilation and moisture performance in various climates.

The authors point out that, in 1999, most North American building codes set requirements for attic ventilation (typically a minimum vent area of 1/300th the ceiling area) to minimize the potential for condensation in the assembly during cold weather. Attic temperature control during warm weather, shingle durability and control of ice dams are also seen as benefits of attic ventilation.

TenWolde and Rose discuss several early attic studies. They speculate that Rowley's 1939 laboratory studies were the origin the building code attic ventilation requirements, but question his methodology and conclusions. TenWolde and Rose feel that two other important factors were noted in research work conducted around 1948: Britton identified the importance of air leakage paths; Jordan showed a correlation between elevated attic moisture levels and high indoor humidity levels.

In the second half of this paper TenWolde and Rose look at situations in which attic ventilation may not assist in reducing moisture levels in several instances. Some roof and ceiling geometries and construction techniques (e.g. cathedral ceilings) make it difficult to create an effective attic ventilation system. In wet, cold coastal climates ventilation reduces attic temperature but doesn't remove sufficient moisture to be of any benefit. In warm humid climates the dewpoint temperature of the outdoor air often exceeds the temperatures in the roof assembly so ventilation can actually increase the moisture levels in the roof assembly.

Finally TenWolde and Rose address the issue of shingle temperature. The authors claim that, in 1999 most shingle manufacturers would not warranty their products when installed over unvented roofs because they believed these roofs experienced higher temperatures. This paper references work that Rose did in 1992 to show that ventilation reduced the peak shingle temperature by 6° C (10°F) and contrasts this with a 1997 Simpson and MacPherson study on roof color that showed that the peak temperature on white roofs was as much as 20°C (36°F) cooler than gray roofs and 30°C (54°F) cooler than brown roofs.

3.1.5 Fugler, D.W. (1999)

A second paper on the topic of attics was included in the 1999 ASHRAE summer conference proceedings. Fugler presented a summary of Canada Mortgage and Housing (CMHC) attic research work conducted between 1989 and 1997 in a paper entitled "Conclusions from Ten Years of Canadian Attic Research." The paper references the development of methods developed by BLP and Sheltair in 1989 to test the airtightness of and air changes in attics.

In tests of 15 Ontario and 5 PEI houses the Equivalent Leakage Area at a 10 Pa pressure difference (ELA_{10}) between the house and the attic ranged between 20 cm² (3 sq. in.) and 330 cm² (51 sq. in.) while the average ELA_{10} between the attic and outdoors (i.e. the ventilation area) was 3000 cm² (465 sq. in.), with a range from 800 cm² (125 sq. in.) to an area too large to measure using the equipment on hand. The natural air change rates in the attics of these 20 houses and 6 test houses in another test in Alberta varied greatly (from almost nothing to over 15ACH). Ventilation rates were highest when the wind direction was perpendicular to the soffit vents and showed a strong correlation to wind speed. When winds were less than 2 m/s (4.5 mph) ventilation is much less predictable and is primarily driven by stack effect. Under these conditions the rates are approximately an order of magnitude smaller and rarely exceed 1 ACH, even when temperature differences between the attic and outdoors approach 30°C (16.7°F).

In the above mentioned and other tests moisture contents of the wood framing and sheathing materials were monitored by hand over the course of several seasons/years. Results were inconclusive; in some cases ventilated attics had lower moisture levels while in others sealed attics had lower levels. Fugler concludes that the results do not support the reduction of code requirements for ventilation, but they may suggest the need to allow alternate design approaches to control attic moisture levels.

3.1.6 Rose, W.B. and TenWolde, A. (2002)

Rose and TenWolde recast their 1999 paper for an October 2002, ASHRAE Journal entitled "Venting of Attics and Cathedral Ceilings." This article is essentially the same as the conference paper; however it provides a more thorough review of attic ventilation as it relates to ice dams. The authors point out that attic ventilation was not considered to play a role in controlling ice dams until Baker introduced the "cold roof" concept in a 1967 Canadian Building Digest entitled "Ice on Roofs." In their review of papers on the topic of ice dams, Rose and TenWolde identify i) the provision of adequate ventilation, ii) elimination of air leakage between the heated space and iii) the attic and removal of any heat sources from the attic all as having more important roles than attic ventilation.

3.1.7 Lstiburek, J.W. (2006)

Building Science Corporation (BSC), a MA based consulting company, has been responsible for a number of research projects and papers on the topic of attic ventilation. In an April 2006 article for the ASHRAE Journal entitled "Understanding Attic Ventilation," Lstiburek summarizes current industry theory regarding attic ventilation. He writes "The choice to vent or not vent is a design and construction choice, not a requirement determined by physics or by building codes," suggesting that both strategies can be successful and designers should not be forced into working with one over the other, however he points out that different climates require different unvented roof assembly designs.

Lstiburek suggests that attic ventilation can be beneficial in cold climates to reduce roof surface temperatures, thereby preventing ice dams or to dry out moisture that is introduced to the attic by air leaks from the warm humid conditioned space below. In warm climates ventilation can reduce attic temperatures, thereby reducing the cooling load on the house. Lstiburek suggests that unvented roof system designs can also be developed to address these issues.

Lstiburek favors unvented roof designs when roof and ceiling geometries are complicated by dormers, valleys, hips, skylights, cathedral ceilings, coffers, roof trays, etc. In these situations he suggests that it is too difficult to create reliable ventilation path on the cold side and a sufficient air barrier system on the warm side of the roof assembly. He also prefers an unvented approach when HVAC equipment and ductwork located in the attic because it is not possible to effectively insulate or air seal these systems. Lstiburek also recommends unvented roof designs in high wind areas (especially if these are coastal) because they are not prone to precipitation being driven by the wind up through the vent openings and into the roof systems. A similar logic sets the preference for unvented roof designs in wild fire regions where hot embers can be blown into vent openings, starting fires inside the assembly.

Finally Lstiburek proposes that unvented roof designs fall into two categories: those that control condensing plane temperature those that do not. The temperature of the first condensing plane (usually the underside of the roof deck) does not need to be controlled when the average monthly roof deck temperature is greater than 7°C (45°F), permitting the use of air- and vapor-permeable insulations such as fiberglass and cellulose. Where the average monthly temperature of the roof deck is less than 7°C (45°F) there is too great a risk for condensation on and extended, elevated moisture content levels in the sheathing. Here Lstiburek suggests that insulation be installed on the outside of the roof deck to increase the temperature of the condensing plane or an air-impermeable insulation such as closed-cell sprayed polyurethane foam be installed on the underside of the roof deck to create a new first condensing plane (i.e. the inside face of the foam).

3.2 Field Performance

3.2.1 Parker, D.S. and Sherwin, J.R. (1998)

Parker and Sherwin authored a paper entitled “Comparative Summer Attic Thermal Performance of Six Roof Constructions,” for the proceedings of the 1998 ASHRAE summer conference. The paper summarizes a study undertaken by the Florida Solar Energy Center (FSEC) to examine the summer cooling load and energy requirements associated with six different roof assemblies installed in their Flexible Roof Facility (FRF) in Cocoa FL. The FRF attic test bays measure 7.3 m (24 ft) long by 1.8 m (6 ft) wide. The experimental program evaluated variations in color of roofing (black vs. red vs. white), ventilation (1:300 vs. 1:150 vent ratios), roof thermal mass (concrete barrel tiles vs. asphalt shingles vs. standing seem steel) and the use of radiant barrier systems (RBS) installed in the rafter spaces below the roof sheathing. Unvented roof systems were not considered as part of the testing.

Measurements were recorded over the months of June through September 1997. On a hot summer day the ambient temperatures reached 33.4°C (92.2°F). The highest attic temperature, 57.2°C

(134.9°F), was recorded in the control (i.e. conventional) roof assembly which employed black asphalt shingles installed over an attic with a 1:300 vent area evenly distributed between the soffit and the ridge vents. The lowest temperatures were recorded in the test panel that had white concrete barrel tiles installed directly on the sheathing (i.e. not on battens) and over an attic with similar venting to the conventional roof assembly. In this assembly the peak attic temperature of 33.1°C (91.5°F) did not occur until after 3 in the afternoon while the average attic temperature was 27.1°C (80.8°F), only half a Celsius degree above the average diurnal ambient temperature. Over the course of the summer, this roof assembly reduced the total cooling requirement by 76%. Parker and Sherwin concluded that attic temperatures and cooling requirements are reduced through the use of roofing materials that have greater thermal mass, lighter colors and assemblies that have higher ventilation rates.

The authors also showed that the use of the radiant barrier system increased the peak temperature of the black asphalt shingles from 81.8°C (179.3°F) to 84.3°C (183.8°F).

As expected, the highest average relative humidity, 75%, was recorded in the assembly that with the white concrete barrel tiles (i.e. the coolest attic) while the lowest average relative humidity, 53%, was recorded in the conventional roof assembly (i.e. the hottest attic). While the incidence of dew formation on the exterior surface of the roofing was recorded, moisture content was not, making it more difficult to assess the long term moisture exposure of the framing and sheathing materials.

3.2.2 Winandy, J. E. et al. (2000)

The United States Department of Agriculture – Forest Products Lab (USDA-FPL) has generated a significant amount of research into wood-based building products and the performance of wood-framed building systems. In December 2000 USDA-FPL published a report on "Roof Temperature Histories in Matched Attics in Mississippi and Wisconsin," authored by Winandy, Barnes and Hatfield. The objective of this work was to collect temperature data for attics and the associated structural components to assist in the understanding of premature deterioration of fire-retardant-treated (FRT) wood sheathings.

Five test huts were constructed in Madison WI (i.e. a northern US climate) in 1991 and five matching test huts in Starkville MS (i.e. a southern US climate) in 1994. The huts measured 4.9 m (16 ft) long by 3.7 m (12 ft) wide, consisted of a single 3:12 roof slope (i.e. shed roof) framed with rafters, and were located in an open field and spaced so the roof structures would not see any shade. Two of the WI test huts were roofed with white fiberglass shingles while the other three WI test huts and all five of the MS were roofed with black fiberglass shingles. The roofs were not insulated or intentionally ventilated, nor were the huts themselves insulated, heated or cooled. One of the black-roofed WI test huts and two of the MS test huts were artificially humidified using cool-mist humidifiers to >85% relative humidity. Note that the WI test huts were only humidified in the summer.

In essence each hut represents a large attic space. The authors don't explain the thinking behind this approach; they don't say that their intent was to test unvented attics; they acknowledge the lack of ventilation and heat transfer to and from an insulated ceiling result in data that may not be representative other (i.e. more common) roof assemblies.

Over the course of the 8 year WI study the maximum temperatures recorded in the black-roofed WI test hut were 75°C (167°F) at the top of the sheathing, 59°C (138°F) at the bottom of the sheathing and 54°C (129°F) in the rafter. The corresponding maximum temperatures in the white-roofed WI test hut were 64, 53 and 49°C (147, 127 and 120°F). In these uninsulated, unventilated roof assemblies the shingle color appeared to reduce the maximum sheathing temperatures by 5-11°C (9-19.8°F).

The maximum temperatures recorded in the black-roofed MS test huts were 78°C (172°F) at the top of the sheathing, 63°C (145°F) at the bottom of the sheathing and 58°C (136°F) in the rafter. For these uninsulated, unvented roof assemblies the climate appeared to increase the maximum temperatures by approximately 3°C (5.4°F). While there was little difference in the maximum temperatures recorded in the two climates, there was a larger difference in the number of hours that the elements were exposed to higher temperatures. The sheathing in the black-roofed WI huts spent only a few hundred hours above 50°C (122°F) while the sheathing in the MS huts spent more than twice the hours above this temperature.

The authors noted that the maximum sheathing temperatures were usually controlled by solar gain and not outdoor air or attic air temperature. The rafter temperatures were usually controlled by attic air temperature and only influenced by solar gain on a few days.

Maximum temperatures in the humidified test huts were virtually the same as in the test huts that were not humidified, except on the hottest days, when the temperature was slightly cooler. The authors speculate that this is the effect of evaporative cooling.

Although focus was on temperatures of attics, sheathing and framing, Winandy et al. provided some discussion moisture contents measured periodically with a hand held moisture meter. The wood moisture contents in WI roofs varied between 13 to 16% in the winter (when none were humidified) and 8 to 12% in the summer (when half of the WI huts were humidified). The authors don't distinguish between the MC in the dry (i.e. not humidified) and wet (i.e. humidified) WI huts. At the MS site roofs in the dry test huts varied between 7.5% in the summer to 1.5% in the winter; roofs in the humidified test huts varied between 17% in the winter and 4% in the summer.

3.2.3 Blom, P. (2001)

In July 2001 the Journal of Thermal Envelopes published a paper entitled "Venting of Attics and Pitched, Insulated Roofs." The paper, written by Peter Blom of the Norwegian Building Research Institute, summarizes the results of a study of various ventilation strategies for the roofs of single family houses.

In this study 12 different cathedral ceiling roof assemblies were constructed over a 64 m² (690 sq. ft) heated, dry (presumably this means not humidified) test hut in Trondheim Norway. The roof test panels measured 0.6 m (2 ft) wide by 5.9 m (19.3 ft) long, at a slope of 22°, from soffit to ridge. Six of the test panels had asphalt roof installed over 19 mm (3/4 in) plywood over a ventilated air space of

23, 48 or 98 mm (7/8, 1-3/4 or 3-7/8 in). Three of these had ridge vents while three were only vented at the soffit. Four of the test panels had concrete tiles installed on battens over an underlayment on plywood over a ventilated airspace (i.e. there are two ventilated air spaces: one between the tiles and the sheathing and a second between the sheathing and the insulation). The remaining two test panels had concrete tiles installed on battens over an underlayment applied directly over the rafters without any sheathing (i.e. a single ventilated airspace exists immediately under the tiles). All twelve test panels were insulated with 200 mm (8 in) of mineral fiber.

Climate conditions, temperatures in the assemblies and air velocities in the ventilation spaces were monitored continuously. Moisture content measurements were periodically made using a manual resistance-type moisture meter.

Blom concluded that the temperature increase between the ventilation air inlet and the outlet was large when wind velocities are low and more than 250 mm (10 in) of snow as on the roof. Temperature increases of over 5.5°C (10°F) were measured on the roof that had the 23 mm ventilation space but no ridge vent. The lowest temperature increase, approximately 2°C (3.6°F), was measured on the roof that had the 98 mm ventilation space and a ridge vent. The author noted that the smallest difference between the outdoor air temperature and the sheathing temperature at the ridge was recorded in the roof that had the 48 mm ventilation space and a ridge vent.

Blom extended his test results using a simulation program, ROOFTEMP, to predict roofing temperatures for the tested assemblies using climate conditions for Rena. From this he predicted that the test panel with asphalt roofing, a 48 mm ventilation space and a ridge vent would melt approximately 590 kg of snow, roughly 40% less than the same roof with a 23 mm ventilation space and no ridge vent.

The author reports moisture content measurements for the sheathing in the test panels with 23 and 98 mm ventilation spaces. In the 23 mm panel the MC ranged between 8% in the summer and 14% in the winter. In the 98 mm panel the MC ranged between 10% in the summer and 18% in the winter. The difference between panels that had and did not have ridge ventilation was only slight (i.e. less than 1%). Blom suggests that the higher measurements in the panels with the larger ventilation spaces are the result of more contact with cold, moist outdoor air. This would mean that there was more water vapor available for the wood to adsorb (i.e. the sheathing was able to get closer to achieving an equilibrium with the high winter relative humidity in the ventilation air).

3.2.4 Rose, W.B. (2001)

Research architect Bill Rose authored a conference paper entitled “Measured Summer Values of Sheathing and Shingle Temperatures for Residential Attics and Cathedral Ceilings” for the Thermal Performance of the Exterior Envelopes of Buildings Conference, VIII, held in Clearwater Beach FL in December 2001. The paper describes a study conducted at the University of Illinois in Champaign IL. The objective of this work was to collect data on shingle and sheathing temperatures for various sloped residential-type roof assemblies and develop a method for presenting the data so that the impact of temperature on shingle durability can be estimated.

The test hut consists of 8 test bays, each with 4 m (13 ft) north and south facing roof at a 5:12 pitch. Five of the 8 test bays are framed with trusses to create horizontal ceiling planes while the other three are framed with nominal 2x12 rafters to create cathedral ceilings. The truss roofs were insulated with RSI-5.28 (R-30) fiberglass batt installed on the top of the ceiling drywall. Two of these attic roof assemblies were constructed without any vent openings while the other three had a vent area ratio of 1:150. One of the vented attic test bays has white shingles while the remaining test bays all have black shingles.

The first two of the cathedral ceiling roofs were insulated with nominal 250 mm (10 in) thick RSI-5.28 (R-30) kraft-faced batt stapled to the underside of the rafters to leave an air space between the top of the insulation and the bottom of the roof sheathing. No effort was made to ensure the dimension or continuity of this air space. One of these roof assemblies is vented at 1:150 while the other is sealed as an unvented roof. Both of these bays have black shingles.

In the third cathedral ceiling roof assembly a 25 mm (1 in) thick layer of polyisocyanurate insulation was installed between the top of the rafters and the bottom of the roof sheathing. RSI-5.28 (R-30) fiberglass batts were also installed between the rafters on this assembly, bringing the total nominal RSI to 6.34 (R-36) and creating an unvented roof assembly. This bay also has black shingles.

The researchers faced several equipment challenges and could only use several years from the data set in their analysis. The new analysis method was developed for the purpose of this study: shingle or sheathing temperatures for a given assembly (i.e. the test roof) are plotted on the x-axis against the corresponding shingle or sheathing temperatures for the reference assembly (conventional ventilated attic construction with black shingles) plotted on the y-axis. A linear regression is then done on the data set and the slope and intercept of the resulting line compared to a line with slope=1 and intercept=0. Rose proposed that the relationship between the temperatures be determined by (1-slope)*100 so that a slope of 0.77 would suggest that the roof in question is 23% warmer than the reference. Note that this method assigns an equal weight to all temperatures. The “crossing point” is defined as the temperature at which the regression line crosses the line with slope=1 and intercept=0. At this point the temperature is the same on both the test roof and the reference roof; above or below this point the temperature on the test roof is either greater than or less than the reference.

Rose determined that, on the south slope of a ventilated attic assembly, white shingles reduced the sheathing temperature by 20% at the eaves and 22% at the ridge relative to the same assembly with black shingles (i.e. the reference roof). The sheathing in the cathedral ceiling assembly with the polyisocyanurate foam insulation was 23% warmer than the reference roof. This demonstrates that ventilation has roughly the same effect on shingle temperature as color.

3.2.5 Samuelson, I. (1998)

Samuelson measured temperature and relative humidity in six attics: 2 mechanically ventilated to 2 ACH; 2 unvented; and 2 naturally ventilated to the Swedish Building Regulations. “Historically, the purpose of ventilation has been to keep the outer surface of the roof sufficiently cold to prevent snow from melting. Nowadays, no ventilation is needed for this purpose, as the amount of heat leaking through a well-insulated ceiling and roof is very small. Best performing assemblies (i.e. lowest monthly average relative humidity) were unvented. The higher the ventilation rate, the higher the moisture levels in the attic. However it should be noted that the test laboratory had airtight ceilings ant the conditioned space was negatively pressurized; these ideal conditions are not always realized in practice.

3.2.6 Thiis et al. (2007)

A group of researchers from Norway measured snow deposition in six full-scale ventilated attic roof assemblies from Norway and Greenland: 1 with fully open eave, 1 with slot vent at facia, 1 with slot vent at wall, 1 with slot vent at wall and wind deflector, 2 with baffles to velocity and snow to drop as air enters vent. The tests modeled the movement of fine, dry snow through the eave vents and into the attic space. Snow accumulated in attics of roof assemblies with open eaves at 7 times the rate that it did on the ground. Roof assemblies with slot vents at the wall experienced accumulation rates of approximately 3 to 3.5 times the ground accumulation rate. The roof assembly with the slot vent at the facia experienced an accumulation rate of approximately 0.7 while the two roof assemblies that employed baffled ventilation strategies experienced accumulation rates of only 0.04 to 0.07 times the ground accumulation rate.

3.2.7 Walker, I. S. and Forest, T. M. (1995)

A group of researchers in Alberta monitored conditions in two gable end attics; one attic had roof vents and soffits sized according to building code requirements with a measured 4 Pa leakage area of 1542 cm^2 and the other had no vents or soffits and a leakage area of 456 cm^2. Focus was placed on the measurement of attic ventilation rates and indoor attic exchange rates. A database of more than 8000 hourly averaged ventilation and exchange rates was collected over a two year period in each house.

Attic ventilation rates were generally driven by wind pressures and the highest rates were measured when the wind direction was perpendicular to the soffit. The average ventilation rates in the sealed and code ventilated roof assemblies were 2 and 10 ACH respectively. When attic ventilation is driven by temperature differences (i.e. stack effect) the rates are approximately an order of magnitude smaller. Leakage between the house and the roof space is generally driven by temperature differences, although the scatter suggests some influence by wind.

Walker and Forest used a dual blower test method, depicted in Figure 3.1, to achieve a neutral pressure difference between the house and the attic, allowing them to identify the air leakage rate of the house, the ventilation rate of the attic and the air leakage rate between the house and the attic.

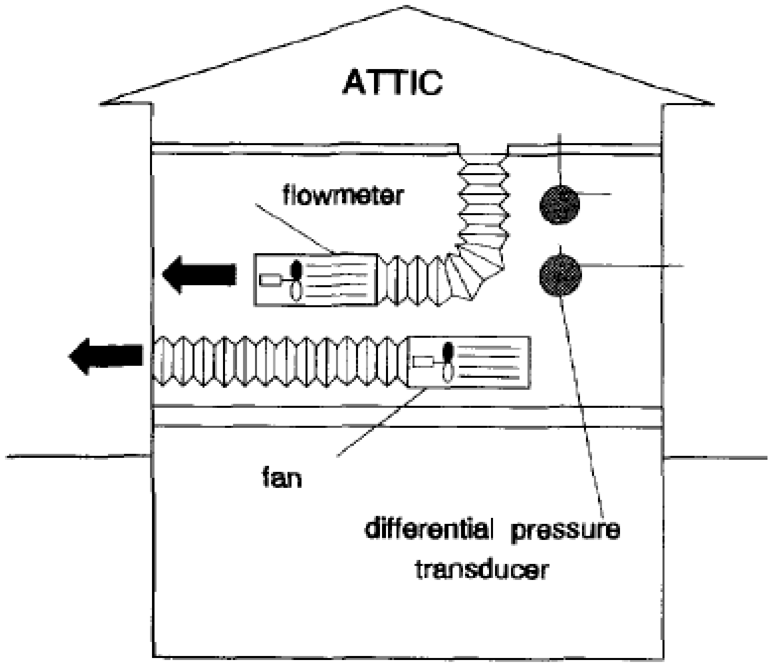


Figure 3.1 – Dual blower setup to estimate house to attic leakage rate
(Walker and Forest 1995)

3.2.8 Guertin, M (2005)

In 2005 an article entitled "Roof Ventilation for Coastal Homes" was published in the Coastal Contractor. In this article Guertin identifies driving rain as a major source of wetting in ventilated roof assemblies in coastal climates and proposes several shielded vent strategies to minimize wind driven rain entry. The author supports the unvented roof concept, but cites building code challenges as the major reason for its slow adoption in the construction industry.

3.3 Prediction

3.3.1 Burch, D. (1995)

In the early 1990s the National Institute for Standards and Technology developed a computer program called MOIST for predicting the one-dimensional transient heat and moisture movement in building assemblies. Doug Burch, one of the program's authors, produced several papers describing the application of the MOIST program to a variety of building performance problems. One such paper, entitled "An Analysis of Moisture Accumulation in the Roof Cavities of Manufactured Housing," was published in the Airflow Performance of Building Envelopes, Components and Systems, ASTM STP 1255. This paper describes a study of the hygrothermal performance of the roofs of manufactured homes using MOIST. The roofs of manufactured homes are constructed differently then insulated, sloped, wood-framed roofs, but the physics are still applicable.

The MOIST program accounts for

- vapor diffusion and capillary transport
- variation in thermal conductivity as a function of moisture content
- heat stored in dry and wet materials
- latent heat
- the convective coupling of air and other non-storage layers (i.e. fiberglass insulation) to indoor or outdoor air

The program ignores

- two- and three-dimensional effects
- effect of snow on the surface of a roof

The MOIST program uses an implicit solution technique to solve coupled mass and heat transfer equations. Burch states that there is no need to iterate between moisture and temperature solutions when time steps of an hour are used.

In his analysis of roofs for manufactured housing Burch considers a base case assembly that comprises asphalt shingles over and asphalt underlayment over roof sheathing over a 100 mm (4 in) air space over RSI 2.5 (R-14) fiberglass batt with a kraft facing for vapor control and a painted drywall finish.

Four attic ventilation rates were analyzed: 0, 0.012, 0.085 and 0.42 L/s m^2 (0, 0.14, 1 and 5 ft^3/hr ft^2) representing perfectly sealed, no-vent openings but poorly ventilated through cracks, well ventilated through vent openings and mechanically ventilated.

Four air leakage rates between the conditioned space and the attic were analyzed: 0, 0.013, 0.025 and 0.051 L/s m^2 (0, 0.15, 0.30 and 0.60 ft^3/hr ft^2) representing a perfectly sealed ceiling, a well sealed ceiling, a typical ceiling and a leaky ceiling.

Indoor temperatures were fixed at 21°C (70°F) and the relative humidity at 50% and a parametric study was conducted using data for the climate of Madison WI. Burch concluded that air leakage from the living space into the roof assembly had "a profound effect," increasing the magnitude and the duration of the sheathing moisture content curve that peaks in the winter. The sheathing in the well sealed roof was predicted to exceed fiber saturation (i.e. >28%).

Ventilation of the roof assembly also has a significant effect. In the naturally ventilated roof assembly the peak sheathing moisture content was reduced to below fiber saturation. In the mechanically ventilated roof assembly the peak moisture content was reduced to below 15%. The author noted that his simulations assumed that an increase in ventilation rates would not induce any increase in air leakage between the living space and the roof, which might introduce more moisture to the roof sheathing.

Burch went on to study the impact of a reduction in indoor relative humidity from 50% to 35%. This caused the peak moisture content to drop from roughly 35% to 25% and the duration of the peak to be reduced significantly (i.e. from approximately 5 months above 20% to only 2 months above 20%.

Finally Burch made two other interesting conclusions: the amount of insulation in the roof assembly had little effect on the peak moisture contents predicted in the roof sheathing, and the solar absorptivity of the roofing had a large impact on the magnitude and duration of the peak moisture contents (i.e. dark roof materials absorb more sun, resulting in higher temperatures and a greater drying rate).

3.3.2 TenWolde, A. (1997)

In April 1977 USDA-FPL published a paper entitled "FPL Roof Temperature and Moisture Model Description and Verification." Author Anton TenWolde explains that the program was conceived to study attic winter conditions but was later used to study summer conditions to assist in understanding the fire retardant treated (FRT) sheathing problems mentioned in the Winandy report.

The FPL attic model uses hourly weather data for any geographic location to predict sheathing temperature and moisture content and attic temperature and humidity. The model is based on previous models by Burch and Luna and Cleary.

The model accounts for

- the moisture sorption of sheathing (n.b. I believe he means instantaneous)
- different radiation balances on opposite roof slopes
- moisture transfer between the attic air and a thin surface layer in the sheathing
- moisture transfer between the thin surface layer and two interior layers of sheathing
- varying heat transfer coefficients as a function of temperature, wind speed and direction of heat flow
- the insulating effect of snow on the roof surface
- the effect of mechanical ventilation running continuously or intermittently on a timer, humidistat or photosensor

The model ignores

- moisture storage in other hygroscopic materials in the attic (e.g. framing, cellulose insulation)
- heat storage in attic materials
- liquid moisture flows
- influence of the fan on air exchange between the attic and the living space below

The model solves sequential heat balance and moisture balance equations for each 10 minute period using interpolated hourly weather data. The program reports moisture content data for the last 10 minute period of the preceding hour and temperature data for the first 10 minute period of the reporting hour. An iterative process is used to calculate the heat transfer coefficients and solve the heat balance equation. The resulting temperatures are used to calculate the moisture balance and the latent heat flows. The heat balance equation is solved again using the latent heat flows the process is repeated until the latent heat flows converge to within 5%.

The FPL attic model was validated against data collected by Rose and Gordon in 1993 at the University of Illinois in Champaign-Urbana. See 3.2.4 for more details regarding the experimental program and results. The model had a tendency to predict changes in the temperature of materials before they occurred. This was attributed to the fact that this simple model did not include the heat capacity of building materials.

In the winter the model temperature predictions were within 3°C (5.4°F) during the day and 6°C (10.8°F) at night. TenWolde suggests that the error at night occurs because the emissivity of the shingles was other than assumed or the roof received some radiation from surrounding buildings or objects that were not accounted for in the model.

In the summer the model made good predictions of the frequency of occurrence of high sheathing temperatures (i.e. over 49°C or 120°F) but the accuracy of the predicted temperatures was highly dependent on the assumed emissivity and solar absorptance.

Daily, monthly and seasonal moisture content predictions proved much more reliable than hourly; the model was able to predict daily average sheathing moisture contents to within 1%. TenWolde suggested that this could be improved by adding the effect of material mass with moisture storage.

3.4 Summary

Building codes and construction practices are slow to change, especially when radical changes in thinking are involved. Such is the case when it comes to the role that ventilation plays in the hygrothermal performance of insulated, sloped, wood-framed roof assemblies. Attic ventilation has perhaps been the most discussed and research topic in the low-rise residential construction industry for nearly two decades now. The emphasis on attic ventilation is evident in the articles reviewed and, while it is not the focus of this thesis, its importance will be seen in the remainder of the thesis research work

Chapter 4

Theory: Moisture Physics for Roofs

The study of the hygrothermal performance of roof assemblies requires a solid understanding of the movement of heat, air and moisture as well as thermal and hygric storage. This chapter provides a summary review and synthesis of the relevant physics, beginning with heat, moving to moisture and finishing with air.

4.1 Heat

Heat is the form of energy that is associated with the vibration of molecules. Its movement and storage play important roles in the hygrothermal performance of roof assemblies because they determine the potential for moisture problems, the durability of roofing materials and the energy use associated with the roof enclosure elements. This section of the thesis provides a review of the heat transfer and storage mechanisms relevant to the study and analysis of roof assemblies.

Heat transfer moves energy from areas of high temperature to areas of low temperature through three mechanisms: conduction, convection and radiation. These can take place separately or in combination. In most real situations heat flow occurs simultaneously in three dimensions as a transient process, however it is still possible to analyze many roof assembly problems using simple one-dimensional steady state calculations over short time steps.

4.1.1 Conduction

Conduction is the transfer of heat energy by direct contact between molecules. Conductive heat transfer can take place between adjacent molecules within a material or between the adjacent molecules of two separate materials that are in contact with one another (i.e. at an interface). One can calculate the rate of heat flow by conduction through a material using:

$$Q = U \cdot A \cdot \Delta T = k/l \cdot A \cdot (T_1 - T_2) \tag{1}$$

where

Q = heat flow through material (W)

U = material conductance (W/m^{2}K)

k = material conductivity (W/mK)

l = material thickness (m)

A = area of material (m^2)

T_1 = temperature of warm surface (°C)

T_2 = temperature of cold surface (°C)

Table 4.1 lists typical thermal properties for a range of materials commonly used in the construction of insulated, sloped, wood-framed roof assemblies.

Table 4.1 – Thermal properties of common sloped roof assembly materials

Material	Density (kg/m³)	Conductivity (W/m·K)	Conductance (W/m²K)	Heat Capacity (kJ/kg·K)
Roofing				
Asphalt shingles			12.9	1.3
Wood shingles			6	1.3
Structural Materials				
Plywood	400 - 600	0.08 - 0.11		1.5
OSB	575 - 725	0.09 - 0.12		1.7
Gypsum board	800 - 900	0.16		1.1
Softwood lumber	510	0.1 - 0.14		1.4
Hardwood lumber	720	0.15 - 0.18		2.4
Carbon steel	7680	40 - 80		0.50
Aluminum	2800	160 - 200		0.90
Insulations				
EPS Type 1	16	0.039		1.2
EPS Type 2	24 - 32	0.034		1.2
EXPS Type 3 and 4		0.029		1.2
Batt insulation		0.036 - 0.048		0.85
Polyurethane		0.024		1.6
Polyisocyanurate		0.02 - 0.024		1.6
Cellulose fiber	37 - 51	0.039 - 0.046		1.4
Other				
Fresh snow	190	0.19		
Compacted snow	400	0.43		
Ice at -1° and -20 °C	920	2.24 - 2.45		2.04 - 1.95
Water at 20 °C	1000	0.6		

4.1.2 Convection

Fluids are similar to solids in that conductive heat transfer takes place every time a fluid molecule collides with another fluid molecule or a molecule at the surface of a solid. Fluids are unique in that they are able to flow, carrying molecules and the heat energy they store from one region to another (i.e. move heat through the mechanism of convection). Convection is the transfer of heat energy by the movement of the molecules in a fluid (i.e. gas or liquid).

4.1.2.1 Convective Heat Transfer across a Surface

In the study of building enclosure assemblies, there is often a need to assess the heat transfer related to the movement of a fluid (usually air) across a solid surface. The rate of convective heat flow to/from the surface of the solid can be estimated from:

$$Q = h_C \cdot A \cdot \Delta T = h_C \cdot A \cdot (T_S - T_\infty)$$

where

Q = heat flow through material (W)

h_C = convective heat transfer coefficient (W/m^2K) (2)

A = area of material (m^2)

T_S = temperature of surface (°C)

T_∞ = temperature of fluid (°C)

Heat transfer across the indoor surfaces of and any still airspace in the building enclosure is often governed by natural convection. Natural convection describes air movement that is driven by the temperature related differences in the density of the fluid from one region to another. During sunny afternoons the roof sheathing will be hot and will heat the air next to it, causing the density of the air to decrease and the air to rise. The rising air is replaced by cool air from below and the process continues. Conversely, when the roof sheathing is cool at night, it will cool the air next to it, causing the density of the air to decrease and the air to fall. Again, the falling air is replaced with warmer air from above and the process continues.

When the temperature difference between the surface and the fluid is small, as is usually the case for the indoor surfaces of building assemblies, the airflow will be laminar. The coefficient for laminar natural convection to or from a vertical surface is given by:

$$h_C = 1.87 \cdot \Delta T^{0.32} \cdot H^{-0.05} \tag{3}$$

Laminar natural convection *against* buoyancy (i.e. down from a hot ceiling or down to a cold floor) is given by:

$$h_C = 0.59 \cdot (\Delta T / L)^{0.25} \tag{4}$$

Laminar natural convection *with* buoyancy (i.e. up to a cold ceiling or up from a hot floor) is given by:

$$h_C = 1.32 \cdot (\Delta T / L)^{0.25} \tag{5}$$

where

L = $4 \cdot A / P$ = characteristic dimension (m)

A = area (m^2)

P = perimeter (m)

H = wall height (m)

When the temperature difference between the surface and the fluid is large (i.e. >10°C), as may be the case on a calm, sunny day when the roof is heated well above the air temperature, the airflow will be turbulent. The coefficient for turbulent natural convection upward from a heated horizontal surface (i.e. with buoyancy) is given by:

$$h_C = 1.52 \cdot (\Delta T / L)^{0.33} \tag{6}$$

The coefficient for turbulent natural convection to or from a vertical surface (i.e. a sun-heated gable wall) is given by:

$$h_C = 1.31 \cdot (\Delta T / L)^{0.33} \tag{7}$$

On windy days natural convection is overwhelmed, forced convection dominates and the orientation of the surface and direction of heat flow become insignificant. The rate of heat flow depends primarily on the velocity of the air. Hagentoft has proposed the following relations:

$$h_C = 5.6 + 3.9 \cdot V, \text{ for } V = 1 \text{ to } 5 \text{ m/s} \tag{8}$$

$$h_C = 7.2 \cdot V^{0.78}, \text{ for } V = 5 \text{ to } 30 \text{ m/s} \tag{9}$$

where

V = velocity (m/s)

4.1.2.2 Bulk Convective Heat Transfer

In a ventilated roof assembly air movement is encouraged so that heat (and moisture) can bypass the sheathing, underlayment and roofing layers. This strategy is not intended to specifically address heat transfer to or from the surfaces in the roof assembly, but rather to move volumes of potentially warm (and moist) air out of the attic and replace it with cool (and dry) outdoor air. One of the fundamental equations used to calculate the bulk convective heat transfer is:

$$q = \dot{m} \cdot c \cdot \Delta T \tag{10}$$

where

$\dot{m}$ = the mass flow rate of the fluid (kg/s)

c = the heat capacity of the fluid (J/kgK)

ΔT = the temperature difference (K)

In roof analysis the fluid is typically air. This is a mass-based equation as the volume of air changes with temperature.

4.1.3 Radiation

Radiation is the transfer of heat energy through voids by electromagnetic waves. The void can be occupied by a gas or a vacuum. Radiation is emitted from all surfaces that are above absolute zero. Objects radiate heat to and receive radiant heat from all objects that are in their field of view. It is the net radiant transfer that is of interest when analyzing problems in building science.

Radiant heat transfer is important in the study of roof assemblies because it has a strong effect on many of the critical temperatures experienced by materials in the roof. The relevant mechanisms are discussed in the sections that follow.

4.1.3.1 Solar Radiation

Solar radiation plays an important role in the hygrothermal performance of roof assemblies because the daytime roofing and sheathing temperatures are primarily a function of the short wave radiation absorbed from the sun. The sun provides much of the energy necessary to dry moist materials. It can also elevate the temperatures to levels that may cause damage to or premature deterioration of some materials.

The amount of solar radiation that is absorbed by a surface (i.e. the heat transfer from the sun) can be estimated using:

$$q_s = \alpha \cdot I_{sw} \tag{11}$$

where

q_s = amount of solar energy absorbed by surface (J)

α = the solar (shortwave) absorptivity

I_{sw} = the solar (shortwave) radiation intensity on the surface (W/m^2)

The ASHRAE Handbook of Fundamentals recommends calculation methods to estimate the solar radiation on a surface given the day of year, hour, latitude of the building, azimuth (i.e. orientation) and slope of the surface (ASHRAE 2001)

4.1.3.2 Radiation to Surroundings

The net long wave radiation between a relatively small object and its much larger surroundings can be estimated using the Stefan-Boltzmann equation:

$$q = Q / A = \varepsilon \cdot \sigma \cdot (T_s^{\,4} - T_a^{\,4}) \tag{12}$$

where

q = the net radiant heat transfer per unit area (W/m^2)

ε = long wave emissivity

σ = the Stefan-Boltzmann constant (5.67x10^{-8} W/m^2×K^4)

T_s = surface temperature (K)

T_a = the surrounding temperature, usually assumed to be ambient (K)

This equation is useful for estimating the radiation between the outside surface of a roof assembly and the sky. Many roof assembly moisture problems have been linked to "night sky cooling", a depression of the roofing temperature below ambient, caused by radiation to the sky.

4.1.3.3 Radiation between Facing Surfaces

When two surfaces of similar size are located a short distance apart, the net long wave radiation can be determined from:

$$q_{1-2} = \sigma \cdot F_E \cdot F_A \cdot (T_1^4 - T_2^4) \tag{13}$$

where

q_{1-2} = the net radiant heat transfer between from surface 1 to 2 (W/m^2)

σ = the Stefan-Boltzmann constant (5.67x10^{-8} W/m^{2}K^4)

T_1 = surface 1 temperature (K)

T_2 = surface 2 temperature (K)

$F_E = \dfrac{1}{1/\varepsilon_1 + 1/\varepsilon_2 - 1}$ = emissivity factor

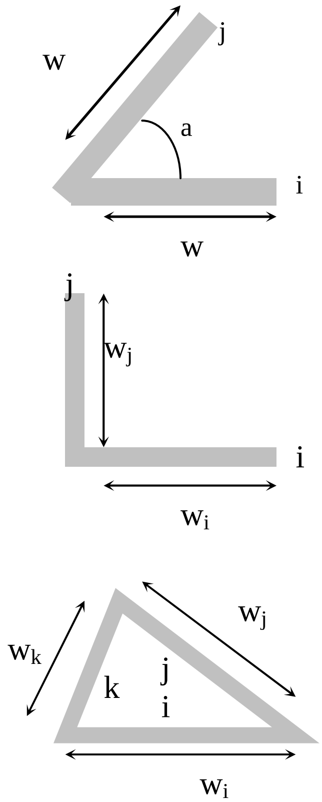
F_A = view factor

ε_1 = long wave emissivity for surface 1

ε_2 = long wave emissivity for surface 2

This equation is useful in analyzing the performance of any roof assembly that incorporates an air space between the bottom of the sheathing and the top of the insulation. As roof temperatures are elevated by the sun radiation can become the dominant heat transfer mechanism.

If the two surfaces are parallel to each other and very large relative to the space, the view factor will be unity. The view factor must be calculated for any other situation. Figure 4.1 illustrates several view factors for common situations in building enclosures. The top and bottom diagrams may be useful for assessing radiant heat transfer between the bottom of roof deck and the top of the ceiling or insulation on the horizontal. The middle diagram may be useful for assessing radiant heat transfer between a gable wall and the ceiling or insulation on the horizontal.



$$F_{ij} = 1 - \sin(\frac{a}{2})$$

$$F_{ij} = \frac{1 + (w_j / w_i) - [1 + w_j / w_i)^2]^{1/2}}{2}$$

$$F_{ij} = \frac{w_j + w_i - w_k}{2w_i}$$

Figure 4.1 – View factors for common situations in building enclosures (Hagentoft 2001)

Finally, a radiative heat transfer coefficient can be developed for simplicity:

$$h_r = \frac{F_E \cdot \sigma \cdot (T_s^4 - T_a^4)}{(T_s - T_a)}$$

where

h_r = the radiative heat transfer coefficient (W/m²K)

$F_E = \frac{1}{1/\varepsilon_1 + 1/\varepsilon_2 - 1}$ = emissivity factor (14)

ε = long wave emissivity

σ = the Stefan-Boltzmann constant (5.67×10^{-8} $W/m^2 \times K^4$)

T_s = surface temperature (K)

T_a = the surrounding temperature, usually assumed to be ambient (K)

4.2 Moisture

Moisture is at the center of many building science problems. In roof assemblies it is responsible for the formation of ice dams, frost accumulation, leaks, attic condensation, mold growth on and decay of sheathing and framing members, paint peeling and ceiling stains.

Early roof research was initiated over concerns regarding attic condensation and paint peeling. The resulting attic ventilation requirements were made to address these moisture concerns. This section of the thesis provides an overview of the physics of moisture in air, moisture in building materials and moisture in roof assemblies.

4.2.1 The Four Physical States of Moisture

In the field of building science, the term moisture is most often used to refer to water in its liquid, vapor or adsorbed states. Ice tends to be addressed as if it is a different material even though it is the solid state of water. Figure 4.2 illustrates the four moisture states and the processes that permit it to change from one state to another.

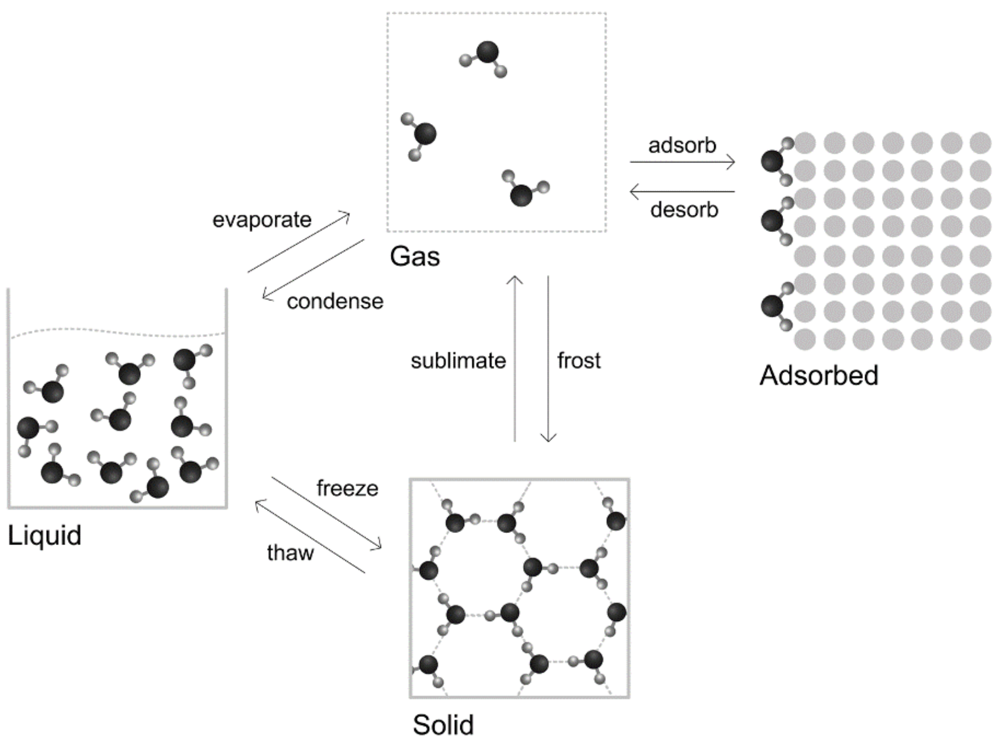


Figure 4.2 – Moisture states and state changes (Straube and Burnett 2005)

All four states play roles in the hygrothermal performance of roof assemblies. For example, water vapor in air can condense on the underside of the roof sheathing as frost on a cold night and then melt the following day to cause a "leak".

4.2.2 Moisture Storage in Air: Psychrometrics

The moisture content of air can be measured on a mass basis (e.g. humidity ratio in $kg_{water\ vapor}$ / $kg_{dry\ air}$) or as a partial pressure. Dalton's law states that the pressure of a mix of gasses is the sum of the pressures of the individual gasses. Water vapor acts like a gas and hence, as the moisture content of the air increases the pressure due to water vapor increases.

Psychrometrics is the science that deals with the properties (e.g. temperature, pressure, water vapor content) of moist air (i.e. a mixture of moisture and dry air) and the processes that permit these properties to be changed. The psychrometric chart, illustrated in Figure 4.3, depicts the relationship between the air temperature and its water vapor content (i.e. moisture content).

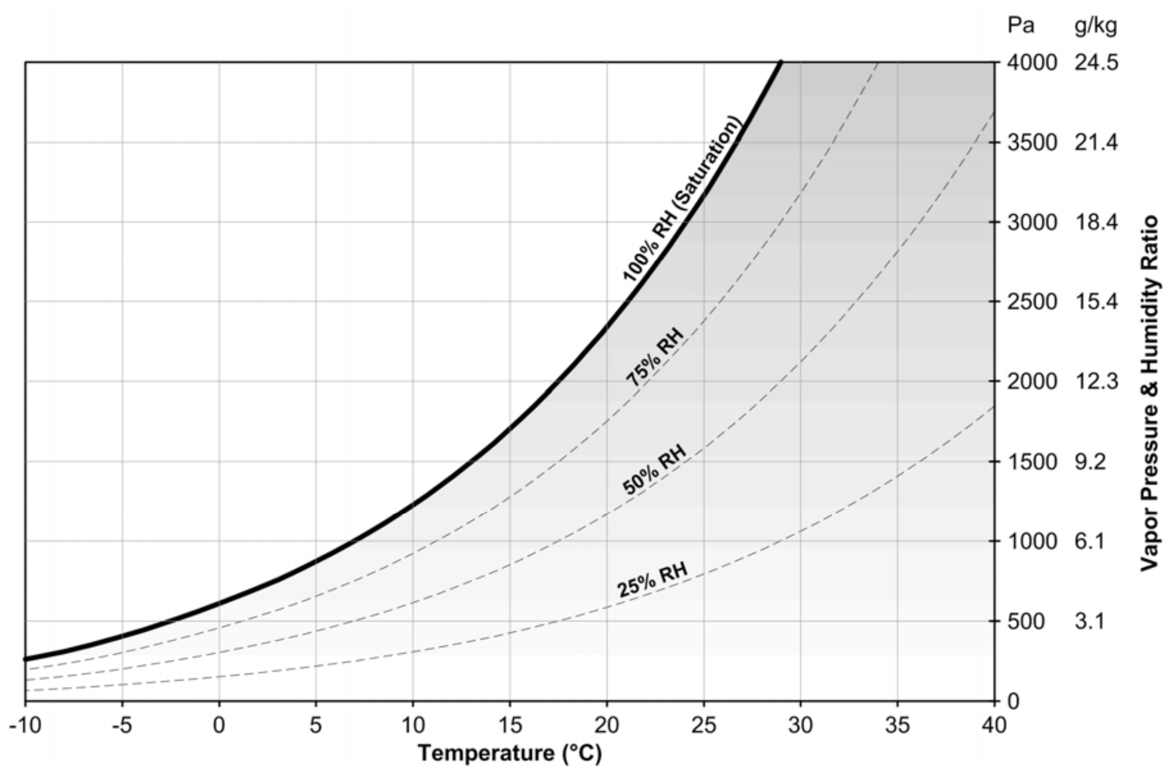


Figure 4.3 – Psychrometric chart

Temperature determines the maximum amount of water vapor that can be "stored" in a fixed volume of air. This maximum, when expressed as a partial vapor pressure at saturation (i.e. the saturation vapor pressure), is depicted in Figure 4.3 by the heavy black line. The saturation vapor pressure over water (i.e. temperatures of 0 to 200°C) can be calculated from:

$$\ln(p_{ws}) = C_8/T + C_9 + C_{10} \cdot T + C_{11} \cdot T^2 + C_{12} \cdot T^3 + C_{13} \cdot \ln T$$

where

$C_8 = -5.8002206\ \mathrm{E}+03$

$C_9 = 1.3914993$

$C_{10} = -4.8640239\ \mathrm{E}-02$ (15)

$C_{11} = 4.1764768\ \mathrm{E}-05$

$C_{12} = -1.4452093\ \mathrm{E}-08$

$C_{13} = 6.5459673$

T = temperature (K)

p_{ws} = saturation vapor pressure (Pa)

The saturation vapor pressure over ice (i.e. temperatures of -100 to 0°C) can be calculated from:

$$\ln(p_{ws}) = C_1/T + C_2 + C_3 \cdot T + C_4 \cdot T^2 + C_5 \cdot T^3 + C_6 \cdot T^3 + C_7 \cdot \ln T$$

where

$C_1 = -5.6745359\ \mathrm{E}+03$

$C_2 = 6.3925247$

$C_3 = -9.6778430\ \mathrm{E}-03$

$C_4 = 6.2215701\ \mathrm{E}-07$ (16)

$C_5 = 2.0747825\ \mathrm{E}-09$

$C_6 = -9.4840240\ \mathrm{E}-13$

$C_7 = 4.1635019$

T = temperature (K)

p_{ws} = saturation vapor pressure (Pa)

Air has the capacity to mix with and, for all practical purposes, "store" moisture in its gaseous state (i.e. water vapor). Air can move this stored moisture great distances and through small openings with ease. Moist air is responsible for many moisture problems in roof assemblies (e.g. attic condensation and frost accumulation). It is useful to express the water vapor content of the air as a humidity ratio (i.e. ratio of mass of water vapor to mass of dry air). The saturation humidity ratio is:

$$W_{ws} = \frac{0.622 \cdot p_{ws}}{p_t - p_{ws}}$$

where

W_{ws} = saturation humidity ratio ($\mathrm{kg_{water\ vapor}/kg_{dry\ air}}$) (17)

p_t = total atmospheric pressure (Pa)

p_{ws} = saturation vapor pressure (Pa)

However, air isn't always saturated so it is convenient to express its relative saturation as a fraction. Relative humidity is the term given to the ratio of the actual amount of water vapor in the air to the maximum amount that air can hold at a given temperature:

$$\theta = RH = \frac{w_w}{w_{ws}} = \frac{p_w}{p_{ws}} \qquad (18)$$

where

θ = relative humidity as a fraction

w_w = actual mass of water vapor in sample (kg)

w_{ws} = mass of water vapor at saturation (kg)

p_w = actual vapor pressure of sample (Pa)

p_{ws} = saturation vapor pressure (Pa)

For a given temperature, the saturation vapor pressure cannot be exceeded without the air becoming super saturated, producing fog. Condensation or "dew" will form on any surface when its temperature is below the temperature at which the current air-water vapor mixture would be saturated (i.e. the dewpoint temperature). For temperatures in the range of 0 to 93°C the dewpoint temperature can be calculated using:

$$t_d = C_{14} + C_{15} \cdot \alpha + C_{16} \cdot \alpha^2 + C_{17} \cdot \alpha^3 + C_{18} \cdot (p_w)^{0.1984} \qquad (19)$$

where

t_d = dewpoint temperature (°C)

$\alpha = \ln(p_w)$

$C_{14} = 6.54$

$C_{15} = 14.526$

$C_{16} = 0.7389$

$C_{17} = 0.09486$

$C_{18} = 0.4569$

p_w = water vapor partial pressure (kPa)

And for temperatures below 0°C:

$$t_d = 6.09 + 12.608 \cdot \alpha + 0.4959 \cdot \alpha^2 \qquad (20)$$

where

t_d = dewpoint temperature (°C)

$\alpha = \ln(p_w)$

p_w = water vapor partial pressure (kPa)

4.2.2.1 Applications

The saturation vapor pressure of air at room temperature, 20°C (68°F), using Eq.(15), is 2339 Pa. The saturation humidity ratio, using Eq.(17), is 14.35 g/kg. If the indoor relative humidity were 50%, the actual vapor pressure would be $\theta \cdot p_{ws}$ or 0.5 x 2339 = 1169 Pa and the actual humidity ratio would be $\theta \cdot w_{ws}$ or 0.5 x 14.7 = 7.17 g/kg. The dewpoint temperature of this air, using Eq.(19), is 9.3°C. If air at these conditions were to leak from the indoor space into the attic, it would condense on any solid surfaces that had a temperature less than 9.3°C.

The air leakage condensation potential can be estimated from the difference between the humidity ratio of the indoor air and the saturation humidity ratio at the condensing surface. If the temperature at the underside of the roof sheathing was 0°C, the saturation humidity ratio would be 3.77 g/kg and the condensation potential would be 7.35 – 3.77 = 3.58 g/kg. In other words, every kg of indoor air that leaked into the attic may provide 3.58 g of condensed water to the inside of the sheathing. This process is illustrated by the line labelled "cooling" in Figure 4.4.

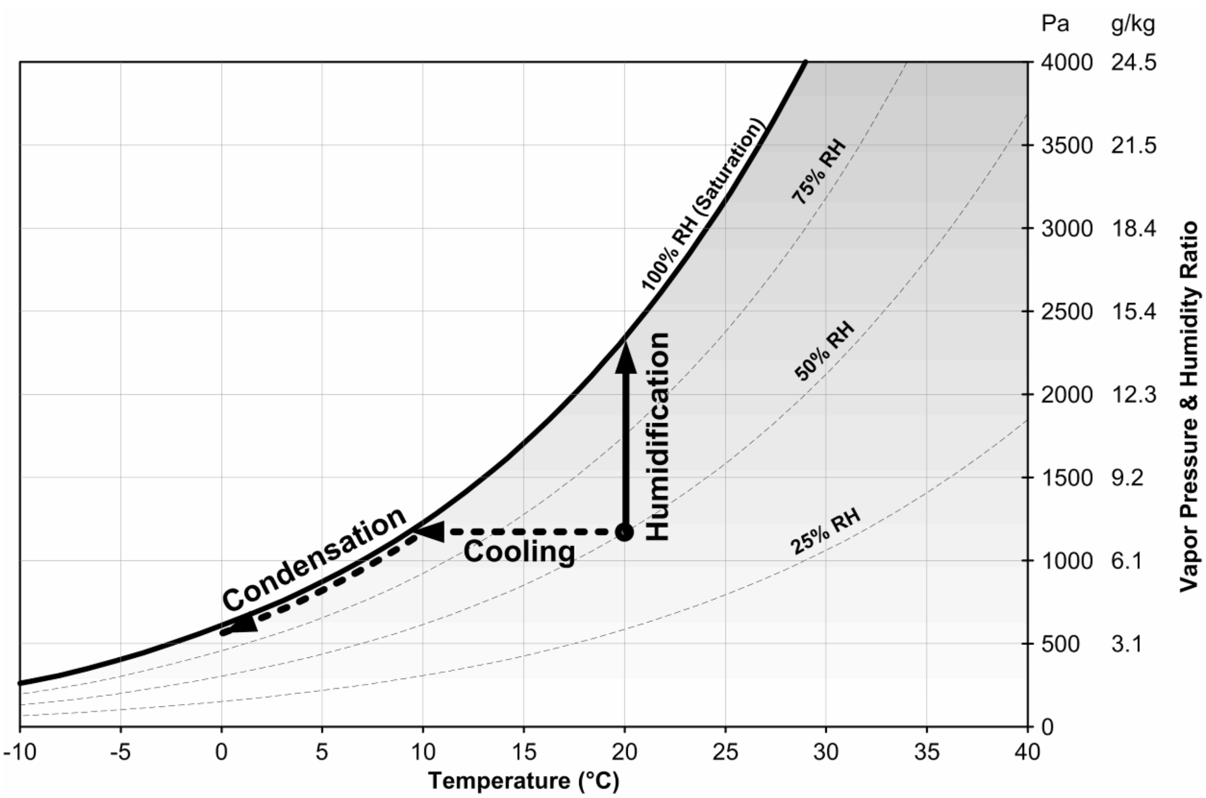


Figure 4.4 – Saturation processes on the psychrometric chart

Cooling is one of two processes that will bring air to saturation; the other is wetting. Figure 4.5 uses a container analogy to demonstrate each of these processes. When air is cooled, its moisture capacity is reduced, effectively making the container smaller. The amount or "volume" of water in the container will not change until the dewpoint is reached, after which condensation will occur.

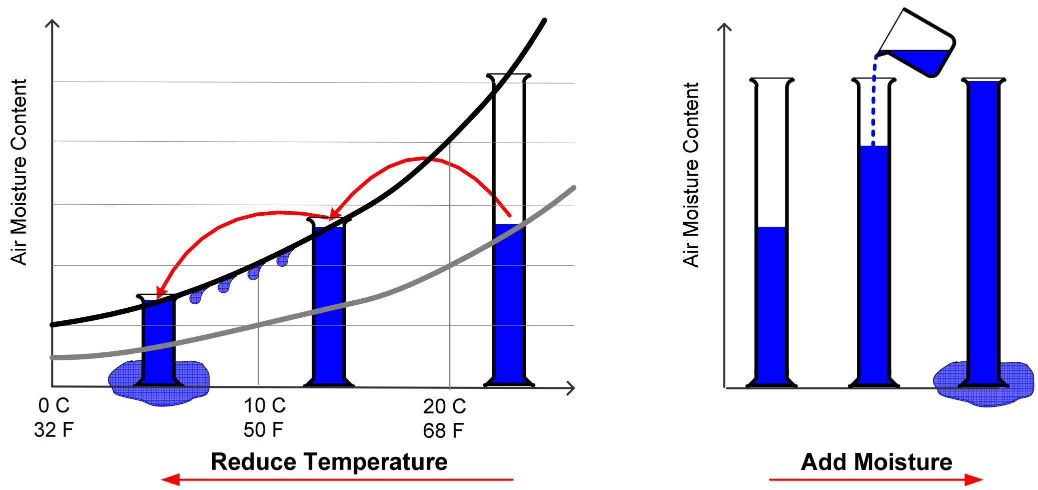


Figure 4.5 – Analogous saturation processes (cooling left, humidification right)

The wetting analogy assumes that the temperature, and therefore the size of the container, remains constant. In this scenario moisture is added to the system by evaporation of liquid water or mixing with air that has more water vapor (i.e. higher vapor pressure and humidity ratio). Moisture can be added until the saturation point is reached, after which any additional moisture will form condensation and / or be prevented from evaporation. This process is represented on the psychrometric chart in Figure 4.4 by the line labelled "wetting".

4.2.3 Moisture Storage in Building Materials

Just as air "stores" moisture, so too do many of the materials used in the construction of insulated, wood-framed roof assemblies. All wood-based structural products (e.g. plywood, OSB, trusses, dimensional lumber, etc.) and some of the most common insulation products (e.g. cellulose) are porous and hygroscopic in nature (i.e. they attract water vapor molecules to their surface). This enables them to store and facilitate the movement of moisture in all four of its states.

Porous materials, while appearing solid to the naked eye, actually comprise a solid particle matrix surrounding a network of voids or "pores". Both particles and pores are irregular in shape and size. Some materials have pore networks which form well connected tunnels that continue deep into (i.e. dead-end pores connect to the exterior) or even completely through to the opposite side (i.e. open-cell materials); others are composed primarily of dead end pores that trap air rather than communicate with the surrounding environment (i.e. closed-cell materials).

Air and water vapor molecules are able to move in and out of any of the pores that are connected to the exterior, so that some water vapor is stored in the air, in the pores. This "free water vapor" represents a very small amount of the water vapor that can be stored in a porous material.

Significantly more water can be stored on the surfaces of the pores and in their volume. Figure 4.6 depicts a generic moisture storage function for a hygroscopic porous material. The moisture storage function relates the moisture content of a material to the relative humidity of the air that surrounds it.

Figure 4.7 presents moisture storage functions for several materials that are commonly used in the construction of insulated, sloped, wood-framed roof assemblies.

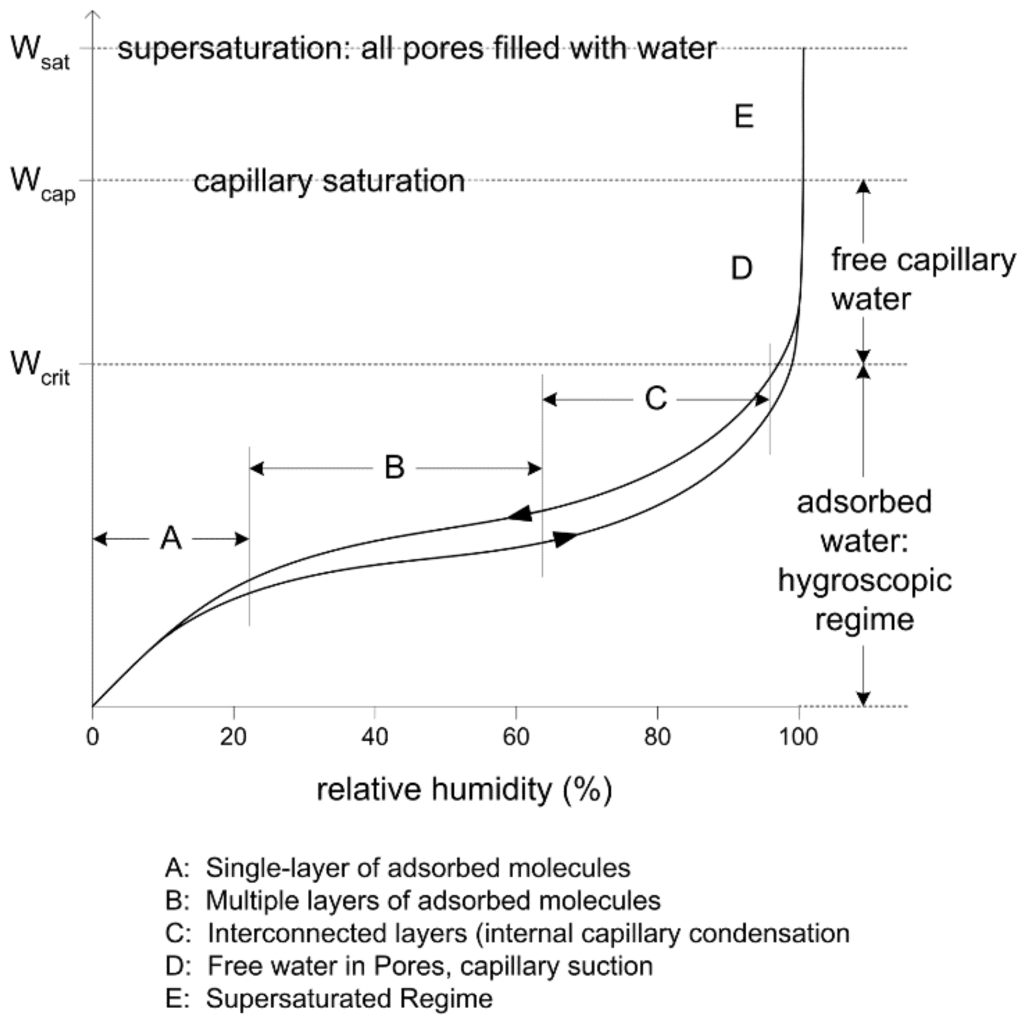


Figure 4.6 – Generic Moisture Storage Function (Straube and Burnett 2005)

The moisture storage function consists of three regimes: adsorbed water, free capillary water and supersaturated. These regimes are explained in the sections that follow.

4.2.3.1 Adsorbed Water

Hygroscopic materials attract water molecules that are close to their surface. Water molecules are held or *adsorbed* to the material surface for a time, after which they escape and are eventually replaced by another water molecule such that a dynamic equilibrium is achieved. The thickness of the adsorbed layer of water molecules increases as the relative humidity increases (i.e. as the density of water vapor molecules in the air increases).

As the adsorbed layer of water molecules increases in thickness it can actually fill the smallest pores. This is referred to as capillary condensation. Capillary condensation continues until all but the largest pores are filled with water. These pores cannot be filled by adsorption because the adsorbed layer of molecules cannot get any thicker. The moisture content at which this condition occurs for almost all small pores designates the critical moisture content of the material (W_{crit}).

4.2.3.2 Free Capillary Water

The same attractive forces are responsible for the capillary suction that causes the pores to *absorb* moisture when placed in contact with liquid water. The amount of water absorbed depends on the distribution of the pore sizes in the material (e.g. smaller pores have less cross-sectional area but higher capillary suction so they lift water higher above the liquid surface) and the force of attraction between water molecules and the material's surface (i.e. the wetting angle). When all pores that can absorb liquid water are full the moisture content is defined as the capillary saturation moisture content, W_{cap}.

4.2.3.3 Supersaturated Pores

If water under pressure is applied to the surface of the material, all but the smallest dead end pores will fill with liquid water. The material is said to be supersaturated because the water will drain out and the moisture content will return to W_{cap} when the water pressure is removed. The volume of water that can be forced into the material depends on the porosity (i.e. the fraction of the volume that is void) and the fraction of pores that are open and connected to the exterior. When all of these pores are filled with liquid water the material is said to have reached its saturation moisture content, W_{sat}.

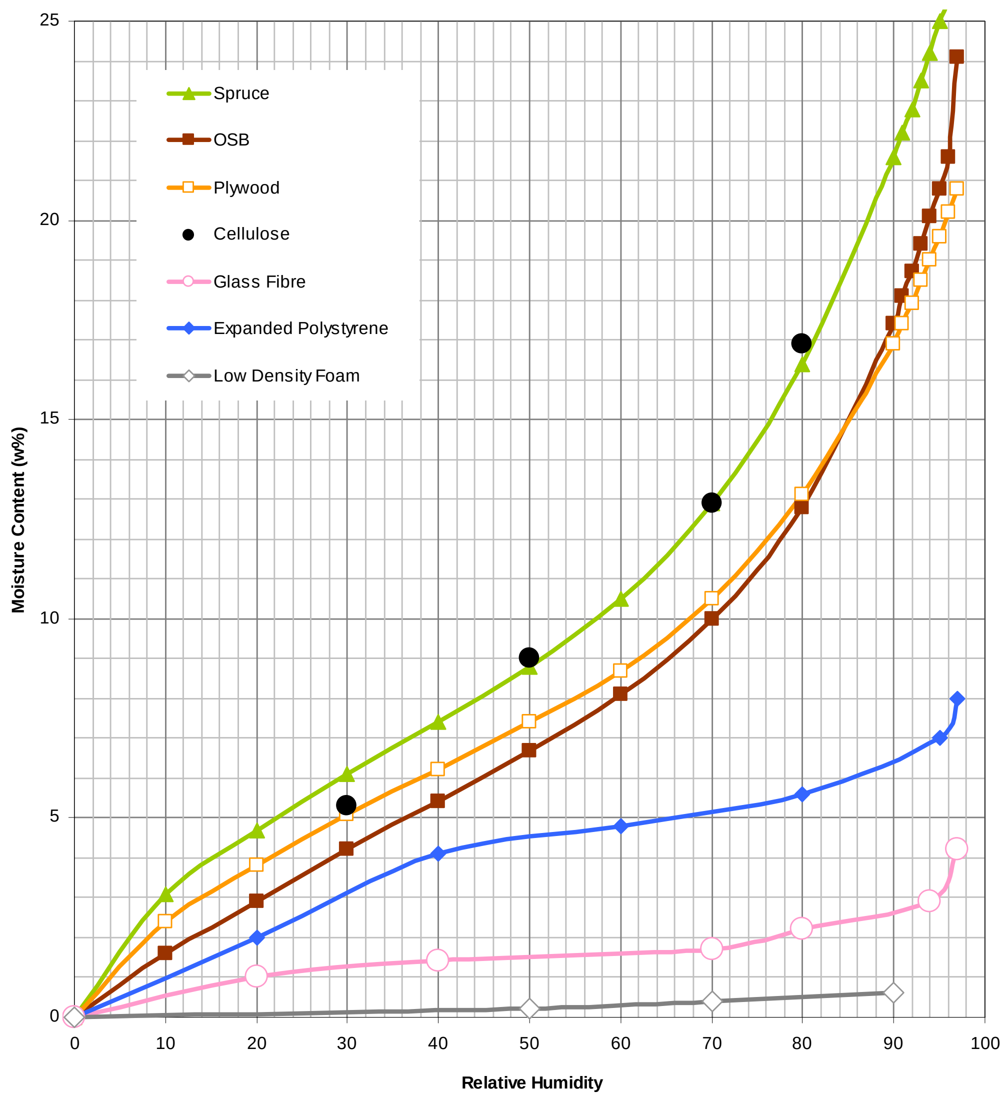


Figure 4.7 – Moisture storage functions for common roof assembly materials (ASHRAE 2002)

4.2.4 Bulk Moisture Storage in Roof Assemblies

The previous sections addressed the storage of moisture in air and in hygroscopic porous building materials. Both of these consider moisture physics at a molecular level, however moisture can also be stored in greater quantities in its liquid and solid forms both on the surfaces of the materials that form the building enclosure (e.g. on the roofing, on the underside of the roof sheathing) and in any spaces that it encloses (e.g. in a vented soffit). This section addresses the storage of bulk moisture in roof assemblies.

4.2.4.1 Liquid State

In its liquid state water can pool in low lying areas, however in roof assemblies it is more often a problem when it deposited and accumulates on cold surfaces by condensation. Moisture can be stored on smooth surfaces at rates of 30 to 100 g/m² (Smegal 2006). The German moisture standards permits as much as 500 g/m² of condensation to be stored on a non-absorbent, rough and non-vertical surface (DIN 4108-3 2001).

4.2.4.2 Solid State

Moisture, in its solid state, can be stored as ice on the surface of a roof and in the eaves, as snow blown into the attic or airspace through vent openings and as frost on the cold surfaces inside a roof assembly. When moisture is in its solid state it does not interact with or move through building materials and assemblies in the same way as liquid or vapor. Moisture in its solid form cannot be adsorbed or absorbed into hygroscopic materials; it cannot be drained; it can sublimate, but this is a slow process (i.e. it is the rate limiting step) so ventilation does little to remove accumulating ice, frost and snow.

In its solid state moisture can pose a problem to roof assemblies. It has the potential to cause several forms of mechanical damage: it expands as it freezes, potentially causing the failure of any container that holds it (e.g. splitting of gutters and downspouts); it adheres to surfaces, causing materials to separate and break off as the ice is pulled from the building (e.g. tearing off of shingles and trim as icicles and ice dams fall); it causes impact damage as heavy pieces of falling ice land. Ice can also cause problems when it accumulates in sufficient quantities to render moisture removal systems useless (e.g. frozen drains). Finally, snow and frost can change state quickly, overwhelming the ability of the assembly to dry itself out (e.g. melting frost).

4.2.5 Moisture Transport

Moisture storage acts as a buffer between periods of wetting and drying while moisture transport mechanisms move moisture to and from storage. Any study of the hygrothermal performance of roofs must therefore include some discussion of the transport mechanisms.

4.2.5.1 Drainage

One of the primary functions of every roof enclosure assembly is the control or exclusion of liquid water (e.g. rain, melt water). Sloped roof assemblies are designed to drain liquid water from the surface of the roofing to prevent head pressures driving liquid water through small gaps and to move water away from capillary active joints and cracks.

4.2.5.2 Liquid Moisture Transport

Flow through porous materials occurs as a combination of vapor diffusion (i.e. the movement of free water vapor molecules from high concentration to low), surface diffusion (i.e. the movement of adsorbed molecules from high relative humidity to low), capillary flow (i.e. the movement of liquid water under capillary suction from larger, filled pores to smaller empty pores) and possibly saturated flow (i.e. the movement of liquid water, through full pores, under external pressure).

Liquid moisture transport may be of interest for predicting the flow of moisture through porous roofing materials such as cedar shingles or concrete or clay tiles, however it is be reasonable to simplify most other aspects of the hygrothermal analysis of roof assemblies using the assumption that diffusion dominates the flow of moisture through materials, and airflow dominates vapor flow in air spaces.

4.2.5.3 Vapor Diffusion Transport

Water vapor diffusion occurs through any porous material that has open interconnected pores with access to the exterior. Vapor diffusion is driven by differences in the concentration of water vapor molecules and can be estimated using:

$$Q_v = M \cdot A \cdot \Delta P_w = \bar{\mu}/l \cdot A \cdot (P_{w1} - P_{w2}) \tag{21}$$

where

Q_v = water vapor diffusion rate through material (ng/s)

M = material permeance ($\mathrm{ng/Pa \cdot s \cdot m^2}$)

$\bar{\mu}$ = material permeability ($\mathrm{ng/Pa \cdot s \cdot m}$)

l = material thickness (m)

A = area of material ($\mathrm{m^2}$)

P_{w1} = vapor pressure of high side (Pa)

P_{w2} = vapor pressure of low side (Pa)

Measured values of material permeance and permeability typically include the combined effects of vapor diffusion, surface diffusion and capillary flow even though the latter two are driven by differences in relative humidity and liquid concentration rather than vapor pressure. As a result of this the permeance of many materials is a function of the relative humidity of the air in and around the pores. Figure 4.8 shows the effect of relative humidity on the measured permeance of two materials that are quite common to the construction of sloped, wood-framed roof assemblies: plywood and oriented strand board (OSB) sheathings. Table 4.2 shows the vapor permeability of a variety of materials commonly used in the construction of sloped, wood-framed roof assemblies.

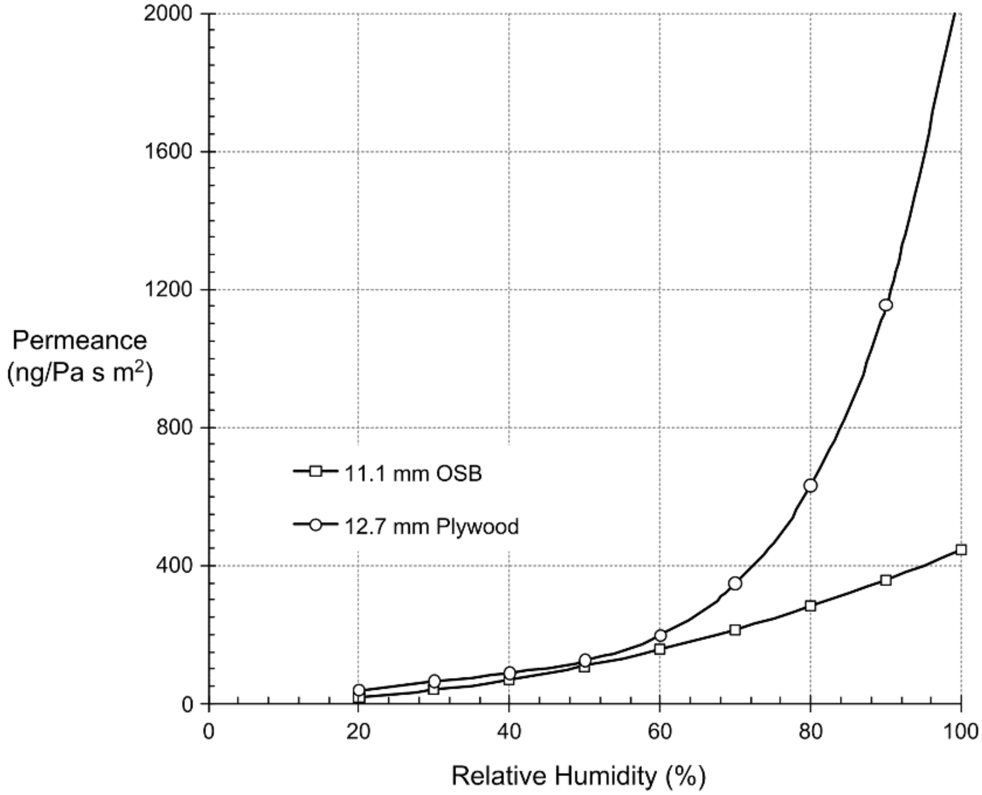


Figure 4.8 – Effect of Relative Humidity on Permeance of OSB and Plywood Sheathing

Table 4.2 – Vapor Permeability of common sloped roof assembly materials

Material	Permeability (ng/Pa·s·m)			Notes
	Dry Cup (0-50% RH)	Wet Cup (50-100% RH)	Other Tests	
Structural Materials				
Plywood	0.5 - 1.5	2 - 8	20 - 30	Other = saturated
OSB	0.5 - 1.5	1.5 - 3	4 - 5	Other = saturated
Gypsum board	25			
Softwood lumber			0.58 - 7.8	RH dependent
Carbon steel	0	0	0	
Aluminum	0	0	0	
Insulations				
EPS Type 1	4 - 7.5			
EPS Type 2	3 - 6			
EXPS Type 3	1 - 3			
EXPS Type 4	0.8 - 1.7			
Batt insulation		245		
Polyurethane	2.86 - 3.85			
Polyisocyanurate		0.01		
Cellulose fiber			110	RH dependent

4.2.5.4 Convective Moisture Transfer across a Surface

Section 4.1.2.1 of this thesis addressed convective heat transfer across a surface. A similar equation is used to describe the convective moisture transfer across a surface:

$$q_w = h_w \cdot (P_{ws} - P_\infty) \tag{22}$$

where

q_w = rate of water vapor convection (g/s)

h_w = convective water vapor transfer coefficient ($\mathrm{g/Pa \cdot s \cdot m^2}$)

P_{ws} = the water vapor pressure at the surface (Pa)

P_∞ = the water vapor pressure of the fluid (Pa)

For convenience the convective water vapor transfer can be expressed as a function of the convective heat transfer coefficient:

$$h_w = \frac{h_c}{R_{wv} \cdot T \cdot \rho_{air} \cdot c_p} \tag{23}$$

where

h_w = convective water vapor transfer coefficient ($\mathrm{g/Pa \cdot s \cdot m^2}$)

h_c = convective heat transfer coefficient ($\mathrm{W/m^2 \cdot K}$)

R_{wv} = the gas constant for water vapor ($\mathrm{J/g \cdot K}$)

T = the absolute temperature (K)

ρ_{air} = dry density of air ($\mathrm{g/m^3}$)

c_p = the specific heat capacity of air ($\mathrm{J/g \cdot K}$)

4.2.5.5 Bulk Convective Moisture Transfer

Even very small airflows are capable of moving significant amounts of moisture, often orders of magnitude more than diffusion.

Bulk convective heat transfer was addressed in Section 4.1.2.2. This was identified as a particularly useful equation for assessing the benefit and effectiveness of ventilation strategies in roof assemblies. A similar equation is applied to the estimation of the moisture transferred in flowing air:

$$m_w = \rho_{air} \cdot W \cdot Q_{air}$$

where

m_w = rate of convective water vapor movement (kg/s)

ρ_{air} = dry density of air (kg/m^3) (24)

W = the humidity ratio (kg$_{water}$ / kg$_{dryair}$)

Q_{air} = volumetric flow rate of air (m^3/s)

4.3 Air

Airflow is a central issue in the competing design philosophies for insulated, sloped, wood-framed roof assemblies. Ventilated roof assemblies seek to encourage airflow to reduce roof surface temperatures and encourage drying. Unvented roof assemblies seek to eliminate airflow to exclude wind-driven rain, snow, fire and water vapor entry. An air-tight ceiling plane is important for all roof assemblies, regardless of the ventilation strategy. This section addresses the pressure-flow relationships that are important in the study of roof assemblies.

4.3.1 Air Leakage

Air leakage and diffusion are identified as the two mechanisms that move moist indoor air through the ceiling plane into the roof assembly. Of these, air leakage is more critical because it is capable of moving 10-100 times more moisture than diffusion.

Two things are necessary for air leakage to occur through the building enclosure: a path for the air to flow through and an air pressure difference to drive it. Consider a straw in a glass of iced tea – although the straw provides a path for the iced tea to flow through, no iced tea will move until someone sucks on the straw, creating a negative pressure to draw the iced tea up out of the glass. Conversely, if the straw were plugged, a person would not be able to draw iced tea up out of the glass no matter how hard they sucked on the straw.

Three pressures drive air leakage: wind, stack effect and mechanical equipment (i.e. fans). In buildings, only the mechanically created pressures can be controlled. Wind pressures and stack effect (i.e. buoyancy) are not as easily influenced; therefore in practice one tries to measure, understand and eliminate the flow paths. Figure 4.9 illustrates a selection of the air leakage paths that typically connect the living space to an attic roof assembly in a wood-framed house.

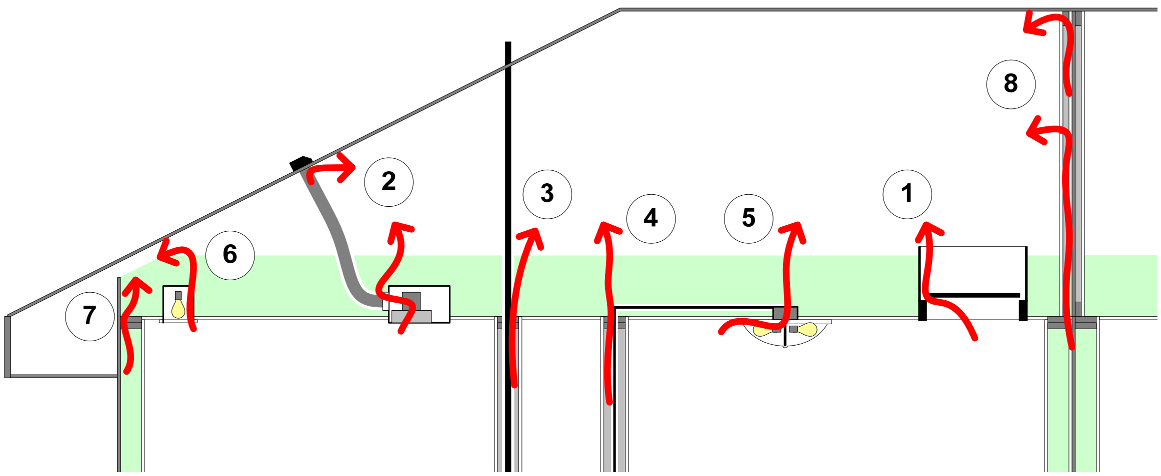


Figure 4.9 – Air leakage paths between the living space and attic

4.3.1.1 Bulk Airflow

A significant number of leakage paths may exist in any wood-framed house. It is not practical to test each path individually. However, it is common to depressurize an entire house using a special fan installed in a doorway (i.e. a blower door) so that the impact of all leakage paths may be identified and the overall air leakage performance of the house assessed on the basis of the total or bulk airflow.

Figure 4.10 – Blower door test setup

The relationship between bulk air flow and pressure is given by the power law equation:

$$Q = C \cdot (\Delta P)^n$$

where

Q = bulk air flow rate (i.e. through all holes) (m^3/s) (25)

C = flow coefficient ($m^3/s \cdot Pa$)

n = the flow exponent

This approach provides a measure of all of the leakage through the building enclosure system. Some interesting information can be obtained from the results. If the flow were through a single, perfect orifice, it would be in the turbulent regime and the flow exponent, *n*, would be 0.5. If the leakage paths consisted of a network of well distributed small holes, the flow would be in the laminar regime and the flow exponent would be 1. In real situations however, the flow is through a series of parallel, tortuous paths and the flow exponent lies between 0.5 and 1. A flow exponent of 0.65 is typically assumed for hypothetical calculations.

The blower door test results can also be used to express the airtightness of the building as an equivalent leakage area:

$$A_L = 10000 \cdot Q_r \cdot \frac{\sqrt{\rho / 2\Delta p_r}}{C_D} \tag{26}$$

where

A_L = equivalent air leakage area (cm^2)

Q_r = predicted airflow rate ate Δp_r from measured data (m^3/s)

ρ = air density (kg/m^3)

Δp_r = reference pressure difference (Pa)

C_D = discharge coefficient

4.3.2 Ventilation of Roof Assemblies

Historically ventilation has been employed as the primary mechanism for the removal of moisture from attic and cathedral ceiling roof assemblies. It is therefore useful to consider the physics of flow through the various components of ventilation systems, namely flow through vent openings and flow through air spaces.

4.3.2.1 Flow through Vent Openings

Vent openings for roof assemblies typically take one of three forms: numerous evenly distributed small openings (e.g. perforated aluminum soffit), discrete vent openings (e.g. larger holes drilled in a solid soffit, mushroom vents), and continuous slots (e.g. soffit slot vents, continuous ridge vents).

Airflow through a discrete vent opening can be estimated using a form of the orifice equation:

$$Q = 0.61 \cdot A \cdot \sqrt{\Delta P} \tag{27}$$

where

Q = air flow rate through opening (m^3/s)

A = area of the opening (m^2)

ΔP = pressure difference across opening (Pa)

The orifice flow equation can be used to estimate the airflow through a single hole in a perforated material. The total airflow would then be the product of the flow through a single hole, the hole density (i.e. number of holes per unit area) and the area of the perforated material.

Airflow through a slot vent opening is described by:

$$Q = \frac{b \cdot d}{0.6 \cdot \varepsilon} \cdot \sqrt{\Delta P} \tag{28}$$

where

Q = air flow rate through slot opening (m^3/s)

b = slot width (m)

d = slot lenght (m)

ΔP = pressure difference across slot opening (Pa)

ε = friction factor:

0.5 for enterance

0.88 for exit

$0.885 \cdot (b_1/b_2)^{-0.86}$ for an elbow with widths b_1 and b_2

Flow through slots is greatly affected by changes in direction. Figure 4.11 illustrates the friction factors for common slot vent configurations.

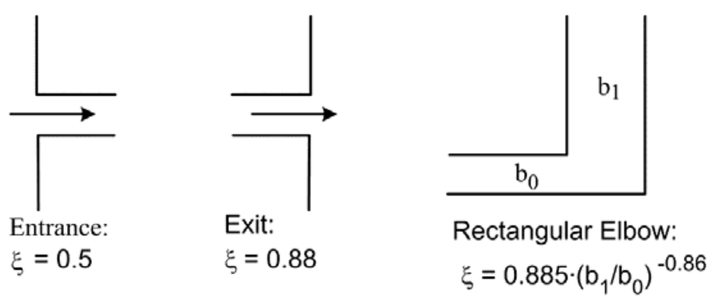


Figure 4.11 – Friction factors for slot vents

4.3.2.2 Flow through an Air Space

Under most natural conditions ventilation flow through air spaces in building enclosure assemblies can be assumed to be laminar. It can be estimated using (Straube and Burnett 1995):

$$Q = \frac{4610\gamma \cdot b \cdot d \cdot \Delta P}{h}$$

where

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

d = the cavity depth (m) (29)

b = the cavity width (m)

h = the cavity height (m)

γ = a blockage factor

ΔP = pressure difference across the cavity (Pa)

Air flow networks in roof assemblies typically consist of an entry vent, an air space and an exit vent. The preceding equations can be solved for the pressure difference term and the sum of the pressure differences over the three components set equal to the driving pressure on the assembly. The resulting equation can then solved for the flow through the roof assembly.

4.3.3 Driving Forces

Air leakage and ventilation air flows are driven by air pressure differences that are generated by the wind, stack effect and mechanical equipment (i.e. fans). These are addressed in this section of the thesis.

4.3.3.1 Wind

Wind pressures are proportional to the square of the velocity and may be calculated from Bernoulli's equation:

$$P_{stag} = \frac{1}{2}\rho_{air} \cdot v^2$$

where

P_{stag} = wind stagnation pressure (Pa) (30)

ρ_{air} = dry density of air (kg/m^3)

v^2 = the wind velocity (m/s)

Wind speeds fluctuate dramatically over small time steps e.g. 1 sec), however it is possible to estimate the average driving pressure exerted by the wind on a roof assembly using wind speeds averaged over a longer period (e.g. 15 min to 1 hr).

The ASHRAE handbook of fundamentals provides methods for estimating the wind pressures on buildings of varying shapes and sizes (ASHRAE 2001).

4.3.3.2 Stack effect

Stack effect pressures are generated by thermal induced air density gradients (i.e. buoyancy). The stack induced pressure difference can be estimated:

$$\Delta P_{stack} = 3645 \cdot \Delta h \cdot \left(\frac{1}{T_1} - \frac{1}{T_2}\right) \tag{31}$$

where

ΔP_{stack} = stack effect pressure (Pa)

Δh = vertical distance (height) between entry & exit (m)

T_1 = air temperature outside the space (K)

T_2 = air temperature inside the space (K)

4.3.3.3 Fans

Mechanical ventilation is sometimes used to induce flow in the airspaces in roof assemblies. This is done more often to reduce attic temperatures than it is to address elevated moisture levels. The fan resulting pressure and the flow rate are dependant on both the fan curve and the flow resistance of the air space network in question.

Chapter 5
Investigation and Measurement

Chapters 2 and 3 of this thesis identified reasons to consider the use of unvented cathedralized attic and unvented cathedral ceiling roof assemblies. Further research needs to be done to better understand the problems experienced in conventional ventilated roof assemblies and predict the long term hygrothermal performance of unvented assemblies. The research needs can be grouped into five categories:

1. Roof leaks
2. Air leakage
3. Vapor diffusion
4. Roof temperature
5. Ice dams

This thesis describes research work that addresses issues 2, 3 and 4. Issues 1 and 5 are broad topics requiring significant discussion regarding detailing and construction sequence, hence they are not included in the scope of this thesis. This chapter presents a summary of a collection of four field investigation and measurement projects that focused on the hygrothermal performance of insulated, sloped, wood-framed roof assemblies. The moisture physics of Chapter 4 are applied to the analysis of an Ottawa ON field investigation, and three field research studies: a test house in Vancouver BC, a test hut in Coquitlam BC and a test hut in Atlanta GA. Figure 5.1 shows the location of each project on Lstiburek's climate map of North America.

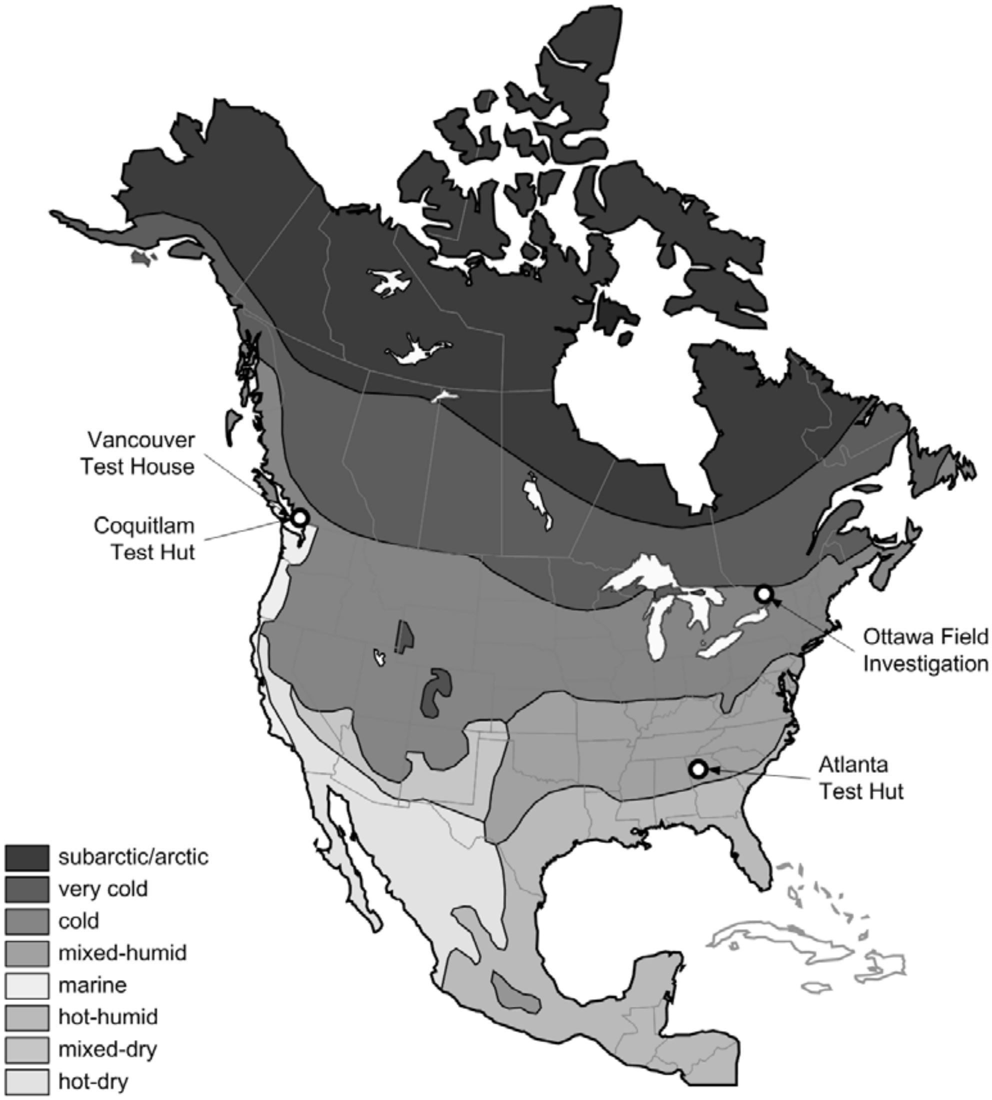


Figure 5.1 – Location of field projects

Each project summary includes an explanation of the background, a statement of project objectives, a detailed description of the approach to the project, a review of the results and a discussion of the initial analysis.

5.1 Ottawa ON Field Investigation

The Ottawa field investigation was a forensic investigation rather than a research project. It has been included in the thesis because it served as the inspiration for and sets the context for the three academic research projects that follow.

The project comprised an investigation into attic frost problems reported by the owners of several new Ottawa townhouses in the winter of 2004. Investigation revealed that significant amounts of frost were accumulating in the attic, as evident in the image of Figure 5.2. This supports theoretical assumptions regarding the significance of moisture storage on the surface of roof sheathing products. The frost subsequently melted, drained to the ceiling plane and, in several instances, found its way through gaps in the polyethylene vapor barrier and proceeded to wet the drywall ceiling.

Figure 5.2 – Homeowner's photo of heavy frost in attic

The homeowners questioned the appropriateness of the attic ventilation and a roofing contractor was contacted to inspect the problem attics. The contractor verified that the installed perforated soffit and mushroom vents met the requirements of the Ontario Building Code, but recommended the addition of a large passive rooftop ventilator on each of 60 houses at a cost of $500 per house.

The builders felt that they lacked sufficient information and sought the opinion of building scientists to gain a better understanding of the attic frost problem, its cause and possible remedies.

5.1.1 Objectives

This project afforded the opportunity to apply the moisture physics and theory presented earlier to a real-life roof moisture problem. The objectives of this project were:

- Collect and document evidence of the mechanisms of heat and moisture transfer in insulated, sloped, wood-framed roof assemblies.
- Advance the industry understanding of the moisture physics related to attic condensation and frost problems.

5.1.2 Approach

The field investigation began with a site visit to the worst of the problem houses, pictured in Figure 5.3. The homeowner was interviewed and the history of the symptoms and prior investigation were reviewed. The damaged ceiling and attic were both examined. Attic air temperature and relative humidity were measured, as were the temperature and moisture content of the OSB sheathing on each roof orientation. Finally, the house was reviewed to identify moisture sources that might result in elevated indoor humidity levels. Indoor temperature, relative humidity and the moisture content of furniture were measured.

Weather data was collected from the Ottawa International Airport and a simple air mixing model and parametric study were prepared to assess the influence of attic ventilation rate, indoor to attic air leakage rate and indoor relative humidity on the potential for frost formation and the moisture removal capacity.

Figure 5.3 – Photo of Ottawa field investigation house

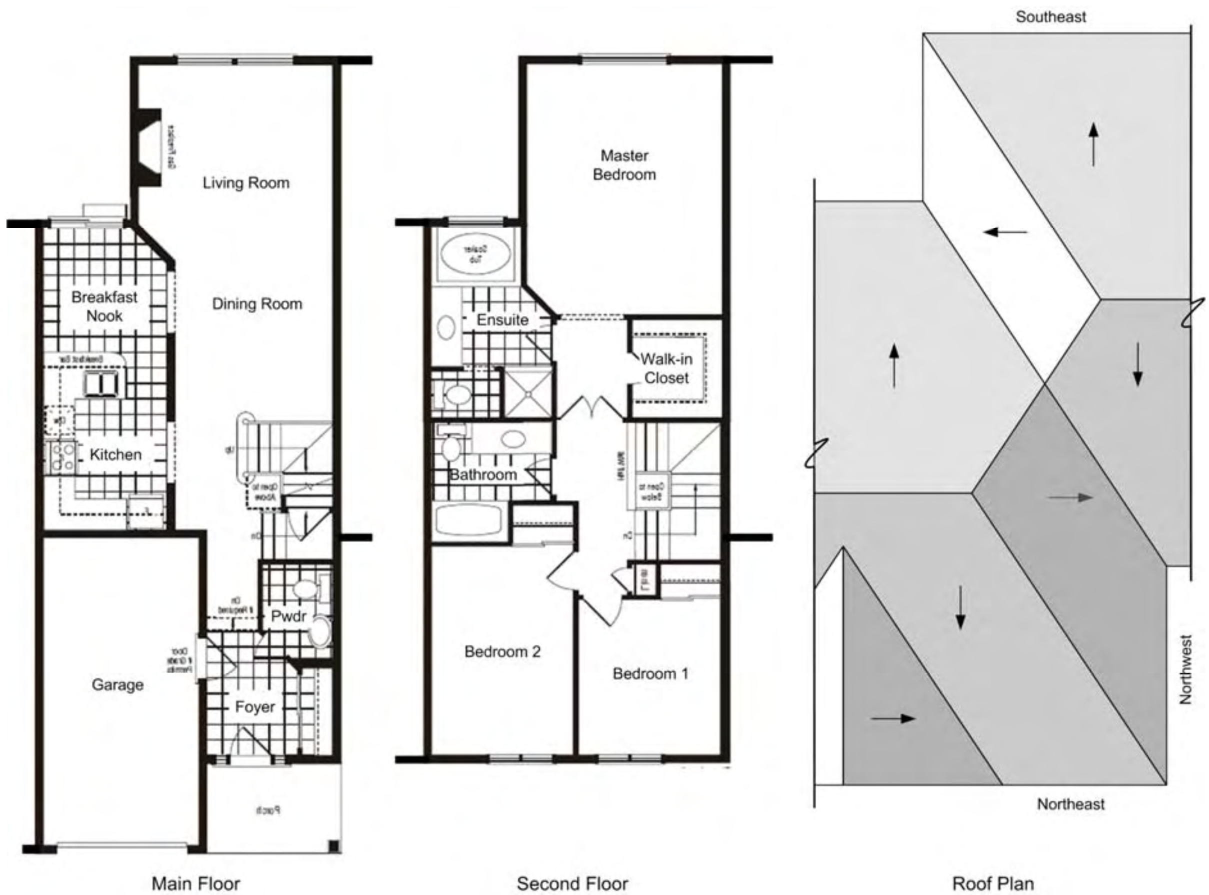


Figure 5.4 – Ottawa field investigation house plan

5.1.3 Results

A site visit was made to the worst of the problem houses in late February 2004. The outdoor conditions were measured upon arrival (i.e. at approximately 9:30 am):

- Outdoor temperature: -8.0°C (17.6°F)
- Outdoor relative humidity: 50%
- Outdoor dewpoint: -15.7°C (3.7°F)
- Wind speed (at ground): 1.4 m/s (3.1 mph)
- Sky condition: Clear, Sunny

The house is in the middle of a block of six townhouses, a "notch" in the block layout, seen on the right-hand side of the photo in Figure 5.3, exposes most of that side of the house to the exterior. The roof plan is complicated by the notch and a gable on the front of the house and the fact that the living room and master bedroom are pushed past the breakfast nook at the back. Figure 5.4 shows the plans for the main floor, second floor and roof.

5.1.3.1 Homeowner Interview

Water stains and moisture damage were discovered on the ceilings of Bedrooms 1 and 2 in early to mid February. Both the homeowners and the builders assumed that the roof was leaking, demonstrating the need for further research and training on the topic of the hygrothermal performance of roof assemblies.

In the days that followed the initial discovery several inspections of the attic were made. It was during one of these inspections that significant frost build up was noted on the underside of the roof sheathing and the photo of Figure 5.2. The frost build up was at its worst after several days of very cold weather.

5.1.3.2 Ceiling and Attic Conditions

Figure 5.5 provides an example of the water stains and damaged drywall on the ceilings of Bedrooms 1 and 2. In both rooms the damage was at the bottom of a northeast-facing roof slope. North-facing roofs receive less solar radiation than other orientations. This means that the sheathing on north-facing roofs remains below freezing for longer periods of time, encouraging the formation of thicker layers of frost, and the storage of more moisture that can create problems when it thaws.

Figure 5.5 – Moisture damage on bedroom ceiling

The roof comprises light grey asphalt shingles installed on a felt paper underlayment over OSB sheathing on wood trusses. The trusses create an attic space that is approximately 4 m (13 ft) at high at the peak. A 6 mil polyethylene vapor barrier and drywall finish are installed on the underside of the trusses. The ceiling is insulated with approximately 250 mm (10 in) of blown-in insulation.

The roof assembly uses the conventional ventilated attic approach to control moisture. Adequacy of the vent area had been confirmed by a roofing contractor, however the effectiveness of the ventilation was questioned. Trusses run two directions to achieve the complex form of the roof. In several locations (e.g. the gable at the front of the house) the roof sheathing extends below the roof line, effectively dividing the attic into compartments that are connected by 400 x 600 mm (16 x 24 in) ventilation openings as visible in Figure 5.6. This arrangement complicates the airflow and reduces the effectiveness of the ventilation.

Figure 5.6 – Ventilation opening between attic compartments

Conditions were measured in the attic:

- Attic air temperature: 3.0°C (36.4°F)
- Attic relative humidity: 41%
- Attic dewpoint: -8.0°C (17.6°F)
- Sheathing temperatures:
  NE: -1°C (30°F)
  NW: -4°C (25°F)
  SW: -3°C (27°F)
- Sheathing moisture contents: >30% using Tramex Moisture Encounter
- Truss moisture content: 12-14% using Tramex Moisture Encounter

Neither frost nor condensation were evident on the underside of the sheathing, however all of the sheathing moisture contents were elevated. The attic dewpoint was lower than the sheathing temperatures, but was almost 8.0°C (14.4°F) higher than the outdoor air, indicating that some moisture was added to the outdoor air after it entered the attic.

5.1.3.3 Indoor Conditions and Moisture Sources

Elevated attic moisture levels suggest the influence of moisture from the occupied space below. Indoor conditions were measured immediately following the measurements in the attic:

- Indoor air temperature: 20.7°C (69.3°F)
- Indoor relative humidity: 40%
- Indoor dew point: 6.7°C (44.0°F)
- Moisture content of oak table: 11%
- Moisture content of wood floor: 12%
- Pressure difference across ceiling (i.e. between 2nd floor & attic): 3.4 Pa
- Pressure difference across the front door: -3.2 Pa

The indoor relative humidity was on the high end of the recommended range for outdoor temperatures near -10.0°C (14.0°F). The elevated moisture levels might be attributed to the fact that this was the first winter since the house was completed and built-in moisture (i.e. moisture in the wood, concrete and other materials) can take one to two years to dry out. It was noted however that the attic frost problems were not common to all of the townhouses in the block, suggesting that there may be other moisture sources of influence.

Wood is a hygroscopic material and its moisture content will reach equilibrium with the air around it. Oak moisture contents of 11-12% suggest a relative humidity of 50%. Further discussion with the homeowner revealed that a console humidifier had been run to maintain indoor relative humidity levels during extended cold spells. No other exceptional indoor moisture sources were discovered.

5.1.4 Analysis

This section provides further analysis of measurements and observations made during the site visit. Weather data was collected and a simple air mixing model was prepared. A parametric study is used to examine the influence of attic ventilation rate, indoor to attic air leakage rate and indoor relative humidity on the potential for frost formation and the moisture removal capacity.

Hourly weather data was collected from Ottawa International Airport, approximately 10 km (6 miles) from the problem house. The data include temperature, relative humidity, wind speed, wind direction, air pressure and weather events such as sun, cloud and snow. Figure 5.7 shows the outdoor temperature and relative humidity recorded over the first two months of 2004. On January 4th the temperature dropped below freezing and did not return to positive temperatures until February 9th. The temperature was less -10.0°C (14.0°F) for 654 hrs during this period. This extended cold period ends around the time that the moisture damage was noticed on the ceilings, lending support to the theory that exceptional frost accumulation and its eventual thaw were behind the moisture damage.

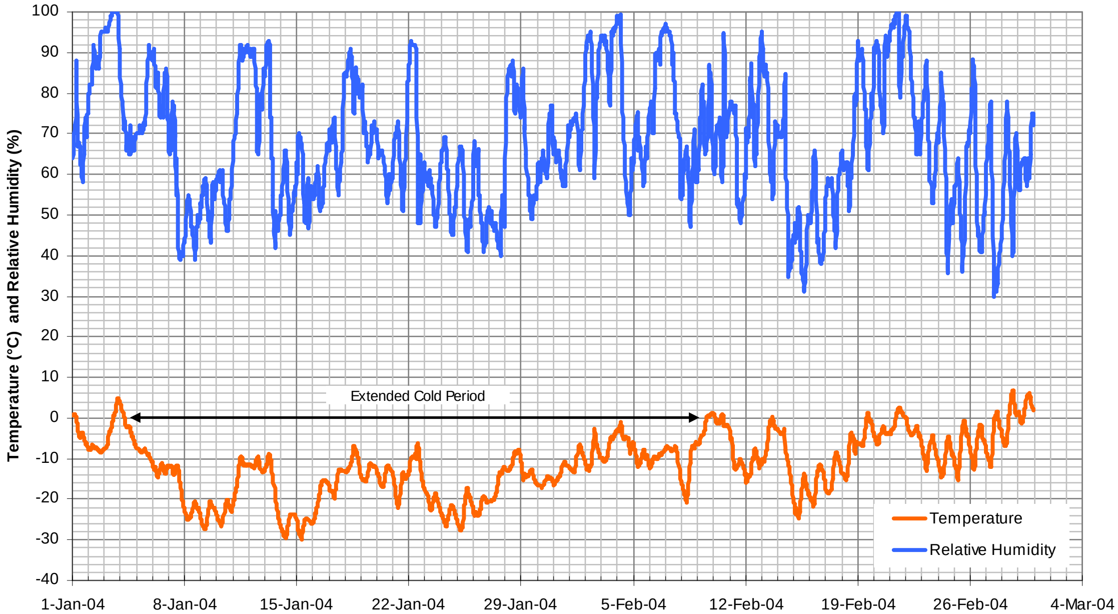


Figure 5.7 – Outdoor Temperature and Relative Humidity at Ottawa Airport

Indoor to outdoor air temperature differences generate the stack effect that drives air movement (i.e. leakage) between the indoor space and the attic. This pressure difference can be calculated using Eqn. (31), assuming an indoor temperature of 20.7°C, a floor height of 2.65 m and a neutral pressure plane at the second floor. Figure 5.8 shows the predicted pressure difference for various outdoor temperatures. Note that the predicted pressure difference for -8°C is 3.4 Pa, very close to measured.

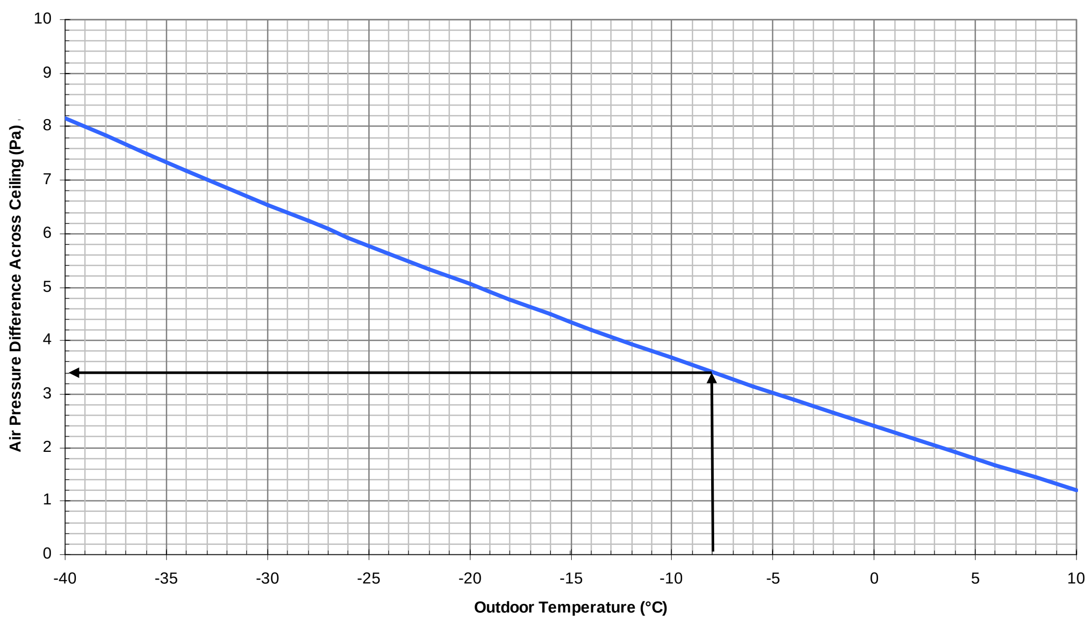


Figure 5.8 – Influence of Outdoor Temperature on Stack Effect

If the stack pressure and air leakage area of the ceiling are known the air leakage rate between the house and the attic can be estimated using the power law equation. Few measurements of the leakage area between house and attic have been made, however Fugler (1999) reported results from CMHC studies of 20 Canadian houses. The average measured equivalent leakage area was 330 cm² at a pressure difference of 10 Pa (ELA_{10}). One R2000 house had an ELA_{10} of 20 cm². Figure 5.9 shows the estimated indoor to attic air leakage rates for a range of ELA_{10} and outdoor temperatures. Walker and Forest (1995) reported that the ELA_4 of test houses 5 and 6 at the Alberta Home Heating Research Facility were 12 and 10 respectably. These translate to ELA_{10} of approximately 13 and 12.5. For the purposes of this thesis these have been considered covered by lower bound of the CMHC measurements.

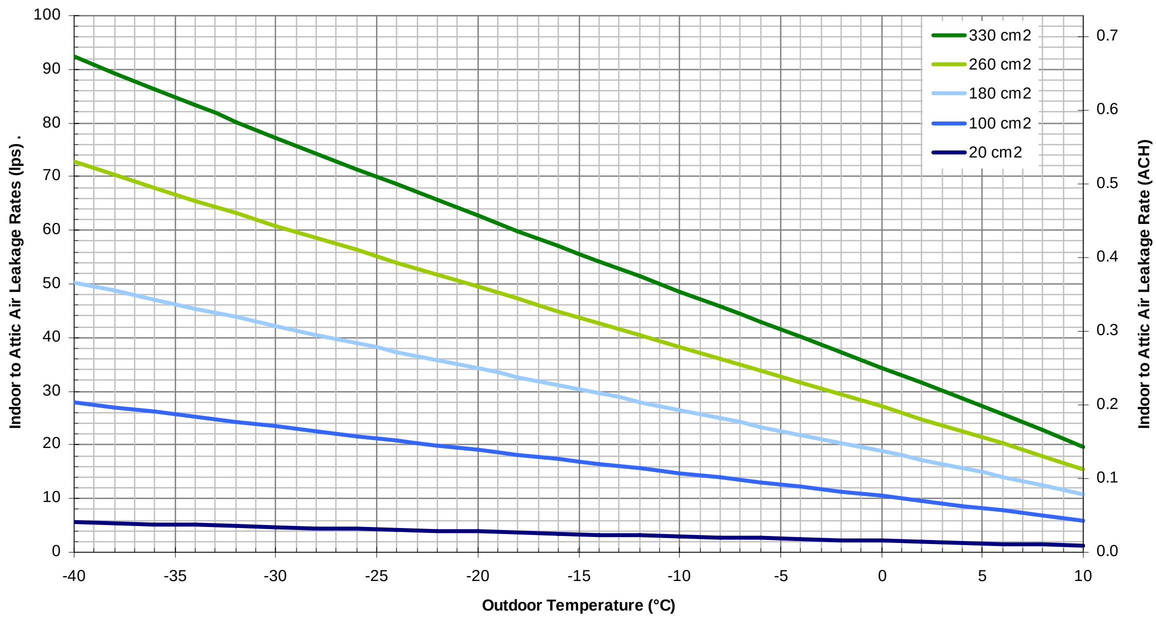


Figure 5.9 – Air Leakage Rates

For outdoor temperatures in the range of 0 and -30°C, estimated leakage rates would be on the order of 4 to 76 lps. These are approximately equivalent to 0.05 to 0.55 ACH (relative to the house volume) for the field investigation house in Ottawa.

Walker and Forest found that attic ventilation was only driven by stack effect when the wind speeds were less than approximately 2 m/s. At these low wind speeds there was much variability in the measurements but the average ventilation rate appeared to vary from approximately 2 ACH (relative to the attic volume) when the attic to outdoor temperature difference was low (i.e. 3°C) to 4 ACH when the temperature difference reached 17°C. At higher wind speeds Walker and Forest found that the code vented attic achieved 10 ACH when the wind approached from an unsheltered direction while the "sealed" attic achieved only 2 ACH.

Figure 5.10 shows the wind speed and direction in Ottawa recorded over the months of January and February 2004. There were few calm hours during the extended cold period, suggesting that the ventilation rates are wind pressure dominated.

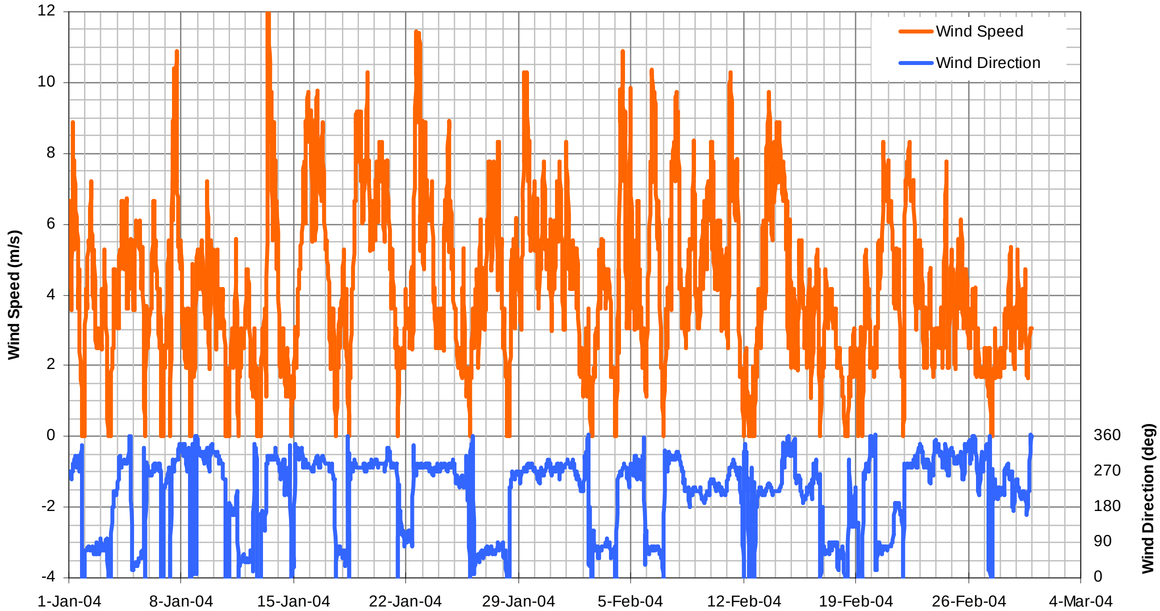
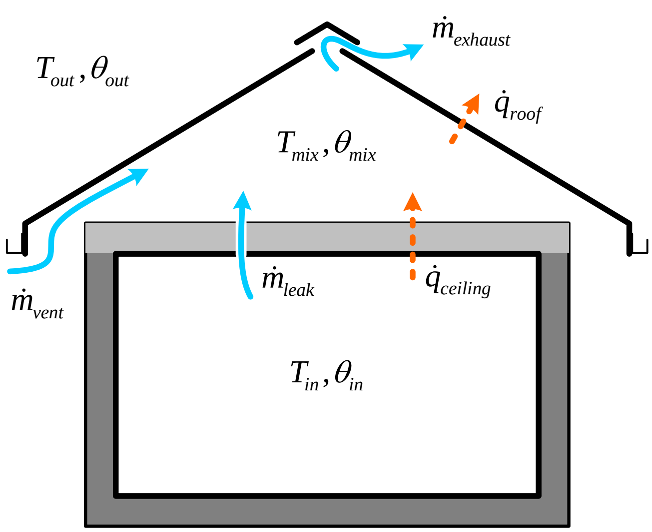


Figure 5.10 – Wind Speed and Direction at Ottawa Airport

A simple mixing model was created to assess the roles played by the indoor to attic leakage rate, the attic ventilation rate and indoor relative humidity. Figure 5.11 summarizes the parameters considered and the resulting energy and mass balance. The model does not consider the effect of solar radiation, which can have a significant impact on roof surface temperatures and predicted condensation hours.



Mass Balance:

$$\dot{m}_{exhaust} = \dot{m}_{vent} + \dot{m}_{leak}$$

Energy Balance:

$$\dot{q}_{vent} + \dot{q}_{leak} + \dot{q}_{ceiling} = \dot{q}_{exhaust} + \dot{q}_{roof}$$

Figure 5.11 – Simple Attic Mixing Model

The model was used to predict the conditions (i.e. temperature and relative humidity) in the attic given air leakage rate, ventilation rate, indoor temperature and humidity and outdoor temperature and humidity. The moisture load is defined as the rate at which the air leak introduces moisture to the attic (referenced to the moisture in the outdoor air). The ventilation capacity is defined as the maximum rate at which the ventilation air can remove moisture (assuming that mixing would allow it to reach saturation). Figure 5.12 shows the predicted attic temperature, moisture load and ventilation capacity for the months of January and February, assuming an indoor to attic leakage rate of 0.3 ACH_{house} or 40 lps, a ventilation rate of 6 ACH_{attic} or 281 lps and an indoor relative humidity of 30%.

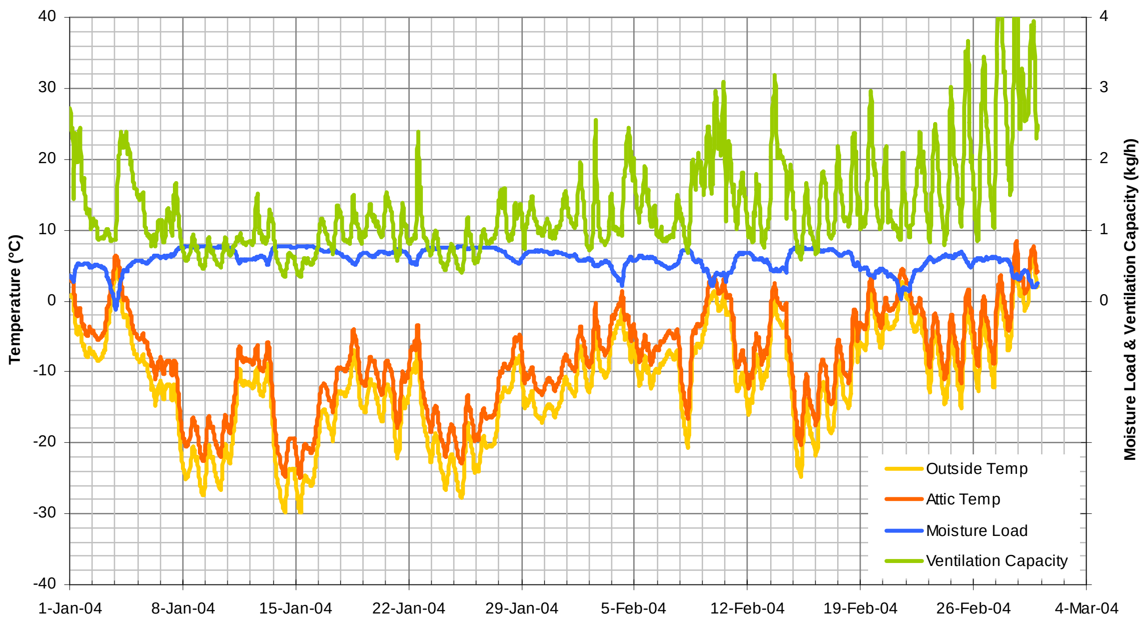


Figure 5.12 – Predicted moisture load and ventilation capacity

Moisture load and ventilation capacity are read off the right hand axis. The ventilation capacity is overwhelmed by the moisture load (and condensation or frost will form) whenever the blue line crosses above the green line. While this occurs for 10% of the hours over the two month period, the moisture load is near the ventilation capacity for a significant portion of the hours, suggesting that there is not much “safety factor” in the system.

Further calculations were prepared as part of a parametric study:

- Indoor to attic leakage rates: 7, 24, 40, 57 and 74 lps
- Attic ventilation rates: 94, 188, 281, 375 and 469 lps
- Indoor relative humidities: 15, 22.5, 30, 37.5 and 45%

The results of the parametric study have been summarized in Figure 5.13 through Figure 5.15, a series of “hygrothermal influence lines” that illustrate the impact of each parameter on the predicted performance of the assembly. The hygrothermal influence lines were generated by holding two of the parameters at their mean values while the parameter of interest is varied.

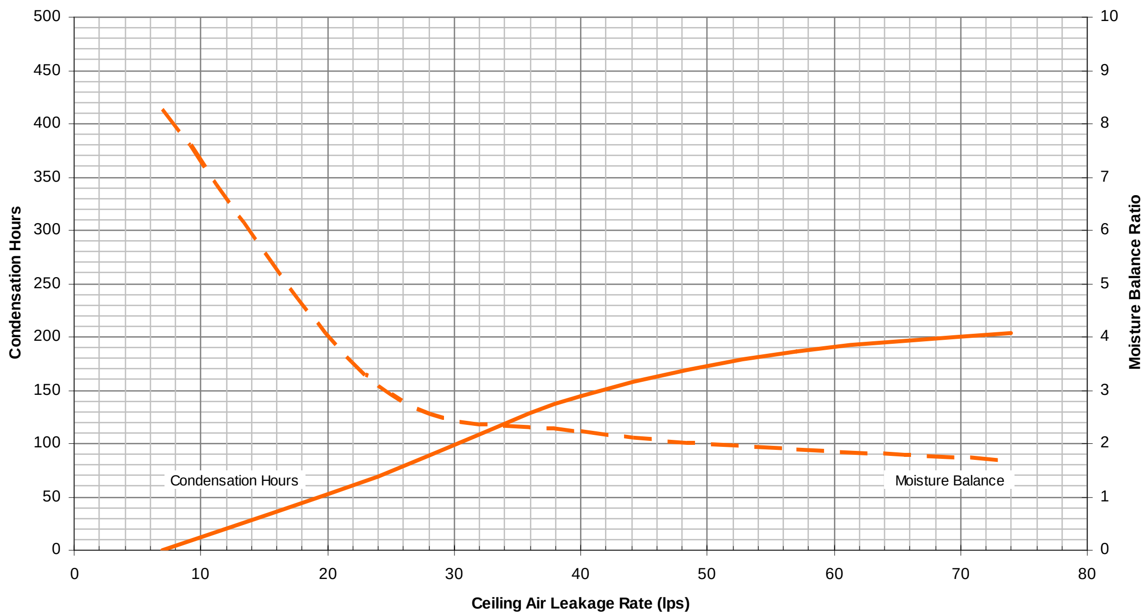


Figure 5.13 – Ceiling air leakage hygrothermal influence line

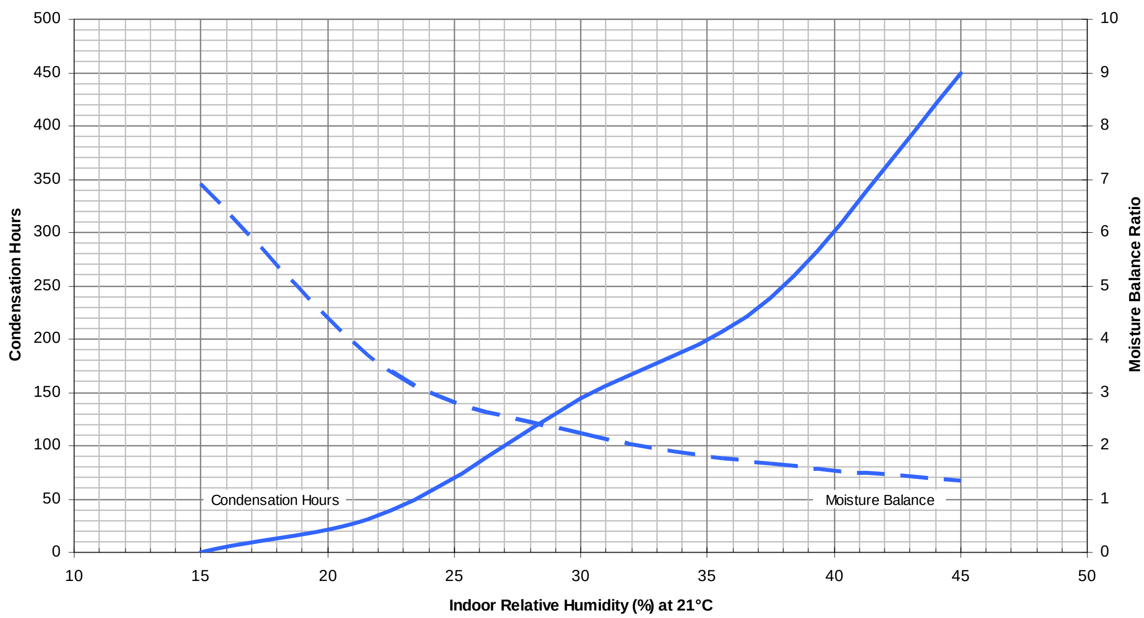


Figure 5.14 – Indoor relative humidity hygrothermal influence line

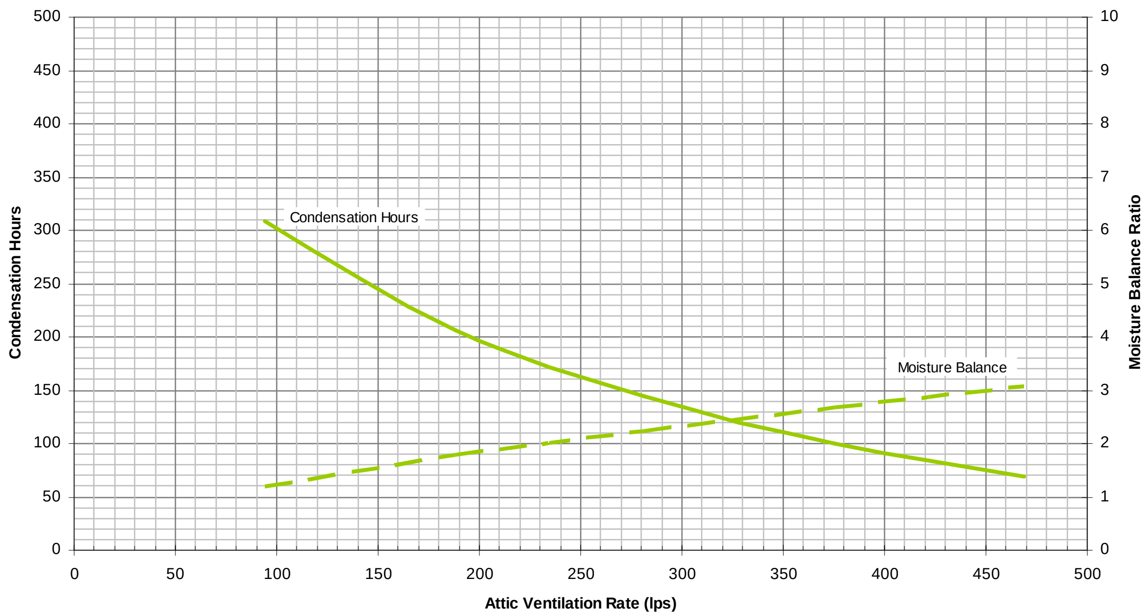


Figure 5.15 – Attic ventilation rate hygrothermal influence line

The influence of a parameter is assessed by studying its impact on i) the predicted hours of condensation (read on the left hand axis), totaled over the months of January and February (1440 hours), and ii) the moisture balance ratio (read on the right hand axis) for the same time period. The moisture balance ratio is calculated:

$$\text{moisture balance ratio} = \frac{\sum \text{ventilation capacity (kg)}}{\sum \text{moisture load (kg)}} \qquad (32)$$

A moisture balance ratio of less than 1 means that the ventilation capacity is not able to remove the moisture introduced to the attic through the air leakage. Ratios of greater than 1 mean that the moisture load is handled. Obviously larger moisture balance ratios infer more robust hygrothermal performance.

The influence lines suggest that reductions in indoor relative humidity will have the biggest impact in reducing condensation hours and increasing the moisture balance ratio. Reductions in ceiling air tightness produce only modest improvements until the ceiling becomes very airtight (e.g. ELA_{10} of less than about 100 cm^2). This rather odd result occurs because very high air leakage rates increase the attic temperature. Finally, increases in ventilation result in a slow but steady reduction in condensation hours. Increases in ventilation rate appear to have the least impact on the moisture balance ratio.

5.1.5 Conclusions & Recommendations

The field investigation revealed that the roof assembly did suffer from moisture problems even though the code required vent areas had been provided. The complex geometry of the roof assembly likely impeded the internal flow such that some areas of the attic were stagnant and the effectiveness of the ventilation was reduced.

Analytical investigations were used to assess the relative impact of air leakage from the living space into the attic, the interior relative humidity and ventilation of the roof assembly. Air leakage was found to have the most significant role in controlling attic moisture levels whereas attic ventilation rate played the smallest role. In the case study home indoor relative humidity was too high.

5.2 Vancouver BC Test House

The Vancouver BC Test House project was conceived to study the hygrothermal performance of an unvented cathedral ceiling roof assembly in the cold wet climates of the Pacific Northwest and lower mainland British Columbia.

Unvented cathedral ceiling (UCC) and unvented cathedralized attic (UCA) roof assemblies have a proven track record in hot humid and mixed humid climates where they are used in lieu of ventilated attics to avoid moisture problems associated with outdoor air that has a high dewpoint temperature. Building scientists have debated the potential performance of UCC assemblies and need for vapor barriers in these assemblies in colder climates.

Recent changes to the US model building codes permit the construction of UCC roof assemblies in marine and cold climates. In 2006 edition of the International Residential Code (IRC), Section R806.4, sentence 4 requires that unvented cathedralized attics be designed such that:

> "In Zones 3 through 8 as defined in Section N1101.2, sufficient insulation is installed to maintain the monthly average temperature of the condensing surface above 45°F (7°C). The condensing surface is defined as either the structural roof deck or the interior surface of an air-impermeable insulation applied in direct contact with the underside/interior of the structural roof deck. "Air-impermeable" is quantitatively defined by ASTM E 283. For calculation purposes, an interior temperature of 68°F (20°C) is assumed. The exterior temperature is assumed to be the monthly average outside temperature."

Under this code provision it is permissible to construct a UCA assembly using an air impermeable, low-density, open-cell sprayed polyurethane foam installed between framing members, directly on the underside of the roof deck. This concept has been used as the basis for an unvented cathedral ceiling assembly proposed for houses in the cold wet coastal climates of Seattle WA and Vancouver BC.

The proposed UCC roof assembly, illustrated in Figure 5.18, is insulated using a low-density, open-cell polyurethane foam insulation and comprises (from outside to inside):

- Asphalt shingles
- 12.5 mm (1/2 in.) COFI plywood sheathing
- 38 x 89 mm (2 x 4 in.) strapping @ 406mm (16 in.) O.C.
- 38 x 228 mm (2 x 10 in.) rafters @ 406mm (16 in.) O.C.
- 266 mm (10.5 in.) of low-density, open-cell sprayed polyurethane foam
- No polyethylene vapor barrier
- 12.5 mm (1/2 in.) drywall painted

The IRC code requirement does not make any reference to the provision or exclusion of a vapor barrier. Some designers and contractors maintain that it is not necessary while others question this contention, arguing that the relatively high permeance of the interior drywall and the low-density, open-cell polyurethane foam make the roof sheathing in this system prone to excessive moisture content accumulation during the winter season. The need for additional vapor control was a major part of the focus of the research project.

5.2.1 Objectives

The objectives of the Vancouver Test House project were to:

- Extend past research on the field performance of unvented cathedral ceiling roof assemblies from hot- and mixed-humid climates to a cold wet climate.
- Investigate the need for additional vapor control layers and determine if an assembly without these layers can safely accommodate the accumulation of moisture during the winter months and dry quickly enough during the summer months.

5.2.2 Approach

A foam insulation manufacturer arranged for the construction of a test house in Vancouver BC and secured the necessary approvals from the building department. The experimental program was developed to monitor the moisture performance of the UCC using a series of temperature, humidity, moisture content and weather sensors so that the direction of moisture movement, driving forces and amount of moisture stored in the assembly could be determined.

A moisture monitoring system was designed and installed during construction of the Vancouver test house. The system allows temperature, relative humidity (RH) and moisture content (MC) at to be measured at discrete locations on a 5 minute cycle. This method provides excellent temporal resolution, but is limited in spatial resolution; sensors only respond to conditions in their immediate vicinity so if they must be located near the action to return useful results.

The indoor RH and temperature are monitored on two floors of the house; however the indoor conditions are controlled by the occupants and not the monitoring system.

The outdoor RH and temperature are also measured, as are the solar radiation on a horizontal surface and the incidence of wetting (i.e. incidence of rain or dew) on the roof slope). Wind speed & direction and quantity of rainfall are not measured; instead this data was collected from a weather station at the University of British Columbia.

Industry experience has demonstrated that stick-built assemblies insulated with sprayed polyurethane foam insulation have higher levels of airtightness than conventionally constructed, batt insulated assemblies. No blower door test or sub assembly air tightness tests were conducted on the Vancouver test house. It was assumed that air leakage did not have any effect on the measured performance.

During the second fully occupied summer, a visit was made to the site to cut some openings in the assembly, conduct visual inspection of the plywood roof sheathing, make comparative measurements with hand-held meters and to collect samples of the painted drywall for permeance testing. It was not possible to collect samples of the plywood sheathing.

The permeance of the painted drywall samples was determined in the laboratory using ASTM E96 (dry cup method). Wet cup permeance tests were not conducted.

5.2.2.1 Setup

The moisture monitoring system for the Vancouver test house is based on the techniques and equipment proposed by Straube et al. (2002). Temperature (T) is measured using 10k NTC thermistors (accuracy +/- 0.2°C); relative humidity (RH) is measured using capacitive based sensors with onboard signal conditioning (accuracy +/- 3% between 10 & 90% RH); and moisture content (MC) is measured via in-situ electrical based resistance measurements between corrosion resistant insulated pins. Electrical resistance measurements were converted to %MC by weight, correcting for temperature and species using the Garrahan equation. The data acquisition equipment uses a 13 bit A/D with auto ranging (full scale of +/- 2.5 mV to +/- 2500 mV).

Moisture performance was measured at 4 locations on the south-facing roof slope and 4 locations on the north-facing roof slope as illustrated in Figure 5.16 and Figure 5.17 respectively. Two wall locations were also monitored on each of the north- and south-facing walls, although these are not discussed in this thesis.

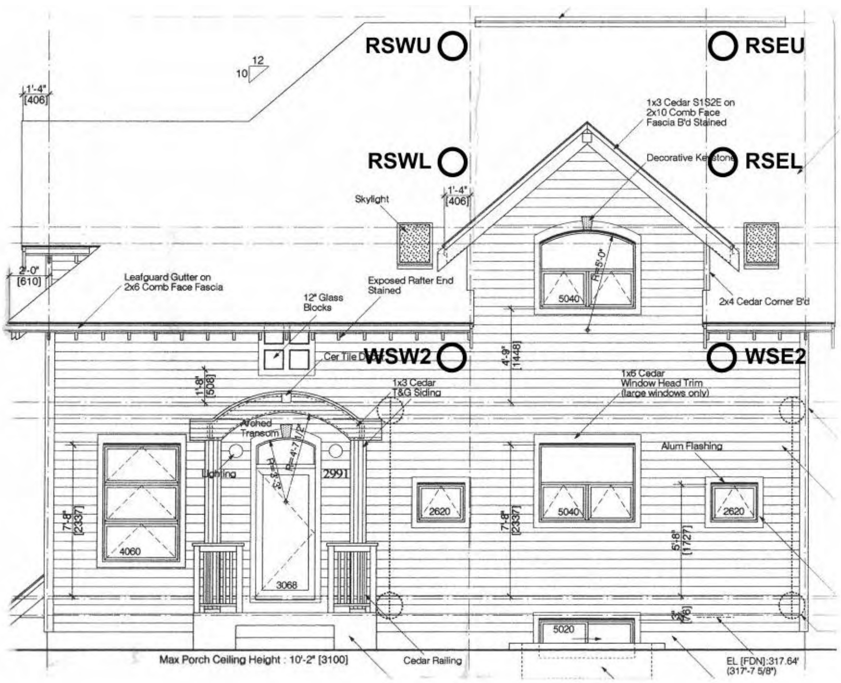


Figure 5.16 – Front (South) elevation of Vancouver test house showing monitoring locations

Figure 5.17 – Rear (North) elevation of Vancouver test house showing monitoring locations

Each monitoring location was given a unique name as an identifier (e.g. RSWU). The four characters of the identifier indicate whether it is a roof or wall location, the elevation, the lateral location and the vertical location. The identifier RSWU, for example, represents the Roof monitoring on the South face, at the West and Upper position.

On the south side of the house, the roof monitoring locations are in the storage room (RSWU & RSWL) and the hall (RSEU & RSEL), both on the attic (third) floor. On the north side, the monitoring locations are in the second floor landing (RNEU & RNEL) and in the seating area (RNWU & RNWL) on the attic floor. In all instances, the upper roof monitoring locations are 406 mm (16 in.) below the ridge line while the lower roof monitoring locations are 3.05 m (10 ft) below the ridge line.

In northern climates, the exterior sheathing moisture content is often used as the critical parameter for assessing the performance of roof assemblies that do not have vapor retarders. The MC& T of the sheathing are measured at all eight roof monitoring locations (the Basic Sensor Set). Additional measurements were made at the RNWU and RSWU locations (the Comprehensive Sensor Set): MC & T were measured near the interior edge of the rafter; RH & T were measured near the interior and exterior faces of the foam insulation. Figure 5.19 illustrates the layout of the comprehensive sensor set installed at the UCC roof assembly.

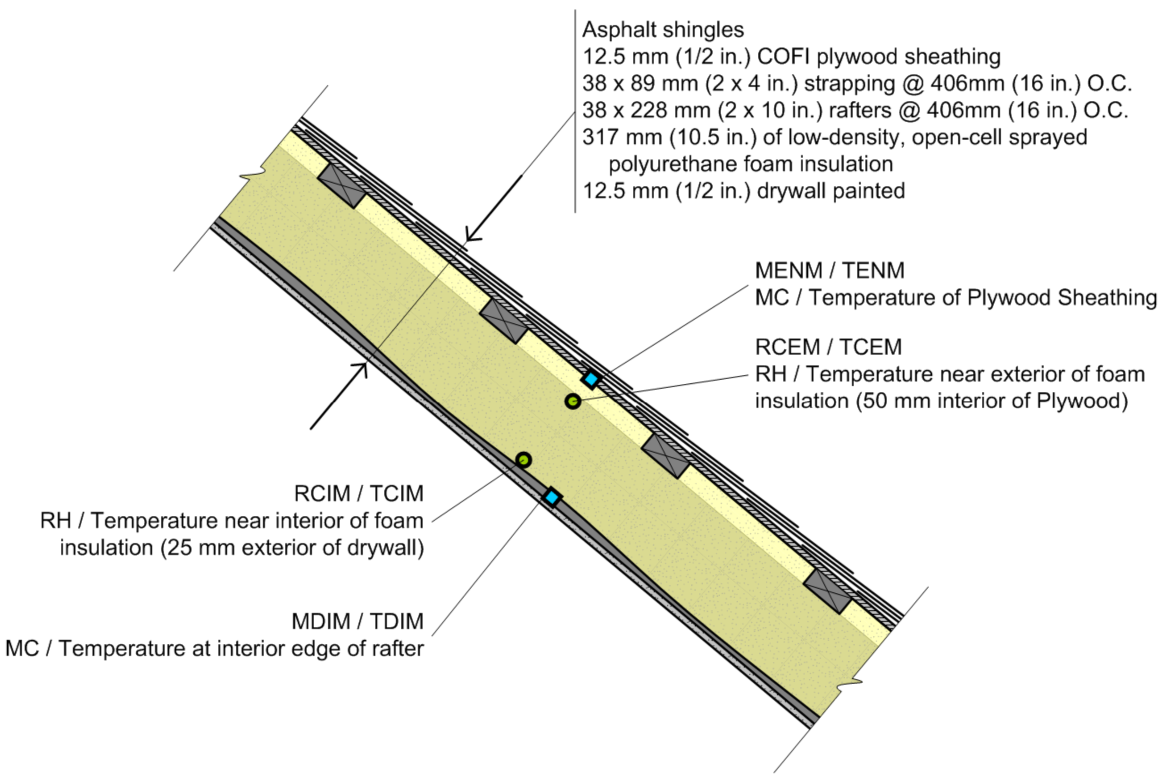


Figure 5.18 – Layout of comprehensive sensor set

Figure 5 shows a photo of the sensors installed in the rafter bay at monitoring location RNWU. The rafters can be seen resting on the top of a load bearing wall. A 38 x 89 mm (2 x 4 in.) piece of strapping can be seen just above the whiteboard. The two RH/T sensor sets are packaged in a Tyvek® case to protect them from liquid water and the form insulation. They can be seen suspended on taught wires mounted at the appropriate depth in the rafter space. The low-density open-cell polyurethane foam easily envelopes these packages when it is spray applied.

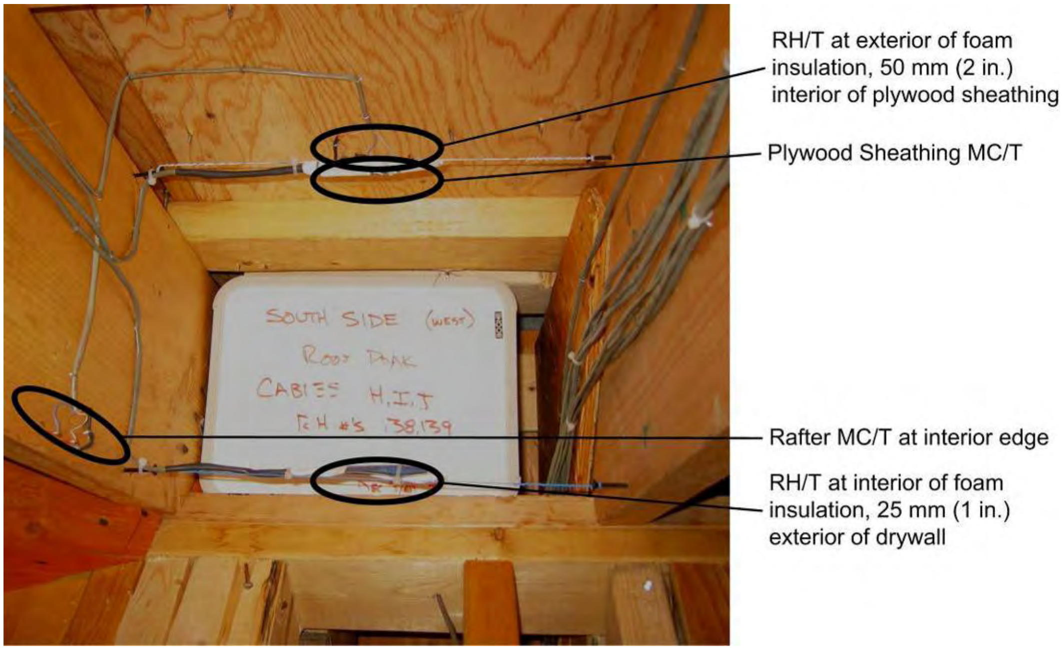


Figure 5.19 – Comprehensive sensor set, north-facing roof at west end, upper location

The MC/T pins are installed so the active tip is 1/8in. (3mm) below the surface of the plywood and framing. An MC/T pair was installed at the inside edge of the rafter to measure for any increase in moisture content associated with redistribution of moisture from the sheathing in the early summer.

5.2.3 Results and Analysis

Figure 5.20 shows the hourly outdoor temperature (orange trace) and RH (blue trace) recorded over the first two years of the monitoring program. The 3 black traces indicate the maximum, normal and minimum daily average temperatures from the 1971-2000 Canadian Climate Normals. For the most part the 2006-2007 outdoor temperatures have been higher than suggested by the 30 year climate normals.

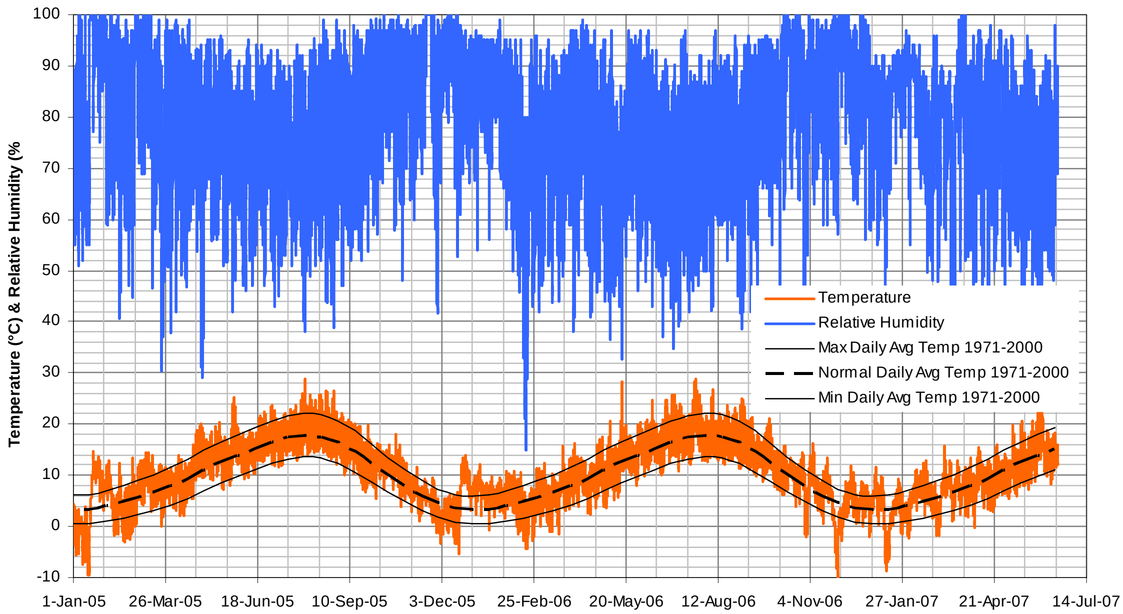


Figure 5.20 – Vancouver outdoor temperature and relative humidity

Figure 5.21 shows the hourly indoor temperature (2 orange traces), RH (2 blue traces) and dewpoint (2 green traces) recorded at two locations in the house: location 1 (darker traces) is on the 3rd floor, in a sitting area next to the logging room while location 2 (lighter traces) is on the 2nd floor in the hallway outside the master bedroom. The house is heated with radiant floors and year round ventilation is provided by an HRV. A small ductless split provides air-conditioning for only the master bedroom and dressing room.

As warm air rises the temperatures and moisture levels are slightly higher at location 1 (on the topmost floor) during the summer months. Little difference can be seen between the conditions at the two monitoring locations during the winter months.

It is likely that construction moisture was still drying out in the first winter. This process would be accelerated by ventilating the house with dryer (winter) outdoor air, however the homeowner did not understand how to properly operate the heat recovery ventilation (HRV) system and did not switch it to ‘Winter’ mode until December of 2005. This switch was made in October of 2006 so the unit ran at a higher ventilation rate for all of the second winter, and as a result, indoor temperatures were slightly cooler and RH levels at both locations were noticeably lower during the second winter. The dewpoint temperatures were further analyzed for the periods indicated by the two black squares (Nov 1st through February 28th of each winter).

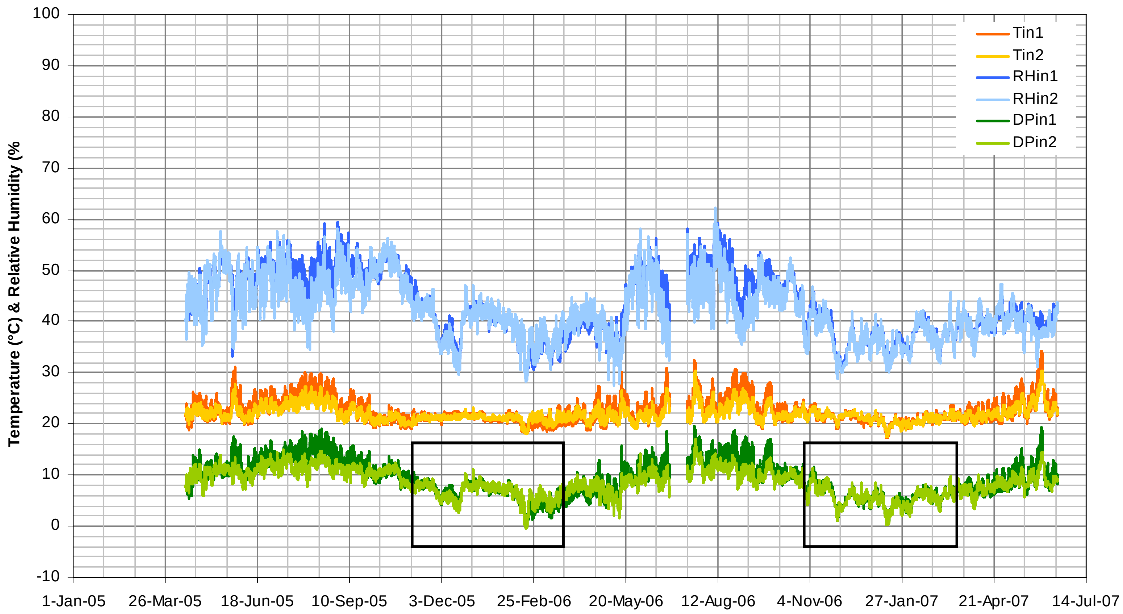


Figure 5.21 – Indoor temperature, relative humidity and dewpoint

Figure 5.22 shows the distribution of the outdoor and indoor dewpoint temperatures for the 17134 hours between Nov 1st through Mar 31st of the 2005-06 and 2006-07 winters. There was little difference between the outdoor conditions in the first winter (06) and those in the second winter (07). Conversely, the indoor dewpoint temperatures were noticeably lower the second winter. During the first winter the interior dewpoint exceeded 7°C for roughly 41% of the hours while this threshold was exceeded fewer than 17% of the hours the second winter.

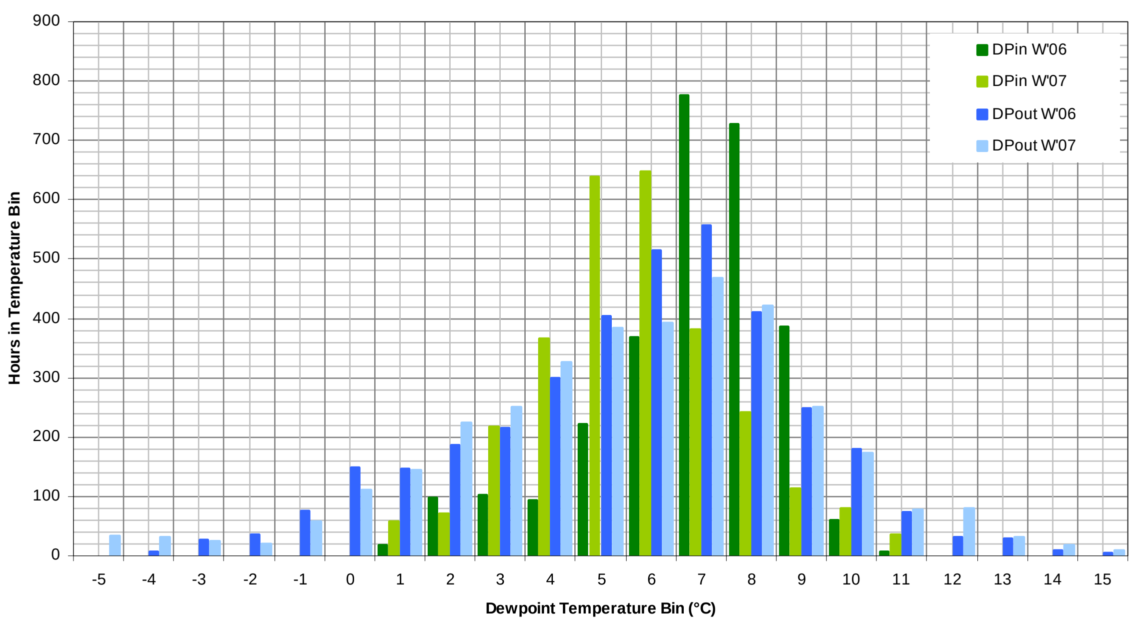


Figure 5.22 – Indoor and outdoor dewpoint temperature distribution

Figure 5.23 shows the daily average roof sheathing temperatures measured at East end of the house on the North-facing (blue traces) and South-facing roofs (orange traces). As expected, the South-facing roof experiences warmer temperatures than the North-facing. The 10/12 pitch of the roof is steep enough to allow the South-facing slope to capture the small amount of sunlight that is available in the winter so that it is remains slightly warmer than the North-facing, even during the winter.

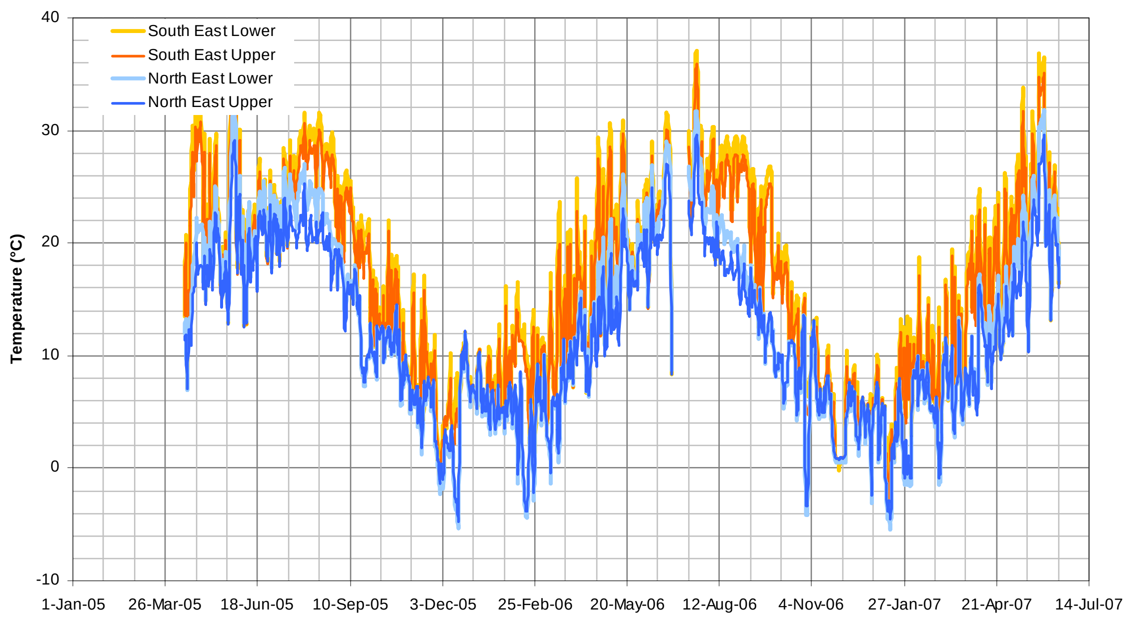


Figure 5.23 – Daily average roof sheathing temperature

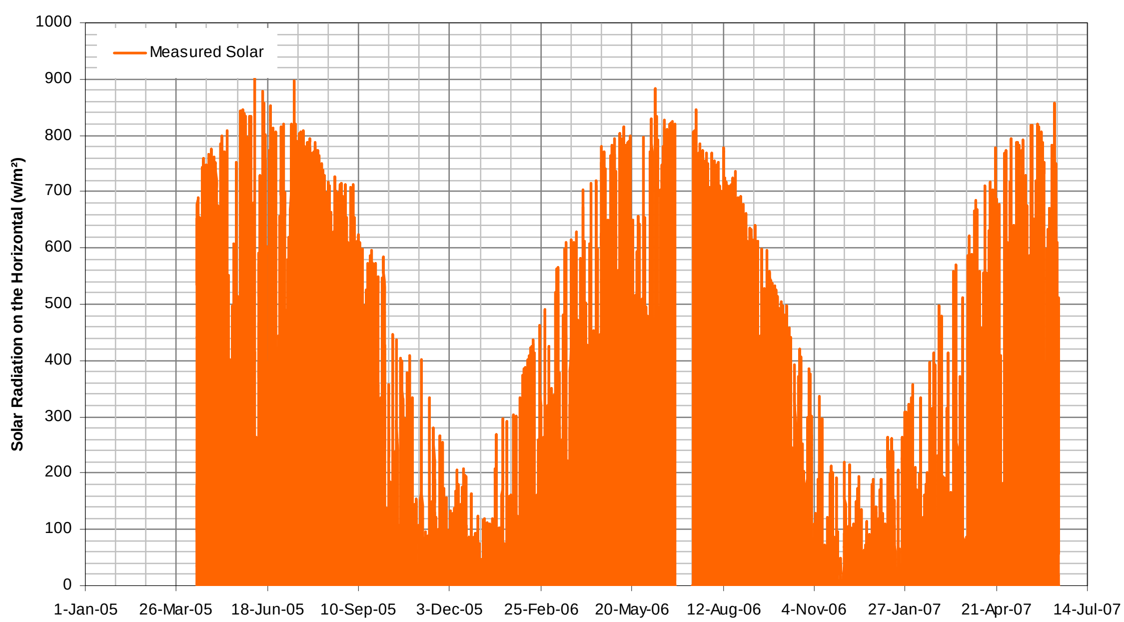


Figure 5.24 – Vancouver solar radiation on the horizontal

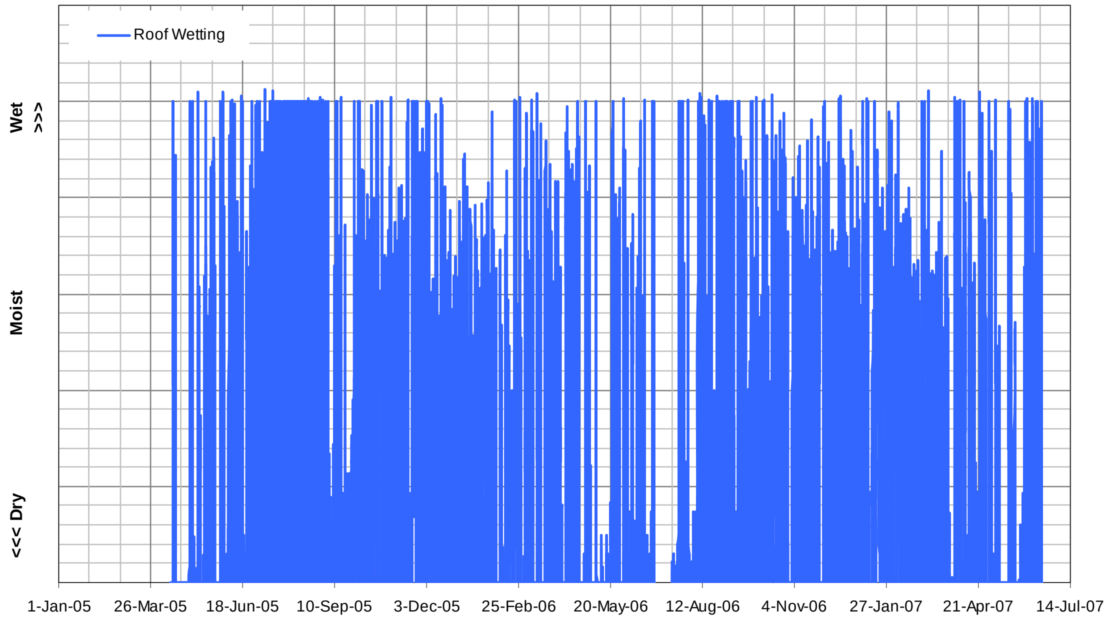


Figure 5.25 – Occurrence of condensation on surface of shingles

Figure 5.26 shows the distribution of the roof sheathing temperatures measured over the course of the monitoring (May 1st 2005 through May 1st 2007). Maximum roof sheathing temperatures are approximately 80°C and 50°C for the South- and North-facing roofs. The South-facing roof sheathing experiences roughly 2000 hrs/yr at temperatures over 20°C while the North-facing roof sees only 1500 hrs.

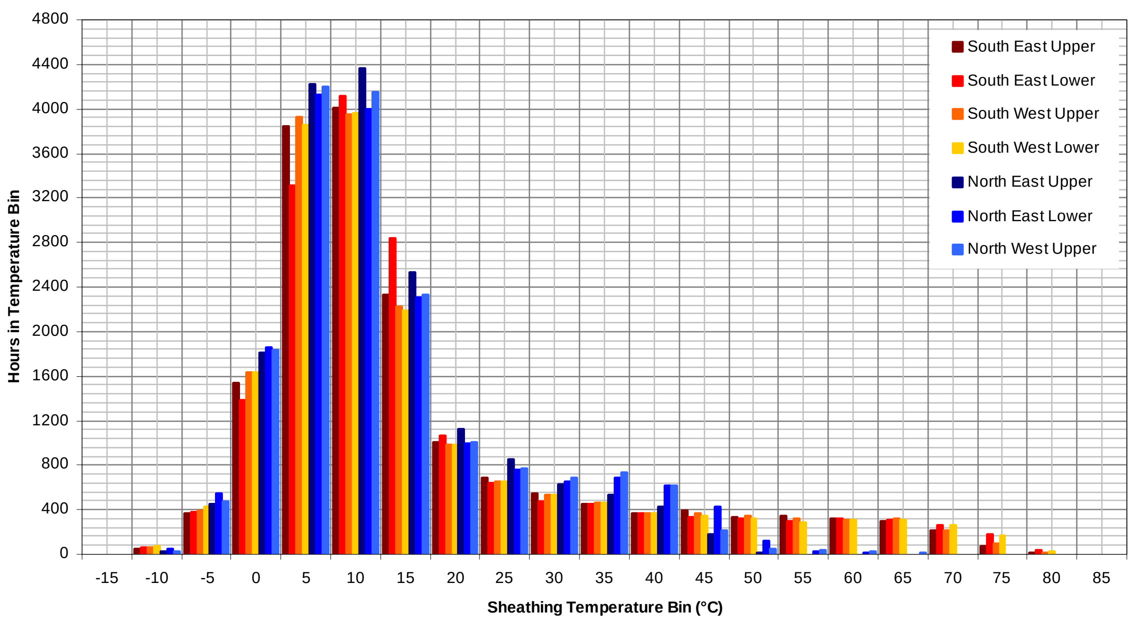


Figure 5.26 – Roof sheathing temperature distribution

Figure 5.27 shows the daily average roof sheathing moisture content (MC) measured at the North-facing (blue traces) and South-facing (orange traces) over the two year monitoring period. Portions of three winters can be seen on the graph.

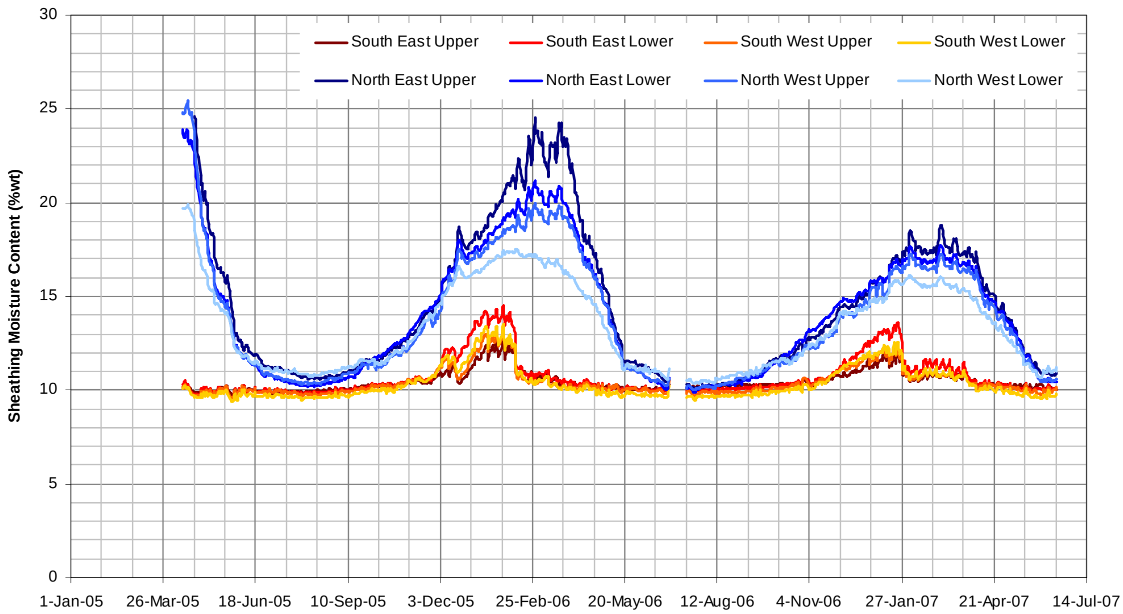


Figure 5.27 – Daily average roof sheathing MC (corrected for temperature & species)

The North-facing measurement locations show initial high MC readings (e.g. in the range of 20-25% MC) as a result of high indoor moisture levels associated with the finish work (i.e. drywall mud, painting, cleaning, etc.) completed January through March of 2005. This effect could barely be seen on the South-facing roof which had dried significantly by the time the monitoring system began recording data.

The following winter (i.e. 2005-06, the first fully occupied winter) the sheathing MC at the North-facing locations increased by 7-14% to the high teens and low twenties while the sheathing MC at the South-facing locations only increased 2-4% to the low teens. The South-facing roof appears to dry quickly by mid February while the North-facing roof appears to increase in MC until the end of February and then dry down during mid March through mid May. Since the indoor conditions are similar for all monitoring locations, it is hypothesized that the increased solar exposure and average daily temperatures on the South-facing roof play a significant role in reducing the magnitude of the MC increase and accelerating the drying.

In the third winter (i.e. 2006-07, the second fully occupied winter) indoor moisture levels were lower and the increase in MC is not as significant. The sheathing MC at the North-facing monitoring locations increased 5-7% to the mid to high teens while the sheathing MC at the South-facing locations increased by 1.5-3%. Since the outdoor conditions were not significantly different from the previous year, it is hypothesized that the reduced interior dewpoint play a significant role in the lower levels of moisture accumulation in the sheathing.

5.2.3.1 Field Visit

Some concern was raised over the elevated MC levels measured on the North-facing roof. A visit was made to the test house in early June 2006 (i.e. the second fully occupied summer) to make a visual inspection of the plywood roof sheathing. Roof test cuts were made through the drywall and the foam insulation at locations near RNEL, RNWL and RSWL. A plywood jig was used to cut a 150 mm (6 in.) diameter centerless core through the drywall so the finished drywall sample could later be used for permeance testing. These samples were sealed in plastic bags and placed in a wooden box to protect the painted surfaces from damage during shipping.

A 75 x 75 mm (3 x 3 in.) square hole was then cut through the depth of the foam insulation to expose the interior face of the plywood roof sheathing as seen in Figure 5.28. None of the test cuts showed any signs of mould or decay, the interior surface of the plywood was clean and the material resisted penetration of a pocket knife just as new plywood sheathing would.

Figure 5.28 – Jig & core through drywall (left) and foam cut to interior face of plywood (right)

The test cuts confirmed that there was good continuity of the sprayed foam insulation and a tight bond between it and the roof sheathing / furring, supporting the assumption that air leakage had no effect on the hygrothermal performance of the monitored roof assembly.

5.2.3.2 Vapor Permeance of Painted Drywall

The vapor permeance of the finished drywall samples was determined (using the ASTM-E96 dry cup method) to be approximately 450 ng/Pa s m² (8 US Perms) for samples finished with 2 coats latex paint and 1500 ng/Pa s m² (30 US Perms) for samples finished with a knock-down coating (‘California Ceiling’). Both of these values were significantly higher than expected.

Numerous vapor retarding primers are available that have a demonstrated permeance in the range of 35 to 57 ng/Pa s m² (0.6 to 1 US Perms), 10 to 30 times lower than measured. It is hypothesized that the use of these primers will significantly reduce the diffusion through the assembly so that the winter time moisture content of the North-facing roof sheathing does not exceed 20%.

5.2.4 Conclusions & Recommendations

The monitored data suggests that increased solar exposure and temperature dramatically affect the rate at which the roof sheathing dries in the summer and accumulates moisture in the winter. Construction moisture dried faster on the South-facing roof slope than the North- although both dried to approximately 10-12% MC by weight. During the first winter the moisture content of the North-facing roof sheathing rose to 17-24% MC by weight while the moisture content of the warmer South-facing sheathing only rose to 12-14%.

Outdoor conditions were similar the second winter, but the indoor dew point temperature was maintained at a lower level by the ventilation system. The increase in sheathing moisture content during the second winter was lower with the North- and South-facing roof sheathing reaching 15-17% MC and 11-13% MC respectively. This demonstrates the influence of indoor humidity levels on the moisture performance of insulated, sloped wood-framed roof assemblies.

Through inspection openings the foam insulation was observed to have good continuity (i.e. minimal voids) and strong adhesion to the sheathing and furring. None of the test cuts showed any signs of mold or decay and the interior surface of the plywood appeared clean and sound.

ASTM E96 tests on samples collected from the test house revealed that the permeance of the finished drywall was several times higher than expected. If indoor humidity levels cannot be sufficiently controlled, it is recommended that a vapor retarding paint be used in unvented roof assemblies in the Northwest. Modeling should be conducted to establish the vapor permeance required reduce to winter time vapor diffusion so that the moisture content of the North-facing roof sheathing does not exceed 20%.

5.3 Coquitlam BC Test Hut

The Coquitlam BC test hut offered an opportunity for further research on the hygrothermal performance of roof assemblies in cold wet climates. Controlled side-by-side monitoring was performed on a conventional ventilated attic roof assembly and two unvented cathedralized attic roof assemblies in a full-scale environmental field-testing facility.

5.3.1 Objectives

The objectives of the Coquitlam test hut project were to:

- Demonstrate the performance of unventilated cathedralized attic roof assemblies (using vapor permeable insulation) in direct comparison with a conventional ventilated attic roof assembly.
- Examine the effects of applying a modest vapor control coating to the surface of the vapor permeable low-density oc-foam insulation in an unvented UCA roof assembly.

5.3.2 Approach

An 84 m^2 (900 sq. ft.) field exposure test facility was designed and constructed in the Coquitlam suburb of lower mainland BC. The facility, illustrated in Figure 5.29 through Figure 5.31, permits the side by side construction and comparison of seven 1.2 x 2.4 m (4 x 8 ft) test wall panels on each cardinal orientation (for a total of 28 wall test panels) and three 1.8 x 4.8 m (6 x 16 ft) roof panels on the north and south facing roof slopes (for a total of 6 roof test panels). The roof test panels are the focus of this section of the thesis.

The design of the building is such that the interior of each test panel is exposed to the same conditions. The roof test panel structure consists of trusses installed on 600 mm (24 in) centers as illustrated in Figure 5.31. Roof test panels are isolated from one another using 50 mm (2 in) of foil-faced polyisocyanurate with taped and caulked joints to prevent the movement of heat, air and moisture from one panel to the next. Air is allowed to move between the north and south ends of the attic in each test panel (i.e. Roof North 1 and Roof South 1 share a common attic). A buffer panel is located on either end of the test hut to ensure roof panels have as uniform an exposure as possible.

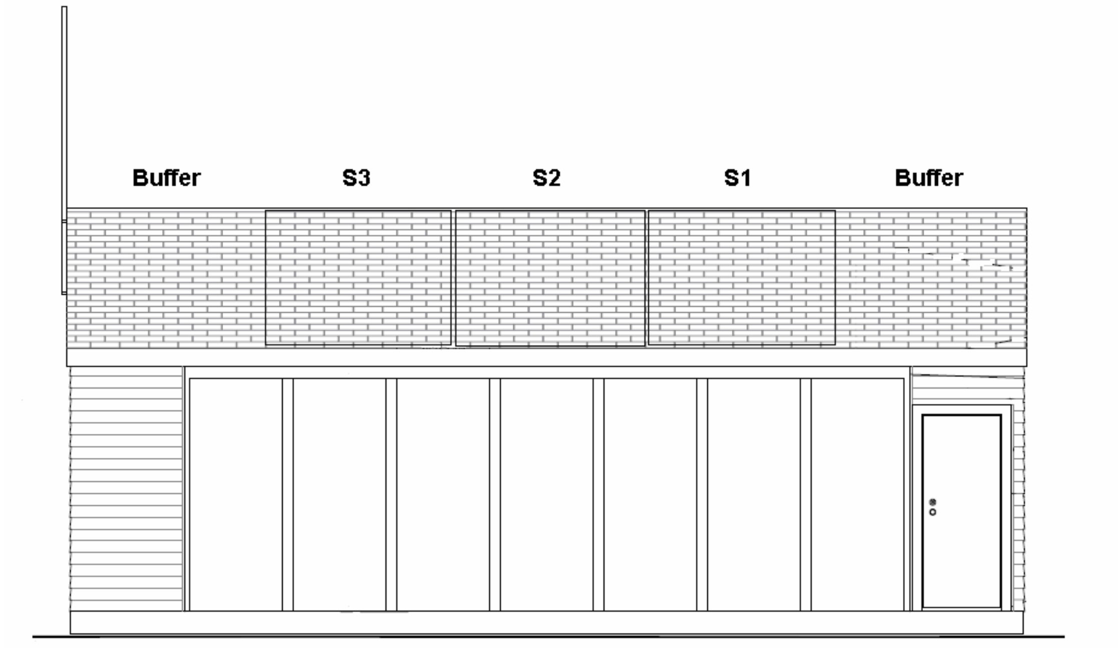


Figure 5.29 – Coquitlam test hut: South elevation (North similar)

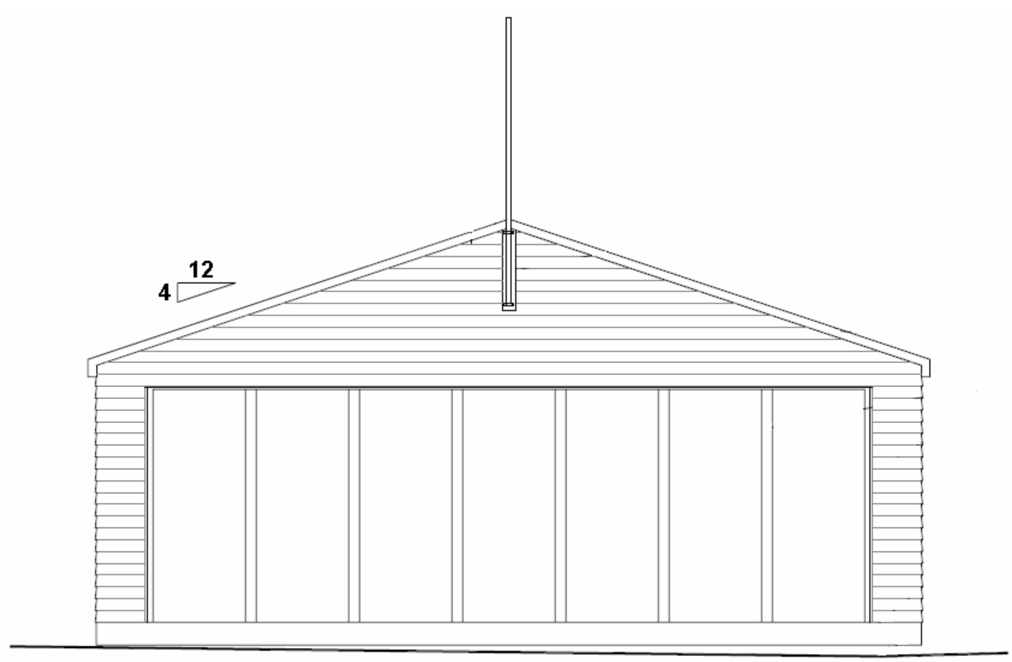


Figure 5.30 – Coquitlam test hut: East elevation (West similar)

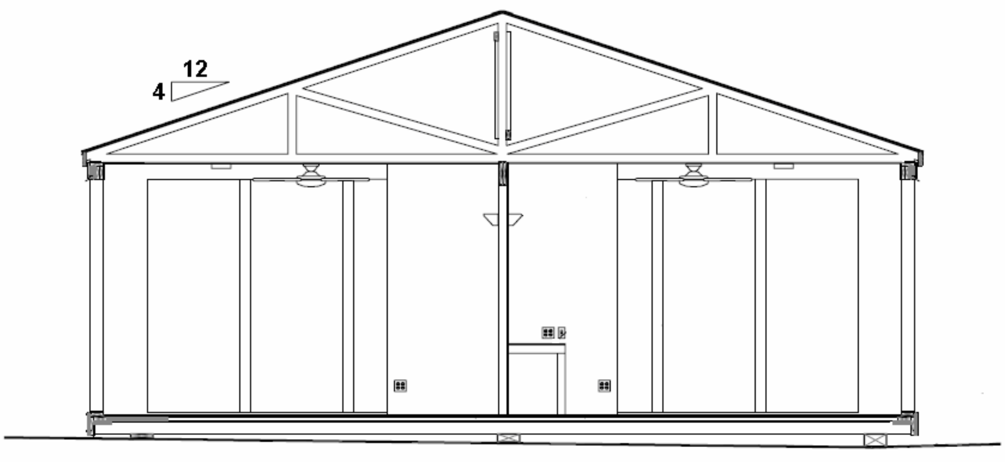


Figure 5.31 – Coquitlam test hut: Cross section

The test facility was constructed on the roof of a low rise office building. The rooftop location of the test hut results in higher wind exposure than that of a normal house, however it is similar to a 3 or 4 storey walkup. Rooftop equipment and steps in the flat roof height might also influence the solar exposure and night sky view of the walls on the west side of the hut, although these are not likely to impact the roof panels.

Figure 5.32 –Coquitlam test hut as seen from the elevated roof on the west side

A 650 channel monitoring and control system measures and records weather conditions and the hygrothermal performance of the test panels. The system, pictured in Figure 5.33, also controls interior temperature and humidity conditions. Data collection is facilitated through an internet connection that permits the data to be viewed from abroad.

Figure 5.33 – One of two logging and control modules that make up the monitoring system

A steel mast on the east end of the facility's roof supports a weather station at height of 22 ft above the roof of the office building and 50 ft above ground level. The monitoring system continuously collects weather data including:

- Outdoor temperature and relative humidity
- Solar radiation on the horizontal
- Solar radiation on each wall orientation
- Wind speed and direction
- Rainfall
- Driving rain on the east and south orientations

Figure 5.34 – Weather station

The monitoring system also measures the indoor temperature and humidity and an instrumentation package in each test panel. The instrumentation package varies from panel to panel depending on construction and includes 16 to 20 sensors to monitor moisture content, temperature, and relative humidity at multiple locations in the test panel assembly. The sensors are measured every 5 minutes and the average saved to memory every hour. Further details about the sensor package are provided in the following section.

5.3.2.1 Research Program

Table 5.1 summarizes the composition of the three roof panels that were constructed, instrumented and monitored as part of the research for this thesis. The ventilated attic roof assemblies (Roof Panels S1 & N1) are representative of most modern insulated, sloped, wood-framed roof assemblies constructed in the lower mainland of BC. Roof panels S1 and N1 were outfitted with a slot vent at the soffit, ventilation chutes and a mushroom vents near the ridge. The ventilation area was designed to meet the building code 1:300 requirement. These roof assemblies are intended to serve as the datum to which the hygrothermal performance of the other panels will be compared.

Table 5.1 – Roof test panel composition for Coquitlam test hut

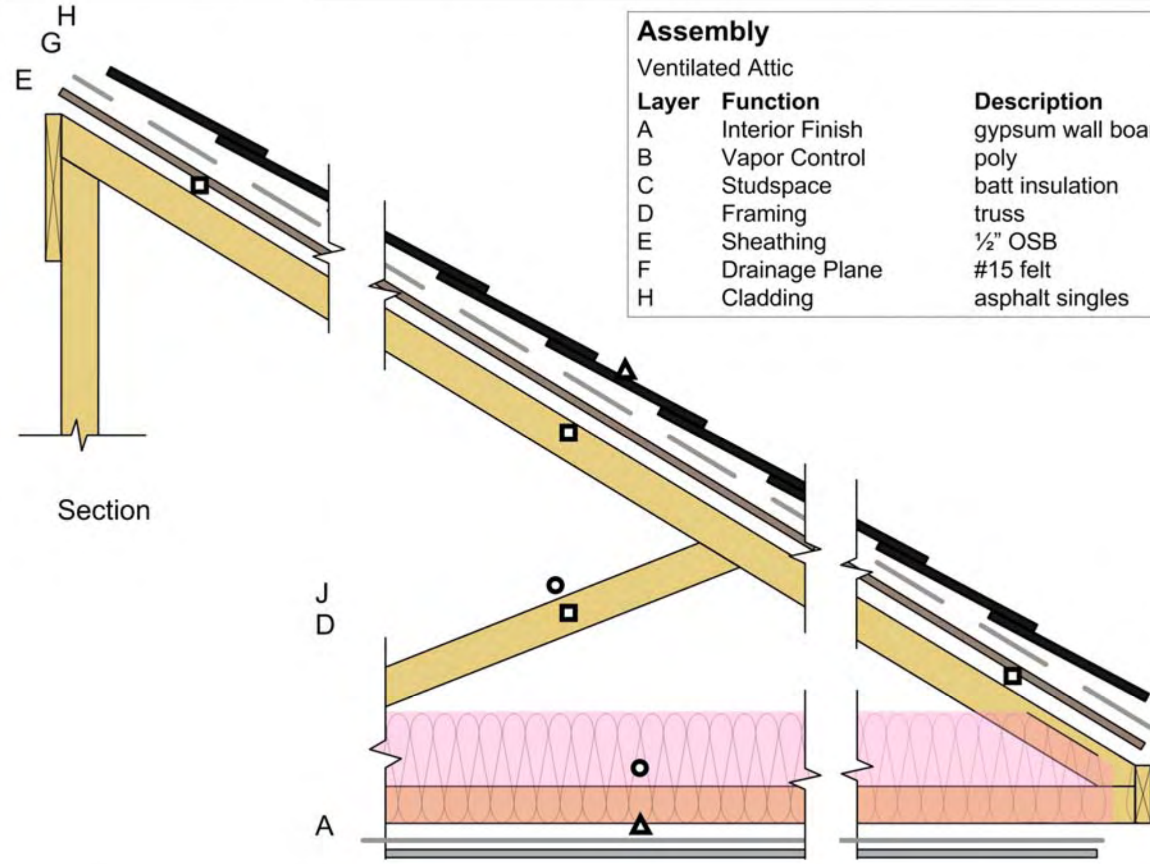
No.	Roof Panel	Cladding	Ventilation	Underlayment	Shthg	Frame	Insulation	Vapor Control	Finish
1	S1/N1	Asphalt Shingle	ventilated attic	30 min bldg paper	OSB	2x4 truss	Fiberglass Batt	poly	GWB
2	S2/N2	Asphalt Shingle	none	30 min bldg paper	OSB	2x4 truss	0.5 pcf oc-SPF	paint	GWB
3	S3/N3	Asphalt Shingle	none	30 min bldg paper	OSB	2x4 truss	0.5 pcf oc-SPF	none	GWB

Roof panels S3 and N3 are representative of one of the most common unvented cathedralized attic assemblies. Low-density open-cell sprayed polyurethane foam applied directly to the underside of the OSB roof sheathing, as pictured in Figure 5.35, serves as insulation and air barrier. Open-cell SPF is however not a vapor retarder and hence the diffusion-related performance of the assembly is of special interest. Roof panels S2 and N2 are the same as S3 and N3 with the addition of 2 heavy coats of latex paint, which was spray applied to the inside surface of the foam to examine the effect of modest vapor control on the performance of UCA roof assemblies in marine climates.

Figure 5.35 – Low-density oc-SPF and cathedralized attic inside of Roof Panel S2

The construction and sensor layout of the three pairs of roof panels are presented in Figure 5.36 through Figure 5.38.

North/South 1 | Shingles, Ventilated Attic, ½" OSB, Batt insulation, Poly



Assembly

Ventilated Attic

Layer	Function	Description
A	Interior Finish	gypsum wall board
B	Vapor Control	poly
C	Studspace	batt insulation
D	Framing	truss
E	Sheathing	½" OSB
F	Drainage Plane	#15 felt
H	Cladding	asphalt singles

Sensor Package

Layer	Code	Location
A	taem	Interior finish, exterior face, mid panel
C	r/tcnm	Batt insulation, interstitial
D	m/tdnm	Framing truss, interstitial
D	m/tdem	Framing truss, exterior edge
E	m/tenu	Sheathing, interstitial, 16" from top plate
E	m/tenl	Sheathing, interstitial, 16" from bottom plate
H	them	Cladding, exterior surface, mid panel
J	r/tjnm	Attic airspace, interstitial, mid panel

- ○ Relative Humidity and Temperature Sensor Package
- □ Moisture Content Pins and Temperature Sensor Package
- △ Temperature Sensor
- ⧅ Moisture Content Wafer and Temperature Sensor Package
- = Moisture Content Pins

Figure 5.36 – Test Roof 1: Conventional Ventilated Attic, construction and sensor layout

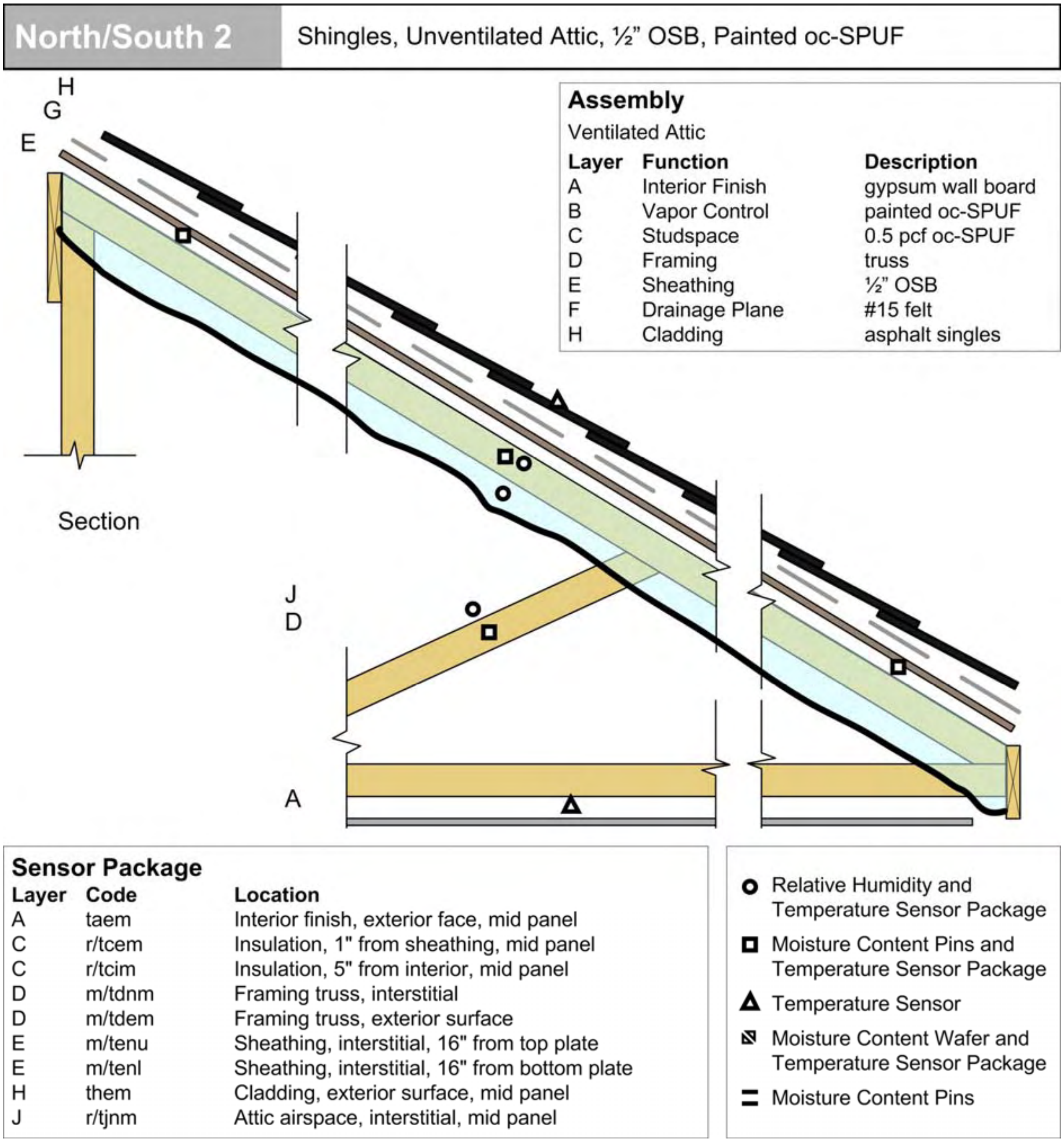


Figure 5.37 – Test Roof 2: UCA with painted foam, construction and sensor layout

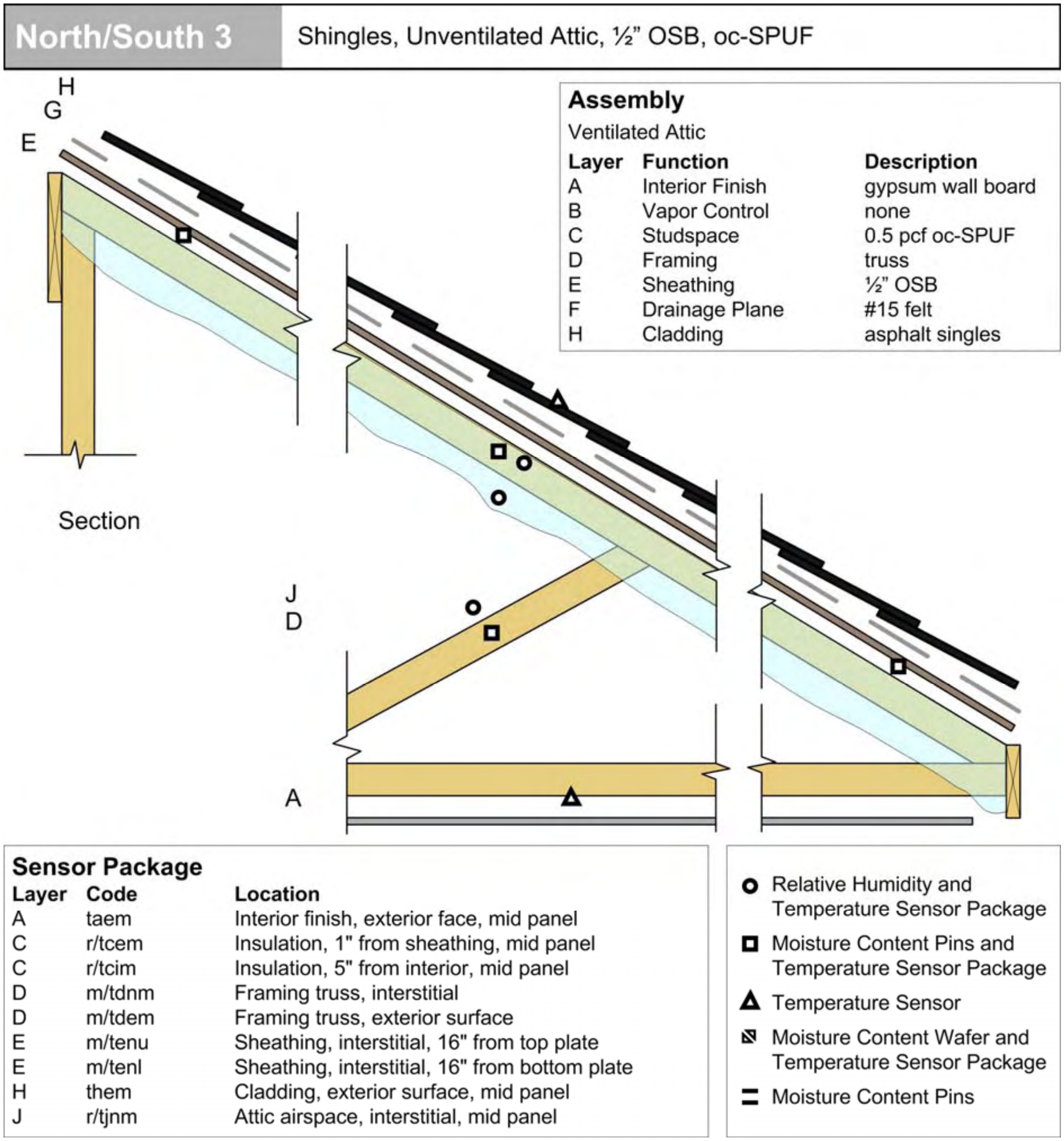


Figure 5.38 – Test Roof 3: UCA with plain foam, construction and sensor layout

Sheathing moisture content and attic relative humidity are the two primary variables for assessing the hygrothermal performance of the roof assemblies. Moisture content pins were installed 400 mm (16 in) from the peak and heal of the truss, near the top and bottom of the roof panel. This positioning placed the lower moisture content pins directly in front of ventilation chutes in Roof panels S1 & N1 as seen in Figure 5.39. Relative humidity and temperature sensors were suspended in the attic space of each panel. One additional RH and temperature sensor was installed in the middle of the batt insulation in roof panels S1 and N1. Two additional RH and temperature sensors were installed in the foam insulation of roof panels S2, S3, N2 and N3. These were suspend approximately 25 mm (1 in) and 125 mm (5 in) from the inside of the roof sheathing using a method similar to that described in the Vancouver test house project section.

Figure 5.39 – Moisture content pins and sheathing temperature at ventilation chute

5.3.3 Results and Analysis

Figure 5.40 shows the hourly outdoor temperature (orange trace) and RH (blue trace) recorded by the Coquitlam test hut weather station since commissioning in the fall of 2005. The 3 black traces indicate the maximum, normal and minimum daily average temperatures from the 1971-2000 Canadian Climate Normals. The outdoor temperatures recorded during the summers of 2006 and 2007 appear slightly higher than suggested by the 30 year climate normals. This trend was also noted in the data collected at the Vancouver test house over the same period.

Figure 5.41 shows the hourly indoor temperature and RH. In the summer of 2006 no effort was made to control indoor temperature and relative humidity levels. In the summer of 2007 the ventilation system was operated to keep indoor temperatures close to 21°C and relative humidity levels close to 50%. The intent was to emulate the operation of a typical non-air-conditioned Vancouver residence.

Recorded wind speed and direction are presented in Figure 5.42. The average hourly wind speed was less than 2 m/s while the majority of hours had average wind speeds of less than 4 m/s.

Figure 5.43 shows the hourly average solar radiation measured on a horizontal surface. Note the difference between the amount of radiation received in the summer months relative to that received in the winter months. The influence of the solar energy is evident in the moisture performance of the roof test panels presented later in this section.

The hourly rainfall is presented in Figure 5.44. Most of the rainfall is received in the fall and winter months. While it rains frequently in Vancouver the majority of the rainfall events have intensities of less than 5 mm/hr.

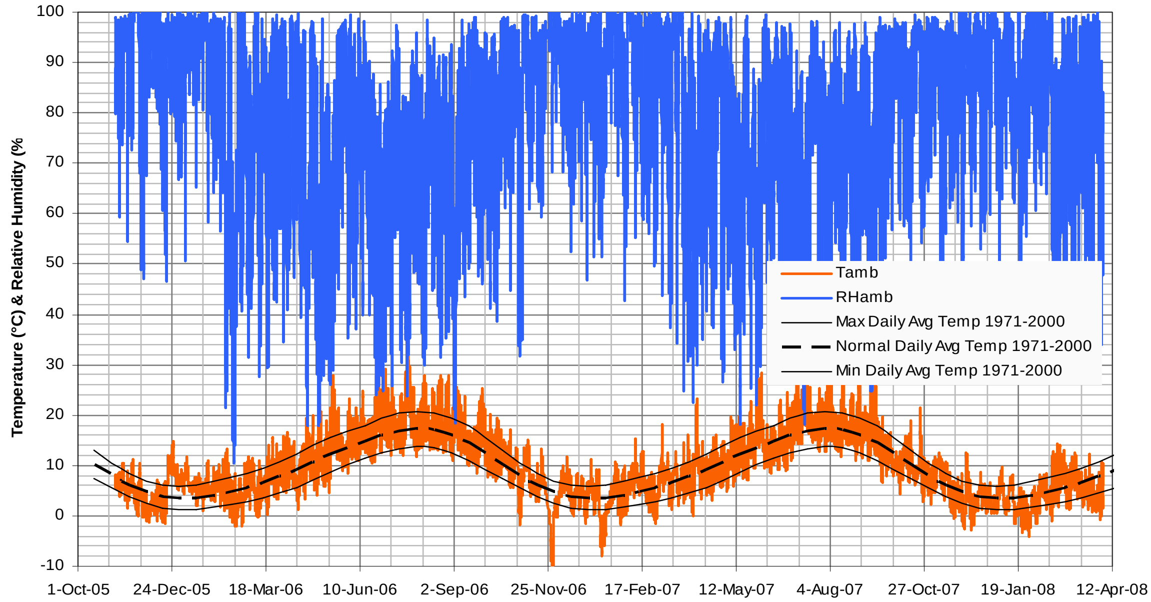


Figure 5.40 – Coquitlam outdoor temperature and relative humidity

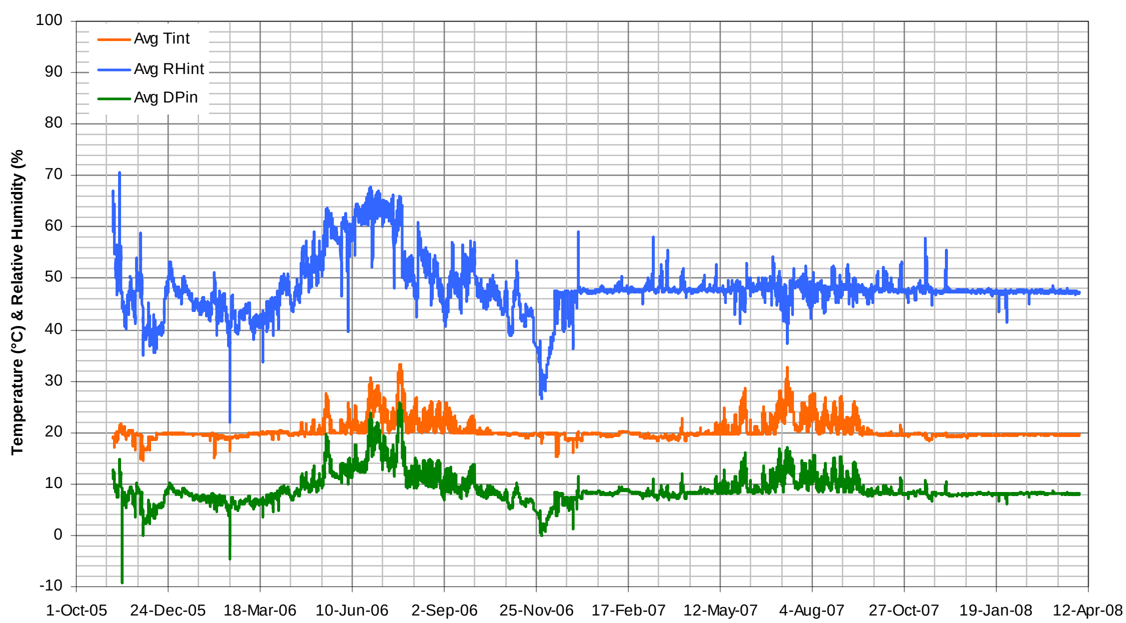


Figure 5.41 – Indoor temperature, relative humidity and dewpoint

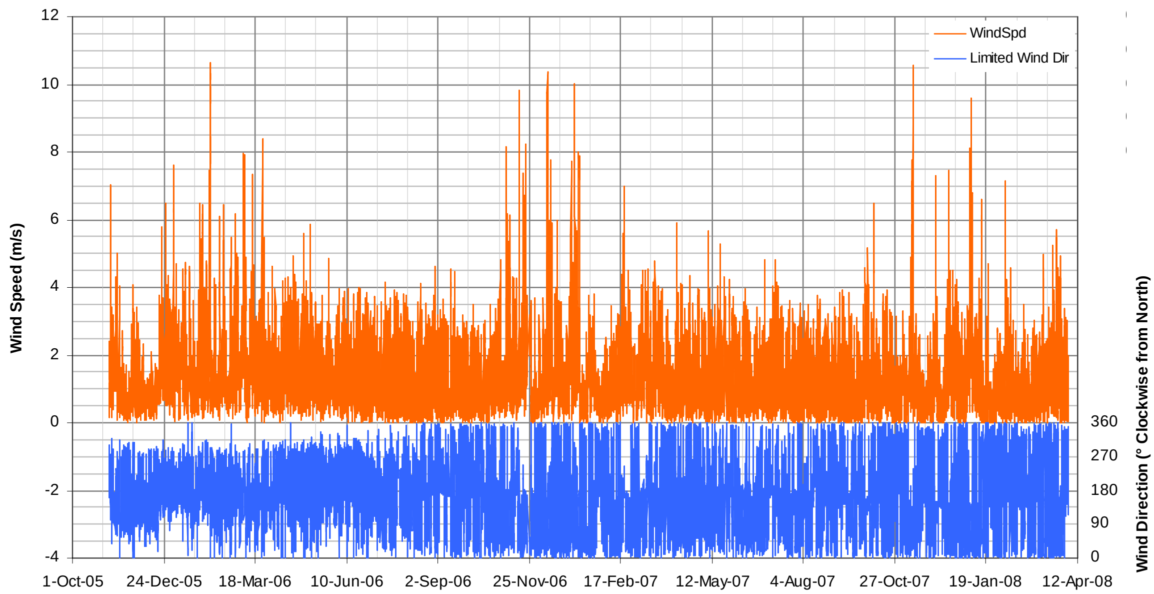


Figure 5.42 – Coquitlam wind speed and direction

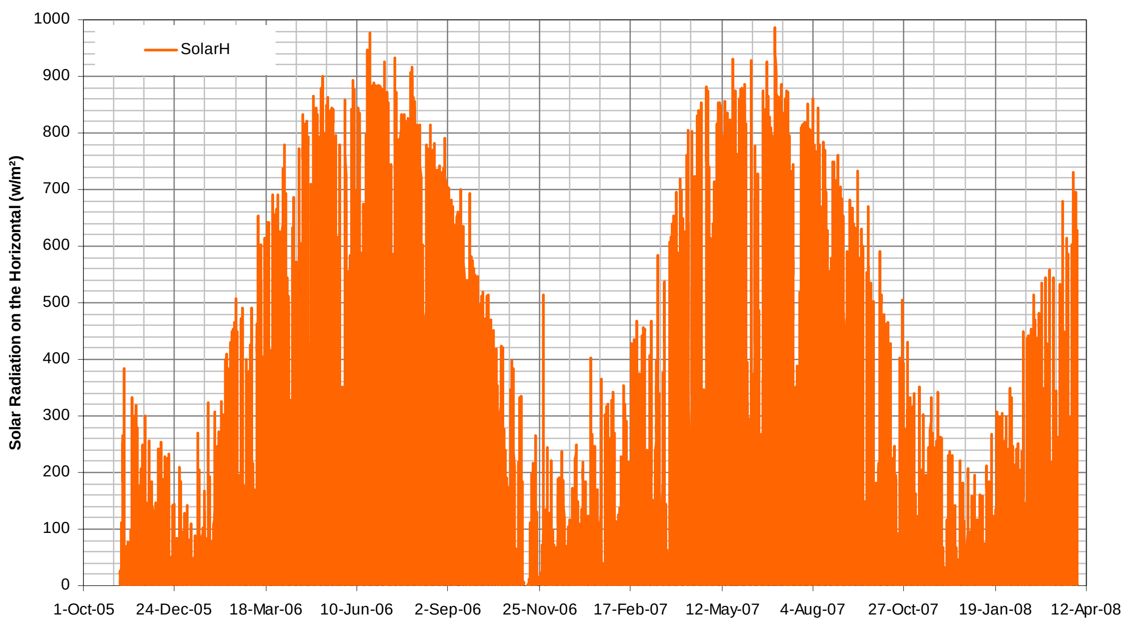


Figure 5.43 – Coquitlam solar radiation on the horizontal

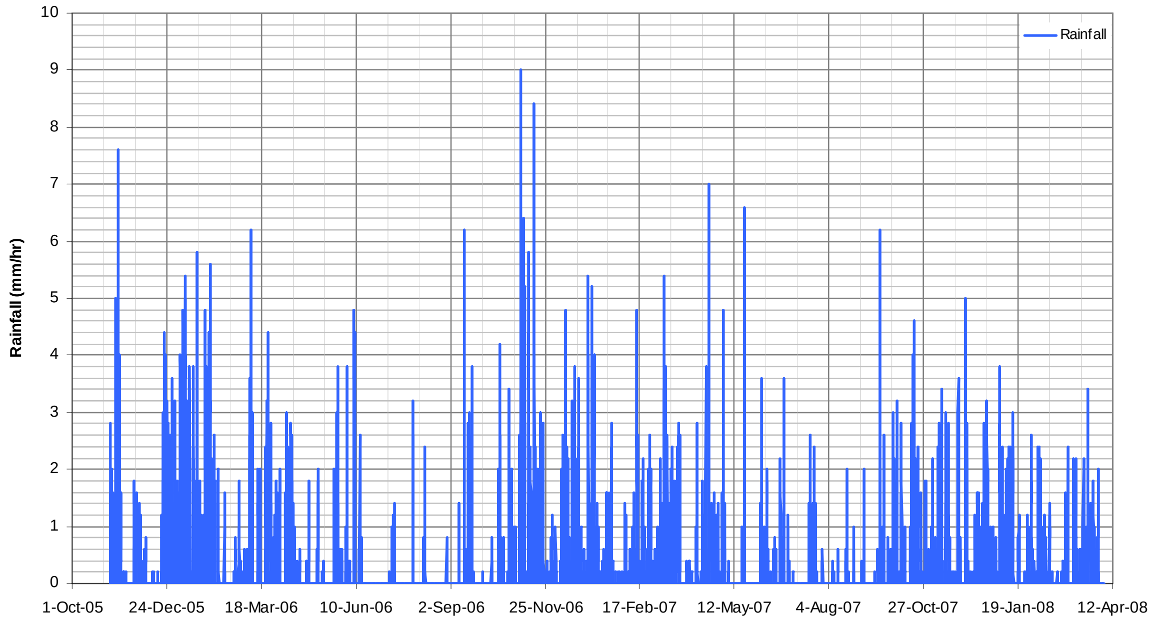


Figure 5.44 - Coquitlam hourly rainfall

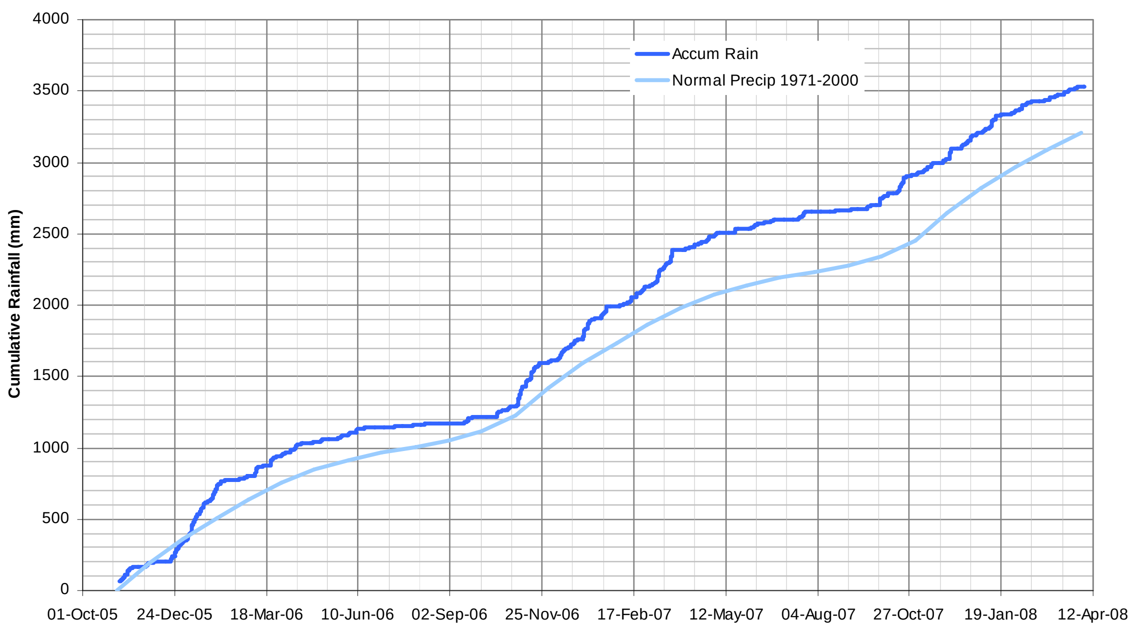


Figure 5.45 – Coquitlam accumulated rainfall

Figure 5.46 and Figure 5.47 show the relative humidity measured on the north and south sides of the ventilated attic space that is enclosed by roof panels N1 and S1. In these plots the light blue trace represents the measured average daily outdoor relative humidity while the dark blue trace represents measured average daily relative humidity in the attic. During the summer months the relative humidity in the attic space is 10 to 20% lower than outside because the incident solar radiation heats the roof assembly resulting in higher attic temperatures and lower RH. During the winter months there is less solar radiation so the temperature and relative humidity in the attic are closer to the outdoor temperature and relative humidity. Winter time daily average attic relative humidity levels were always greater than 80% and often exceeded 90%. As the attic relative humidity approaches 100% the potential for condensation on the underside of the roof sheathing increases. Even when condensation does not occur, the moisture content of the roof sheathing will tend to seek equilibrium with the relative humidity of the air next to it as described in section 4.2.3. If the attic relative humidity is greater than approximately 90% for a sufficient amount of time, the roof sheathing can reach equilibrium moisture contents in excess of 20% by weight.

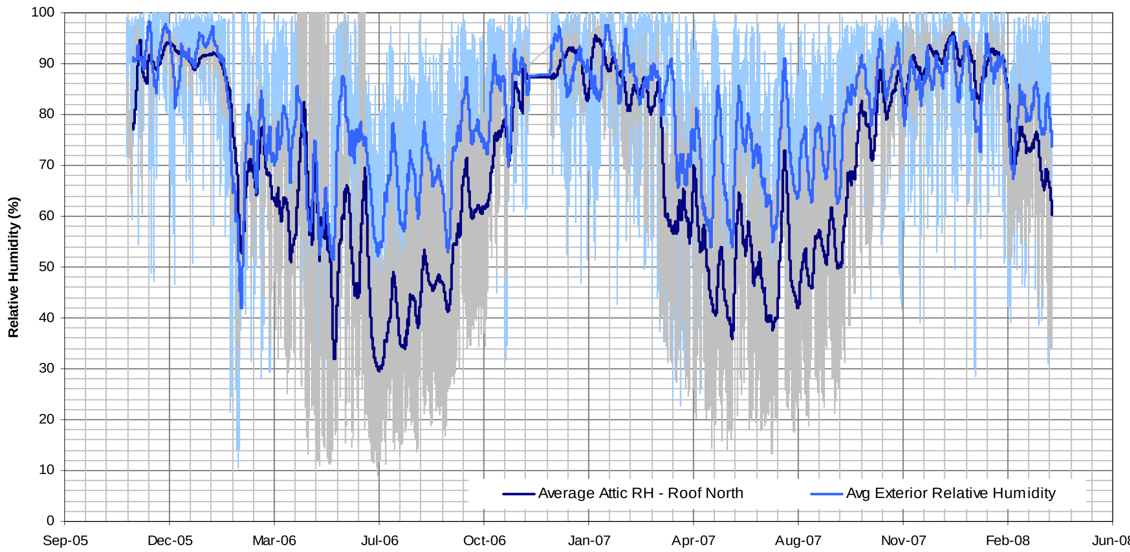


Figure 5.46 – Ventilated attic relative humidity, Roof N1

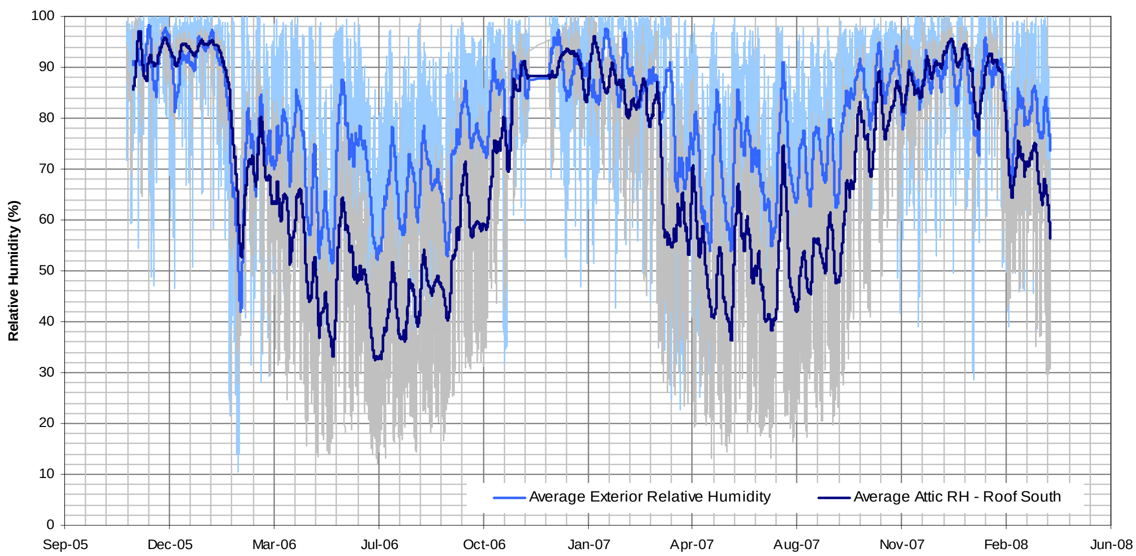


Figure 5.47 – Ventilated attic relative humidity, Roof S1

Figure 5.48 shows the average daily moisture content measured in the sheathing of the north- (blue trace) and south-facing (red trace) ventilated roof assemblies. Unfortunately moisture content data was not saved over the first year of monitoring, however it is expected that the measured moisture content in the first year would have been similar to that measured in the second given that the relative humidity of the air in the attic space was similar year to year. The average daily moisture content in the sheathing of the north-facing ventilated roof panel (N1) reached a peak of approximately 14% in mid February while the moisture content of the sheathing in the south-facing ventilated roof panel (S1) reached a peak of just over 12% near the end of February. While orientation has some influence over the moisture content of the sheathing in the ventilated roof assemblies, the difference between north- and south-facing roof slopes appears to be less pronounced than it is for unvented roof assemblies. This is likely the result of the fact that the two roof slopes are both exposed to the same well mixed air in the attic space.

The moisture content of the sheathing in the unvented roof assemblies is presented in Figure 5.49 (N2 & S2, with 2 coats of latex paint as vapor control) and Figure 5.50 (N3 & S3, without vapor control layer). The average daily winter time sheathing moisture contents reached peaks of 11-12% on the north-facing slopes and 17-19% on the south-facing slopes. No significant difference can be seen between the moisture contents measured in the roof panels that had the two layers of heavy latex paint and those that did not, suggesting that the paint did not have any effect on the moisture performance of the assembly. Although testing by others is ongoing, initial ASTM E96 test results suggest that two layers of latex paint on open-cell sprayed polyurethane foam insulation do not result in an appreciable change in the vapor permeance.

The monitoring therefore shows that, for an indoor relative humidity of 40% RH during winter conditions in Vancouver the roof sheathing moisture content stayed below 19%. This is commonly accepted as a safe moisture content level for wood building products (Morris 1998).

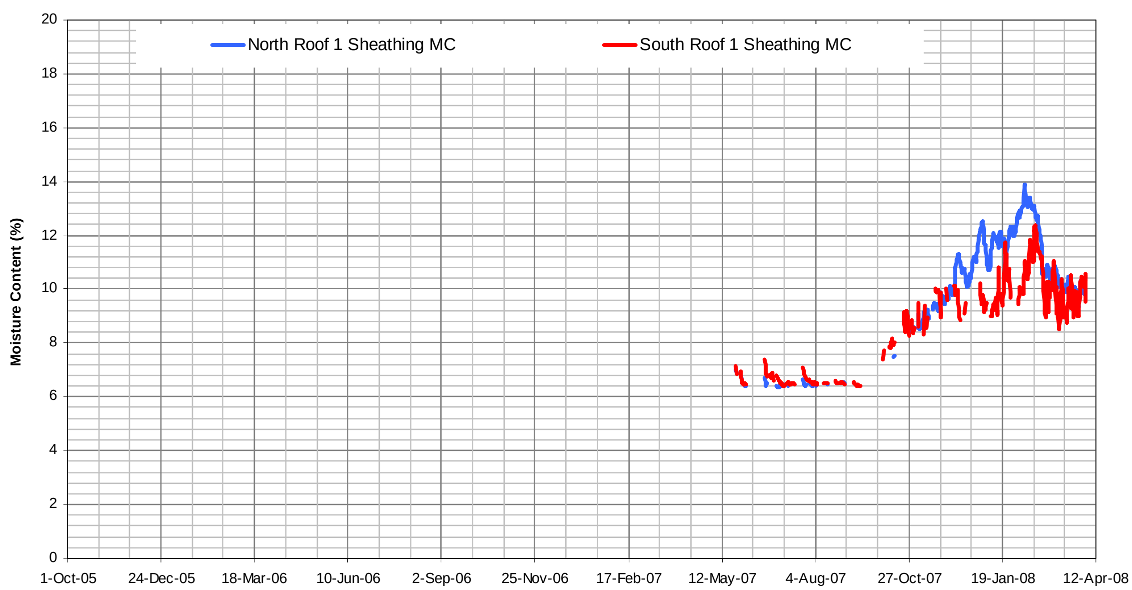


Figure 5.48 – Sheathing moisture content, Roofs N1 & S1

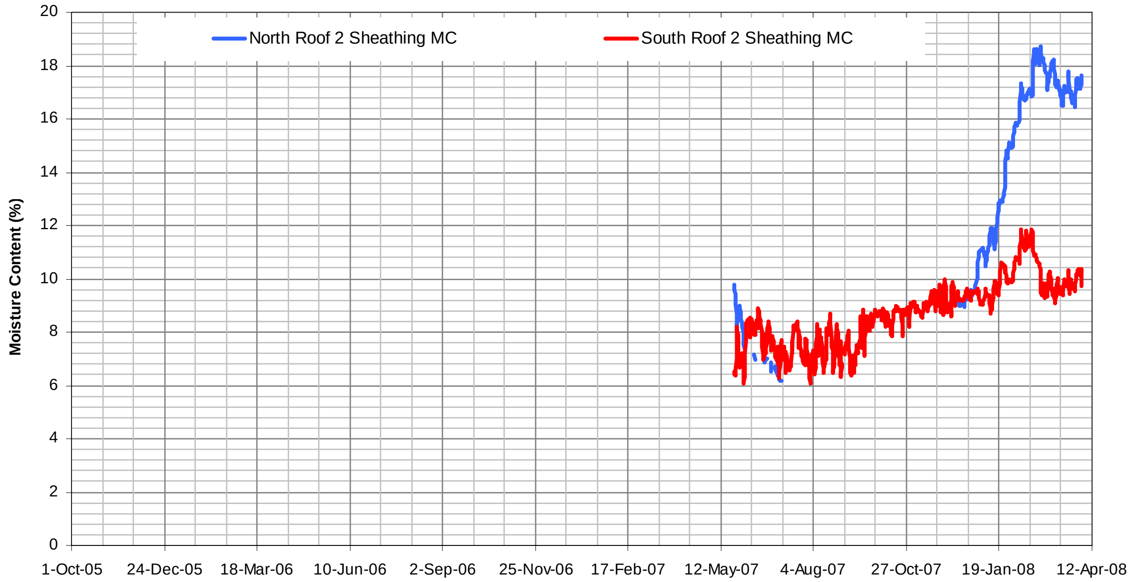


Figure 5.49 – Sheathing moisture content, Roofs N2 & S2

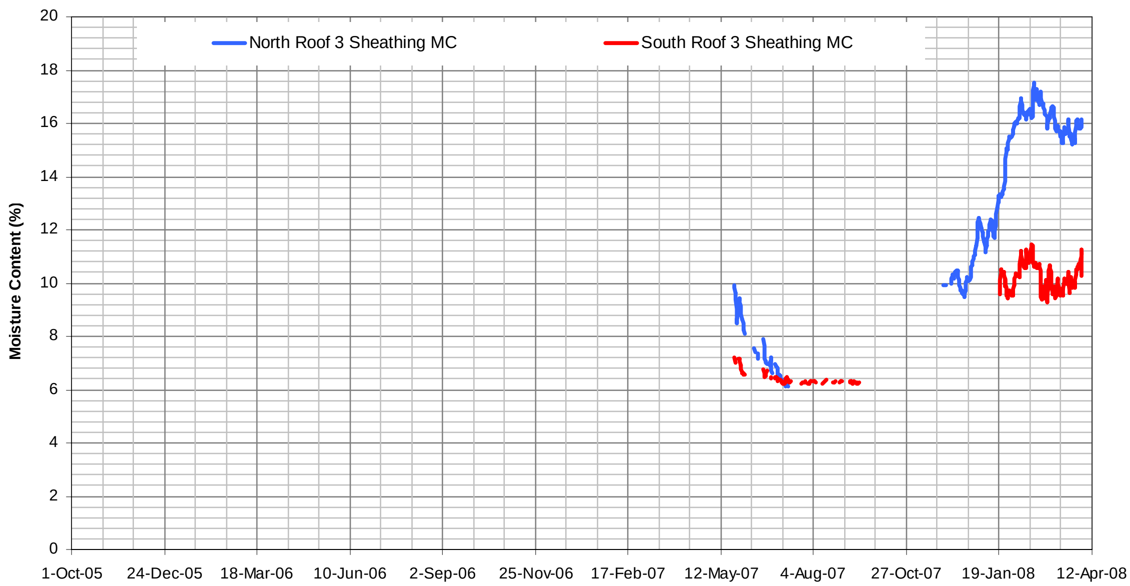


Figure 5.50 – Sheathing moisture content, Roofs N3 & S3

5.3.4 Conclusions & Recommendations

The sheathing in the ventilated attic roof assemblies reached peak winter time moisture contents of 14% and 12% on the north and south roof slopes respectfully. The sheathing in the unvented roof assemblies reached peak moisture contents of 17-19% and 11-12% on the north and south roof slopes.

When indoor relative humidity level is controlled (i.e. less than 40% in Vancouver during winter months) the unvented cathedralized attic roof assemblies show acceptable performance, even without the use of vapor barriers. When air leakage between the indoor space and attic is controlled, the conventional ventilated attic assemblies are likely to exhibit slightly lower sheathing moisture contents than the unvented assemblies.

No difference could be detected in the hygrothermal performance of the unvented cathedralized attic assembly that had two heavy coats of latex paint applied and the assembly that had plain foam.

5.4 Atlanta GA Test Hut

The Atlanta GA test hut facility is capable of testing 6 cathedral ceiling and 6 attic roof assemblies on each of the north and south orientations for a total of 24 roof test panels. The Atlanta test hut research project has been included in this thesis because its southern location produces a significant number of hours with high roof temperatures. Furthermore, the size and asymmetrical roof slopes on this test hut make it well suited to the study of a range of roof parameters in controlled side-by-side comparison. A parametric field monitoring study was undertaken to assess the impact of ventilation on the sheathing and shingle temperatures in eight test panels.

5.4.1 Objectives

The objectives of the Atlanta test hut project were to:

- Examine the impact that ventilation of attic and cathedral ceiling roof assemblies has on sheathing and shingle temperatures in a hot-humid climate.
- Establish a temperature history for eight north-facing and eight south-facing roof assemblies tested simultaneously (i.e. exposed to the same conditions).

5.4.2 Approach

A 102 m² (1100 sq. ft.) full-scale field exposure test facility was designed and constructed in the Maysville GA, 100 km north of Atlanta. The facility, illustrated in Figure 5.51 through Figure 5.53, permits the side by side construction and comparison of ten 1.2 x 2.4 m (4 x 8 ft) wall test panels on the north and south orientations and two more wall test panels on the east and west orientations (for a total of 28 wall test panels). The Atlanta test is designed to accommodate twelve 1.2 x 7.0 m (4 x 23 ft) roof test panels at a 4:12 pitch on the south- facing roof slope and an additional twelve 1.2 x 2.4 m (4 x 8 ft) roof panels at a 10:12 pitch on the north-facing roof slope for a total of twenty four roof panels. The low slope of the south-facing roof maximizes summer solar gain and roof temperatures while the relatively steep slope of the north-facing roof minimizes solar gain and roof temperature.

A large girder truss runs underneath the ridge and the entire length of the building as illustrated in Figure 5.53. The girder truss supports a system of air-tight, insulated box rafters that separate one test panel bay from the next and support a ridge beam as illustrated in Figure 5.54. Attic roof assemblies were constructed by attaching the roof trusses to the girder truss as shown in Figure 5.55. Cathedral ceiling roof assemblies were constructed by attaching the rafters to the ridge beam as illustrated in Figure 5.56 and Figure 5.57.

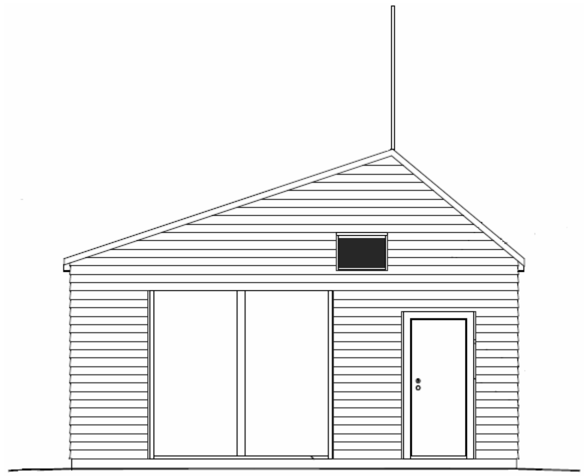


Figure 5.51 – Atlanta test hut: East elevation (West similar)

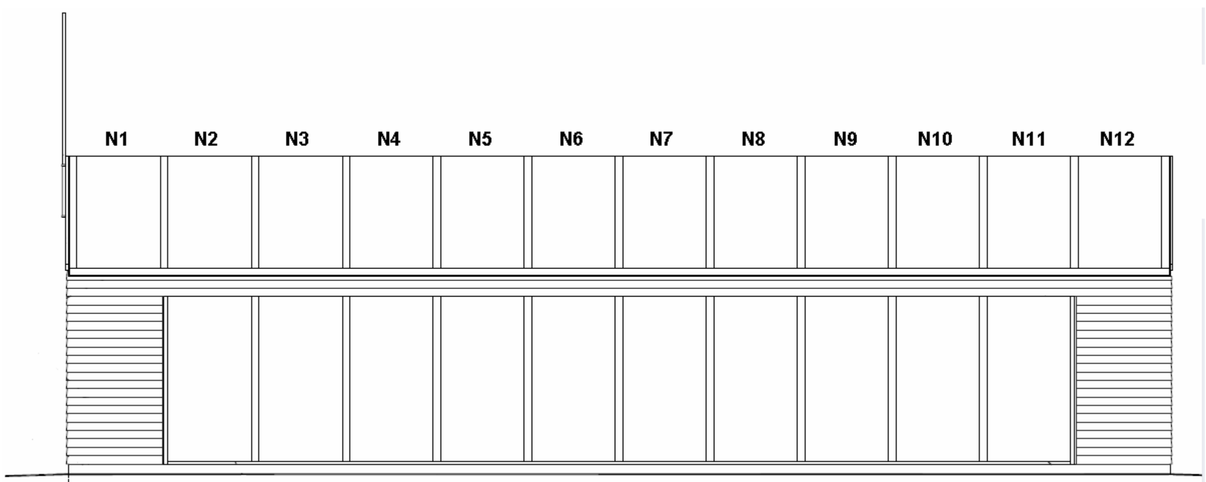


Figure 5.52 – Atlanta test hut: North elevation (South similar)

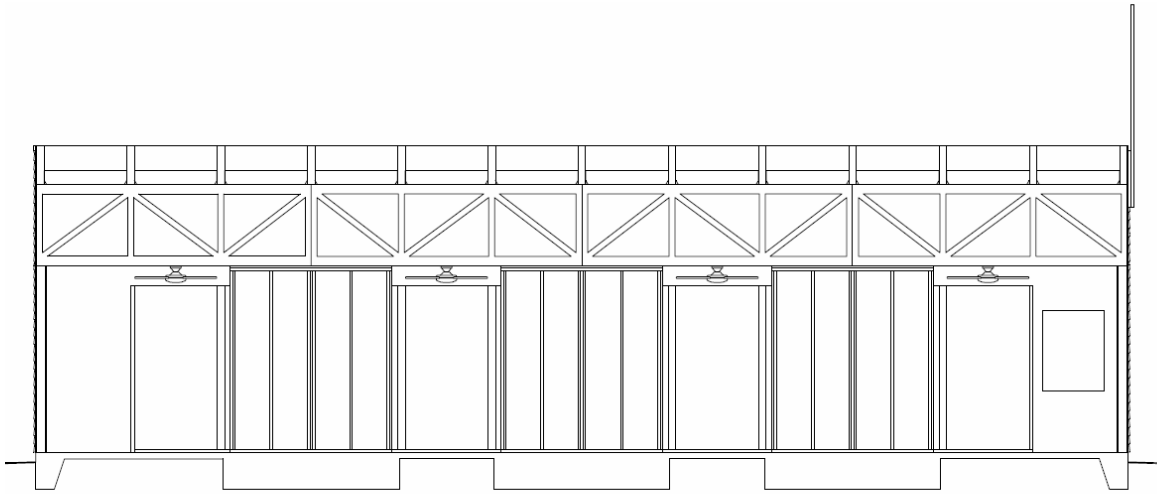


Figure 5.53 – Atlanta test hut: Longitudinal section

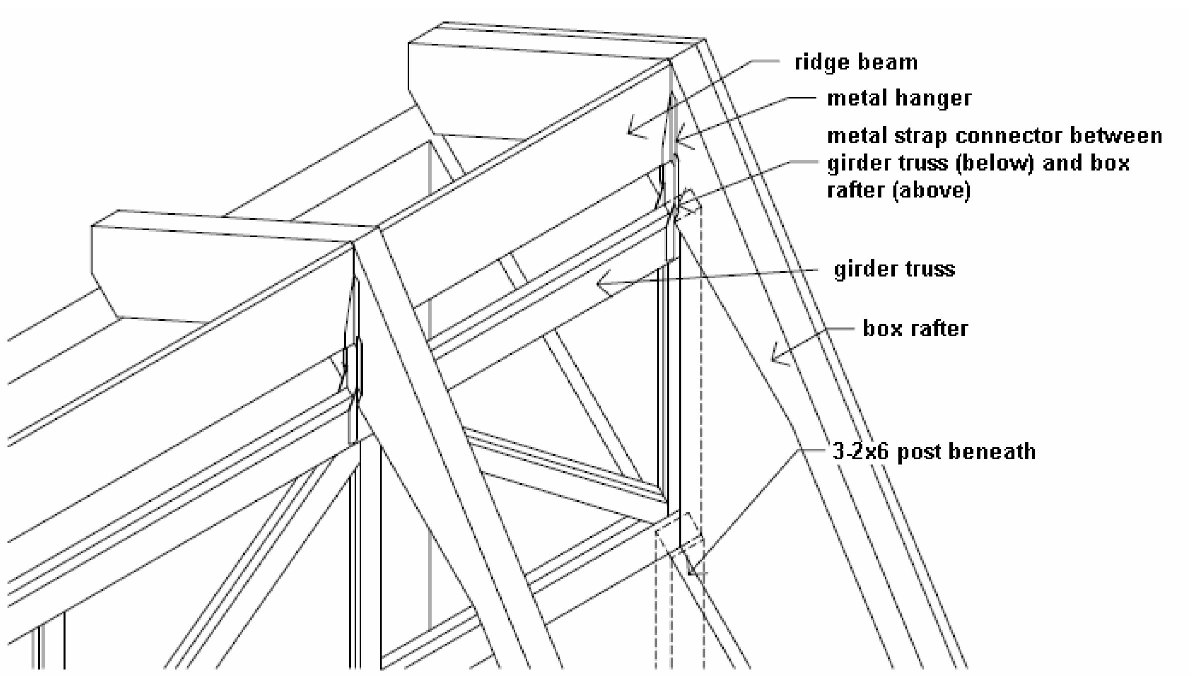


Figure 5.54 – Box rafter system of panel separators

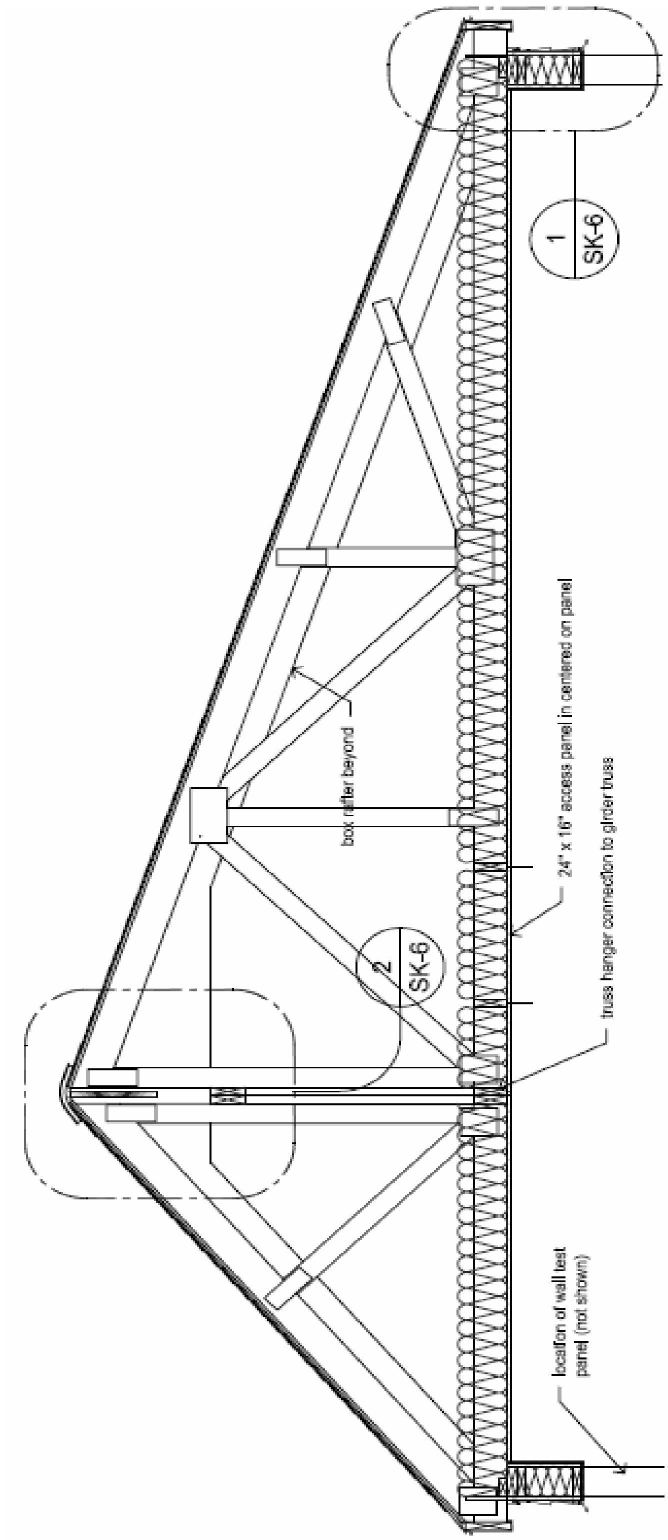


Figure 5.55 – Vented attic roof assembly

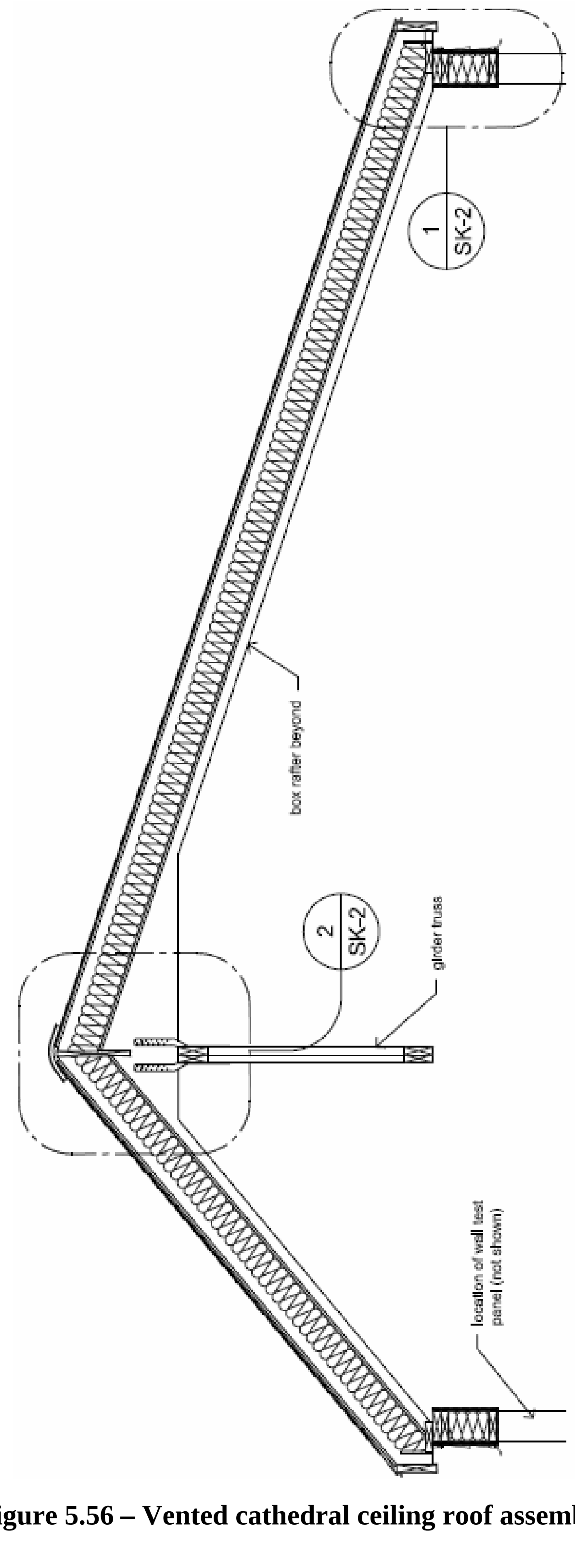


Figure 5.56 – Vented cathedral ceiling roof assembly

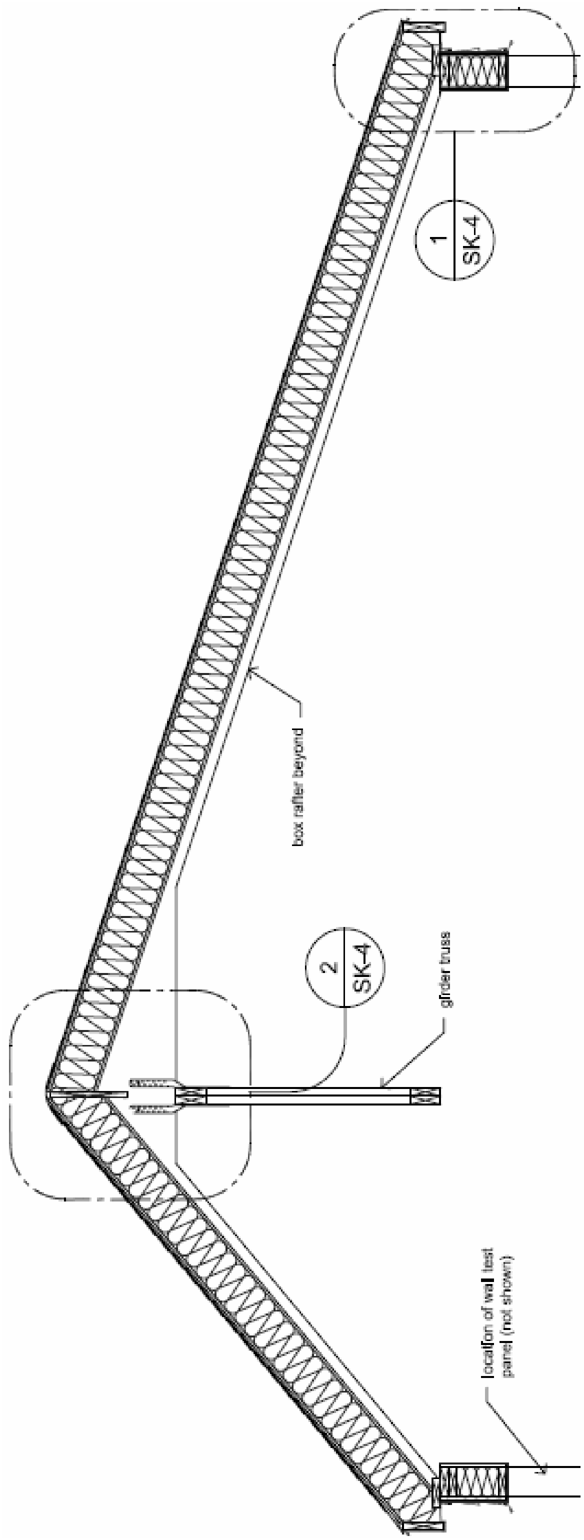


Figure 5.57 – Unvented cathedral ceiling roof assembly

Figure 5.58 shows a view of the nearly completed Atlanta test hut from the north-east corner. In this early morning photo frost is visible on the north-facing vented and unvented cathedral ceiling roof assemblies but not the north-facing vented attic roof assemblies. This could be because the air inside the attic spaces is heated by the roof surfaces on the south-facing slope, causing the frost on the north to melt.

The test hut is located on the back lot of a sheathing manufacturer's research facility, has good wind exposure and is free of all solar shading.

Figure 5.58 – Atlanta test hut

A 1200 channel monitoring and control system measures and records indoor and outdoor conditions and the hygrothermal performance of the test panels. The system, which includes four Campbell Scientific CR10X data logging and control modules, is divided into two subsystems: one for monitoring the wall test panels and one, illustrated in Figure 5.59, for measuring the roof test panels.

A weather station, visible in Figure 5.58, is supported on a steel mast at the east end of the test hut. The monitoring system continuously collects weather data including:

- Outdoor temperature and relative humidity
- Solar radiation on the horizontal
- Solar radiation on the north- and south-facing walls
- Wind speed and direction
- Rainfall
- Driving rain on the north- and south-facing walls

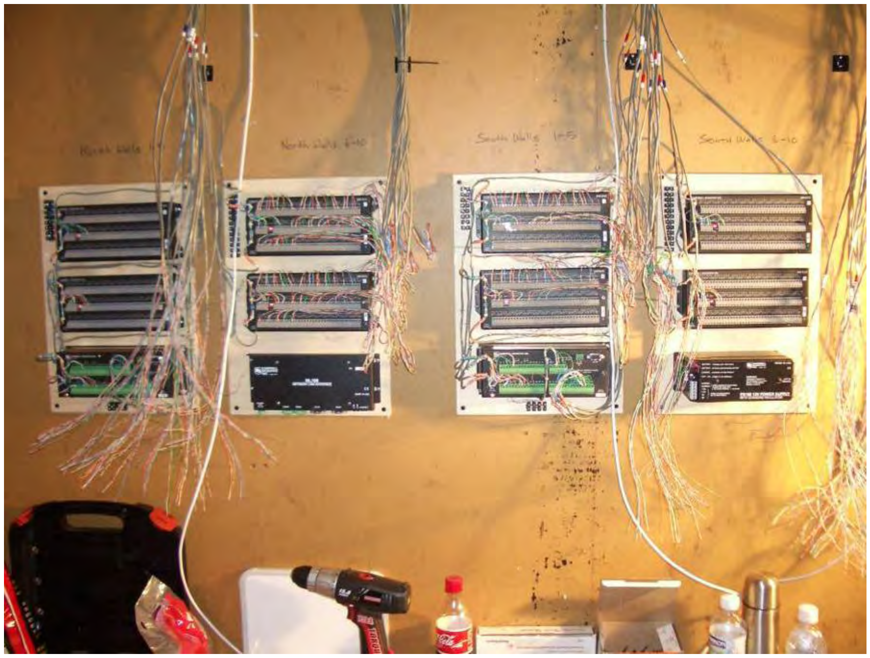


Figure 5.59 – One half of a 1200 channel monitoring system

The monitoring system also measures the indoor temperature and relative humidity conditions at three locations in the test hut. Finally, the monitoring system records data from an instrumentation package in each test panel. The package varies from panel to panel depending on construction and includes 16-24 sensors to monitor moisture content, temperature and relative humidity at multiple locations in the panel. Sensors are measured every 5 minutes and the average saved to memory every hour. Further details on the sensor packages employed can be found in the following section.

5.4.2.1 Research Program

Twelve different roof panels were constructed on each of the north- and south-facing roof slopes of the Atlanta test hut as part of a research program to monitor the hygrothermal performance of roof assemblies with different ventilation strategies and roof sheathings. The research for this thesis considers only four of these test panels and focuses on the relationship between shingle temperature, sheathing temperature and ventilation strategy. Table 5.2 summarizes the composition of the four roof panels that are addressed by this thesis.

All four of the roof panels are finished on the outside with the same black asphalt shingles installed over a #15 felt paper underlayment. Roof panels S7 and N7 are typical of the ventilated attic assemblies that are common all over North America. These test panels were provided with the code required ventilation, evenly distributed between the soffit and the ridge as illustrated in Figure 5.60 and Figure 5.61, and having a total area equal to 1:300 of the insulated ceiling area.

Table 5.2 – Roof test panel composition for Atlanta test hut

No.	Roof Panel	Cladding	Ventilation	Underlayment	Shthg	Frame	Insulation	Vapor Control	Finish
1	S5/N5	Asphalt Shingle	Poorly Vented Attic (1:600)	#15 felt	OSB	truss	Fiberglass Batt	paint	GWB
2	S6/N6	Asphalt Shingle	Code Vented Cathedral Ceiling (1:150)	#15 felt	OSB	2x8	Fiberglass Batt	paint	GWB
3	S7/N7	Asphalt Shingle	Code Vented Attic (1:300)	#15 felt	OSB	truss	Fiberglass Batt	paint	GWB
4	S8/N8	Asphalt Shingle	Unvented Cathedral Ceiling (None)	#15 felt	OSB	2x8	Dense packed Cellulose	paint	GWB

Roof panels S5 and N5 are also conventional attic roof assemblies, however they have only been provided with a vent area equal to 1:600 of the insulated ceiling area. This was done to assess the impact of ventilation that is poorer than that required by code.

Roof panels S6 and N6 are ventilated cathedral ceiling roof assemblies. These were constructed using methods that are commonly used in the southeastern United States; foam insulation baffles were used to create a continuous air space (i.e. an "air chute") between the top of the insulation and the underside of the roof sheathing. Figure 5.62 shows the insulation installer fitting the air chute in above the cathedral ceiling insulation. Note that the chute covers a width of approximately 350 mm (14 in.), nearly half of the 600 mm (24 in.) rafter space. Since it is possible for the insulation to be pushed past the foam insulation baffle on either side, the airspace is only "guaranteed" inside the chute. Moisture, heat and air inside the batt insulation cannot move into the chute, only into the space beside it. If an air leak between indoors and the insulation were the source of a moisture problem in this assembly, the airspace outside of the foam insulation baffle would provide the only path for moisture removal.

Finally, roof panels S8 and N8 are unvented cathedral ceiling roof assemblies. These were constructed using dense pack cellulose insulation as is often done in the southeastern United States. This construction method is not used for UCC roof assemblies in northern climates because the insulation is air permeable. Unintentional openings at the soffit and the ridge were sealed using beads of spray applied polyurethane foam before installing the cellulose.

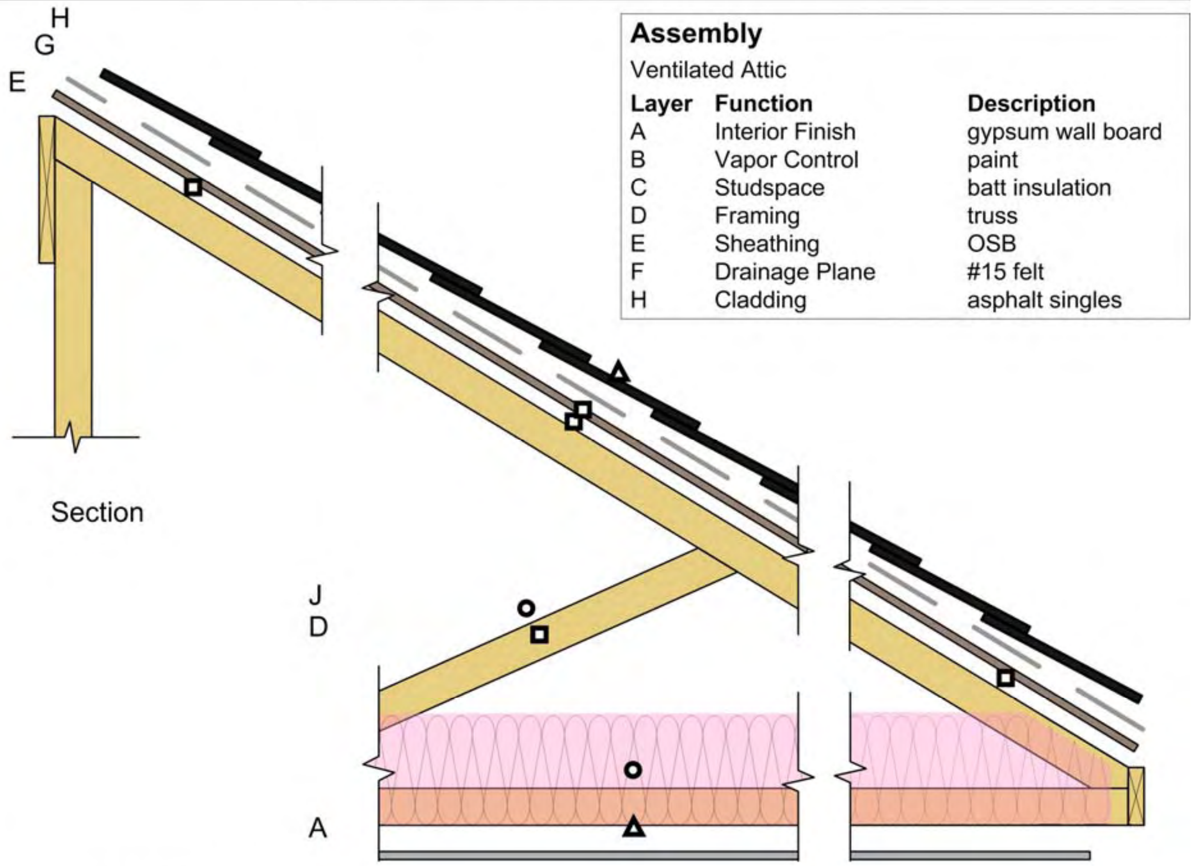
The construction and sensor layout of the four pairs of roof panels are presented in Figure 5.63 through Figure 5.66.

Figure 5.60 - Soffit vent openings

Figure 5.61 – Ridge vents

Figure 5.62 – Conventional ventilated cathedral ceiling with continuous air chute

North/South 5	Shingles, Poorly Ventilated Attic, ½" OSB, Batt insulation, GWB



Assembly

Ventilated Attic

Layer	Function	Description
A	Interior Finish	gypsum wall board
B	Vapor Control	paint
C	Studspace	batt insulation
D	Framing	truss
E	Sheathing	OSB
F	Drainage Plane	#15 felt
H	Cladding	asphalt singles

Sensor Package

Layer	Code	Location
A	taem	Interior finish, exterior face, mid panel
C	r/tcnm	Batt insulation, interstitial
D	m/tdnm	Framing truss, interstitial
E	m/tenm	Sheathing, interstitial, mid panel
E	m/teem	Sheathing, exterior, mid panel
E	m/tenu	Sheathing, interstitial, 16" from top plate
E	m/tenl	Sheathing, interstitial, 16" from bottom plate
H	thnm	Cladding, exterior surface, mid panel
J	r/tjnm	Attic airspace, interstitial, mid panel

- ○ Relative Humidity and Temperature Sensor Package
- □ Moisture Content Pins and Temperature Sensor Package
- △ Temperature Sensor
- ⊠ Moisture Content Wafer and Temperature Sensor Package
- = Moisture Content Pins

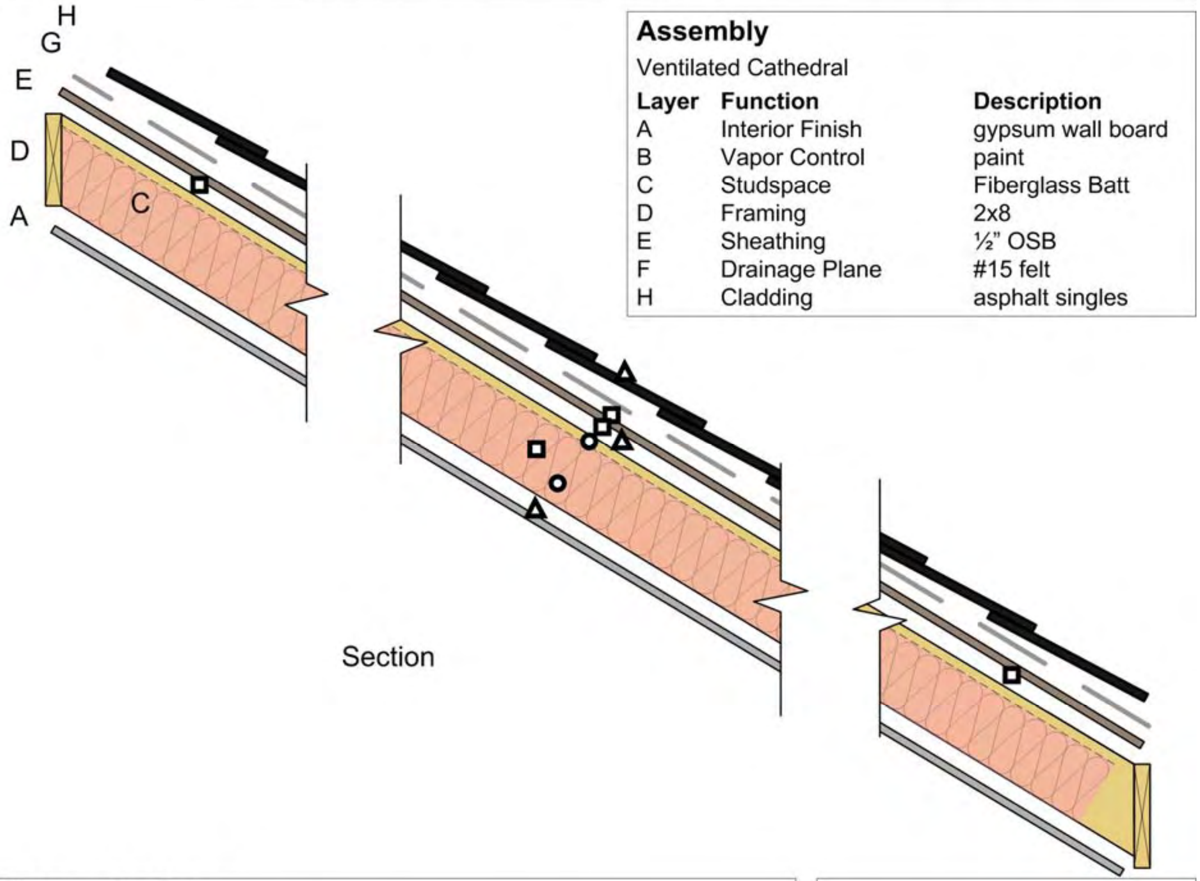
Figure 5.63 – Atlanta Roof 5: Conventional Ventilated Attic, construction and sensor layout

North/South 6	Shingles, Ventilated Cathedral, ½" OSB , FG Batt, GWB

Assembly

Ventilated Cathedral

Layer	Function	Description
A	Interior Finish	gypsum wall board
B	Vapor Control	paint
C	Studspace	Fiberglass Batt
D	Framing	2x8
E	Sheathing	½" OSB
F	Drainage Plane	#15 felt
H	Cladding	asphalt singles



Sensor Package

Layer	Code	Location
A	taem	Interior finish, exterior face, mid panel
C	r/tcnm	Insulation, interstitial, mid panel
D	m/tdnm	Framing truss, interstitial
E	teim	Sheathing, interior, mid panel
E	m/tenm	Sheathing, interstitial, mid panel
E	m/teem	Sheathing, exterior, mid panel
E	m/tenu	Sheathing, interstitial, 16" from top plate
E	m/tenl	Sheathing, interstitial, 16" from bottom plate
J	r/tjnm	Ventilated cavity, interstitial, mid panel
H	them	Cladding, exterior surface, mid panel

- ○ Relative Humidity and Temperature Sensor Package
- □ Moisture Content Pins and Temperature Sensor Package
- △ Temperature Sensor
- ▧ Moisture Content Wafer and Temperature Sensor Package
- = Moisture Content Pins

Figure 5.64 – Atlanta Roof 6: Ventilated Cathedral Ceiling, construction and sensor layout

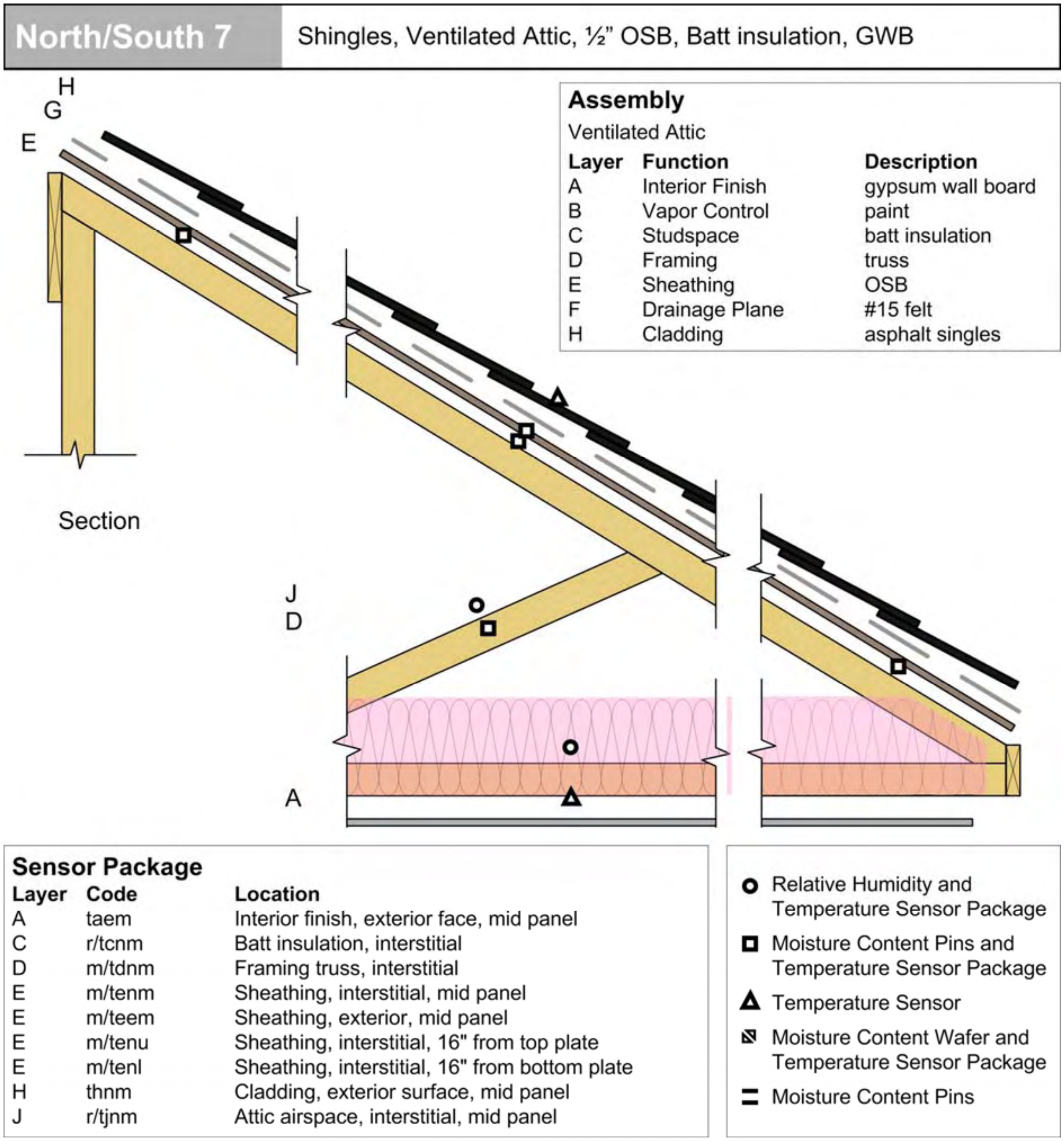


Figure 5.65 – Atlanta Roof 7: Poorly Ventilated Attic, construction and sensor layout

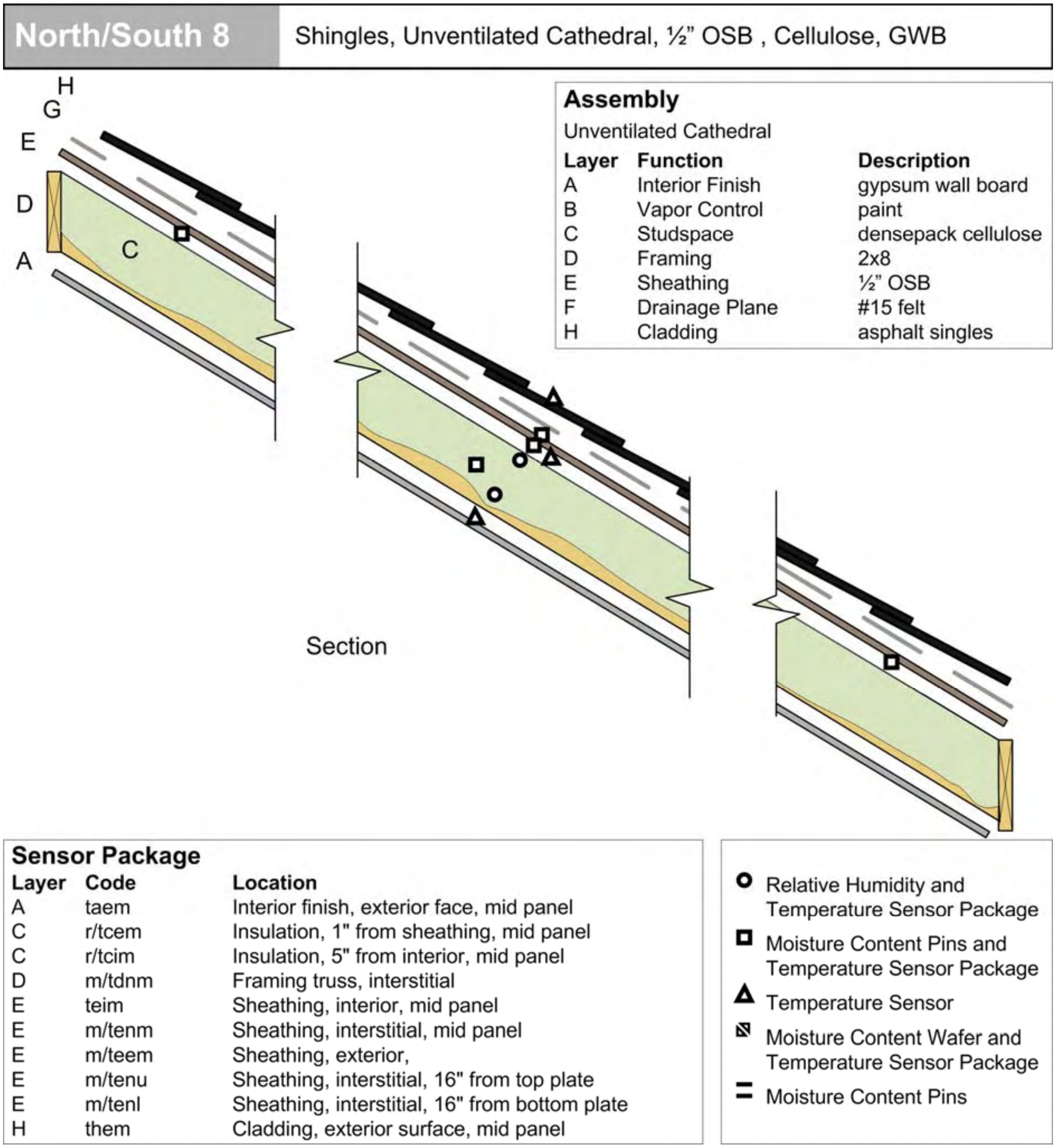


Figure 5.66 – Atlanta Roof 8: Unvented Cathedral Ceiling, construction and sensor layout

Only the shingle surface temperature (sensor "them") and the sheathing temperature at the mid height of the roof test panel (sensor "tenm") are considered in this thesis.

5.4.3 Results and Analysis

Figure 5.67 shows the hourly average solar radiation measured on the horizontal surface. The peak summertime solar radiation is just under 1000 W/m², similar to that measured at the Vancouver test house and the Coquitlam test hut, however there is much less seasonal variation in the amount of solar radiation received in Atlanta than there is in the lower mainland of British Columbia. It is quite common for the solar radiation in Atlanta to exceed 500 W/m² during the winter months. There is an abundance of solar radiation in this southern climate. As a result, average shingle and sheathing temperatures are higher and there is more drying potential and greater temperatures stress in Atlanta than in northern climates.

Figure 5.68 plots the hourly average wind speed and direction. Winds at this site were lighter than at the sites in lower mainland BC, with the hourly average wind speed close to 1 m/s and the majority of the hours having average wind speeds of less than 3.5 m/s.

The hourly average outdoor (i.e. ambient) temperature and relative humidity are presented in Figure 5.69. Freezing temperatures were recorded more often at the Atlanta test hut than at the Vancouver test house and the Coquitlam test hut even though the last two sites are much further north. This demonstrates the buffering effect that the ocean has in marine climates. The greater temperature extremes of the continental climate are also evident in the summer time temperatures recorded at the Atlanta test hut. The outdoor temperature reached highs over 35°C for a significant number of hours.

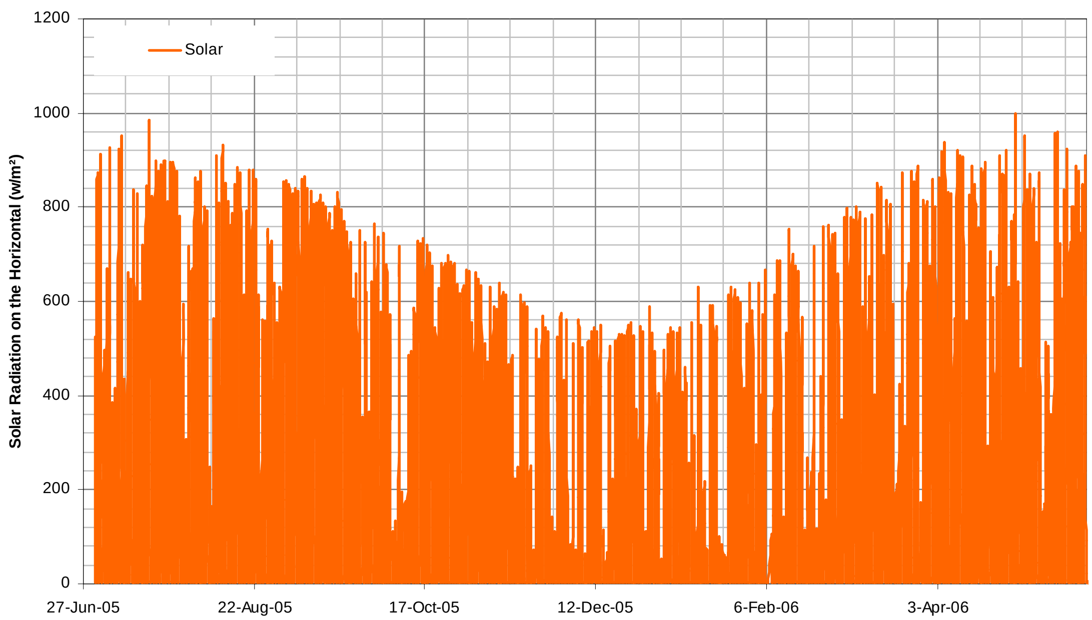


Figure 5.67 – Atlanta solar radiation

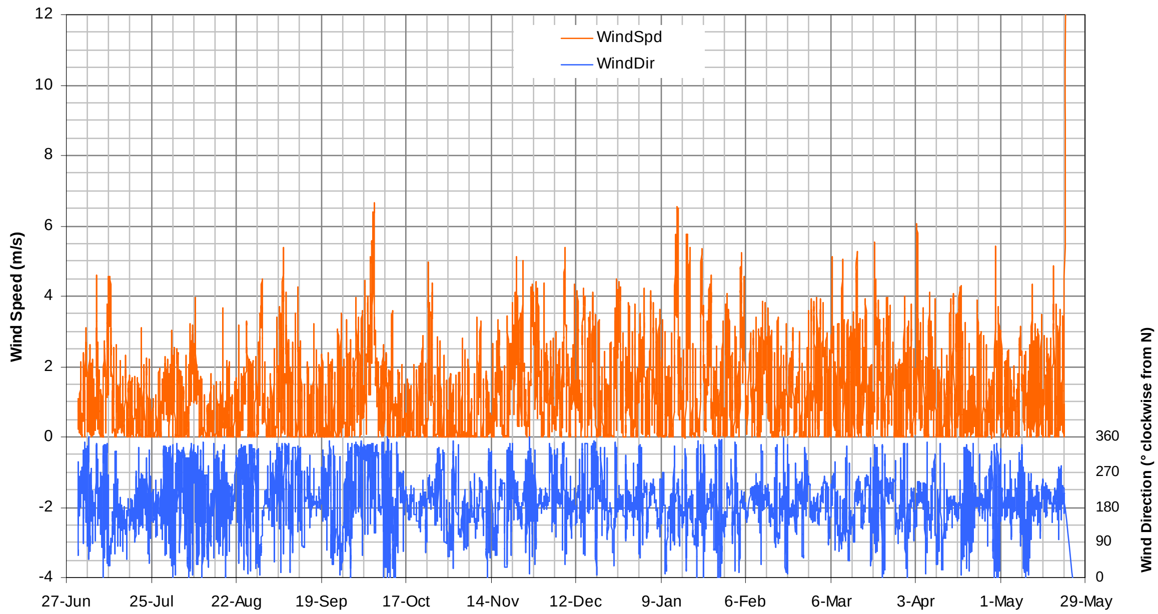


Figure 5.68 – Atlanta wind speed and direction

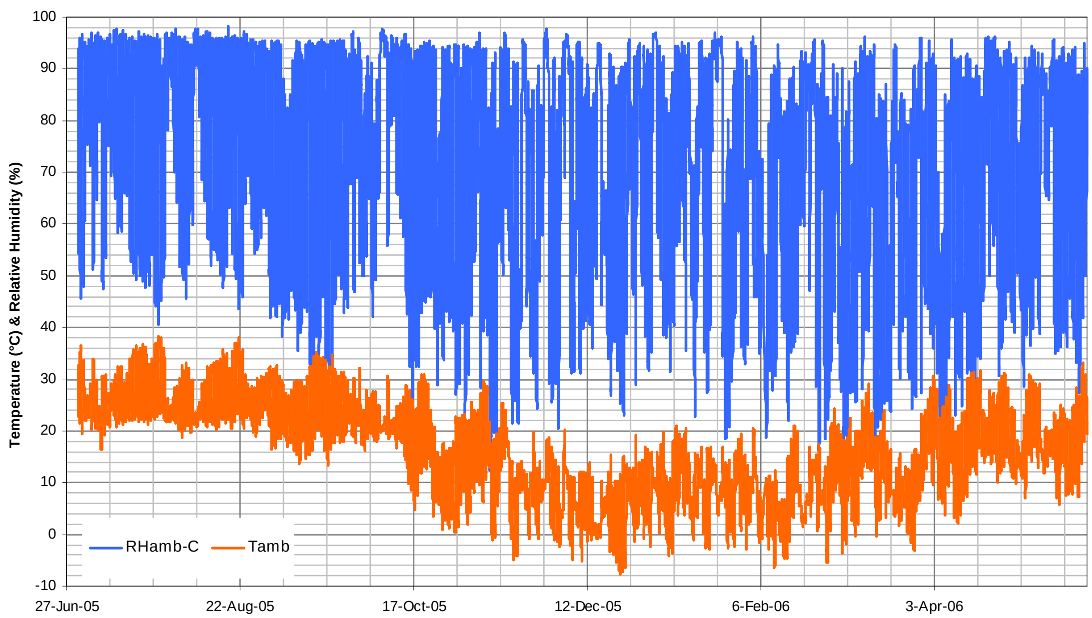


Figure 5.69 – Atlanta outdoor temperature and relative humidity

Figure 5.70 shows the distribution of the hourly average outdoor temperatures recorded at the Atlanta test hut between April 11, 2005 and March 16, 2006. This time period represents 8098 hours without any missing data. The temperatures on the x-axis represent the mean of a series of 5°C temperature bins. The -5°C temperature bin for example, includes all hours for which the recorded average temperature was greater than or equal to -7.5°C and less than -2.5°C.

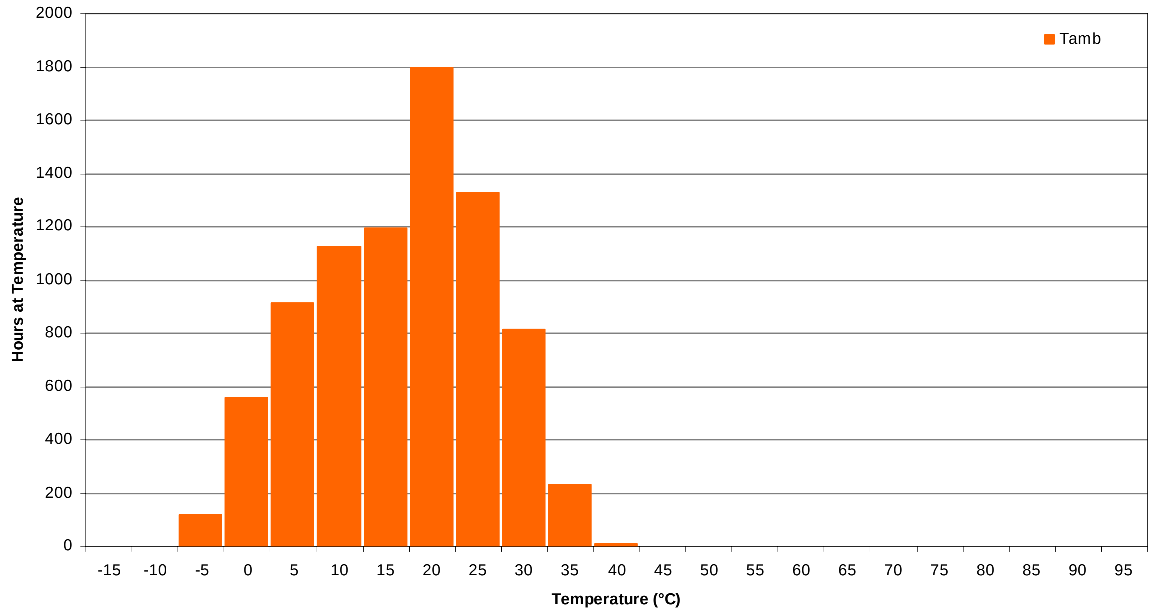


Figure 5.70 – Hourly average ambient temperature distribution

Figure 5.71 and Figure 5.72 present similar distribution plots for the hourly average shingle temperatures recorded on the south- and north-facing slopes respectively. A peak temperature of 88.5°C was recorded on the shingles of the unvented cathedral ceiling roof assembly while the peak temperature on the shingles of the code ventilated attic, poorly ventilated attic and code ventilated cathedral ceiling roof assemblies reached 83.3, 84.9 and 87.5°C. The distribution plots suggest that there is also little difference between the temperature history of the shingles on the unvented cathedral ceiling roof assembly and that of the code ventilated cathedral ceiling roof assembly and it would be unfair to consider shingles on unvented roof assemblies to be more susceptible to thermal deterioration.

The distribution of the hourly average sheathing temperatures recorded on the south- and north-facing roof slopes are presented in Figure 5.73 and Figure 5.74. Here a greater difference in temperature history is evident. On the south-facing roof slope, the sheathing temperature exceeded 80°C for 75 hrs on the unvented cathedral ceiling roof assembly, however this temperature was never exceeded at the sheathing on any of the other roof assemblies. The distribution plots clearly show the impact that ventilation has on reducing peak sheathing temperatures. Peak sheathing temperatures on the south-facing roof slope were only a few degrees cooler than those measured at the Vancouver test house, however the peak temperatures measured on the north-facing roof slope were some 20°C higher than those measured in Vancouver.

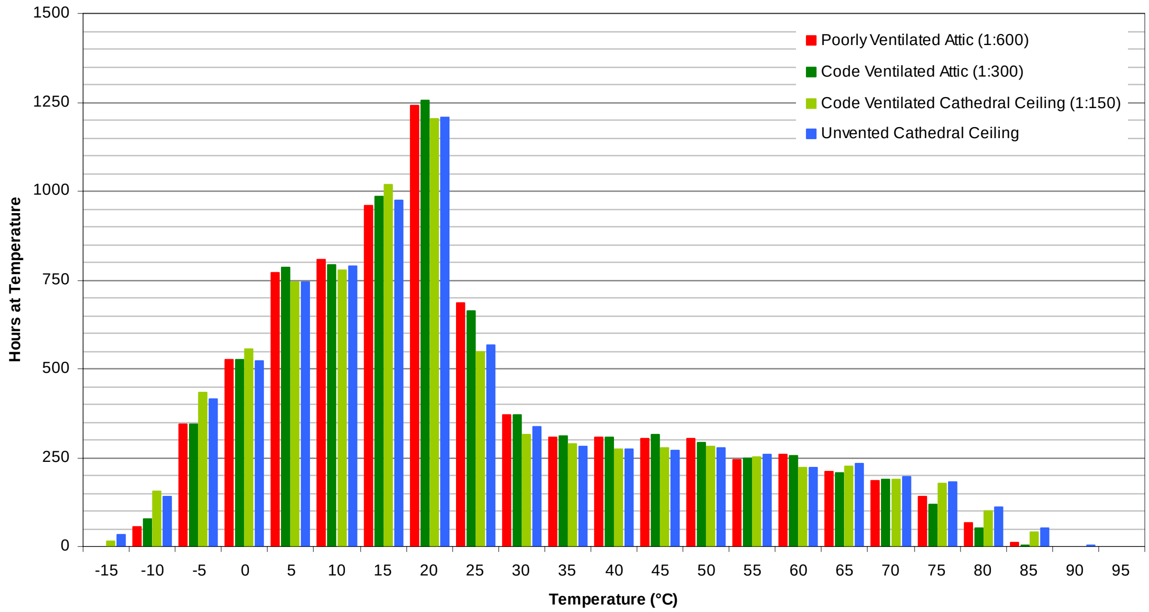


Figure 5.71 – Hourly average shingle temperature distribution (South-facing)

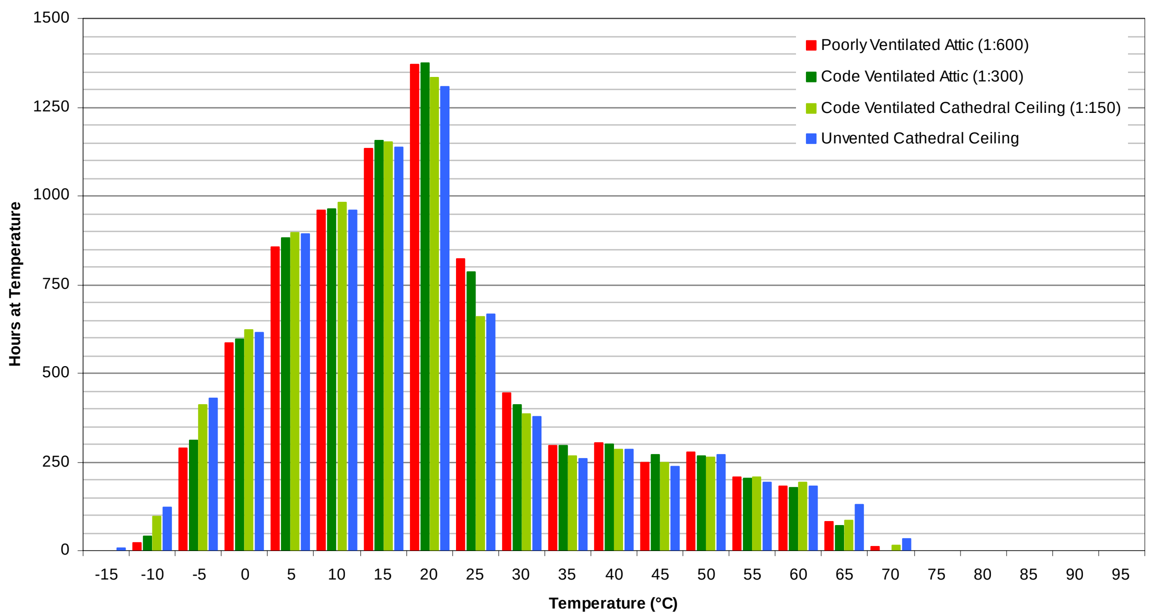


Figure 5.72 – Hourly average shingle temperature distribution (North-facing)

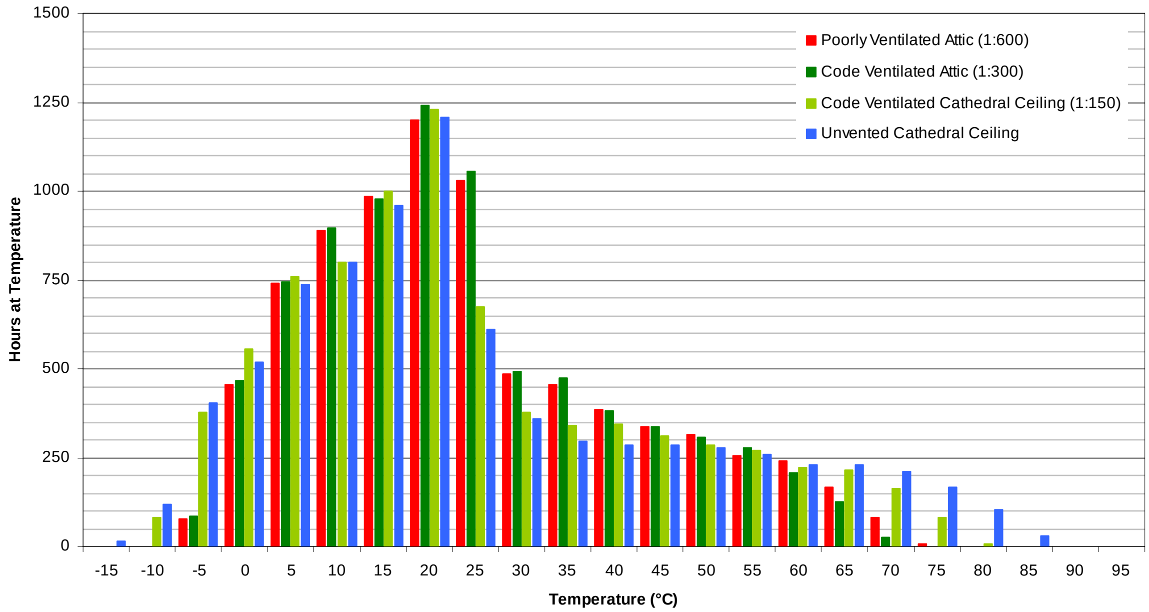


Figure 5.73 – Hourly average sheathing temperature distribution (South-facing)

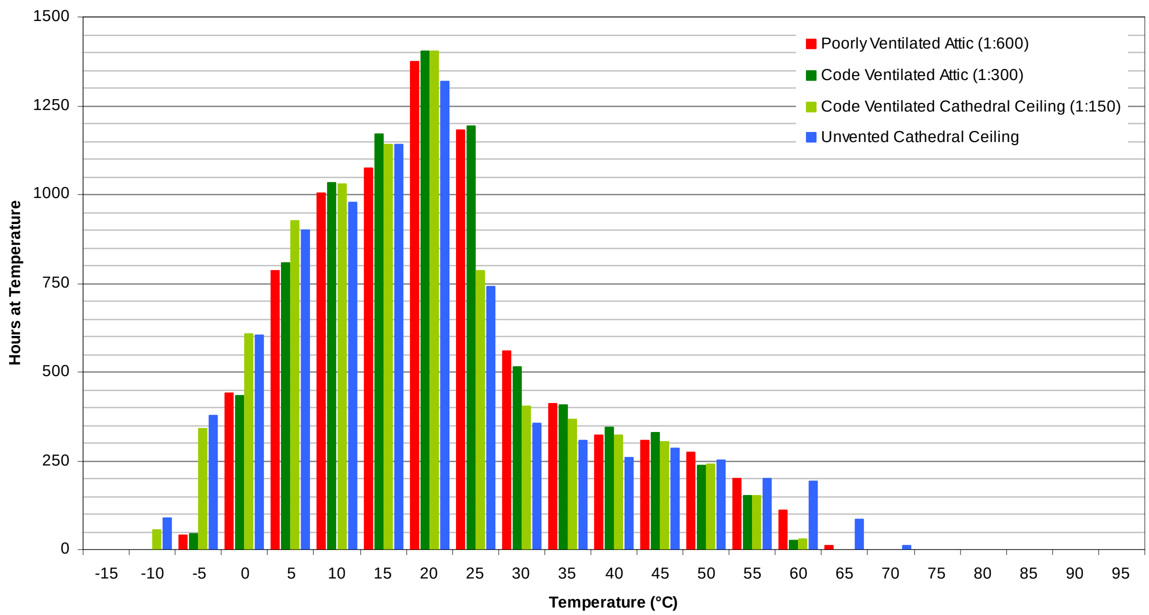


Figure 5.74 – Hourly average sheathing temperature distribution (North-facing)

5.4.4 Conclusions and Recommendations

The shingles on unvented and code ventilated cathedral ceiling roof assemblies reach peak summer time temperatures that are approximately 5°C warmer than ventilated attic assemblies, however the number of hours at high and low temperatures are approximately the same. Shingles on all of the roofs spend less than 2% of annual hours above 77.5°C regardless of ventilation strategy and orientation. Shingles on both the unvented and ventilated cathedral ceiling roof assemblies spend less than 10% of annual hours above 62.5°C while the shingles on the ventilated attic roof assemblies only spend 8% of annual hours above this same temperature.

Ventilation strategy has a bigger impact on the recorded roof sheathing temperatures than on shingle temperatures. The sheathing temperature in the unvented cathedral ceiling roof assembly exceeds 62.5°C for roughly 9% of the annual hours while the sheathing temperature in the ventilated attic roof assembly only exceeds this temperature for 3% of the annual hours. This demonstrates the role that airflow plays in controlling maximum sheathing temperatures.

Peak sheathing temperatures on the south-facing slope of the unvented cathedral ceiling roof assembly were approximately 87°C, only slightly warmer than those measured in Vancouver (86°C). Peak sheathing temperatures on the north-facing slope were almost 70°C, roughly 20°C warmer than those measured on the unvented cathedral ceiling roof assembly in Vancouver.

At the outer surface layers the thermal performance of an unvented roof assembly is difficult to discern from a ventilated cathedral ceiling, therefore any heat-related shingle deterioration can be expected to be similar.

Chapter 6
Predicting Performance

The hygrothermal performance of roof assemblies can be predicted using simple one-dimensional steady-state models that consider one variable to complex models that consider the coupled movement of energy and mass in multiple dimensions under transient conditions. A simple air mixing model was used earlier in the analysis of the Ottawa field investigation.

This chapter explores the use of a complex hygrothermal simulation model, WUFI 4.1 Pro, to predict the performance of the unvented cathedral ceiling roof assembly from the Vancouver test house field study. The simulation results are compared to monitored data and recommendations are made to extend the research to other climates, indoor conditions and material selections through future parametric analyses.

6.1 WUFI 4.1 Pro

The WUFI 4.1 Pro computer model was used to simulate the movement of heat, air and moisture through the roof assembly of the Vancouver test house. WUFI is one of the most advanced commercially available hygrothermal moisture programs in use today. Its accuracy has been verified (by the Fraunhofer Institut Bauphysik in Holzkirchen, Germany – www.wufi.de) against numerous full-scale field studies of enclosure performance (roofs, walls, foundations, parking garage decks, etc.) over a number of years. A portion of the field verification work supporting the model has dealt with the hygrothermal performance of ventilated cathedral ceiling roof assemblies in Europe.

WUFI 4.1 Pro is one of the few models in the public domain that can properly account for rain absorption, night sky radiation (i.e. cooling of surfaces below the ambient temperature) and different water absorption/redistribution for arbitrary material data and boundary conditions. Given the appropriate material data, WUFI calculates heat and moisture flow every hour under the influence of sun, rain, temperature and humidity (see also www.wufi.de). The analysis is, however, only as accurate as the assembly data, the material properties, and the interior and exterior conditions input.

6.1.1 Boundary Conditions

For the majority of transient hygrothermal building simulations, the analyst must have access to hourly weather records which contain sufficient information and are collected at or near the location of the subject building. Weather data was collected at the site of the Vancouver test house, however atmospheric counter radiation and cloud cover were not among the parameters monitored. These are necessary for the explicit calculation of the radiation balance and ultimately the accurate prediction of roofing and sheathing temperatures.

Canadian Weather for Energy Calculations (CWEC) data files were used for that purpose in this research. CWEC weather files were developed for the prediction of building energy performance, not hygrothermal performance. It was therefore necessary to create a custom weather file that combined

CWEC and Canadian Climate Normals data to predict the hourly rainfall and counter radiation. The later was estimated using Bliss' approximation for the sky temperature (Bliss 1961) and then adjusting for cloud cover. Rainfall and counter radiation can be important for the prediction of evaporative and night sky cooling effects on the exterior surfaces of roof assemblies.

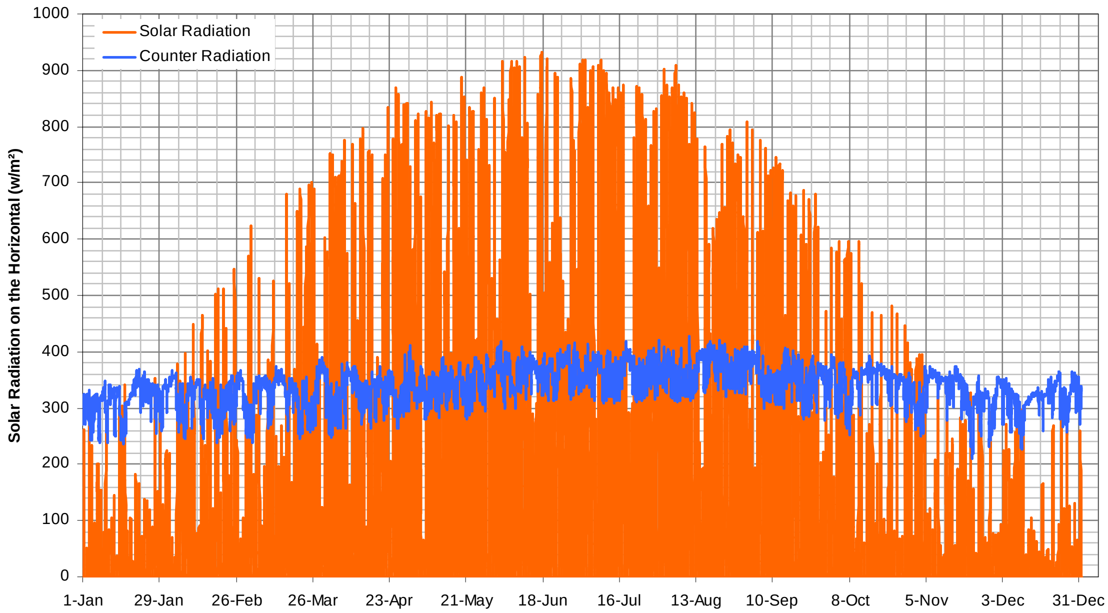


Figure 6.1 – Vancouver solar and counter radiation for simulations

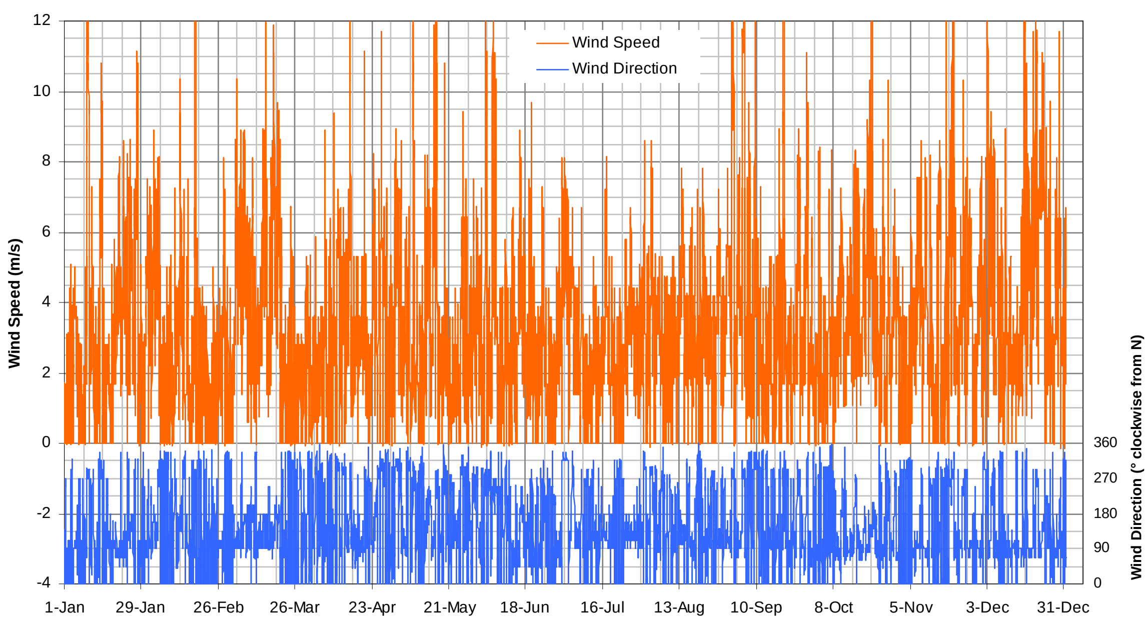


Figure 6.2 – Vancouver wind speed and direction for simulations

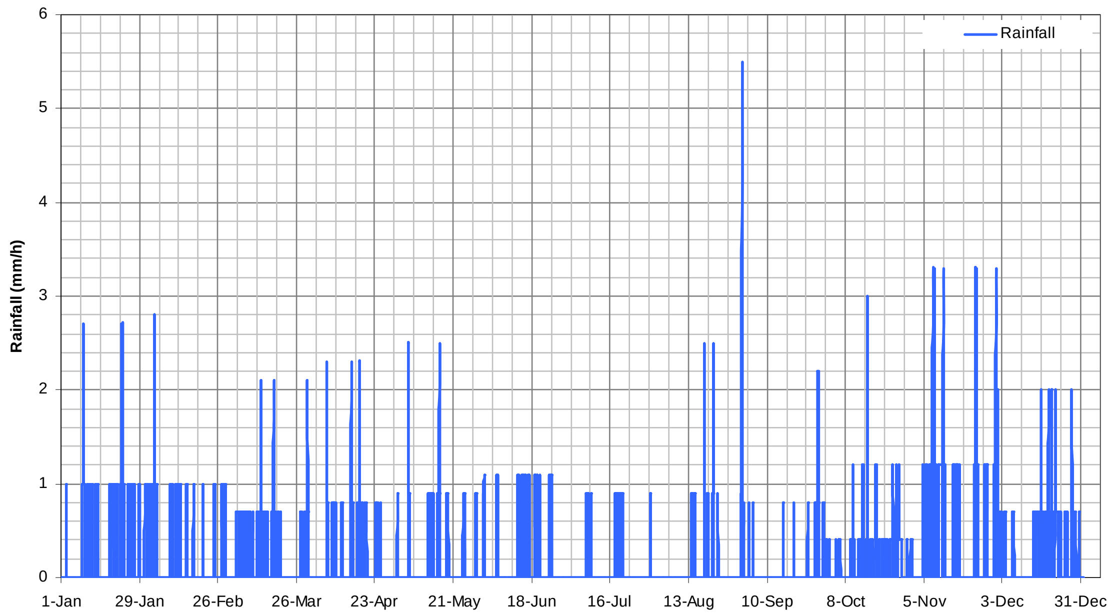


Figure 6.3 – Vancouver hourly rainfall for simulations

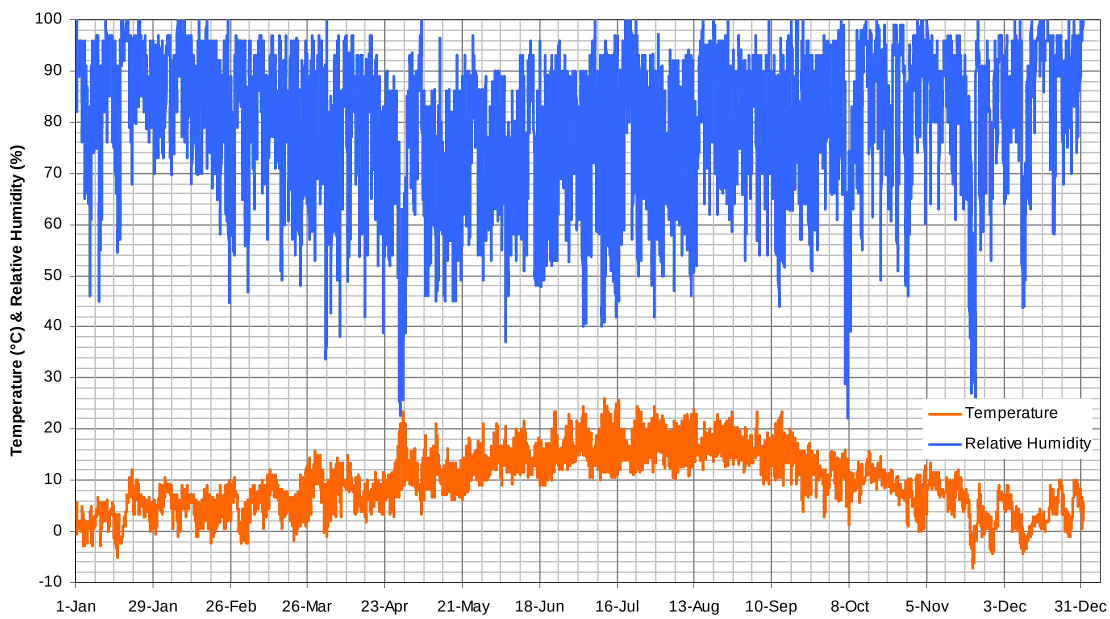


Figure 6.4 – Vancouver outdoor temperature and relative humidity for simulations

Indoor temperature and relative humidity can have a large impact on the hygrothermal performance of roof assemblies, however they are difficult to predict. For simplicity it is often acceptable to approximate both indoor temperature and relative humidity as sinusoidal with peaks in June and August respectfully. Upper and lower limits (i.e. the mean and amplitude) were set to reflect conditions measured in the Vancouver test house and the Coquitlam test hut.

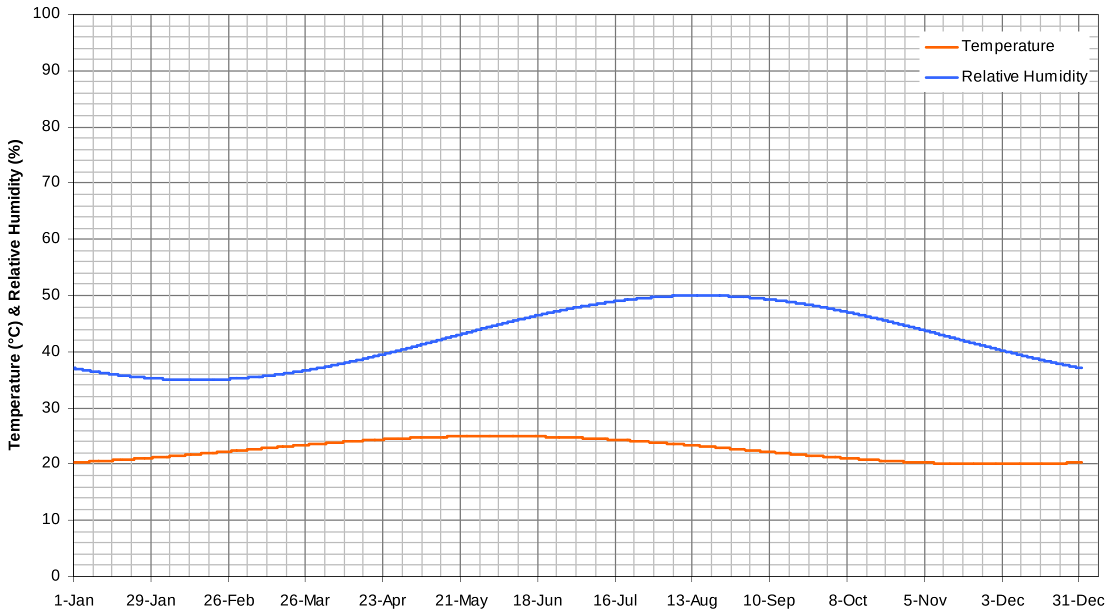


Figure 6.5 – Assumed indoor temperature and relative humidity for simulations

6.1.2 Surface Transfer Coefficients

The transfer of heat and mass from the air adjacent to an enclosure element is not perfect. Equivalent surface transfer coefficients are used to account for the combined conduction, convection and radiation effects. In all of the simulations, interior and exterior heat transfer coefficients of 7.7 W/m²K and 17.8 W/m²K respectively were used. Both of these coefficients are valid for average, (not extreme) conditions. The mass transfer coefficients are generally very high relative to the resistance of the materials (e.g. a permeance of 15 000 -75 000 metric perms). In this case the mass transfer coefficient for the exterior surface was set to infinity and the mass transfer coefficient for the interior surface was set to approximately 600 ng/Pa·s·m² (i.e. a vapor diffusion thickness or Sd value of 0.3 m). This is representative of a relatively permeable painted gypsum wall board (GWB) interior finish.

6.1.3 Material Properties

The default material property files provided with the WUFI model were used as a basis for the inputs. Information from the recent ASHRAE/MEWS material characterization projects was incorporated as necessary. In some cases, the data was slightly changed based on results from on-going research at the University of Waterloo.

The material properties are listed for each material in Appendix A. This is the data used in the simulations, directly from the WUFI files, including all functional dependencies.

6.2 Results and Discussion

The results of the WUFI simulations were compared to the monitored data from the Vancouver test house field study to assess whether or not the simulations captured the measured performance of the roof assembly. Figure 6.6 draws comparisons between the predicted and measured sheathing temperatures on the north-facing roof. The light blue scatter represents the predicted sheathing temperatures for every hour over the course of a two year simulation using the generated weather and indoor climate data. The measured sheathing temperatures are represented by the light orange scatter that appears behind the predicted results. The dark blue and red traces represent 24 hr rolling averages of the predicted and measured sheathing temperatures respectively.

The simulation results effectively capture the diurnal and seasonal cycles of the measured data, although there is some discrepancy between the predicted and measured peak temperatures. This may be the result of using generated rather than recorded weather data of differences between the assumed and actual shingle solar absorptance and long wave emissivity.

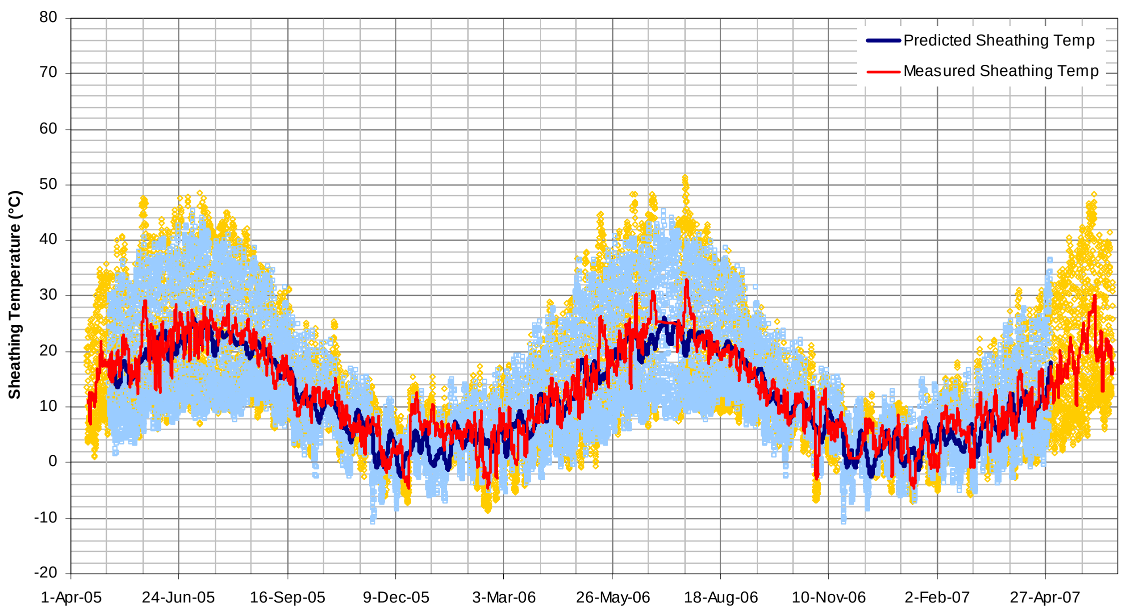


Figure 6.6 – Predicted and measured sheathing temperatures, North-facing roof

A comparison of the predicted and measured sheathing temperatures for the south-facing roof slope is provided in Figure 6.7. The strong influence of the sun is evident in both the predicted and measured temperatures, however the simulations under predict the summertime peak temperatures by 10-20°C. The differences between predicted and measured peaks are large and frequent enough to produce a noticeable shift in the 24 hr rolling averages.

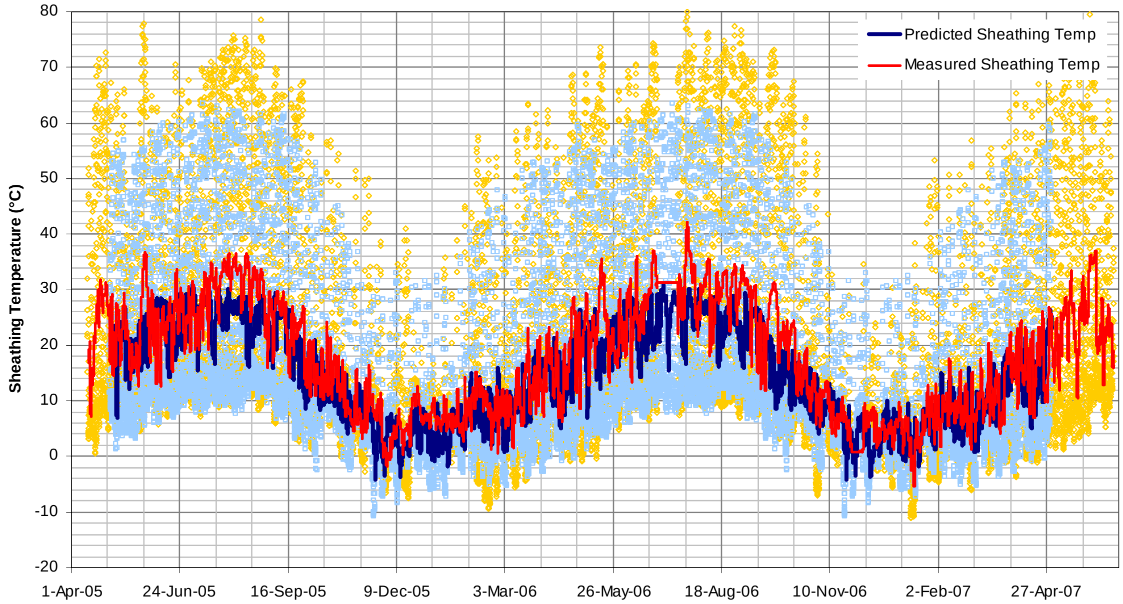


Figure 6.7 – Predicted and measured sheathing temperatures, South-facing roof

Figure 6.8 compares the predicted (dark blue trace) and measured (yellow, orange and red traces) moisture content in the plywood sheathing on the north-facing roof. The simulation appears to do a good job of capturing the initial dryout and subsequent seasonal wetting and drying cycles. This good agreement was only achieved after the moisture storage function of the plywood was modified to increase the amount of moisture stored in the hygroscopic regime (i.e. 0-90% RH).

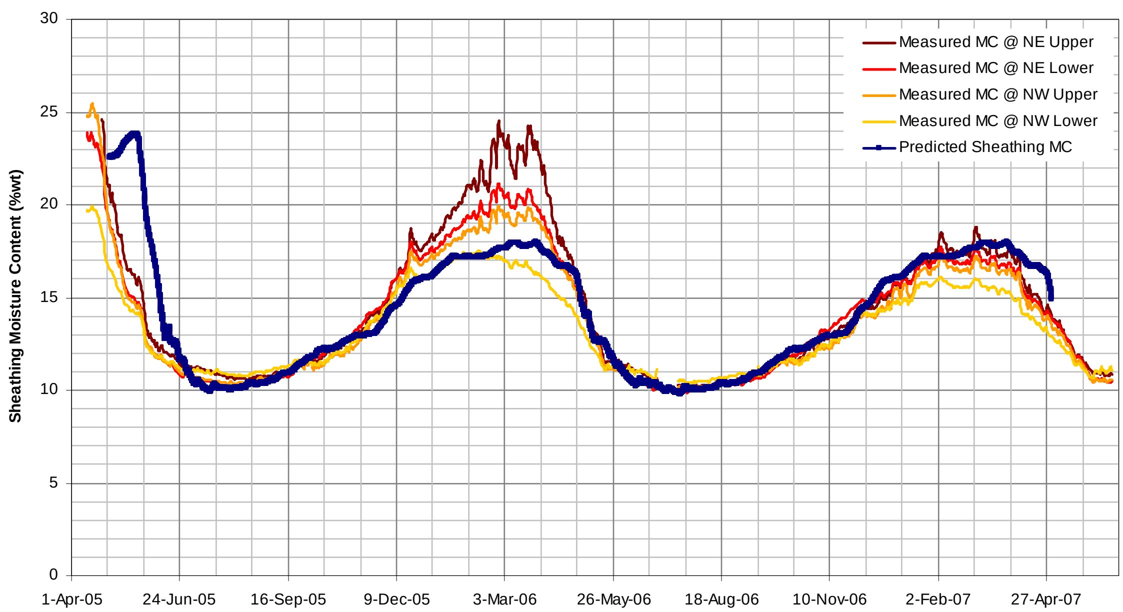


Figure 6.8 – Predicted and measured sheathing moisture content, North-facing roof

The WUFI 4.1 Pro computer program simulates the movement of heat and moisture in a one-dimensional building assembly. Real insulated, wood-framed roof assemblies are three-dimensional systems and it may be that the framing (which has not been included in the model) play a role in adsorbing, storing and releasing moisture. This effect may have been accounted for through the increased moisture storage of the plywood, although it should really be captured as separate mechanism.

Fair agreement was also achieved between the predicted and measured moisture content for the plywood sheathing on the south-facing roof slope. These are compared in the plots of Figure 6.9. In this case, the simulations predict that the moisture content of the plywood increases earlier and dries out later than suggested by the measured field data. It is not known whether this is a result of the lower predicted peak sheathing temperatures, differences between the moisture storage capacity of the model and reality or some other effect. Even so, the differences are small and would not change the assessment of the hygrothermal performance of this roof system.

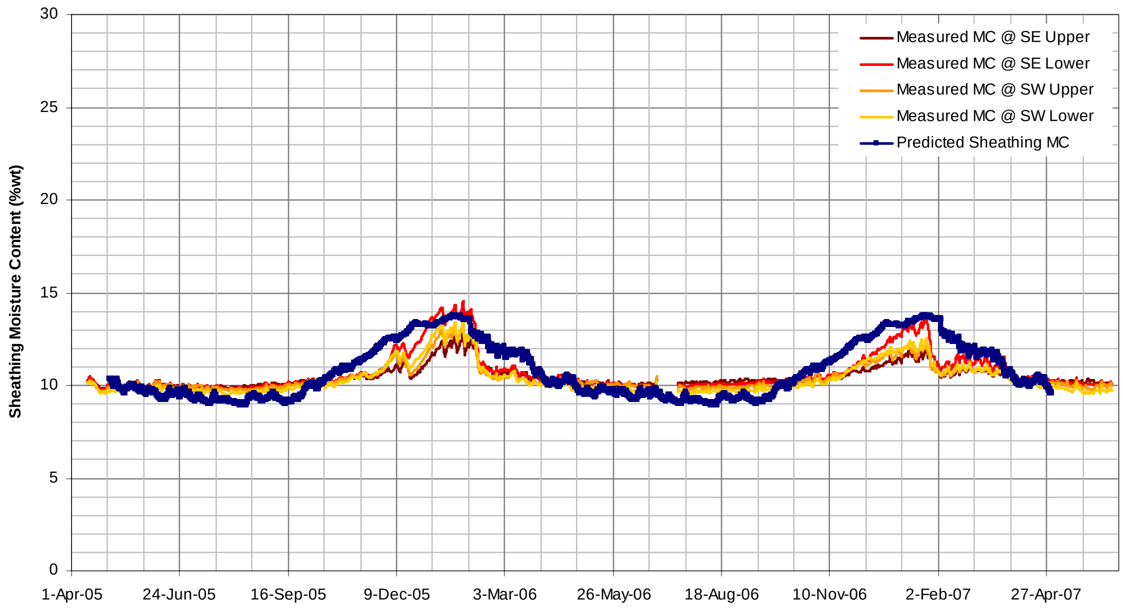


Figure 6.9 – Predicted and measured sheathing moisture content, South-facing roof

6.3 Conclusions and Recommendations

The simulations produced good agreement between predicted and measured sheathing temperatures on the north-facing roof and reasonable agreement on the south-facing roof. Good agreement was also seen between the predicted and measured sheathing moisture contents, however this was only after the moisture storage function of the plywood sheathing was modified to increase the amount of moisture stored throughout the hygroscopic regime.

These initial simulations suggest that the WUFI 4.1 Pro software has the potential to predict the performance of unvented roof assemblies. Further work should be done to assess the impact of moisture storage in the wood framing, material property assumptions and boundary conditions.

WUFI 4.1 is capable of modeling bulk airflow through the airspaces in building enclosures, hence it is recommended that this feature be employed to investigate the hygrothermal performance of ventilated attic roof assemblies.

Chapter 7
Conclusions and Recommendations

For more than 50 years North American model building codes have set requirements for the ventilation of roof assemblies. Ventilated attic and cathedral ceiling roof assemblies have and remain the convention. Ventilation is believed to be the only means of addressing the problems of attic condensation and ice dams in the winter, and high attic, sheathing and shingle temperatures in the summer.

More recently concerns have been raised over several aspects of the performance of ventilated roof assemblies. Vent openings may: facilitate the spread of fire; make possible the pressurization and premature failure of the roof assembly under high winds; allow the entry of wind-driven snow and rain, permit the admission of salt-laden moist air in coastal climates, the provide a path for sound entry. Furthermore, the practicality and performance of ventilated attic assemblies have been challenged by several changes in the low-rise residential market: new requirements for higher insulation levels; wider adoption of more moisture sensitive building materials; growing use of cathedral ceiling (i.e. compact) roof assemblies; and increasing complexity of roof and ceiling geometries. Unvented roof assemblies have been proposed as a solution to address these shortcomings.

Unvented roof assemblies are created by moving the insulation and air barrier layers up off of the horizontal ceiling plane or attic floor and onto the underside of the sloped roof sheathing. Interest in and adoption of unvented roof assemblies has increased since the early 1990s. They have developed as an effective and accepted alternative to conventional ventilated assemblies in the warm, humid climate of the American southeast. However, the technical issues remain unclear and the need exists for further study and demonstration of the hygrothermal performance of both ventilated and unvented roof assemblies in northern climates.

A review of existing literature and current industry experience and practice suggests that further research needs to be done to better predict the performance of and understand the problems encountered in roof assemblies. The research needs can be grouped into five categories: roof leaks, air leakage, vapor diffusion, roof temperature, ice dams. The first and last of these are broad enough in scope that they warrant separate, dedicated study. This thesis describes research work that addresses issues 2, 3 and 4 through the a collection of field investigation and measurement projects.

A forensic field investigation of attic moisture problems in an Ottawa ON home confirmed that air leakage can cause significant levels of frost accumulation on the underside of roof sheathings and possible moisture damage to the interior ceiling finish. Further analysis suggested the most effective preventative and remedial measure is control of indoor relative humidity levels. Ceiling air leakage also plays a role, however its benefit may not be realized until extremely high levels of ceiling airtightness are achieved. Attic ventilation can assist in mitigating moisture problems, but it is not as effective as the preventative measures.

A study of a Vancouver BC test house confirmed that unvented cathedral ceiling roof assemblies insulated with air impermeable, vapor permeable sprayed polyurethane foam can perform adequately in cold wet (i.e. marine) climates without the use of a vapor barrier. However, the study identified a strong connection between indoor humidity levels (i.e. vapor pressure) and sheathing moisture content. This suggests the need for a modest level of vapor control and it is recommended that vapor barrier paint be considered for this purpose.

A side-by-side field monitoring study of six ventilated and unvented roof assemblies at a Coquitlam BC test demonstrated that both ventilated and unvented roof assemblies can perform satisfactorily. The study demonstrated that frost and condensation are not a concern when the indoor humidity is reasonable, the ceiling plane allows minimal air leakage, roof temperatures do not remain cold for extended periods and the ventilation is straightforward. Under these conditions the unvented cathedralized roof assemblies exhibited only slightly higher peak wintertime sheathing moisture contents. The application of two heavy coats of latex paint as a vapor control layer on the inside surface of the foam insulation was demonstrated to be ineffective.

Monitored sheathing and shingle temperatures of sixteen ventilated and unvented roof assemblies in an Atlanta GA test hut confirmed that peak summertime sheathing and shingle temperatures are reduced by ventilation. However, the study also suggested that there is little difference between the sheathing and shingle temperatures recorded in a conventional (ventilated) cathedral ceiling roof assembly and an unvented cathedral ceiling assembly.

Initial simulation work suggests that the WUFI 4.1 Pro software has the potential to predict the performance of unvented roof assemblies. Further work should be done to assess the impact of moisture storage in the wood framing, material property assumptions and boundary conditions. The WUFI 4.1 Pro software should considered for the simulation of ventilated attic roof assemblies.

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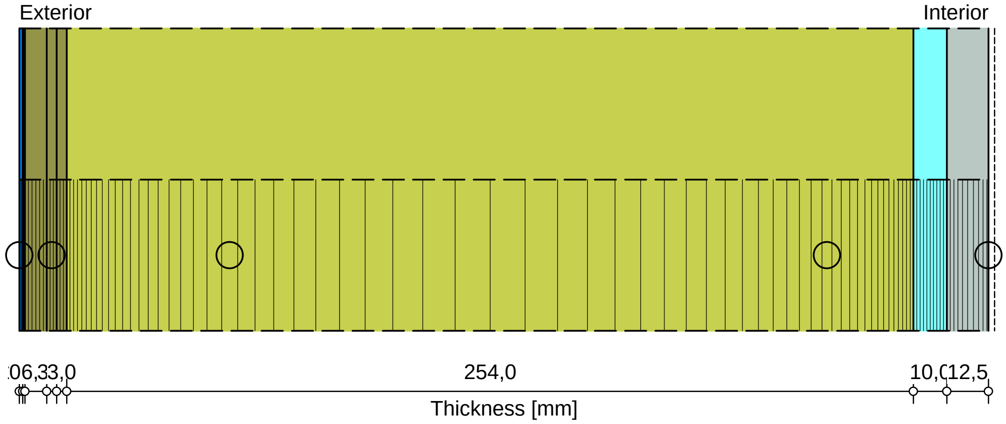
Appendix A

Inputs for WUFI 4.1 Pro Computer Simulations

Component Assembly

Case: Vancouv er Test House North



○ - Monitor positions

Materials :

- Roof Membrane V13
- Bituminous Paper (#15 Felt)
- Plywood Outer
- Plywood Meas
- Plywood Inner
- Icynene 10 inches
- Air Layer 10 mm
- Gypsum Board (USA)

Sd-Value Int. [m]: 0.3

Boundary Conditions

Exterior (Left Side)

Location: Vancouver_BC_CAN.TRY
Orientation / Inclination: North / 39 °

Interior (Right Side)

Indoor Climate: WTA Recommendation 6-2-01/E
User Definied Sine Curve Parameter

Surface Transfer Coefficients

Exterior (Left Side)

Name	Unit	Value	Description
Heat Resistance	[m²K/W]	0.0526	Roof
Sd-Value	[m]	----	No coating
Short-Wave Radiation Absorptivity	[-]	0.9	
Long-Wave Radiation Emissivity	[-]	0.9	
Rain Water Absorption Factor	[-]	1,0	No absorption

Interior (Right Side)

Name	Unit	Value	Description
Heat Resistance	[m²K/W]	0.125	Roof
Sd-Value	[m]	0.3	

Explicit Radiation Balance

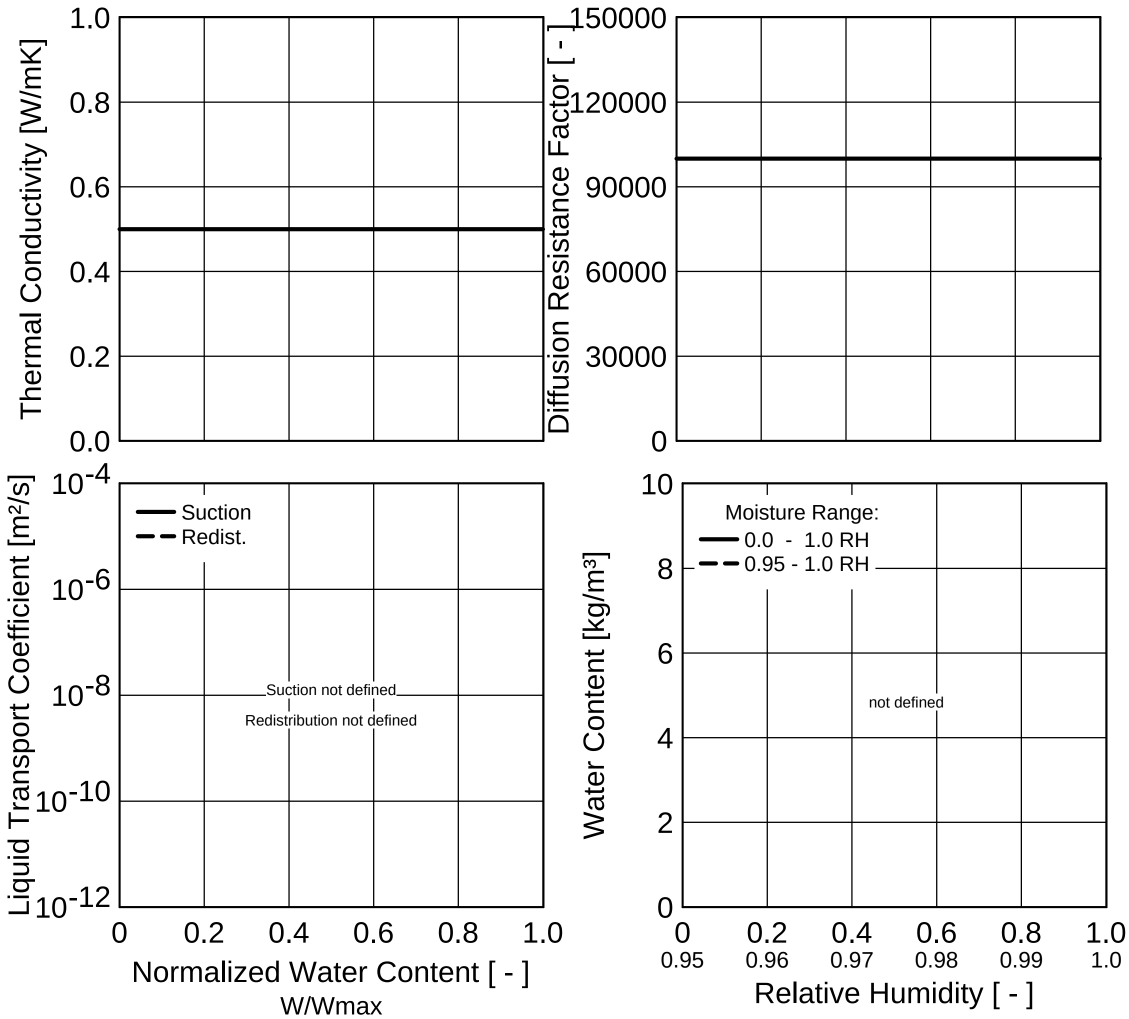
Exterior (Left Side)

Name	Value
Enabled	yes
Heat Transfer Coefficient includes long-wave radiation	yes
Terrestrial Short-Wave Reflectivity [-]	0.20
Terrestrial Long-Wave Emissivity [-]	0.90
Terrestrial Long-Wave Reflectivity [-]	0.10
Cloud Index [-]	0.66

Material : Roof Membrane V13

Checking Input Data

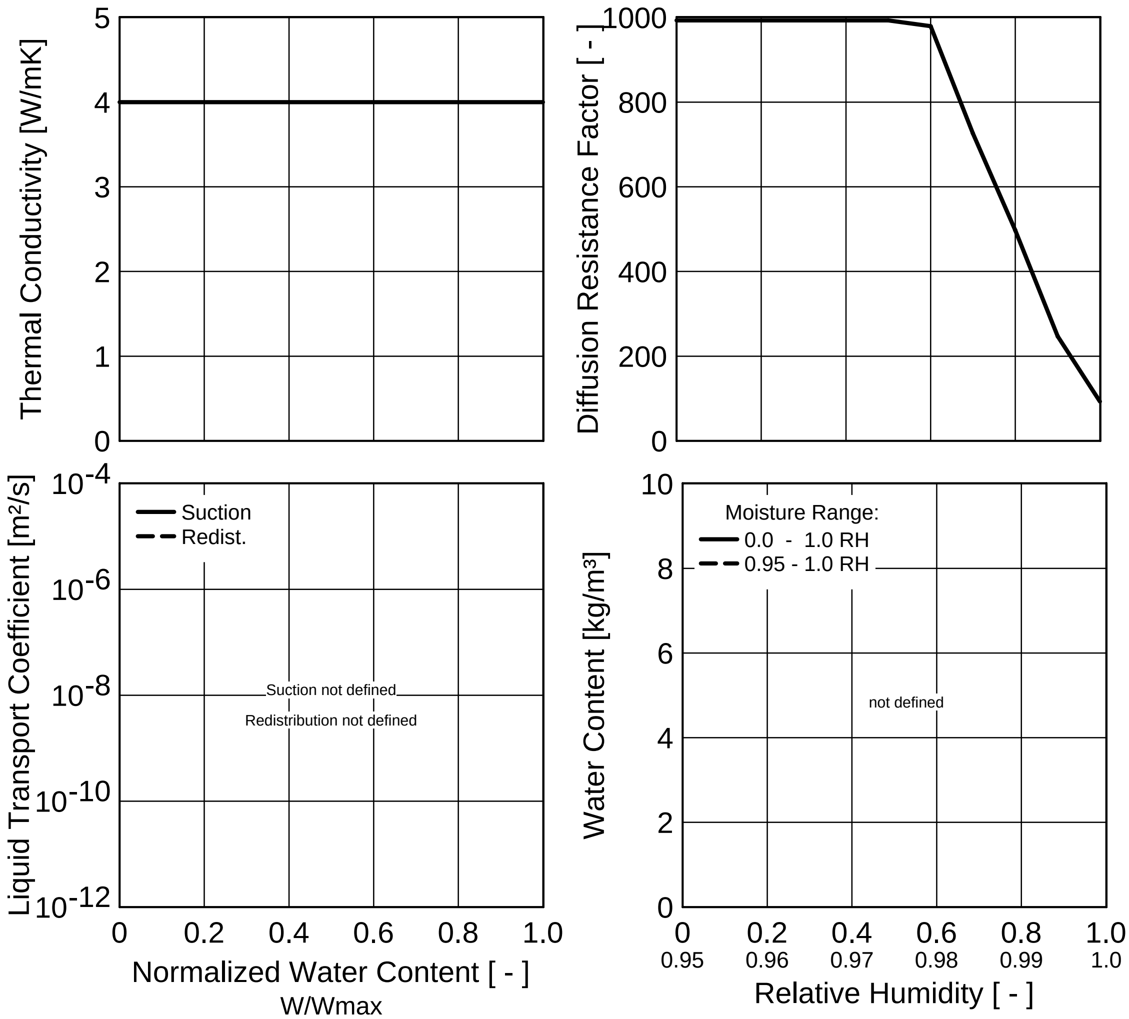
Property	Unit	Value
Bulk density	[kg/m³]	2400,0
Porosity	[m³/m³]	0,001
Specific Heat Capacity, Dry	[J/kgK]	1000,0
Thermal Conductivity, Dry	[W/mK]	0,5
Water Vapour Diffusion Resistance Factor	[-]	100000,0



Material : Bituminous Paper (#15 Felt)

Checking Input Data

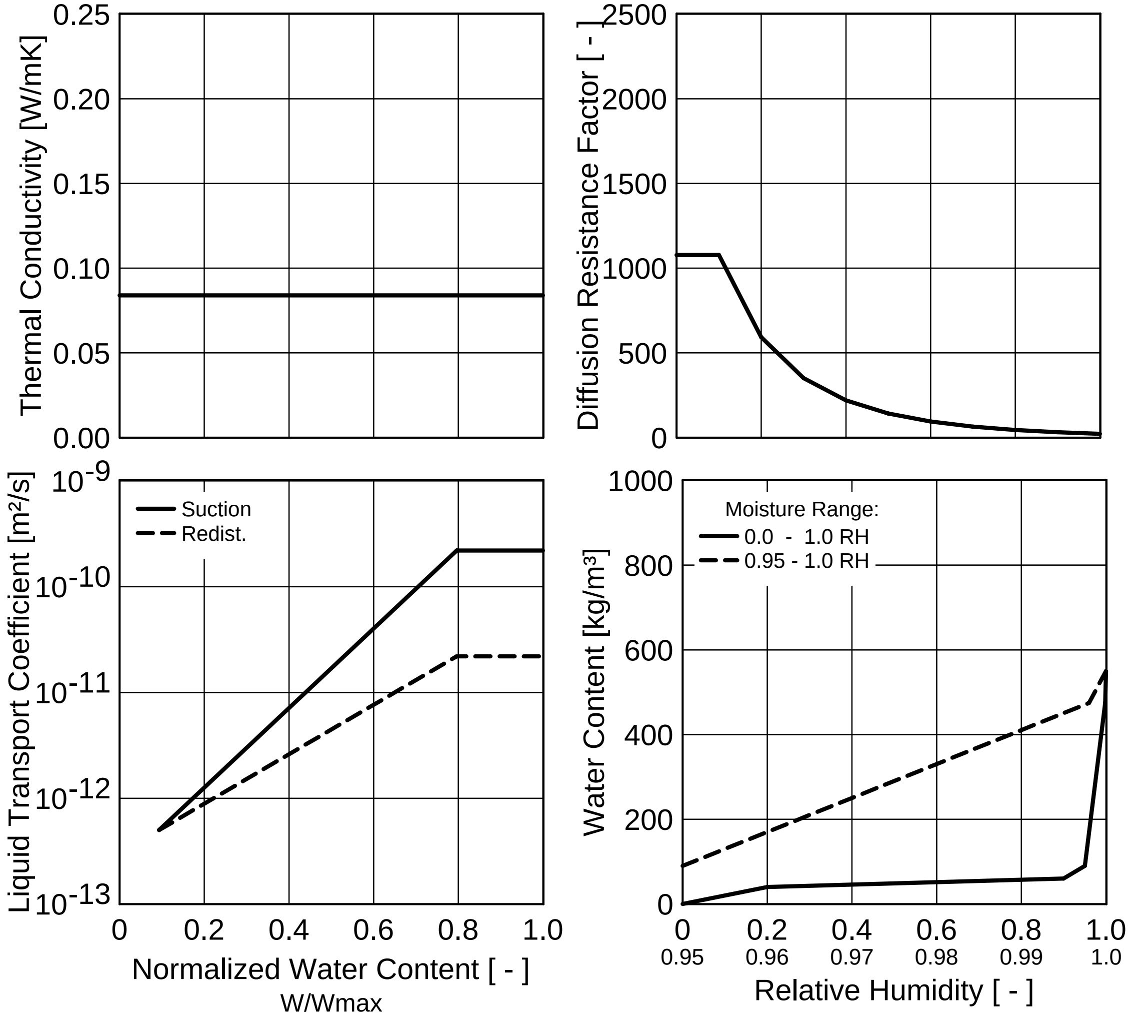
Property	Unit	Value
Bulk density	[kg/m³]	715,0
Porosity	[m³/m³]	0,001
Specific Heat Capacity, Dry	[J/kgK]	1500,0
Thermal Conductivity, Dry	[W/mK]	4,0
Water Vapour Diffusion Resistance Factor	[-]	993,17



Material : Plywood Outer

Checking Input Data

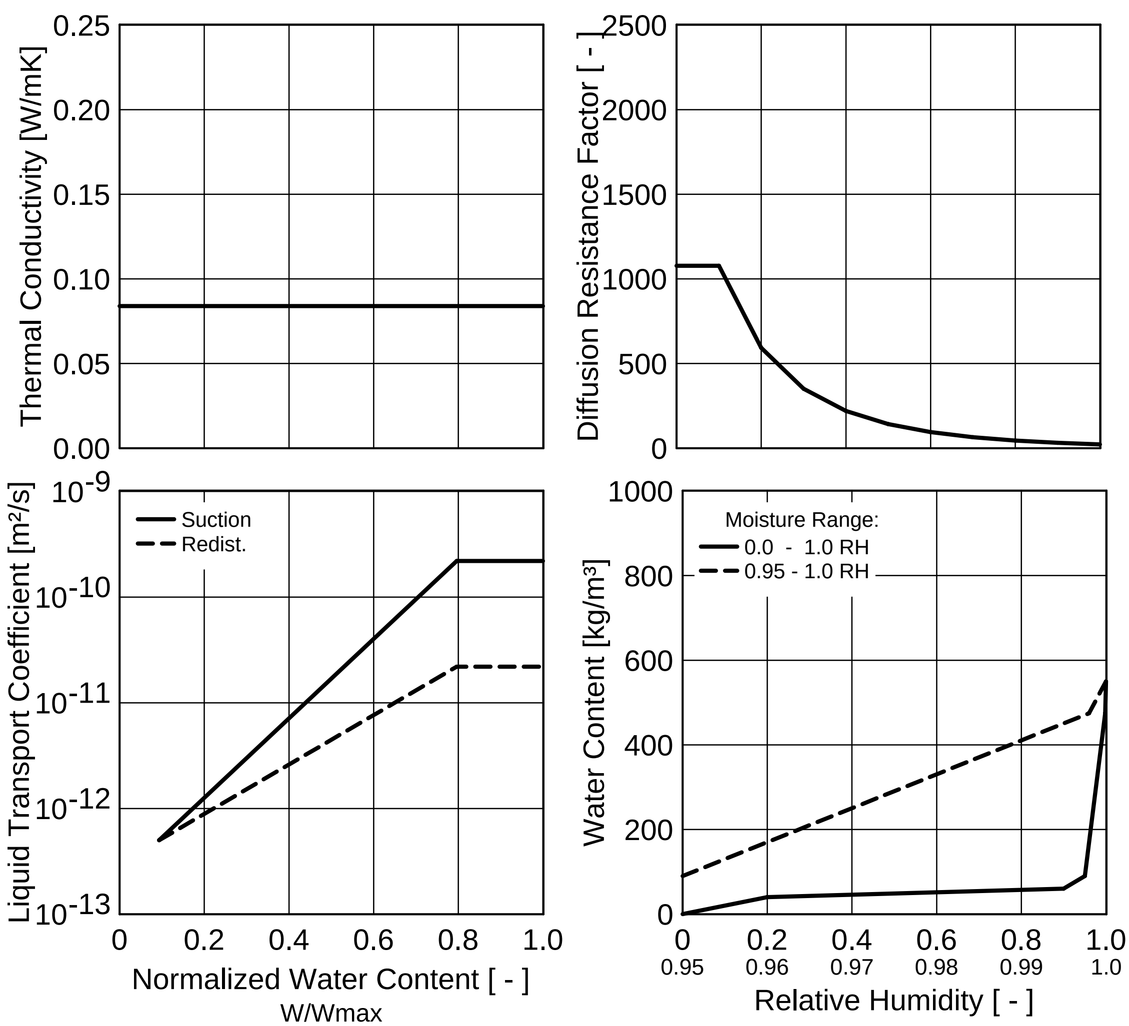
Property	Unit	Value
Bulk density	[kg/m³]	470,0
Porosity	[m³/m³]	0,69
Specific Heat Capacity, Dry	[J/kgK]	1880,0
Thermal Conductivity, Dry	[W/mK]	0,084
Water Vapour Diffusion Resistance Factor	[-]	1078,2
Reference Water Content	[kg/m³]	64,4
Free Water Saturation	[kg/m³]	550,0
Water Absorption Coefficient	[kg/m²s^0.5]	0,0042



Material : Plywood Meas

Checking Input Data

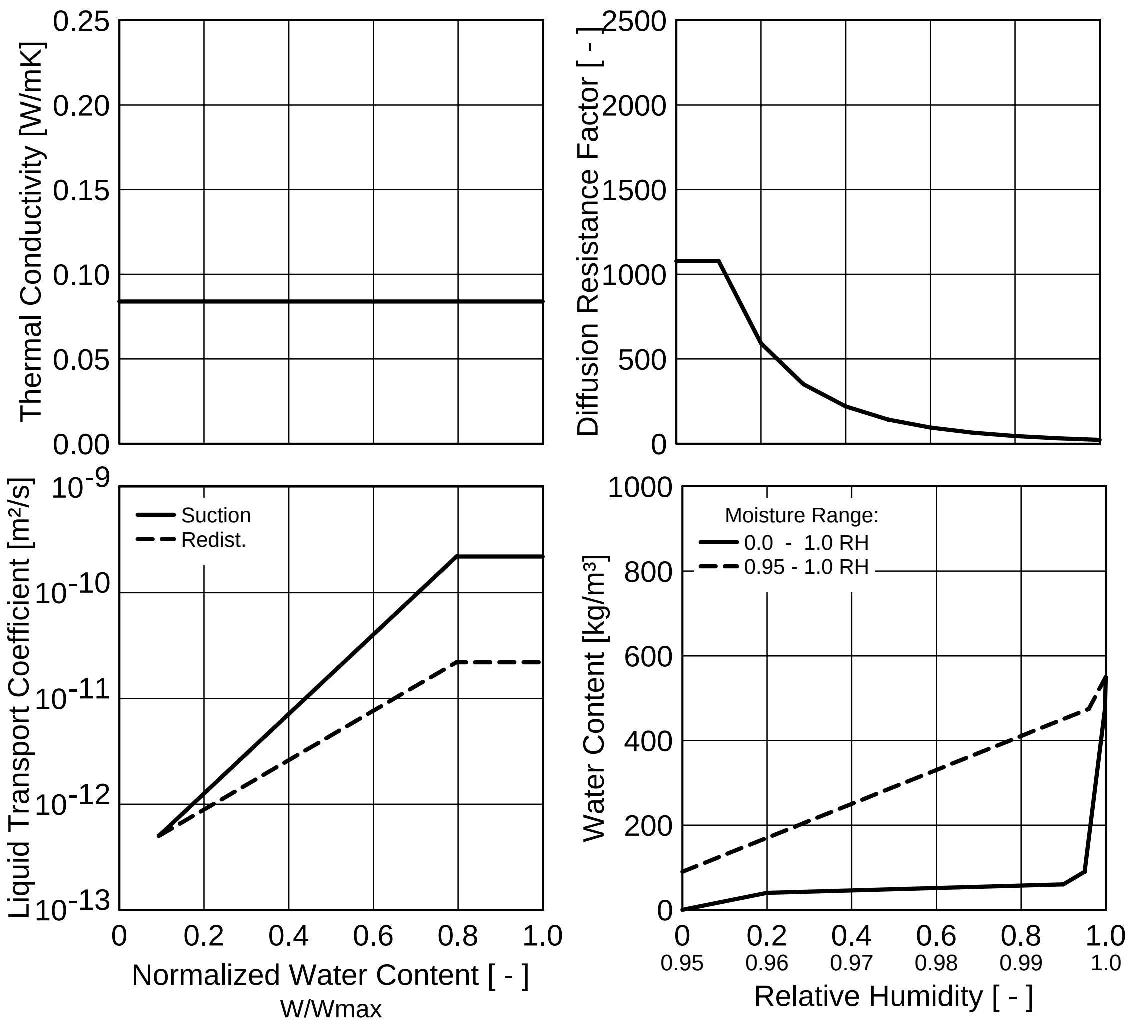
Property	Unit	Value
Bulk density	[kg/m³]	470,0
Porosity	[m³/m³]	0,69
Specific Heat Capacity, Dry	[J/kgK]	1880,0
Thermal Conductivity, Dry	[W/mK]	0,084
Water Vapour Diffusion Resistance Factor	[-]	1078,2
Reference Water Content	[kg/m³]	64,4
Free Water Saturation	[kg/m³]	550,0
Water Absorption Coefficient	[kg/m²s^0.5]	0,0042



Material : Plywood Inner

Checking Input Data

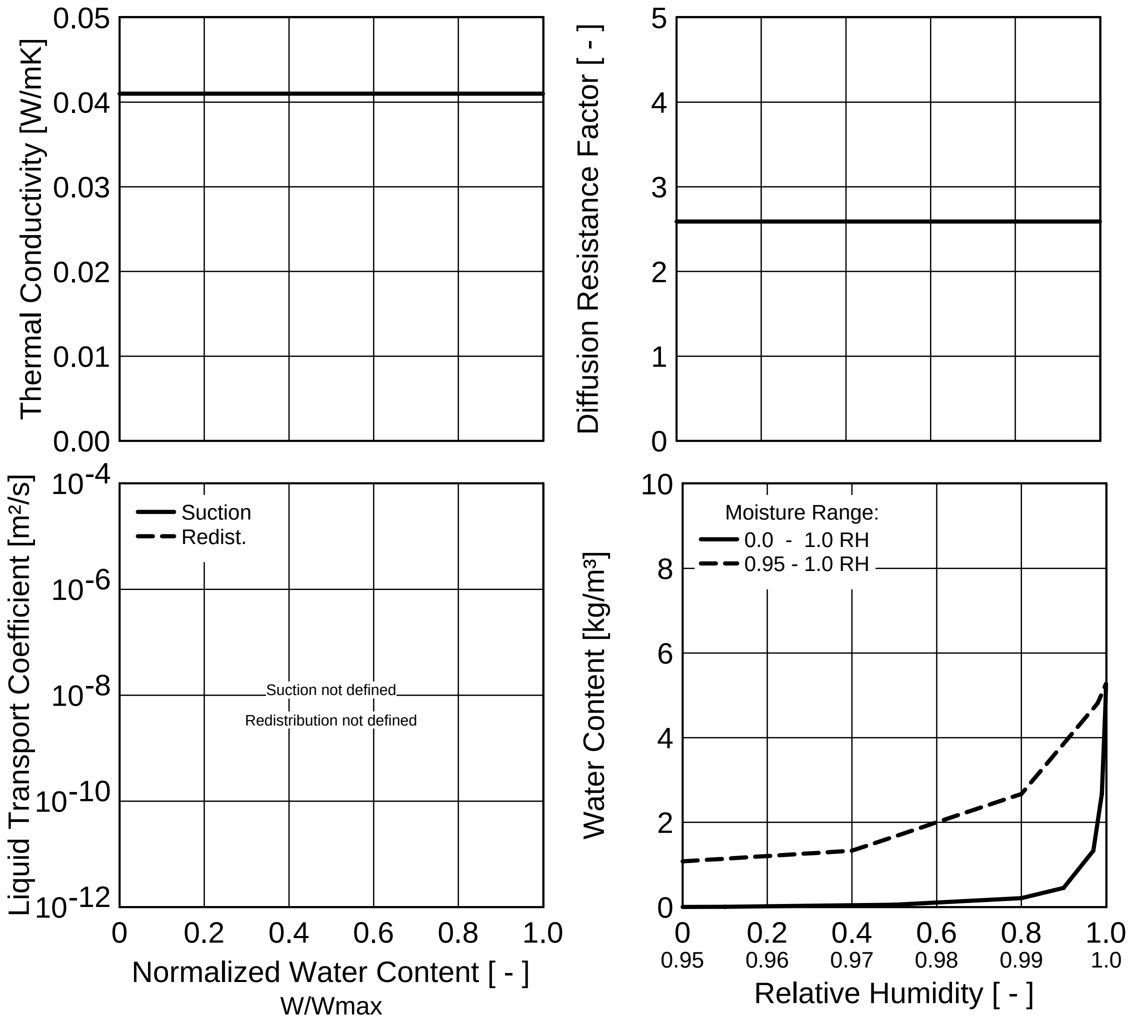
Property	Unit	Value
Bulk density	[kg/m³]	470,0
Porosity	[m³/m³]	0,69
Specific Heat Capacity, Dry	[J/kgK]	1880,0
Thermal Conductivity, Dry	[W/mK]	0,084
Water Vapour Diffusion Resistance Factor	[-]	1078,2
Reference Water Content	[kg/m³]	64,4
Free Water Saturation	[kg/m³]	550,0
Water Absorption Coefficient	[kg/m²s^0.5]	0,0042



Material : Icynene 10 inches

Checking Input Data

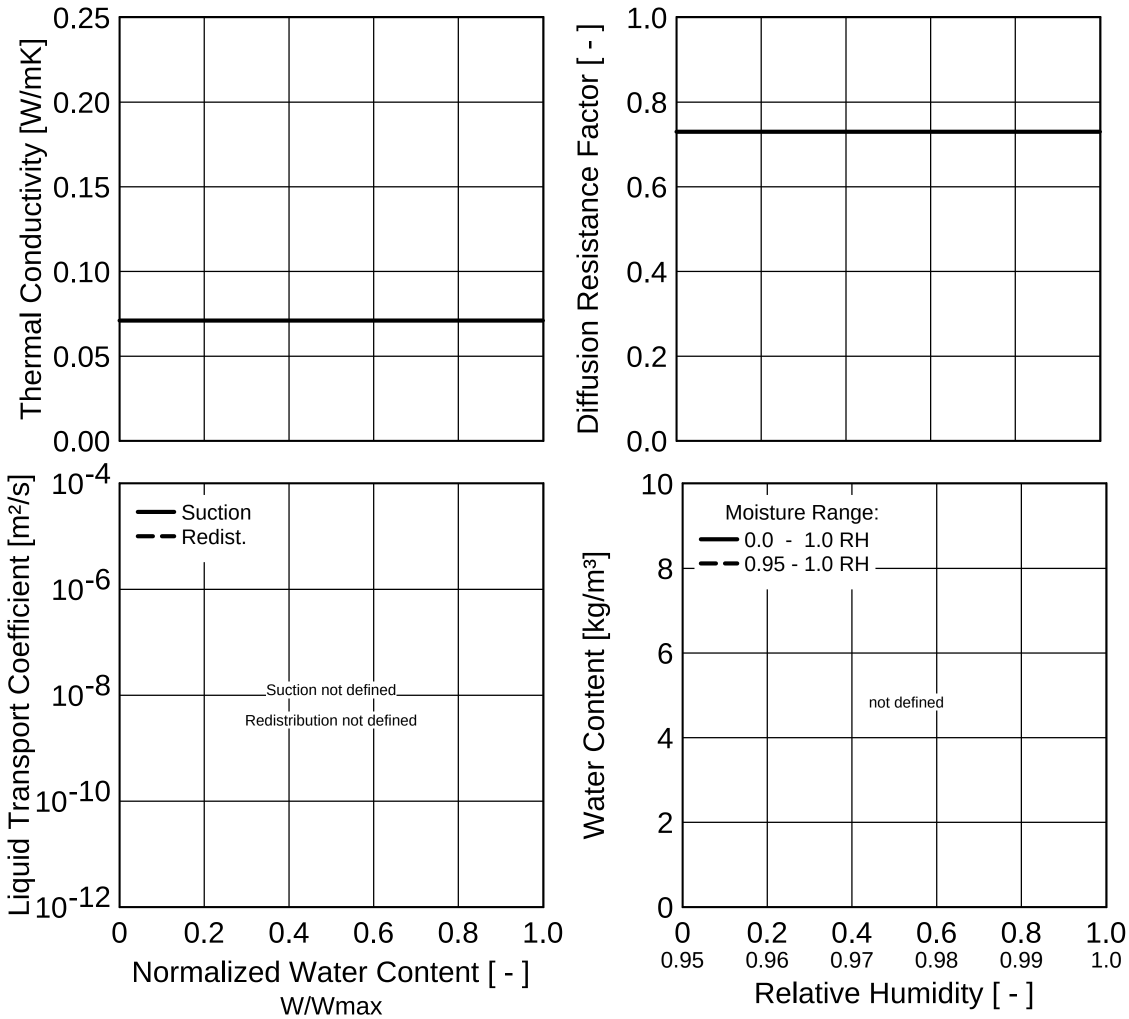
Property	Unit	Value
Bulk density	[kg/m³]	8,0
Porosity	[m³/m³]	0,99
Specific Heat Capacity, Dry	[J/kgK]	1470,0
Thermal Conductivity, Dry	[W/mK]	0,041
Water Vapour Diffusion Resistance Factor	[-]	2,59



Material : Air Layer 10 mm

Checking Input Data

Property	Unit	Value
Bulk density	[kg/m³]	1,3
Porosity	[m³/m³]	0,999
Specific Heat Capacity, Dry	[J/kgK]	1000,0
Thermal Conductivity, Dry	[W/mK]	0,071
Water Vapour Diffusion Resistance Factor	[-]	0,73



Material : Gypsum Board (USA)

Checking Input Data

Property	Unit	Value
Bulk density	[kg/m³]	850,0
Porosity	[m³/m³]	0,65
Specific Heat Capacity, Dry	[J/kgK]	870,0
Thermal Conductivity, Dry	[W/mK]	0,163
Water Vapour Diffusion Resistance Factor	[-]	6,0
Moisture-dep. Thermal Cond. Supplement	[%/M.-%]	8,0